Underwater Acoustic Localisation and Referencing: An Enhanced Subsurface Positioning Method for Archaeological Data Collection of Submerged Cultural Resources

Thesis Research and Fieldwork Case Studies

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Abstract

Traditional and modern optical methods of maritime archaeological site documentation typically lack absolute spatial information as part of submerged cultural heritage surveys in locations where shore-based satellite positioning technologies are not applicable for use. This is due to the inability to use satellite positioning receivers beneath the water surface as a result of the high attenuation rate of electromagnetic waves in a marine environment. The defence and offshore energy industries solved this problem through the incorporation of acoustic ranging systems used in conjunction with satellite positioning receivers. Underwater acoustic ranging equipment, such as ultra-short baseline (USBL) and long baseline (LBL) systems, are commonly used in geophysical surveys and marine construction projects to provide subsurface positioning information of underwater instrumentation such as towed sonar arrays, remotely-operated vehicles (ROVs), and divers. Satellite positioning and underwater acoustic ranging configurations have been in continuous use for more than three decades, and such equipment systems are readily available throughout the world for commercial and scientific applications. Despite the proven effectiveness and accessibility of these systems, maritime archaeology fieldwork practices have not successfully integrated these systems into established underwater data collection techniques. This thesis was established to determine if traditional and modern optical maritime archaeological data collection techniques are capable of being supplemented by a tandem satellite positioning system and USBL acoustic ranging configuration to provide underwater positioning information in accordance with universally-accepted geophysical surveying spatial and equipment standards, such as those published by the International Hydrographic Organization (IHO), Bureau of Ocean Energy Management (BOEM), Historic England, and others. In the absence of recognised spatial standards within the maritime archaeology community, this thesis relied on geophysical surveying spatial and equipment standards as the research parameters upon which the Underwater Acoustic Localisation and Referencing (UALR) methodology was developed. The UALR methodology presented in this thesis successfully incorporated a GPS/USBL configuration for providing subsurface latitude and longitude coordinates for ground control point positions for traditional and modern optical archaeological data collection techniques. The collected datasets were georeferenced using underwater spatial information gathered by the UALR methodology process, and demonstrated that these methods are capable of achieving spatial accuracy and measurement precision in accordance with geophysical surveying specifications. By adhering to these standards, the UALR methodology is applicable for use by archaeologists in support of geophysical surveying operations throughout the world.

“Perhaps these pages are more particularly addressed to poor students. As for the rest of my readers, they will accept such portions as they apply to them. I trust that none will stretch the seams in putting on the coat, for it may do good service to him whom it fits.”

Henry David Thoreau, *Walden, or Life in the Woods* (1854)

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The successful materialisation of this thesis, and its associated archival and field research, are largely due to the contributions from individuals in both personal and professional capacities. Without the guidance and support of the persons listed in this section, the Underwater Acoustic Localisation and Referencing (UALR) methodology concept development would have been an increasingly abstruse endeavour. Considerable sums of direction and experience needed to undertake this thesis research were given in the years preceding my matriculation as a doctoral candidate at the University of Oxford. As a young archaeologist, I was fortunate to be associated with individuals whom provided opportunities and sage advice that undoubtedly contributed to my professional development and fields of expertise. The lessons learned from working alongside distinguished archaeologists and industry professionals undoubtedly benefitted in my recognising the appropriate heading in which to navigate this thesis research. Apart from archaeology and academia, many individuals provided the encouragement required to see this research to its successful conclusion. Their contributions may not be visible in the words that compose this writing; yet, its completion is testament to the continued support received throughout my years of research and concept development.

In acknowledging those who contributed to this research, the best place to start is at the beginning. My journey as an archaeologist began in 2007, as an intern for the North Carolina Underwater Archaeology Branch (UAB), located in Kure Beach, North Carolina. At that time, the UAB was under the direction of Richard Lawrence, and archaeological staff members included Nathan Henry, Julep Gillman-Bryan, and Madeline “Punk” Spencer. These individuals greatly contributed to my initial exposure and experiences with maritime archaeology, thus creating the foundation upon which I have built my academic and professional careers. The UAB

archaeologists and staff members participated in my MA thesis research at Lake Waccamaw, North Carolina, while a graduate student in the Program in Maritime Studies at East Carolina University. Again, they returned to support my doctoral thesis fieldwork in Lake Waccamaw and the Northeast Cape Fear River. I am beyond grateful for the professional and personal relationships I have with these outstanding individuals. The opportunities and experiences they provided throughout my career undoubtedly influenced my transition from entry-level intern to professional archaeologist.

My interests and expertise in underwater acoustics, magnetics, and marine remote sensing initiated this thesis research and ultimately determined the manner in which all fieldwork was performed. Several years of professional experience working on hydrographic surveys and related fieldwork operations provided the practical knowledge needed to recognise what equipment and practises could work, but more importantly, which could not support thesis research objectives. The familiarisation with these equipment systems is largely in part to working alongside Dr. Gordon P. Watts, Jr. and Ralph Wilbanks. Under their mentorship, I acquired the professional experience and confidence not attainable in any classroom, which is only acquired through real-world archaeological surveying. Some days I stared at a sonar computer screen and saw nothing but sand; yet, some days I saw American Civil War blockade runners off the Atlantic coast of North Carolina or searched for a missing passenger plane in the depths of Lake Michigan. The work was not easy, but that is what separates the best from the rest. I am very grateful to have learned archaeological surveying from whom I regard as the best.

My time as a doctoral candidate at the University of Oxford has been a rewarding experience mainly due to the guidance received through my supervisors within the School of Archaeology and advisers at St. Benet's Hall. My thesis supervisors, Dr. Damian Robinson and

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Glossary

1-σ (sigma) - Standard deviation error about a mean value (68% measurement confidence level).

2-σ (sigma) - Two standard deviation error about a mean value (95% measurement confidence level).

Bathymetric coverage - Extent to which an area has been surveyed using a systematic method of measuring the depth and is based on the combination of the survey pattern and the theoretical area of detection of the survey instrumentation (IHO 2020:10).

Confidence level - Probability that the true value of a measurement will lie within the specified uncertainty from the measured value (IHO 2020:10).

Correction - Compensation applied to data to adjust for an estimated systematic effect (IHO 2020:10).

Error - Difference between a measured value and the correct or true value. Errors can be categorised as systematic or random errors (IHO 2020:10).

Feature - Any object, whether natural or manmade, which is distinct from the surrounding area (IHO 2020:10).

Feature detection - Ability of a system to detect features of a defined size (IHO 2020:10).

Feature search - Extent to which an area has been surveyed using a systematic method of identifying features (IHO 2020:10).

Metadata - Data describing a data set and its usage (IHO 2020:10).

Random error - Noise within a measurement caused by factors which vary between measurements and cannot be controlled but can be quantified by statistical means (IHO 2020:10).

Significant feature - Feature that poses a potential danger to navigation or object one would expect to see depicted on a nautical chart or product (IHO 2020:10).

Systematic error - Component of measurement error that remains constant or varies in a predictable manner (IHO 2020:11).

Total horizontal uncertainty (THU) - Component of total propagated uncertainty (TPU) calculated in the horizontal dimension. THU is a two-dimensional quantity with all contributing horizontal measurement uncertainties included (IHO 2020:11).

Total propagated uncertainty (TPU) - Three-dimensional uncertainty with all contributing measurement uncertainties included (IHO 2020:11).

Total vertical uncertainty (TVU) - Component of total propagated uncertainty (TPU) calculated in the vertical dimension. TVU is a one-dimensional quantity with all contributing vertical measurement uncertainties included (IHO 2020:11).

Uncertainty - Estimate characterising the range of values within which the true value of a measurement is expected to lie as defined within a particular confidence level. It is expressed as a positive value (IHO 2020:11).

Underkeel clearance - Distance between the lowest point of the ship's hull and the seabed, riverbed, etc. (IHO 2020:11).

1.0 Introduction

Subsurface positioning and datum point localisation are vital components for thorough archaeological research; however, most traditional and contemporary underwater optical data collection methods lack the capability to provide georeferenced spatial datasets using established coordinate systems (Muckelroy 1978; Green 2004; Smith 2006; Gawlik 2014; Capra et al. 2015:67-72; Diamanti and Vlachaki 2015:93-98). The scope of the research contained in this thesis is to explore what undersea positioning technologies are currently in use that can provide survey-grade geospatial accuracy with precise measurements, then develop an applicable data acquisition methodology that is compatible with archaeological surveying techniques and in alignment with modern geophysical surveying standards (Plets et al. 2013; USACE 2013; BOEM 2020a; BOEM 2020b; IHO 2020). The positioning systems discussed in this research are commonly used throughout marine-related industries for geophysical and archaeological surveys, and accessible in many parts of the world. Given that archaeological research is conducted in various marine and freshwater environments, this research conducted field testing in archaeological sites at Florida and North Carolina, USA, which differed in ecological structure and cultural materials. The field research was initiated in July 2016 and completed in September 2019. During that period, extensive literature research and field testing took place which contributed to the development of the Underwater Acoustic Localisation and Referencing (UALR) methodology. The UALR methodology is a supplemental underwater positioning technique designed to provide latitude and longitude coordinate information to archaeological data collection processes which lack that capability. The underwater positioning information derived from the UALR methodology satisfies current geophysical surveying standards established by the International Hydrographic Organization (IHO), Bureau of Ocean Energy

Management (BOEM), and other governing institutions discussed later in this thesis (see page 42).

1.1 Research Context

Conventional archaeological data collection techniques do not independently produce underwater latitude and longitude coordinates; therefore, what methods are available to georeference the acquired data? This is of particular importance when there is a requirement within specifications of works or permits to record spatial information to particular specifications (see Appendix IHO standards, pg. 328). Traditional archaeological surveying and documentation methods which have been in continuous use for over five decades, typically rely on the use of datum points as relative measurement references particular to a specific site (Bowens 2009:151-156; NOAA 2001:9-2; Green 2004:87; Smith 2006:19). The respective ages of these methods, with exceptions to modern optical data collection systems, predate the commercial availability of GPS receivers for civilian use. Early positioning techniques relied on the use of sextants, transit lines, radio-frequency navigation systems such as LORAN for determining latitude/longitude coordinates, among others for providing a means of locating/relocating archaeological sites (Green 2004; Bowens 2009; USACE 2013). Traditional methods of underwater positioning and survey methods are discussed in greater detail in Section 2.1 (see pg. 41).

The Global Positioning System (GPS) has largely replaced all traditional methods of position fixing on the earth's surface (Green 2004). GPS represents a series of orbital navigation satellites and ground control networks that provide end users with positional coordinates with a relatively high degree of spatial accuracy. GPS has a longstanding history that dates to the Cold War era, in which the idea of satellite positioning was developed by the United States Department of Defense (DoD) as a weaponized platform for positioning nuclear submarines at

sea (Parkinson 1994:42; Worth and Warren 2009:8). Since the late twentieth century, GPS has expanded into the civilian market for terrestrial surveying and navigation applications; thus, revolutionizing the manner in which users calculate their position on Earth's surface. At the time of writing, GPS technology is the most practical navigational and positioning solution for diverse applications that include land surveying, marine surveying, navigation, and scientific research (Martin and Jahn 2000; Lee and Ge 2006:515). The terrestrial archaeological community has a longstanding reputation for successfully incorporating GPS positioning into data collection strategies with positional data comparable to that of professional land-based surveys (Henderson and Burgess 1996:250). Technological advancements and upgraded data collection methodologies for professional surveying operations are routinely adapted by terrestrial archaeological research programs; thus, creating a persistent effort within the terrestrial archaeology community for improving spatial data acquisition and deliverables (Bowens 2009:119-120; Green 2004:40; Henderson et al. 2011:208).

Following the commercial release of GPS receivers on the civilian market, satellite navigation technology was quickly adapted to maritime archaeology fieldwork methods; however, the inability for electromagnetic frequencies to penetrate water presented a challenge for acquiring underwater coordinates (Chandrasekhar et al. 2006:2; Morgado et al. 2010; Morgado et al. 2013:143; Jakuba et al. 2015; Ai et al. 2016:115; Batista et al. 2016:1837; Campos et al. 2016:1; Mandić et al. 2016; Zhang 2018). A simple and inexpensive solution was to use a waterproofed hand-held GPS receiver at the surface which was tethered to a datum point located on the seafloor, and this technique is commonly referred to as the floating or buoyed GPS method (Green 2004:57; Bowens 2009:134). The relative ease and low financial burden to

acquire the equipment contributed to the floating GPS method's popularity among many marine-related disciplines including maritime archaeology, marine biology, and others.

The floating GPS method was a substantial improvement when compared to earlier systems like sextants and transit lines; however, the positional accuracy of handheld GPS receivers is inapplicable to contemporary marine geophysical surveys with sub-metre positioning requirements (Hall et al. 2008; Hussein 2016:162-174). Irrespective of the capability for modern handheld receivers to acquire differential error corrections from local sources or satellite-based augmentation systems (SBAS), such as the Wide Area Augmentation System (WAAS) administered by the United States Department of Transportation, these commercial-grade GPS units are not capable of producing the required horizontal and vertical positional accuracies for current geophysical survey specifications (BOEM 2013; DNV-GL 2016; Fugro 2017; BOEM 2020b; IHO 2020). The documented inaccuracies of error-corrected differential data collected by static handheld units is further exacerbated when used in a floating arrangement. The floating GPS technique greatly suffers from data sampling errors caused by: the inability for the GPS receiver to maintain a static position over a specific point, waypoint averaging is not possible due to constant surface water motion, human errors due to miscommunication, and increasing water depths resulting in enlarged positioning/measurement errors (Kuch et al. 2012:193, Niedzwiedz and Schories 2012:180). The spatial inaccuracy combined with measurement sampling uncertainty limits the floating GPS method for only marking general locations when knowing "about where" positioning accuracy is deemed satisfactory and/or in accordance with permitting requirements. The floating GPS equipment and data collection methods are unparalleled in comparison with the UALR methodology in terms of accuracy and fieldwork application;



FIGURE 1-1. The above image demonstrates the use of a handheld GPS to acquire seafloor satellite coordinates. The diver on the seafloor holds the end of the line over a point while the swimmer at the surface maintains position directly above the point. The line between the diver and swimmer is kept taut in effort to reduce positional error. This technique provides limited positional accuracy and measurement precision due to the inherent error with handheld GPS units and the inability for the swimmer to remain directly over the control point due to surface water movement. (Courtesy of the Maritime Archaeological and Historical Society, 2018).

however, the equipment systems commonly used for the floating GPS method and data acquisition measurement uncertainties are further discussed in Section 2.1.5 in which dedicated research was undertaken to determine the positional accuracy and precision of this underwater positioning method (see pg. 46).

The author's familiarity with the floating GPS method spans over two decades of use as both a recreational SCUBA diver and professional archaeologist. As a method for marking general locations which do not require any type of positional accuracy or measurement precision, the floating GPS method served as an efficient and low-cost tool for recreational diving purposes. In regards to archaeological research, the author utilised the floating GPS method for initial reconnaissance surveys and marking the locations of submerged cultural remains for future marine remote sensing surveys which employed more sophisticated mapping equipment and techniques. As late as June 2018, the author participated in an archaeological field school hosted by the Maritime Archaeological and Historical Society (MAHS) in which participants documented the remains of the so-called "Barrel Wreck" located in the Florida Keys National Marine Sanctuary near Key Largo, Florida. The participants recorded the visible remains of the site using a baseline survey and site illustrations; whereas, the author attempted to georeference the illustrated site map using the floating GPS method and 10 ground control points (GCPs) placed throughout the site in locations that were measured in reference to the baseline (Figure 1-1). The author utilised a Garmin 64csx handheld GPS unit with WAAS-enabled differential corrections; however, despite the amount of consideration and diligence taken during the spatial data collection process, the floating GPS technique produced poor results that in no capacity could be used for modern commercial hydrographic and geophysical surveys. The floating GPS

technique, equipment, and products simply did not satisfy geophysical surveying standards discussed later in this section and in greater detail in Section 2.1.5 (see pg. 46).

GPS positioning for maritime archaeological data collection has a series of limitations which specifically pertain to environmental factors preventing underwater use (Talley et al. 2011:29-39; Stewart 2014:34-36). Maritime archaeologists are unable to use standalone GPS systems for underwater positioning due to the chemical and physical properties of water preventing electromagnetic signal transmission (Hunt et al. 1974; Stewart 1991:230-235; Whitcomb et al. 1999:346-353; Bulusu et al. 2001; Eustice et al. 2008:103; Ebolese et al. 2018:325-330; Zhang et al. 2018:171-177). Even when operating at shallow diving depths, maritime archaeologists are unable to use satellite positioning equipment due to the high signal attenuation rate (Chandrasekhar et al. 2006:2). The inability to use satellite positioning receivers underwater is not a new issue or specific just to maritime archaeology, but a naturally occurring phenomenon commonly experienced by all industries and disciplines requiring underwater positioning. It is a decades-old problem dating to the Cold War era, but has been effectively mitigated by the offshore energy and defence industries through the coupling of satellite units with underwater acoustic ranging technology (Martin and Jahn 2000:851-855; Sturdevant 2007; Thomas 2010:27-40; Stein and Edson 2013; Ponce 2018:10-13). The coupling of underwater acoustic sensors with satellite positioning receivers is a popular and commonly used strategy for acquiring subsea positioning data (Thomas 1998:181-184; Desset et al. 2003:22-27; Yan et al. 2004:11-19; Baily and Durrant-Whyte 2006:108-117; Kinsey et al. 2006:83-88; Kinsey et al. 2006:7; Peng 2009:3-6; Kou 2010:2-10).

Maritime archaeologists routinely incorporate some versions of these coupled technologies for site documentation; however, the acoustic sensors predominantly used for

cultural resources surveys are typically designed to produce specific types of imagery, and not designed as dedicated underwater positioning systems (Caiti et al. 2005:140-152; Shaukat et al. 2013:1-10). The majority of the commonly used acoustic imaging platforms, such as side scan sonar (SSS) and multibeam echo sounders (MBES), produce detailed and georeferenced two- and three-dimensional imagery. Data acquisition for these systems generally requires a survey vessel to be in motion and datasets can suffer from datum alignment issues due to environmental and manmade effects. Although there are may be exceptions in which processed acoustic imagery can be used as an overlay to georeference site features, the likelihood of that dataset being within survey-grade positional accuracy and precision is questionable and likely unquantifiable. As a consequence, archaeological surveys which use conventional or optical methods of site documentation cannot rely on acoustic imaging to provide survey-grade spatial information for georeferencing collected datasets.

For marine geophysical surveys that require strict spatial specifications for acquired datasets, specific acoustic ranging systems are routinely implemented to provide the positional offsets and layback of towed or self-propelled sensors (Caiti et al. 2005:140-152; Jiang and Osler 2013; Shaukat et al. 2013:1-10; Majid and Arshad 2016:26-31; Sendra et al. 2016:4063-4071; BOEM 2020b:7-8). Ultrashort baseline (USBL), short baseline (SBL), and long baseline (LBL) acoustic ranging systems are the most commonly used methods for underwater positioning and have been in continuous use for over two decades (DNV-GL 2016:106; Fugro 2017; BOEM 2020b; Moran 2021:17). When coupled with satellite navigation receivers, these acoustic ranging systems can provide latitude and longitude coordinates in a variety of established reference frames (E.g., UTM, WGS84, NAD83). The benefit of latitude and longitude coordinates is the capability to transfer that spatial information to a variety of modern software programs, digital

databases, and electronic navigation systems such as geographic information systems (GIS) and S-57 electronic navigation charts.

Inshore and offshore marine industries rely on these accurate mapping strategies for subsea projects; whereupon, many of which require cultural resources management plans for approval as part of the permitting and construction processes (USACE 2013; BOEM 2020s:1-2; IHO 2020). As the demand for maritime trade and offshore energy solutions continue to rise in the 21st century, the need for associated infrastructure such as ports, submarine cables, and pipelines have the potential to negatively affect submerged cultural resources. Depending on the associated cultural significance of material remains, additional site documentation may require archaeological investigation, through diver survey, for example, to provide information beyond what is visible in SSS, MBES, and sub-bottom profiler (SBP) records (BOEM 2020b:10-11). As part of the site data collection process, archaeologists perform measurements and document site features using fiberglass tapes, scale bars, and optical imaging systems (Green 2004; Smith 2006; Bowens 2009). Deliverables generated from these data collection techniques are capable of producing illustrated site maps, detailed photographs, digital mosaics and three-dimensional photogrammetric models.

Inshore, offshore, and infrastructure projects requiring geophysical surveys adhere to strict underwater positioning specifications; therefore, associated cultural resources management components for these surveys must be in compliance with those standards (BOEM 2020a:7; IHO 2020). In accordance with most recent positioning requirements issued by the International Hydrographic Organization (IHO), Bureau of Ocean Energy Management (BOEM), Historic England (HE), and the United States Army Corps of Engineers (USACE), archaeological direct sampling methods are to be within the same geophysical survey positioning specifications as

other onboard navigation systems (Plets et al. 2013; USACE 2013; BOEM 2020a:10; IHO 2020). These institutions recommend the use of underwater acoustic ranging systems, specifically USBL, for satisfying positioning and measurement specifications (Plets et al. 2013:13; DNV-GL 2016:106; Fugro 2017:2.16; BOEM 2020a:7-8; BOEM 2020b:7). The primary research problem addressed in this thesis pertains to the failure to successfully integrate modern underwater positioning systems into conventional archaeological workflows equivalent to established geophysical surveying standards. Applicable technological solutions to the problem have been in existence for many years; however, no established method was in common use prior to the start of this thesis.

The lack of modernisation of underwater positioning information for traditional archaeological data collections is problematic in terms of cultural resources management (CRM) programs and continued collaboration with related marine industries. As a primary consideration for granting permits for inshore/offshore marine construction and energy projects, CRM archaeologists are required to review geophysical data and make interpretations concerning the significance of any identified cultural materials. As mentioned above, geophysical surveys may not produce enough information pertaining to a specific archaeological site, therefore requiring supplemental data collection from diver and/or ROV reconnaissance (BOEM 2020a:10). The archaeological data sampling methods must be applicable to diverse marine environments and capable of validating geophysical sensor information; however, in order for data deriving from archaeological assessments to verify the location of geophysical datasets, both sets of data must be of the same spatial standard.

The inability for traditional archaeological methods to produce georeferenced datasets on par with geophysical surveys may result in the damage of submerged cultural resources due to

insufficient mapping strategies, miscommunication of site feature locations, and the inability to properly document site extents. In the event non-renewable submerged cultural remains are damaged or destroyed as a result of insufficient archaeological documentation and mapping methods, future cooperation between archaeologists and marine industries could be placed in jeopardy. In that possible scenario, marine industries may lobby to lessen or remove submerged cultural resources considerations from permitting processes due to archaeological data collection strategies operating without equivalent underwater positioning methods and lacking the capacity to perform at the required spatial standards. Archaeological considerations associated with permitting and construction requirements are based on legislation enacted by publicly elected institutions. Such legislation is always vulnerable to alteration or removal if considered ineffective or preventing infrastructure improvements resulting in a substantial loss of revenue. Hypothetically, the removal of existing legislation would undoubtedly place submerged cultural resources at considerable risk and threaten the employment status of archaeologists in locations throughout the world where submerged cultural resources are under the jurisdiction of such laws.

1.2 Research Questions

The research objectives for this thesis were developed in direct response to the spatial problems associated with archaeological data sampling methods which lack underwater positioning capabilities compatible with geophysical surveying specifications. When considering the issues in effectively supplementing archaeological data collection methods with an updated underwater positioning system, this thesis had to satisfy a series of research questions. The initial research question pertained to traditional archaeological underwater positioning and survey methods in common use (e.g., baseline-offset, trilateration, grid squares, digital photomosaic, and digital photogrammetry); are these techniques capable of integration with survey-grade

underwater positioning systems? This thesis provides a detailed synopsis of these methods and their commercial viability for use before and after integration with the UALR methodology concept (see pg. 162). The geospatial data generated by the UALR methodology should provide archaeologists with more than just positioning information for survey datum, but also satisfy other challenges faced by all archaeologists conducting underwater survey fieldwork. These issues include: the ability to rely on an acceptable number (at least four) reference datum for data localisation, underwater positioning equipment availability and practical use (discussed further in the following paragraph), quantifiable overall survey positional accuracy and measurement precision, reducing the requirement for extensive underwater site survey preparation, increasing the efficiency of underwater data collection, and increased diver safety by allowing the safety officer to track all divers and removing the need for heavy and cumbersome equipment as required for earlier underwater positioning methods (Green 2004; Bowens 2009:108-110). Although the UALR methodology at its core is an underwater positioning technique, the benefits of accurate positioning and diver tracking can greatly contribute to other aspects underwater archaeological survey fieldwork.

The second research question pertained to equipment specification and selection; what GPS satellite navigation and underwater acoustic ranging systems were best suited for this research? In satisfying this question, the previously examined geophysical surveying specifications issued by various agencies throughout the world provided specific positioning equipment requirements and recommendations, but did not list particular manufacturers. Satellite positioning and underwater acoustic ranging systems exist at various levels of accuracy, operating environments, and deployment methods for acquiring subsea positional information. The associated costs for these systems vary according to operating depth, achievable accuracy,

and measurement precision. The more robust the positioning system, the higher the cost; however, the systems examined for this research are readily available throughout the world and can be rented (hired) without significantly burdening project finances. The UALR methodology was developed to satisfy geophysical surveying requirements; however, the reason for considering readily available and affordable positioning systems for this thesis was designed to promote the use of modern underwater positioning systems and methods for all levels of maritime archaeology, ranging from volunteer projects to professional surveys. The selected underwater positioning equipment not only needed to be accessible to all levels of archaeological surveying, but also retain simplistic attributes regarding setup, deployment, data acquisition, and data processing. Consideration of these factors led to the use of the Trimble SPS855 GNSS receiver, Trimble GA530 and Zephyr 3 antennas, real-time network/virtual reference system (RTN/VRS) satellite error corrections, and the Applied Acoustics Engineering, Ltd. Easytrak Alpha Portable USBL acoustic ranging system. The positioning systems and other equipment used for this thesis are thoroughly examined in Sections 3.2 (see pg. 109) and demonstrated in Sections 4 fieldwork case studies (see pg. 183).

The third research question focused on the development of an underwater positioning data collection strategy using the above-listed equipment systems capable of integration with archaeological datum-referenced and digital photogrammetric surveying methods; therefore, how are the positioning systems deployed for data acquisition? Establishing an underwater positioning acquisition method was the most challenging task of this research. The primary consideration for addressing this research question was designing and fabricating a hardware mounting system for the Trimble antennas and USBL transducer to be used in a zero-offset configuration, meaning the GPS antenna and acoustic transducer are in perfect (90°) vertical

alignment. Other factors for the mounting system design included the use of lightweight materials for portability, capable of use on multiple working platforms, ease of installation and breakdown, and inexpensive. Mounting systems used for geophysical surveys generally consist of a pole-mount configuration which is permanently fixed to the survey vessel. Such mounting solutions are customised for that particular vessel and are typically used in conjunction with other non-towed sensors such as MBES or SBP systems. For this thesis research, diving operations were restricted by the University of Oxford diving supervisor to shallow-water environments; thus, not requiring the working platforms and mounting hardware commonly used for offshore geophysical surveys. When considering the working environment and general attention to just underwater positioning, the decision was made to design a pole-mount system capable of use with the GPS/USBL systems, suitable for shallow water operations that satisfied the above-mentioned construction factors.

The thesis consequently examines specific queries regarding the potential integration of a coupled GPS/USBL system with commonly-used underwater archaeological data collection methods while satisfying geophysical survey positioning requirements in regards to positional accuracy and measurement confidence. These research questions highlight the anticipated complexities associated with updating longstanding data collection practices with modern equipment systems. In satisfying these research questions, this thesis carried out a systematic series of literature reviews of archaeological data collection methods and GPS/USBL positioning systems (Section 2.3.1 – 2.3.2, see pgs. 65-85), designed and fabricated a pole-mounting system (Section 3.2.4, see pg. 145), developed a fieldwork methodology capable of data acquisition of all examined archaeological data sampling methods (Section 3.4, see pg. 162), and used positional data formats capable of post-processing in free or readily available software programs

such as Trimble CenterPoint RTX and Microsoft Excel (Section 3.3, see pg. 156). The subsea positional data acquisition and post-processing techniques were combined to form the Underwater Acoustic Localisation and Referencing (UALR) methodology.

1.3 UALR Methodology Hypothesis and Research Expectations

The development of a working theoretical hypothesis for the UALR methodology was based on the combination of many differing technologies and data collection systems into a final construct. It is common knowledge that the various components used to form the UALR methodology work independently of each other. What is not known is if these varying systems and techniques are capable of integration while maintaining strict geophysical surveying requirements. Therefore, this thesis proposes the following hypothesis:

The Underwater Acoustic Localisation and Referencing (UALR) methodology is capable of supplementing existing archaeological data sampling methods with subsea positional information within required geophysical survey specifications. It uses a combined GPS/USBL configuration, real-time satellite error correction services, time-window averaging data collection processes for both GPS and USBL systems, and simplified data post-processing using readily available software systems.

The inner workings of this hypothesis directly correlate to the research questions addressed in Section 1.2. The advantage of the UALR methodology supplementing archaeological research is its ability to adapt to more advanced underwater positioning systems than those used in this thesis, and its capability of integration with future technologies. This methodology is designed as a progressive technique that can evolve with time and positioning requirements for archaeological data collection strategies.

The expectation for the implementation of the UALR methodology as an underwater positioning technique for subsurface data collection is many-folded. The initial expectation is the realisation that traditional archaeological data collection methods from the middle to late

twentieth century are given new life in the form of satisfying strict geophysical survey underwater positioning requirements. These traditional site documentation methods are time-tested and still have an important place within the field of maritime archaeology. Though considered to be "low-tech" in comparison with modern digital photogrammetry and laser scanning methods, these longstanding site recording methods work in nearly all underwater environments, especially on sites with limited or no water visibility. What these traditional methods lacked was the successful integration of modernised underwater positioning capabilities which the UALR methodology now provides. As the primary expectation for this research, it is the most important due to providing maritime archaeologists the option to use a wide variety of traditional and newer digital optical data acquisition methods as required for their respective projects while maintaining the highest levels of underwater positioning standards. The geophysical survey positioning requirements of today are likely to be the standard spatial data procedures of all archaeology projects for tomorrow.

A secondary expectation for this research is to initiate greater discipline-wide emphasis on spatial data for submerged CRM programs resulting in better protection plans for archaeological sites. Common issues with CRM programs are the establishment of effective avoidance zones and proper enforcement to ensure that these protected areas are not violated as a result of accidental encroachment during marine construction, navigation channel dredging, and other similar projects. Improved underwater positioning information associated with archaeological site documentation creates an opportunity to drastically reduce incidental damage to submerged cultural resources. Similar geodetic parameters used by both archaeologists and marine construction firms greatly enhances the ability for both groups to better communicate about where cultural remains are located. As a result, avoidance zones are more effective by

providing exact perimeter positions as to where marine construction equipment is not to be used or placed on the seafloor. Previous archaeological underwater positioning methods, such as sextants, transits, and floating GPS, were incapable of providing this level of detailed information; however, the UALR methodology allows this possibility as an effective means to strengthen and enforce CRM protection plans.

The third and final expectation of this research pertains to equipment accessibility and the eventual change in archaeological surveying underwater positioning requirements. A knowledge gap exists within the maritime archaeological community regarding the use of dedicated underwater positioning systems such as the USBL equipment used for this thesis. The lack of familiarity of these systems is not established on the opinion that the average archaeologist is unable to understand how these systems work, but rather based on the notion most archaeologists do not know they exist. A simple internet search using keywords “maritime archaeology” and “ultra-short baseline” revealed a very small number of archaeological projects using this type of underwater positioning system, and those that do reference USBL used it to track divers and not for georeferencing collected datasets. Increased familiarity in the field, or perhaps instruction as part of the academic curriculum, will equip archaeologists with a working knowledge of available underwater positioning systems and how processes like the UALR methodology can be used to benefit their field research. As a result, the increased understanding and usage of these systems can likely result in partnerships with equipment manufacturers to develop archaeology-specific underwater positioning systems.

2.0 Literature Review

There is an apparent technological and informational gap within traditional and some modern optical archaeological data collection methods in regards to the spatial information needed to reference the location of cultural remains. The objectives of this chapter are to review traditional and contemporary methods of underwater positioning used for archaeological research, analyse relevant literature pertaining to current underwater positioning requirements for geophysical surveys to determine the spatial standards that traditional archaeological data collection methods need to achieve, archaeological data sampling methods and their respective spatial referencing strategies, and to examine applicable underwater positioning systems that satisfy geophysical surveying requirements and are capable of integration with longstanding data collection practices. Chapter 2 also presents a Literature Gap Analysis (Section 2.4, see pg. 94) which reviews all of the literature information presented in this chapter and the apparent omission of underwater acoustic absolute positioning data on an overwhelming majority of archaeological fieldwork over the past 30 years. Information gathered throughout this literature review directly influenced the UALR methodology's concept development and the practical application to archaeological data collection techniques which are presented in the Data Acquisition section in Section 3.2 (see pg. 109).

2.1 Traditional Maritime Archaeological Positioning Techniques and Analyses

Determining the position of submerged cultural materials and their extents are among the most important aspects of maritime archaeological surveys (Bowens 2009:108). Information pertaining to the location of the site in reference to nearby shorelines and other sites contributes to the contextual understanding of how the site was formed, developing theories of the lifeways to whom the cultural materials belonged, maintaining operational control during data acquisition

and excavation, the ability to relocate a site and plot its position on navigational charts, and for developing cultural resources management plans for the protection of significant materials for *in situ* preservation and future archaeological research. Section 2.1 is an overview and analyses of conventional position fixing techniques utilised by maritime archaeologists since the beginning of this discipline to the modern era.

The majority of the techniques and associated instrumentation are technically outdated by modern underwater acoustic and satellite positioning instrumentation and methods (see Sections 2.3.1 and 2.3.2, pgs. 65-85), yet these antiquated practices continue to appear in graduate-level academic textbooks as viable methods of absolute positioning (Green 2004:24-50; Bowens 2009:108-126). Should these methods be taught to aspiring archaeologists? Absolutely, because students need to understand past techniques to determine where previously-surveyed sites are located in the event of a need to provide an updated site analysis. However, the updated archaeological survey should include proven and accepted modern hydrographic instrumentation and techniques, such as those required by the IHO, BOEM, and Historic England (see Sections 2.2, pg. 48, and 2.3, pg. 62). Detailed information pertaining to modern differential and real-time error corrections for GPS and ultrashort baseline (USBL) acoustic ranging systems are not included in Section 2.1, and are discussed in extensive detail in Sections 2.3.1 and 2.3.2 (see pgs. 65-85).

2.1.1 Transits

When reviewing maritime archaeological textbooks for site position fixing techniques, transits are almost always the very first technique discussed by various authors (Green 2004:24; Bowens 2009:111). Transits is a rudimentary method of ascertaining a position fix above the water surface by the coincidence of visual alignment of two or more observable features on

shore. In simplest terms, it is a straight line from the shore to the point above the target location which is generated by lining up observable objects and/or natural features visible capable of plotting on a navigational chart. The reason why this technique is typically presented first is due to its simplicity for plotting a position just offshore, but it was also used in conjunction with older surveying methods prior to the advent of GPS navigation (Green 2004:24-34; Bowens 2009:112). Archaeologists could establish a network of shore-based poles in which boat drivers maintained visual alignment to navigate the survey area. The placements of the poles were plotted in effort to have spatial control of the data generated by the vessel survey.

Prior to the availability of GPS, transits could be used to mark general site locations for area survey work or repeatable navigation to a site. In terms of positional accuracy, the transits method varies widely (meters to kilometres) based on the user and what shore-based features were used for visual alignment (Throckmorton et al. 1973). In many cases of older research projects, the shoreline features used for visual alignment no longer exist or are unrecognisable. A case study example of shoreline variation used for this research occurred at the Rose Hill wreck site, in which specific trees and other shoreline objects were used to determine the wreck location (Wilde-Ramsing 1992). Nearly 30 years separated the original survey and this thesis' case study research, and during that period, extensive residential development and marine construction drastically altered the riverbank. Transits served a specific purpose for general navigation, but was rendered obsolete upon the arrival of commercial GPS receivers and could not be used for georeferencing underwater datum positions.

2.1.2 Sextant

The sextant represents a longstanding history of at-sea navigation and positioning dating from the 19th century to the commercial availability of satellite positioning (Green 2004:34).

While the positional accuracy of sextants could theoretically yield 1 m radius measurements through the measurements of angles to a specified location, it produced coordinates at the water surface with no capability of georeferencing or localising underwater datum positions (Bowens 2009:116). Similar to that of transits positioning, the use of sextants provided a general location for plotting a site on a navigational chart, and its accuracy greatly depending upon the expertise of the user. The advantage the sextant had over the transits method was the ability to calculate latitude and longitude coordinates at sea without the reliance on shore-based features. Also similar to that of transits, the sextant was rendered obsolete upon the availability of satellite positioning systems.

2.1.3 Theodolite / Total Station

Theodolites are a type of telescope used in conjunction with scale bars to measure the horizontal and vertical angles of a specific point, very similar in operation to that of a sextant (Green 2004:41; Bowens 2009:118). Theodolites differ from sextants in that they are solely a shore-based technique and cannot be used from a moving vessel. The theodolite method was very capable of producing nearshore underwater positioning information with quantifiable accuracy and precision, but was limited to shallow water depths (< 8 m) in which a prism or scale bar could be visible above the water surface (Henderson and Burgess 1996; Mahon et al. 2011; Henderson et al. 2012; McCarthy 2014; Balletti et al. 2015; Beltrame and Costa 2018; Pacheco-Ruiz et al. 2018). Maintaining the prism or scale bar above the water surface and atop the datum position could be difficult depending environmental factors such as waves, wind, and bottom type. It is also important to note the difficulties in maintaining the pole/scale bar in 90° vertical alignment with the datum position. Depending on the water depth, a single degree above

or below 90° would introduce positional uncertainty at the top of the pole from which the theodolite calculated a position measurement.

For shallow water survey operations, the theodolite was replaced by digital total stations with integrated GPS receivers and laser range finding technology which retain positional accuracy and measurement precision at the centimetre-level (Green 2004:42). The integrated satellite positioning and laser ranging systems make the total station an ideal method of nearshore surveying and for georeferencing datum positions. However, this is only applicable to shallow water sites which permit the use of a telescoping prism pole or scale bar (Henderson and Burgess 1996; Mahon et al. 2011; Henderson et al. 2012; McCarthy 2014; Balletti et al. 2015; Beltrame and Costa 2018; Pacheco-Ruiz et al. 2018). The modern digital total station in conjunction with real-time kinematic satellite positioning corrections is very much a viable method of shore-based datum georeferencing and localisation. It is merely limited by its operational range and water depth.

2.1.4 Electronic / Radio Positioning

Electronic and radio positioning systems were developed in the 1940s as a means of ship navigation using shore-based stations which emitted navigation information via radio wave and micro wave frequencies (Hastings 1949). Two commonly known electronic methods were DECCA and LORAN C, but both systems suffered from positioning issues and were not considered accurate enough for maritime archaeological surveys (Bowens 2009:120). Although some textbooks, such as the *Archaeology Underwater: NAS Guide to Principles and Practice*, and archaeological field reports, state the positional accuracies of these methods varied between 0.1 – 0.25 nautical miles, the author has encountered numerous survey reports filed with various archaeological and historic preservation offices which plotted site positions using electronic

methods such as RAYDIST (radio wave) , Marinav Trisponder (micro wave), and Si-Text LORAN C EZ-97 (radio wave) (Broadwater 1975; Schurer and Linden 1984; Franklin et al. 1991). As a result, archaeological surveys carried out by the author had to augment the survey areas to "rediscover" a site and provide absolute geospatial data as part of an updated site file. This affected the time and resources necessary to carrying out the archaeological survey. Similar to that of other early positioning methods, electronic methods were effectively replaced by GPS and are no longer used (Bowens 2009:120).

2.1.5 Floating Global Positioning System

At the time of this writing, the Global Satellite Positioning (GPS) system is the standard positioning method in the world. It is utilised by nearly every industry which requires positioning information on the earth's surface. In this section, the author omits technical information pertaining to the GPS system because it is discussed at length in Section 2.3.1 (see pg. 65), and the author assumes the reader has a basic understanding of what a GPS receiver is and how it calculates positions on earth using geometric angles of observable satellites and timed navigation messages. If the reader is not familiar with how the GPS system works, the author refers the reader to Section 2.3.1 for that information.

The information contained in Section 2.1.5 pertains to the use of a floating GPS arrangement, in which a GPS receiver is used in conjunction with a floating antenna or reversed in which the receiver is floated at the surface and connected to a downline which travels through the water column to an object on the seafloor. This is a method that has been popularised by the recreational diving community and has been in continuous use since the availability of commercial GPS receivers to the general public. A number of scientific research projects have used this method of underwater positioning with varying degrees of positional accuracy and

measurements (Arnold 1993; Collins and Baldock 2007; Kuch et al. 2012 Niedwiedz and Schories 2013; Casella et al. 2016). The popularity of this method is based on it being a *relatively inexpensive* method capable of generating underwater positions with *relative accuracy* which can be used for marking site locations.

The positional accuracy of the floating GPS method is directly dependent upon the accuracy of the GPS receiver and the ability for the operators to maintain a known offset caused by surface water movement, wind, and other factors (Kuch et al. 2012:193). The positional capabilities of commercial handheld GPS units range between ±3 – 10 m, which does not account for any positional offset of the GPS receiver from the target location. The offset between the GPS receiver and the target is further increased with water depth. Within the last decade, there have been a number of independent studies which evaluate floating GPS performance as an underwater positioning method (Kuch et al. 2012; Niedzwiedz and Schories 2013). According to a study conducted by Niedzwiedz and Schories (2013), project carried out a systematic review of floating GPS accuracy based on optimal environmental conditions and GPS receiver performance. TABLE 2-1 provides the calculated positional offset of a GPS receiver from a target location in optimal environmental and performance conditions:

TABLE 2-1
FLOATING GPS PERFORMANCE IN OPTIMAL CONDITIONS

Water Depth	GPS Uncertainty	Offset Displacement
5 m	≤ 2.5 m (Optimal)	2.3 m
10 m	≤ 2.5 m (Optimal)	3.2 m
20 m	≤ 2.5 m (Optimal)	4.6 m
30 m	≤ 2.5 m (Optimal)	5.5 m
40 m	≤ 2.5 m (Optimal)	6.8 m

Source: (Niedzwiedz and Schories 2013).

The information provided in TABLE 2-1 provides optimal performance data in the event the GPS receiver has the best attainable positional accuracy and measurement precision, while the sea state is absent of water movement such as tidal, currents, or wind. Real-world archaeology does not take place in optimal environments, nor are archaeological surveys routinely conducted in freshwater or marine environments with no water movement. This research is highly skeptical of the values calculated by the floating GPS research studies, due to the unrealistic application of measuring positional offsets between a GPS receiver at the surface and a target location several meters below in waters with high turbidity and movement. It is not a practical or pragmatic approach to accurate and precise underwater positioning for real-world archaeological fieldwork, especially when operating under permits issued by regulatory agencies with strict spatial standards. The total horizontal and vertical uncertainties of the underwater positional information cannot be quantified and/or applied to reference datum for georeferencing or localisation with any known accuracy or measurement precision. An interesting aspect of the study carried out by Niedzwiedz and Schories (2013), was their acknowledgement of the superiority of underwater acoustic ranging systems such as long baseline (LBL) or GPS Intelligent Buoys (GIBs) when coupled with differential GPS systems for subsurface tracking and positioning (Niedzwiedz and Schories 2013:181). Although this method continues its use in the natural and social sciences, it should be relegated to merely marking general locations during diver reconnaissance and not used for academic or commercial geophysical surveying.

2.2 IHO Standards for Geophysical Surveys

Developing the research parameters of the thesis required establishing operational specifications for the UALR methodology, which involved a review of current high-resolution geophysical (HRG) surveying specifications. Underwater positioning requirements differ

throughout various parts of the world; however, the most commonly recognised standards are those established by the International Hydrographic Organization (IHO), which have been adopted by other prominent institutions such as the Bureau of Ocean Energy Management (BOEM), United States Army Corps of Engineers (USACE), Historic England, International Association of Oil and Gas Producers (IOGP), and the International Marine Contractors Association (IMCA) (Plets et al. 2013:13-14; USACE 2013; IOGP 2019; IHO 2020; BOEM 2020a:7; IMCA 2021). The geophysical surveying standards currently in use by these institutions form the technical basis of this thesis by providing specific requirements pertaining to underwater positioning accuracy, which facilitates a later discussion in Section 2.3 regarding acceptable spatial data acquisition instrumentation (see pg. 62).

Section 2.2 provides a detailed examination of the *IHO Standards for Hydrographic Surveys (S-44)* specifications to familiarise the reader with current geophysical surveying standards commonly used throughout the world. The review of underwater positioning specifications in Section 2.2 focuses on informational gaps directly related to the research questions previously outlined in Section 1.2 (see pg. 34). Section 2.2 examines the currently recognised geophysical surveying standards as criterion for selecting an underwater positioning system capable of satisfying spatial requirements and integration with existing archaeological data collection methods. The underwater positioning requirements issued by each institution reviewed in Section 2.2 undergo routine evaluations by their respective technical committees in an effort to keep up with new technologies and data acquisition methods (IHO 2020:7). The continued revision of these requirements allows archaeologists to know the latest acceptable standards and practices for geophysical surveys. As a result, archaeologists participating in geophysical surveys throughout the world can conduct data acquisition within clearly defined

specifications. Information in this section provides the reader with a fundamental understanding of the metric specifications, the definitions of these values, a sharp perspective of the spatial tolerances, and why such constraints are required for geophysical surveying operations.

The *IHO Standards for Hydrographic Surveys (S-44)* published by the International Hydrographic Organization are the most recognised geophysical surveying standards implemented by public and private institutions. Government and commercial surveying entities rely on the IHO standards for guidance for a wide range of subjects pertaining to geophysical surveys which include bathymetric coverage, bottom sampling, metadata, and data quality management (IHO 2020:9). The IHO standards pertaining to underwater positioning are systematically examined in the context of this thesis and the development of the UALR methodology. Other geophysical surveying underwater positioning standards, such as those issued by BOEM, USACE, and Historic England, are comparatively discussed given those institutions publish similar requirements. The current IHO standards are in their sixth edition, having been revised and updated since the first edition published in January 1968 (IHO 2020:7). Revisions and updates contained within the latest edition were established through a cooperative effort by the IHO and geophysical surveying professionals from all over the world.

The IHO standards do not explicitly mention submerged cultural resources; therefore, all specifications pertaining to archaeological data acquisition and quality control are administered by respective governing legislation and/or permitting institutions. If the IHO standards do not include archaeological considerations, then what is the justification for their use in projects related to submerged cultural resources? Archaeological remains and artefacts are viewed as non-renewable resources which require careful documentation and preservation methods (Plets et al. 2013:6). Throughout the world, government legislation exists for the protection of submerged

cultural resources and dictate the terms in which these remains can be scientifically studied and the proximity at which marine construction operations can take place without negatively affecting the physical remains or bottom sediment. For example, in the United States, nearly all archaeological surveys must be in compliance with guidelines stated in Section 106 of the *National Historic Preservation Act* (NHPA) (36 CFR part 800) and the *National Environmental Policy Act* (NEPA) (BOEM 2020a:1). The United Kingdom has similar legislation such as *The Protection of Wrecks Act* (1973), *The Ancient Monuments and Archaeological Areas Act* (1979), *The Protection of Military Remains Act* (1986), and *The Merchant Shipping Act* (1995) (Plets et al. 2013:5-6). Many European nations and other countries throughout the world have ratified the *UNESCO Convention on the Protection of Underwater Cultural Heritage* (2001) (). These pieces of legislation are designed for the protection, study, and continued preservation of submerged cultural resources; however, they do not specifically address surveying or underwater positioning standards. In the United States and United Kingdom, and other regional custodial and permitting agencies have effectively combined geophysical surveying standards and submerged archaeological site documentation practices into flexible protocols designed for use in shallow water environments such as coastal areas, lakes, rivers, and other bodies of water that are within depths of 200m or less (Plets et al. 2013; USACE 2013; BOEM 2020a).

The validation for using modern geophysical surveying equipment and methods for documenting archaeological sites is based on best practices recommendations contained within the US, UK, and UNESCO legislations. These specifications recommend non-disturbance geophysical surveying methods that do not negatively affect submerged cultural resources or the surrounding environment (UNESCO 2001:13; Plets et al. 2013:6; BOEM 2020a:5-6). According to the *Marine Geophysics Data Acquisition, Processing, and Interpretation Guidance Notes*

published by Historic England in 2013, geophysical surveying instruments and methods are preferred due to their high-resolution, cost-effectiveness, and lack of disturbance to archaeological sites or artefacts (Plets et al. 2013:6). Although this legislation encourages the use of non-disturbance methods using geophysical surveying equipment, the submerged cultural resources regulations mentioned above do not include metric specifications pertaining to underwater positional accuracy, and respective archaeological institutions refer to the IHO standards for guidance (Plets et al. 2013:5; BOEM 2020b:3). Interestingly, submerged cultural resources investigations that are required to operate under geophysical surveying standards use a combined system of specifications that pertain to discrete, yet conjoined components, of an overall survey. Though the IHO standards and the archaeological guidelines issued by the US, UK, and UNESCO are considered separate strategies for achieving different objectives, they all work toward common goals of using accurate data acquisition methods for the study and preservation of submerged cultural remains and natural resources.

The metric specifications detailed in the IHO standards are based on a five-tier hierarchal order system (see Appendix, pg. 328). Each order is distinguished by water depth, bottom sediment type, and the anticipated vessel classes navigating within the proposed survey area (IHO 2020:12). Geophysical surveyors are responsible for determining the applicable IHO order for the proposed survey area and must comply with all order requirements to remain within the order specifications. In some geographical locations, a geophysical survey may be composed of different IHO orders due to changes in water depth or bottom sediment type. During these circumstances, surveyors are required to note any changes to the IHO order type and conduct surveying operations within specifications for the applicable order in that particular location (IHO 2020:12). Permitting institutions and surveying companies throughout the world, such as

BOEM, Historic England, Bundesamt für Seeschifffahrt und Hydrographie (BSH), DNV-GL, Fugro and many others have adopted the IHO order classification system as part of their standard geophysical surveying guidelines (Plets et al. 2013:5; BSH 2014:22; DNV-GL 2016:14; BOEM 2020b:7).

The IHO orders, reference tables, and matrices in the subsequent pages are presented in a specific sequence from the least stringent to the strictest geophysical surveying requirements. Many of the terms used in the IHO orders are not commonly used within archaeological terminology; therefore, the reader is referred to the Glossary for definitions and supplemental descriptions (see pg. *xxiii*). In addition to the Glossary, the reader is also referred to accompanying tables and matrices which provide all order requirements in an effort to assist the reader by providing visual diagrams for comparison (see pgs. 54-57). Information included in the Glossary, supplementary tables, and matrices is taken directly from the *IHO Standards for Hydrographic Surveys (S-44)* (see Appendix, pg. 328). As mentioned in the preceding paragraph, geophysical surveys operating under permitting specifications which adhere to IHO standards will fall under these orders. The definitions associated with each IHO order contains a lot of information that requires clarification, particularly from an archaeological perspective and within the context of this thesis.

The order descriptions include information pertaining to sensor coverage, object detection, data quality, and required underwater positioning specifications for each tier. The importance of this information for this thesis involves specific instances in which supplemental archaeological investigations are needed due to insufficient sensor coverage and/or data quality. Circumstances and applicable archaeological investigation methods are not discussed in the IHO standards, but are included in other permitting agency documentation, such as BOEM's

TABLE 2-2
INTERNATIONAL HYDROGRAPHIC ORGANIZATION CLASSIFICATION OF NAVIGATION SURVEYS

Order No.	Description
2	This is the least stringent order and is intended for areas where the depth of water is such that a general depiction of the bottom is considered adequate. As a minimum, an evenly distributed bathymetric coverage of 5% is required for the survey area. It is recommended that Order 2 surveys are conducted in areas which are deeper than 200 metres. Once the water depth exceeds 200 metres, the existence of features that are large enough to impact on surface navigation and yet still remain undetected by an Order 2 survey is considered to be unlikely.
1b	This order is intended for areas where the types of surface vessels expected to transit the area is such that a general depiction of the bottom is considered adequate. As a minimum, an evenly distributed bathymetric coverage of 5% is required for the survey area. This means some features will not be detected, although the distance between areas of bathymetric coverage will limit the size of those features. This order of survey is only recommended where underkeel clearance is considered not to be an issue. An example would be an area where the bottom characteristics are such that the likelihood of there being a feature on the bottom that will endanger the type of surface vessel expected to navigate the area is low.
1a	This order is intended for areas where features on the bottom may become a concern for the type of surface traffic expected to transit the area but where the underkeel clearance is considered not to be critical. A 100% feature search is required in order to detect features of a specified size. Bathymetric coverage less than or equal to 100% is appropriate as long as the least depths over all significant features are obtained and the bathymetry provides an adequate depiction of the nature of the bottom topography. Underkeel clearance becomes less critical as depth increases, so the size of the feature to be detected increases with depth in areas where the water depth is greater than 40 metres. Examples of areas that may require Order 1a surveys are coastal waters, harbours, berthing areas, fairways and channels.
Special Order	This order is intended for those areas where underkeel clearance is critical. Therefore, 100% feature search and 100% bathymetric coverage are required and the size of the features to be detected by this search is deliberately more demanding than for Order 1a. Examples of areas that may require Special Order surveys are: berthing areas, harbours, and critical areas of fairways and shipping channels.
Exclusive Order	Exclusive Order hydrographic surveys are an extension of IHO Special Order with more stringent uncertainty and data coverage requirements. Their use is intended to be restricted to shallow water areas (harbours, berthing areas and critical areas of fairways and channels) where there is an exceptional and optimal use of the water column and where specific critical areas with minimum underkeel clearance and bottom characteristics are potentially hazardous to vessels. For this order, a 200% feature search and a 200% bathymetric coverage are required. The size of features to be detected is deliberately more demanding than for Special Order.

Source: International Hydrographic Organization (IHO 2020:12-13).

TABLE 2-3
MINIMUM BATHYMETRY STANDARDS FOR SAFETY OF NAVIGATION HYDROGRAPHIC SURVEYS

Criteria	Order 2	Order 1b	Order 1a	Special Order	Exclusive Order
Area Description (Generally)	Areas where a general description of the seafloor is adequate.	Areas where underkeel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas where underkeel clearance is considered not to be critical but features of concern to surface shipping may exist.	Areas where underkeel clearance is critical.	Areas where there is strict minimum underkeel clearance and manoeuvrability criteria.
Depth THU [m] + [% of Depth]	20 m + 10% of depth *Ba5, Bb2	5 m + 5% of depth *Ba8, Bb3	5 m + 5% of depth *Ba8, Bb3	2 m *Ba9	1 m *Ba10
Depth TVU (a) [m] and (b)	a = 1.0 m b = 0.023 *Bc7, Bd4	a = 0.5 m b = 0.013 *Bc8, Bd6	a = 0.5 m b = 0.013 *Bc8, Bd6	a = 0.25 m b = 0.0075 *Bc10, Bd8	a = 0.15 m b = 0/0075 *Bc12, Bd8
Feature Detection [m] or [% of Depth]	Not Specified	Not Specified	Cubic features > 2 m, in depths down to 40 m; 10% of depth beyond 40 m *Be5, Bf3 beyond 40 m	Cubic features > 1 m *Be6	Cubic features > 0.5 m *Be9
Feature Search [%]	Recommended but Not Required	Recommended but Not Required	100 % *Bg9	100 % *Bg9	200 % *Bg12
Bathymetric Coverage [%]	5 % *Bh3	5 % *Bh3	≤ 100% *≤ Bh9	100 % *Bh9	200 % *Bh12

Note: m = metres, all uncertainties at 95% confidence level, * = Matrix Reference.
Source: International Hydrographic Organization (IHO 2020:27).

TABLE 2-4
OTHER MINIMUM STANDARDS FOR SAFETY OF NAVIGATION SURVEYS

Criteria	Uncertainty Type	Order 2	Order 1b	Order 1a	Special Order	Exclusive Order
Fixed Objects, Aids, Features Above the Vertical Reference Significant to Navigation	THU [m]	5 m *Pa4	2 m *Pa6	2 m *Pa6	2 m *Pa6	1 m *Pa7
	TVU [m]	2 m *Pb2	2 m *Pb2	1 m *Pb3	0.5 m *Pb4	0.25 m *Pb5
Floating Objects and Aids to Navigation	THU [m]	20 m *Pc2	10 m *Pc3	10 m *Pc3	10 m *Pc3	5 m *Pc4
Coastline (high, low, MWL water lines, etc.)	THU [m]	10 m *Pd2	10 m *Pd2	10 m *Pd2	10 m *Pd2	5 m *Pd3
Features Above the Vertical Reference Less Significant to Navigation	THU [m]	20 m *Pe2	20 m *Pe2	20 m *Pe2	10 m *Pe3	5 m *Pe4
	TVU [m]	3 m *Pf1	2 m *Pf2	1 m *Pf3	0.5 m *Pf4	0.3 m *Pf5
Overhead Clearances and Range Line, Sector Light Heights	THU [m]	10 m *Pg1	10 m *Pg1	5 m *Pg2	2 m *Pg3	1 m *Pg4
	TVU [m]	3 m *Ph1	2 m *Ph2	1 m *Ph3	0.5 m *Ph4	0.3 m *Ph5
Angular Measurements	[degrees]	0.5 degrees *Pi4	0.5 degrees *Pi4	0.5 degrees *Pi4	0.5 degrees *Pi4	0.5 degrees *Pi4
Water Flow Direction	[degrees]	10 degrees *Wa1	10 degrees *Wa1	10 degrees *Wa1	10 degrees *Wa1	10 degrees *Wa1
Water Flow Speed	[knots]	0.1 knots *Wb5	0.1 knots *Wb5	0.1 knots *Wb5	0.1 knots *Wb5	0.1 knots *Wb5

Note: m = metres, all uncertainties at 95% confidence level, * = Matrix Reference.
Source: International Hydrographic Organization (IHO 2020:28).

MATRIX 2-1
BATHYMETRY MATRIX FOR HYDROGRAPHIC SURVEY

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
B															
a	**Depth** THU [m]	500	200	100	50	20	15	10	5	2	1	0.5	0.35	0.1	0.05
b	**Depth** THU [% of depth]	20	10	5	2	1	0.5	0.25	0.1						
c	**Depth** TVU "a" [m]	100	50	25	10	5	2	1	0.5	0.3	0.25	0.2	0.15	0.1	0.05
d	**Depth** TVU "b" Note 1	0.20	0.10	0.05	0.023	0.02	0.013	0.01	0.007 5	0.004	0.002				
e	**Feature Detection** [m]	50	20	10	5	2	1	0.75	0.7	0.5	0.3	0.25	0.2	0.1	0.05
f	**Feature Detection** [% of Depth]	25	20	10	5	3	2	1	0.5	0.25					
g	**Feature Search** [%]	1	3	5	10	20	30	50	75	100	120	150	200	300	
h	**Bathymetric Coverage** [%]	1	3	5	10	20	30	50	75	100	120	150	200	300	

Note: m = metres, all uncertainties at 95% confidence level.
Source: International Hydrographic Organization (IHO 2020:30).

MATRIX 2-2
OTHER POSITIONING ABOVE THE VERTICAL REFERENCE

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
P															
a	**Fixed Aids, features Significant to Navigation** THU [m]	50	20	10	5	3	2	1	0.5	0.2	0.1	0.05	0.01		
b	**Fixed Aids, Features Significant to Navigation** TVU [m]	3	2	1	0.5	0.25	0.1	0.05	0.01						
c	**Floating Aids and Objects** THU [m]	50	20	10	5	2	1	0.5							
d	**Coastline** THU (high, low, MWL water lines, etc.) [m]	20	10	5	1	0.5	0.25	0.1							
e	**Features Less Significant to Navigation** THU [m]	50	20	10	5	3	2	1	0.5	0.2	0.1	0.05	0.01		
f	**Features Less Significant to Navigation** TVU [m]	3	2	1	0.5	0.3	0.25	0.1	0.05	0.01					
g	**Overhead Clearances and Range Line, Sector Light Heights** THU [m]	10	5	2	1	0.5	0.2	0.1	0.05	0.01					
h	**Overhead Clearances and Range Line, Sector Light Heights** TVU [m]	3	2	1	0.5	0.3	0.1	0.05	0.01						
i	**Angular Measurements** [degrees]	5	2.5	1	0.5	0.2	0.1	0.05							

Note: m = metres, all uncertainties at 95% confidence level.
Source: International Hydrographic Organization (IHO 2020:30).

MATRIX 2-3
WATER FLOW

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
W															
a	**Flow Direction** [degrees]	10	7.5	5.0	2.5	1.0	0.5	0.25	0.10						
b	**Flow Speed** [knots]	2	1	0.5	0.25	0.10									

Note: The use of parameter "b" as a percentage of depth requires the user to multiply it by 100.
Source: International Hydrographic Organization (IHO 2020:31).

MATRIX 2-4
NATURE OF THE BOTTOM

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
N															
a	**Bottom Characteristics Method**	10	7.5	5.0	2.5	1.0	0.5	0.25	0.10						
b	**Bottom Sampling Frequency** approximate [m]	2	1	0.5	0.25	0.10									

Note: PHY = Physical Sampling. VIS = Visual Analysis. LAB = Laboratory Analysis. INF = Inference Technique. w/ = with. GT = Ground Truth. As Req to GT = As Required to Ground Truth any Inference Technique.
Source: International Hydrographic Organization (IHO 2020:32).

Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585 guidance document (BOEM 2020b:2). A detailed analysis for supplemental archaeological investigation methods in support of geophysical surveying operations is reserved for Section 3.4 (see pg. 162). Information in Table 2-2 (see pg. 54) is derived from IHO criteria and specifications provided in Tables 2-3 – 2-4 (see pgs. 55-56) and Matrices 2-1 – 2-4 (see pgs. 57-59). At first glance, the information included in Table 1 can be perceived as daunting to archaeologists unfamiliar with the IHO standards, but the tables and matrices contain the necessary reference information for understanding what requirements are in place for each IHO order. Table 2-1 provides the IHO order number and brief descriptions of the geophysical surveying specifications detailing explicit requirements regarding bathymetric coverage according to survey depth and anticipated types of vessels navigating the survey area. The IHO order descriptions provided in Table 2-1 can be interpretated as a general overview; whereas, specific information pertaining to depth total horizonal uncertainty (THU), depth total vertical uncertainty (TVU), feature detection and search parameters, and bathymetric coverage is provided in Table 2-2 and Table 2-3. The reader will notice matrix reference information (green font) located in the lower right corner of each table grid, and this information is used in conjunction with Matrices 2-1 through 2-4 which define specific requirements for individual order criteria. The IHO states that the information in these matrices do not define specific hydrographic surveying standards, but the accuracy ranges included in the matrices are designed to accommodate geophysical surveys designed for navigation, offshore energy exploration, dredging and other marine-related projects (IHO 2020:29). As mentioned previously, the *IHO Standards for Hydrographic Surveys (S-44)* document is included in this thesis as Appendix I (see pg. 328). The reader is recommended to review this source for any questions pertaining to

the IHO orders, and when IHO standards are referenced in this thesis in regards to archaeological information from custodial and/or permitting institutions such as BOEM, USACE, Historic England, and others.

The inclusion of the IHO standards for this thesis derives from their general acceptance and implementation by established governing institutions and geophysical surveying entities. The geophysical surveying parameters and reporting guidelines offer a general framework that all surveyors and archaeologists can follow. As mentioned on pg. 48 of this thesis, the IHO standards do not state standards or guidelines for submerged cultural resources; however, best practice recommendations and requirements from regulatory institutions supplement the omission of this specific information (Plets et al. 2013; USACE 2013; BOEM 2020a). As stated in the *Marine Geophysics Data Acquisition, Processing, and Interpretation Guidance Notes* published by Historic England, the IHO standards and other referenced guidelines offer a flexible protocol that can be used in shallow-water locations that assist survey participants in marine-related industries and researchers involved with submerged cultural resources and heritage (Plets et al. 2013:5-6). As a continuation of this operating protocol commonly used for geophysical surveys currently in use for offshore projects throughout various parts of the world, this thesis uses the IHO standards as part of its UALR methodology research design parameters. The IHO standards are the universal set of geophysical surveying guidelines that are referenced by numerous permitting agencies throughout the world; however, actual permitting requirements and archaeological considerations for geophysical surveys are dictated at the regional level. Although the spatial parameters for the UALR methodology are aimed at satisfying IHO underwater positioning specifications, the archaeological components of the UALR methodology

must meet permitting agency standards such as those published by BOEM, Historic England, USACE, and other institutions throughout the world.

2.3 U.K. and U.S. Geophysical Survey Requirements and Archaeological Guidelines

The IHO standards outlined in Section 2.2 provide a general set of guidelines that have been adopted by governing institutions throughout the world and integrated with their respective geophysical surveying requirements (Plets et al. 2013; USACE 2013; BOEM 2020a; BOEM 2020b). Regardless of the use of the IHO standards as the specification basis for carrying out high-resolution geophysical surveys, the requirements published by individual governing institutions may vary due to enacted state legislation, geography, and/or the presence of manmade and natural features such as reefs, shipwrecks, or submerged paleolandscapes. Section 2.3 examines geophysical surveying requirements pertaining to underwater positioning and recommended spatial data acquisition instrumentation. The importance of this information is directly related to the development of the thesis research design in regards to the operational parameters for establishing the UALR methodology.

The geophysical surveying requirements reviewed in Section 2.3 are derived from published materials from BOEM and Historic England; however, this thesis acknowledges the existence of additional geophysical surveying requirements published by other governing bodies. The decision to focus on geophysical surveying requirements in the U.K. and U.S. is based upon the author's familiarity with the published guidelines and professional experience as a qualified maritime archaeologist and geophysical surveyor. The author participated in a series of offshore windfarm surveys along the US Atlantic coastline in Maine, Maryland, New York, North Carolina, Rhode Island, and Virginia operating under BOEM and local state historic preservation office (SHPO) geophysical surveying and submerged cultural resources guidelines. The selection

of examining the U.S. geophysical surveying requirements was necessary, given the BOEM regulations are the current de facto geophysical surveying requirements for offshore energy and windfarm development in U.S. territorial waters, and pipeline and/or cable corridors running from offshore installations to land fall under SHPO guidelines (within 3 nautical miles). The USACE also publishes geophysical survey and archaeological guidelines which mirror similar specifications to that of the BOEM guidelines. The U.K. retains comparable geophysical surveying standards in place for coastal and offshore projects; furthermore, it is only fitting to include them in this writing given this thesis is part of a doctoral degree program in a U.K.-based university. The review of the U.K. and U.S. geophysical surveying guidelines in Section 2.3 examine the metric specifications, recommendations for underwater positioning instrumentation, and best practices recommendations as they relate to the development of the UALR methodology research concept.

The U.K. geophysical surveying and archaeological guidelines are accessible to the public in the *Marine Geophysics Data Acquisition, Processing and Interpretation Guidance Notes* (MGDAPAI) published by Historic England. The latest available edition of the MGDAPAI guidance notes were published in 2013 and serve as part of the Aggregate Levy Sustainability Fund's (ALSF) effort to distribute information related to U.K. cultural heritage (Plets et al. 2013:4). The information provided in the MGDAPAI guidance notes is derived from various sources including previous archaeological projects, marine industry professionals, and personal experiences from those who participated in its formation. Through this effort, the MGDAPAI guidance notes are written in an easy-to-read format for users from all backgrounds and technical experience. The U.S. geophysical surveying and archaeological standards issued by BOEM are divided into two discrete documents; yet, both were published to be used

cooperatively for offshore surveys (BOEM 2020b:2). The latest editions of the BOEM *Guidelines for Providing Archaeological and Historic Properties Information Pursuant to 30 CFR Part 585* and *Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585* were published in 2020, and provide the necessary information for geophysical surveyors, maritime archaeologists, and other cultural heritage professionals.

The Historic England and BOEM geophysical surveying and archaeological guidelines operate in direct support of government legislation specifically designed for the protection of submerged cultural materials and maritime landscapes (Plets et al. 2013:4; BOEM 2020a:1; BOEM 2020b:1). The U.K. Parliament enacted four primary pieces of legislation directly pertaining to the maritime archaeology and cultural heritage: *The Protection of Wrecks Act* (1973), *The Ancient Monuments and Archaeological Areas Act* (1979), *The Protection of Military Remains Act* (1986), *The Merchant Shipping Act* (1995); whilst, it should also be noted that additional legislation exists at the regional level throughout the U.K. (Plets et al. 2020:4-5). Similarly, the U.S. government passed a series of legislation designed to protect cultural and natural resources: *The National Historic Preservation Act* (NHPA) and *The National Environmental Policy Act* (NEPA) (BOEM 2020a:1). Section 106 of the NHPA is of primary importance to cultural resources projects and nearly archaeological guidelines are designed to satisfy these requirements. SHPOs typically base their permitting guidelines on Section 106 requirements which generally assists continuity and reducing potential confusion for archaeologists using multiple research guidelines. Both the U.K. and U.S. legislations are designed for the identification and protection of submerged cultural resources and

paleolandscapes, but require the supplementary geophysical guidelines for explicit metric specifications and equipment recommendations.

The metric constraints and underwater positioning equipment recommendations included in the Historic England and BOEM geophysical surveying guidelines serve as this thesis' operational parameters. To familiarise the reader with the various technologies used for vessel navigation, underwater positioning and the associated spatial requirements published by BOEM and Historic England, the author divides this information into subsections according to technology type. Included in these sections are descriptions of the positioning systems, a brief historical overview pertaining to their development and traditional usage, the type of data produced and how it is used for geophysical and archaeological surveys, and the published metric requirements included in the BOEM and Historic England guidelines. In addition to the U.K. and U.S. guidelines, the author draws information about these technology systems from various government, academic, and private sector research projects which provide supplementary material for demonstrating why these systems are the currently accepted standards for navigation and underwater positioning for geophysical surveys.

2.3.1 Satellite Positioning Standards for Geophysical Surveys

The reliance on celestial bodies for navigation transcends thousands of years of human history and was practiced by many civilizations throughout the world. Ancient mariners, overland explorers, and common travellers looked to the sun and stars as means of calculating their position on Earth and guidance while on route to their desired destinations (Kaplan 2006:1-6). While many of these groups may not have fully understood the science of these heavenly figures, they demonstrated their ability to observe seasonal variations in the sun and celestial constellations in order to develop orbital predictions that assisted them in determining position.

While satellite navigation can trace its ancestry to these methods, the means of calculating positional accuracy to within a few meters has only been in existence since the latter half of the twentieth century (Kumar and Moore 2002:80; Thomas 2010:27-28).

The NAVSTAR Global Positioning System, commonly referred to as GPS, is the most commonly used satellite-based navigation system throughout the world (Plets et al. 2013:12). GPS represents a series of orbital navigation satellites and ground control networks that provide end users with positional coordinates with a relatively high degree of spatial accuracy. The system is owned by the United States Department of Defense and currently operated by the United States Space Force (USSF) (NAVSTAR 2020:1). Since its inception during the Cold War as a weaponised platform for providing at-sea coordinates to U.S. Navy nuclear submarines, GPS has developed into a worldwide utility upon which millions of users rely on its services for commercial, recreational, and scientific purposes (Neufeld 1993:91-92; Green and Doershuk 1998:121; Viduka 2006; Sturdevant 2007:331; Evans et al. 2009; Brennan et al. 2016:87; Borelli et al. 2018:14-18). For the foreseeable future, GPS will continue to be the primary satellite-based navigation system; however, other nations have developed global navigation satellite systems (GNSS) and regional systems such as the Chinese BeiDou system, the European Union's GALILEO system, and the Russian GLONASS system. Although these multiple GNSS systems exist, BOEM and Historic England rely on the use of GPS for navigation for geophysical survey operations (Plets et al. 2013:8; BOEM 2020a; BOEM 2020b).

According to the Historic England MGDAPAI guidelines, geophysical survey navigation minimum specifications require the use of differential-grade GPS (DGPS) accuracy; however, the guidelines also state that DGPS vertical accuracy is insufficient for processing bathymetric data. MGDAPAI guidelines recommend the use of real-time kinematic (RTK) or post-processed

kinematic (PPK) GPS data for acquiring the centimetric-level data required as part of bathymetry data collection and processing; however, PPK is only suitable for mapping purposes and not intended for navigation (Plets et al. 2013:12-13). Comparatively, the BOEM *Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585* navigation and positioning specifications require that the onboard navigation system be in compliance with Special Order Survey conditions as defined by the International Hydrographic Organization (Tables 2-2 – 2-4) (see pgs. 54-56) (BOEM 2020b; IHO 2020:27-28). In reference to the IHO standards, BOEM requires that navigation systems must be capable of acquiring positional data with a THU value of 2 m at the 95% confidence level. Parallel to the Historic England requirements, BOEM's specifications for achieving a THU value of 2 m at the 95% confidence interval requires the use of a DGPS receiver and antenna configuration using real-time error correction services.

The Historic England and BOEM navigation system recommendations in the previous paragraph contain a significant amount of information and terminology which require clarification for readers new or unfamiliar with GPS navigation systems. Terms such as "accuracy", "precision", "real-time corrections", and others are commonly used in spatial terminology to describe navigation system performance, exactness of survey data, and data collection practices. Accuracy is typically the term most associated with GPS navigation and positioning data; therefore, it serves as the best place to begin the review. Accuracy, as defined by this research, is the estimated probable error of a calculated distance between a point and its true value. In regards to satellite positioning, the accuracy of a GPS receiver's coordinates is estimated to be within a specific range of the actual coordinates which are typically expressed in a positional error radius. Positional accuracy is a relative expression which exists on multiple

grades that mainly pertain to the types of equipment being used and the desired estimated positional error.

According to the U.S. Geological Survey (USGS), mapping grade satellite positioning equipment is divided into three categories: commercial-grade, differential-grade, and survey-grade (USGS 2020). Commercial-grade accuracy is defined by the USGS as having horizontal positional accuracy of 3 m or greater (USGS 2020). According to the USGS, commercial-grade accuracy is not applicable for general mapping or scientific data collection; therefore, requiring higher grade equipment for enhanced positional accuracy (USGS 2020). Despite the inherent lack of positional accuracy, commercial-grade handheld units have been extensively used for archaeological research since the early 1990s. The considerable inaccuracy of commercial-grade GPS units limits their use for archaeological surveying to marking general site locations. These systems do not satisfy Historic England or BOEM navigation performance, data output, and configuration requirements; therefore, disqualifying their use on geophysical surveys. Commercial-grade GPS receivers are typically handheld-type systems, and a number of academic studies have either compared these types of systems to expensive survey-grade GPS systems or attempted to improve their accuracy through specialised software programs (Fraser et al. 2004; Matosevic et al. 2006:1677-1683; Hall et al. 2008; Kuter and Kuter 2010:3-14; Hussein 2016). For example, Zahraa Ezzulddin Hussein published a study in the *Journal of Engineering* which detailed her experiments with improving low-cost handheld GPS accuracy through the use of a specialised software program and intricate data collection process (Hussein 2016:162-174). Through the use of a dedicated software program and an extensive observational period, the results of the study indicated accuracy improvements based on the root-mean-square-error (RMSE) values which decreased from 6.8 m to 2.4 m.

Differential-grade accuracy is described as having horizontal positional accuracy of less than 1 m (USGS 2020). These DGPS systems are capable of receiving error correction services from both satellite and ground-based augmentation systems, such as the Wide Area Augmentation System (WAAS) and Continuously Operating Reference Stations (CORS) located in the United States, and the European Geostationary Navigation Overlay Service (EGNOS). These error correction services provide navigation data which greatly increases the horizontal and vertical positional accuracies of any capable satellite receiver. While handheld units such as Garmin receivers are capable of achieving positional accuracy under 3 m using WAAS error corrections, these types of units utilise a 50 – 60% confidence interval which does not satisfy the IHO geophysical surveying requirement of a 95% confidence level (IHO 2020). GPS receivers capable of differential-grade positional accuracy are equipped with more advanced antennas capable of receiving at least two satellite frequencies (e.g. L1 and L2), or multiple GNSS constellations such as Galileo (E.U.) and GLONASS (Russia). According to the Historic England geophysical surveying guidelines, a DGPS receiver and resultant positional accuracy are the minimum standards for navigation (Plets et al. 2013:8). BOEM navigation guidelines refer to the IHO standards which require THU to be 2 m at the 95% confidence level, which is achievable using a quality DGPS receiver and applicable antenna array capable of accepting differential corrections from shore or satellite-based augmentation systems (SBAS) (BOEM 2020b:7; IHO 2020:27).

The final and highest level of GPS accuracy is survey-grade. Survey-grade accuracy is defined as the ability to acquire the entire carrier phase wave length of both GPS L1 and L2 satellite frequencies, while tracking a minimum of eight orbiting satellites at all times (USGS 2020). Additionally, all associated hardware and software systems are to be updated to the latest manufacturer's firmware, and all positional offsets of the antenna are to be known to reduce the

possibility of introducing unwanted error. For terrestrial and shore-based archaeological surveying, the use of real-time kinematic (RTK) error correction can reduce positional margins of error to centimetre-accuracy; however, the use of RTK corrections requires expensive hardware and software systems that require constant maintenance and quality control (Gakscatter 2009; USGS 2020). The USGS recommends a baseline range (distance) between the GPS base station and rover be less than 10 km, but can have a maximum of 40 km depending on the signal strength. For geophysical surveying, the use of RTK is limited to coastal projects given that the base receiver must remain static throughout the duration of the survey; therefore, preventing its use on moving vessels or in locations at extended distances from shore. Another option for acquiring real-time error corrections is the application of virtual reference stations (VRS) using a real-time network (RTN), which is accessed via an internet connection. Using cellular communication towers, users can implement RTN/VRS error corrections to provide centimetres-level positional accuracy on offshore sites within range. A distinct advantage for RTN/VRS users is that quality control of reference stations is the responsibility of the administrators and does not require user input beyond standard equipment setup. Survey-grade GPS data exceeds BOEM, Historic England, and IHO standards for surface navigation and positioning.

In review of the various grades of satellite positional accuracy and supplemental error corrections necessary to achieve specific geophysical standards for surface navigation and positioning, this thesis examines a series of variables contributing to satellite positional error and available corrective strategies. Some of these terms and error correction services were mentioned in preceding paragraphs, such as SBAS, RTK and RTN/VRS. In effort to familiarise readers with this subject matter, the author examines satellite navigation signal transmission, sources of positional error, and corrective strategies and services which attain specific positional accuracy

levels. The preferred approach to describing the NAVSTAR GPS network is to start at the orbiting satellite and follow the navigation signal through various atmospheric layers to the user receiver on the earth's surface. At the beginning of Section 2.3.1 (see pg. 65), the author provided a brief overview of the GPS system, its origin, and its impact on modern society; however, this concise description barely scratches the surface of what GPS is and how it works. The common understanding of GPS navigation is that a number of satellites are floating in orbit around the earth and send signals to users on the earth's surface for positioning. While this description is true in the technical sense, there are significantly more components and variables which influence GPS navigation signal transmission in between an orbiting satellite and the user receiver on earth.

Following the declaration of initial operational capability in 1993, the NAVSTAR GPS network has been available to civilian users for commercial, recreational, and scientific endeavours (NAVSTAR 2020:5). The GPS system provides a Standard Positioning Service (SPS) which was initially designed for civil purposes; whereas, the Precise Positioning Service (PPS) is reserved for military applications or civilian users equipped with applicable receivers (Ashjaee 2011; Wright et al. 2012:46). As indicated by the name, PPS has an enhanced positional accuracy when compared to SPS, but since the deactivation of Selective Availability (SA) in 2000 and advances in satellite navigation technology, SPS users have experienced an improvement with surface navigation and mitigating positional error (Martin et al. 2000; Lee and Ge 2006:515). According to the 5th edition of the *Global Positioning System Standard Positioning Service Performance Standard* released in April 2020, the current GPS system is composed of two segments, the Space and Control segments, which are appropriately named for their specific roles within the GPS network (NAVSTAR 2020:4). A third segment, commonly referred to as the User Segment, is not considered part of the GPS system because all operations and quality control depends on the user's

type of navigation unit, how it is used and/or maintained, and user-selected error correction strategies (if any). Although the User Segment is not controlled by the USSF, it ultimately determines the positional accuracy grade and is included in the segment descriptions in the subsequent paragraphs.

The Space Segment, at the time of this writing, is composed of 32 of satellites, in which 24 active satellites orbit in geometrically situated trajectories to provide optimal coverage of the earth's surface (Kumar and Moore 2002:59; NAVSTAR 2020:4). Current GPS satellites generate and transmit pseudorandom noise (PRN) ranging codes which also include navigational information necessary for positioning on Earth's surface. Satellite information and positioning data are broadcasted on L-band frequency carriers L1 (1575.42 MHz) and L2 (1227.6 MHz) containing three specific PRN ranging codes: the precision code (P), the Y-code, and the coarse/acquisition (C/A) code (Figure 2-1) (NAVSTAR 2020:4-5). The P and Y codes are transmitted on the L2 frequency, whereas C/A codes were originally designed for strict use on the L1 frequency. The development of dual-frequency GNSS receivers allowed civilian users the capability to access both L1 and L2 frequencies intended for mitigating ionospheric timing errors (Wright et al. 2012:46). Modern Block II and Block III GPS satellites have the potential to broadcast additional L-band frequencies designed for specific applications and user receivers. Other GNSS systems such as GLONASS, Galileo, and BeiDou utilise similar transmission frequencies that allow users with compatible receivers to implement a tandem configuration for additional global coverage and higher SPS accuracy (Wright et al. 2012:46; Ashjaee 2011).

The Control Segment is a multi-faceted system and serves as the overall management section of the entire GPS network. The Control Segment is divided into four major subgroups where each is assigned specific tasks designed for the maintenance of the entire GPS system

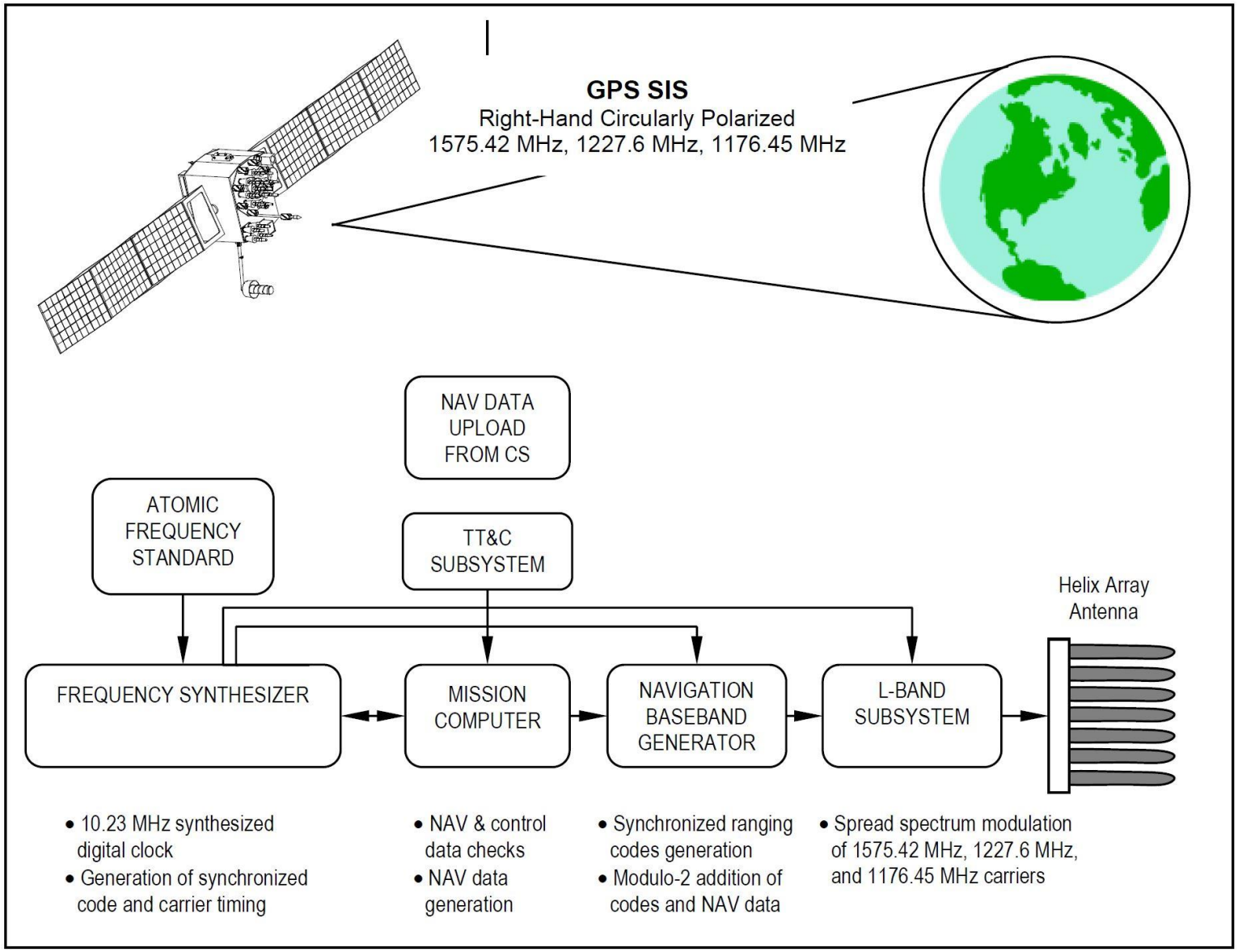


FIGURE 2-1: GPS satellite signal generation flowchart (NAVSTAR 2020:5).

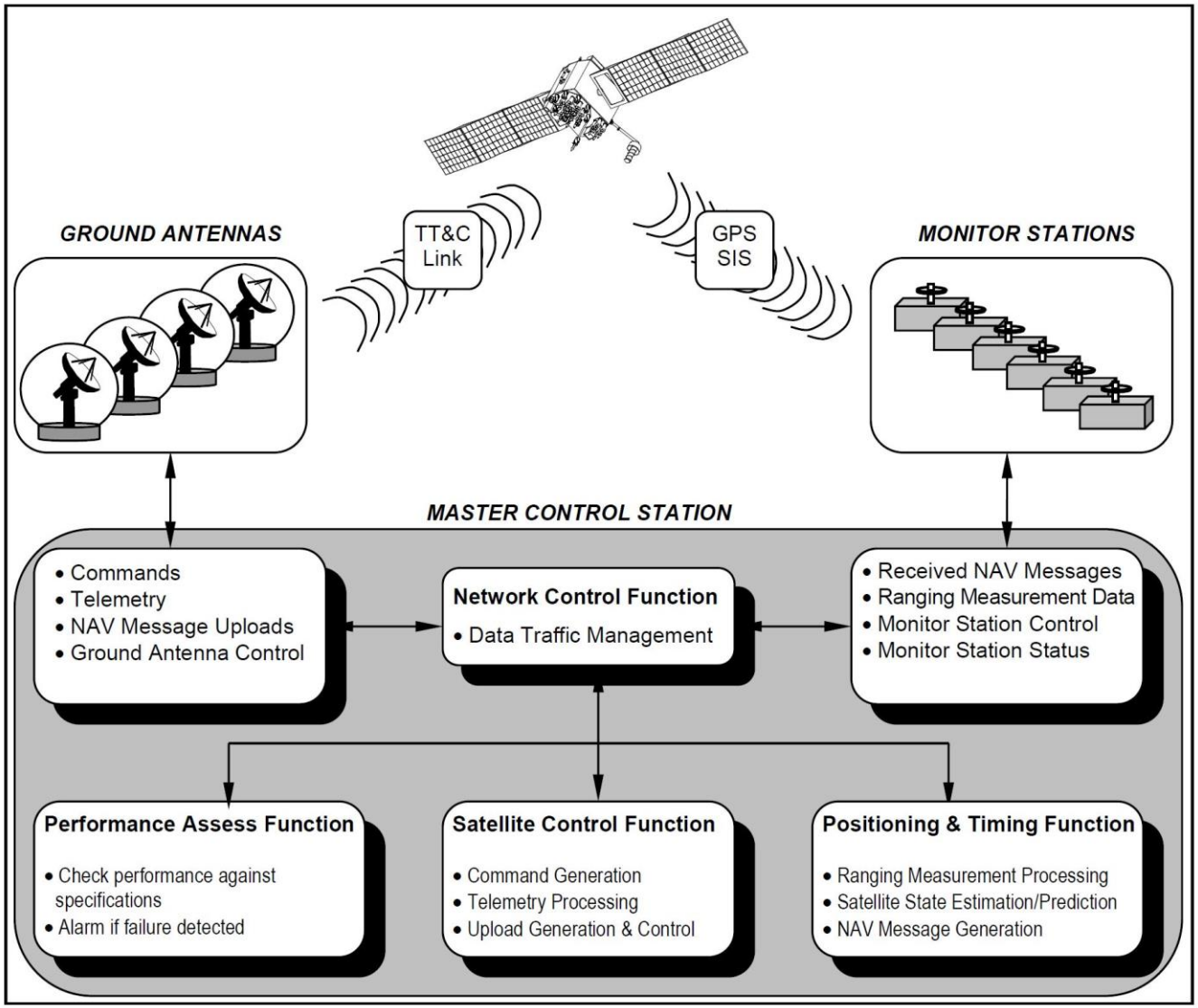


FIGURE 2-2: Master Control Station (MCS) network diagram and functions flowchart (NAVSTAR 2020:8).

TABLE 2-5
SUMMARY OF SPS PERFORMANCE STANDARD METRICS EXAMINED FOR 2019

SPSPS08 Section	SPS PS Assertion	2019 Status	Report Section
3.3.1 SIS Per-Satellite Coverage	100% Coverage of Terrestrial Service Volume	not eval.	3.1.1
3.3.2 SIS Constellation Coverage	100% Coverage of Terrestrial Service Volume	✓	3.1.2
3.4.1 SIS URE Accuracy	≤ 7.8 m 95% Global average URE during normal operations over all AODs ≤12.8 m 95% Global average URE during normal operations at any AOD ≤ 6.0 m 95% Global average URE during normal operations at zero AOD ≤ 30 m 99.94% Global average URE during normal operations ≤ 30 m 99.79% Worst case single point average URE during normal operations ≤ 388 m 95% Global average URE after 14 days without upload	✓ ✓ ✓ ✓ ✓ not eval.	3.2.1 3.2.2 3.2.3 3.2.4 3.2.4 3.2.5
3.4.2 SIS URRE Accuracy	≤0.006 m/s 95% Global average at any AOD	✓	3.2.6
3.4.3 SIS URAE Accuracy	≤0.002 m/s² 95% Global average at any AOD	✓	3.2.7
3.4.4 SIS UTCOE Accuracy	≤ 40 nsec 95% Global average at any AOD	✓	3.2.8
3.5.1 SIS Instantaneous URE Integrity	$\leq 1 \times 10^{-5}$ Probability over any hour of exceeding the NTE tolerance without a timely alert	✓	3.3.1
3.5.4 SIS Instantaneous UTCOE Integrity	$\leq 1 \times 10^{-5}$ Probability over any hour of exceeding the NTE tolerance without a timely alert	✓	3.3.2
3.6.1 SIS Continuity – Unscheduled Failure Interruptions	≥ 0.9998 Probability over any hours of not losing the SPS SIS availability from the slot due to unscheduled interruption	✓	3.4.1
3.6.3 Status and Problem Reporting	Appropriate NANU issue at least 48 hours prior to a scheduled event	✓	3.4.2.1
3.7.1 SIS Per-Slot Availability	≥ 0.957 probability that (a.) a slot in the baseline 24-slot will be occupied by a satellite broadcasting a healthy SPS SIS, or (b.) a slot in the expanded configuration will be occupied by a pair of satellites each broadcasting a healthy SIS	✓	3.5.1
3.7.2 SIS Constellation Availability	≥ 0.98 Probability that at least 21 slots out of the 24 slots will be occupied by a satellite (or pair of satellites for expanded slots) broadcasting a healthy SIS ≥ 0.99999 Probability that at least 20 slots of the 24 slots will be occupied by a satellite (or pair of satellites for expanded slots broadcasting a healthy SIS	✓ ✓	3.5.2
3.7.3 Operational satellite Counts	≥ 0.95 Probability that the constellation will have at least 24 operational satellites regardless of whether those operational satellites are located in slots or not	✓	3.5.3
3.8.1 PDOP Availability	≥ 98% Global PDOP of 6 or less ≥ 88 % Worst site PDOP of 6 or less	✓	3.6.1.1
3.8.2 Position Service Availability	≥ 99% Horizontal, average location ≥ 99% Vertical, average location ≥ 90% Horizontal, worst-case location ≥ 90% Vertical, worst-case location	✓ ✓ ✓ ✓	3.6.2
3.8.3 Position/Time Service Availability	≤ 9 m 95% Horizontal, global average ≤ 15 m 95% Vertical, global average ≤ 17 m 95% Horizontal, worst site ≤ 37 m 95% Vertical, worst site ≤ 40 nsec time transfer error 95% of the time	✓ ✓ ✓ ✓ ✓	3.6.4

Source: *An Analysis of Global Positioning System (GPS) Standard Positioning Service Performance for 2019* (Renfro et al. 2020:5).

(Figure 2-2) (NAVSTAR 2020:7). The Master Control Station (MCS) is located in Colorado at Schriever Air Force Base, and is the primary control centre for the entire GPS system. In the event of a control outage at the MCS, a secondary Alternate Master Control Station (AMCS) can resume system functions and minimise any interruption in the GPS network services. In addition to the MCS and AMCS, are a series of ground antennas and monitoring stations which are strategically placed in various locations throughout the world to ensure the GPS system functions properly and to perform any necessary maintenance to the network.

The GPS SPS undergoes annual performance evaluations as part of its mission to provide the highest possible positional accuracy and coverage for users located throughout the world. The latest published GPS SPS performance report was released in May 2020 (observations from 2019), and the performance analysis was undertaken by the Applied Research Laboratories of the University of Texas at Austin (Renfro et al. 2020). The performance analysis evaluates a series of data in comparison to GPS SPS standards which include: coverage, accuracy, integrity, continuity, availability, and positioning. Table 2-4 (see pg. 56) provides information to which metric standards were evaluated in the latest GPS SPS performance analysis. All of the information in Table 2-4 is thoroughly explained in *An Analysis of Global Positioning System (GPS) Standard Positioning Service Performance for 2019* report and is accessible via the gps.gov website (Renfro et al. 2020). The information contained within these annual reports is useful in understanding the current capabilities of the GPS system and where the technology is leading into the future. Though a majority of the material is not directly pertinent to geophysical surveying, the report serves as a valuable reference in the event of anomalies are present in a dataset that cannot be resolved at the user level.

Geophysical surveyors and archaeologists do not need to know every detail listed in a GPS SPS performance report; however, there are aspects of GPS navigation and positioning within geophysical surveys which require additional understanding beyond the basic functions of a GPS receiver. Among the most important aspects of satellite navigation and positioning are understanding various types of errors which contribute to positional uncertainty and available mitigation techniques. The principal sources of positional uncertainty for satellite navigation and positioning are atmospheric errors introduced during signal transmission through the ionosphere and troposphere (Barker et al. 2000; Betz 2001:227; Fontana et al. 2001; Lohan et al. 2007:767-768). Ionospheric error is attributed to dynamic variations in solar radiation in this region of the upper atmosphere and its predisposition to rapid disparities in electron density impact satellite signal transmission speed (Bilitza 2001:261-275; Budden 2009). Minimal time variations in signal transmission through the ionospheric layer are reported to cause positional uncertainty of ± 5 m (Subirana et al. 2011:1; NovAtel 2018). Irrespective of the substantial positional uncertainty caused by ever-changing solar radiation in the ionosphere affecting signal transmission, this type of error is easily resolved through the use of dual-frequency GPS units which acquire both L1 and L2 frequencies (Trimble 2016:6-7). The dispersion in the ionosphere can be calculated by measuring the delays in the time of reception for both signals. The receiver can then provide a calculated estimate that completely removes ionospheric delay from the pseudorange measurement (Yeh and Liu 1982:324-360; Budden 2009).

Tropospheric error introduces positional uncertainty at a much lower margin when compared to ionospheric error which is estimated to ± 0.5 m (NovAtel 2018). As the lowest atmospheric layer to the earth's surface, the troposphere is susceptible to changes in temperature, air pressure, humidity, and other environmental influences (Hall 1980:219). Reducing

tropospheric error requires supplemental equipment beyond a dual-frequency receiver configuration due to errors present in both carrier phase and coded measurements (Leick and Emmons 1994; Subirana et al., 2011:887; NovAtel 2018). Differential and other real-time error correction methods are commonly used for reducing tropospheric error; however, DGPS corrections do not have sufficient vertical accuracy measurements for processing bathymetric data at the centimetre level and therefore require real-time or post-processed kinematic (RTK / PPK) corrections (Gakscatter 2009). According to Historic England's *Marine Geophysics Data Acquisition, Processing and Interpretation Guidance Notes*, RTK is preferred for its ability to function for both mapping and navigational purposes; whereas, PPK requires specialised software and is limited to mapping only (Plets et al. 2013:13). Traditional RTK is based on the relative positioning of two GNSS receivers that operate in tandem to provide real-time observation data to one or more ground receivers. One receiver serves as the reference base station and remains static throughout the duration of the survey. The base antenna and receiver collect and transmit observation data to the rover antenna and receiver. The rover is moved to multiple unknown locations to determine those positions in locus to the base reference station and orbiting satellites. RTK corrections can produce three-dimensional vector data to centimetre-level accuracy; however, this level of accuracy is entirely dependent upon continuous data stream communication between the base and rover systems via radio frequencies (Donahue et al. 2013:6).

The real-time network/virtual reference station (RTN/VRS) is a more recent error correction concept developed to extend baseline distances between base stations and roving receivers (Chen et al. 2011:1; Donahue et al. 2013:6-7). In the United States, RTN/VRS services vary in regards to the state or region, requiring users to register with respective agencies or

private company and pay any associated service fees (if required, some states offer the service for free). Compared to traditional RTK, RTN/VRS requires less technical experience and user hardware to achieve comparable accuracy to that of RTK surveys with a dedicated GPS base receiver. The primary limitation is the requisite internet connection that provides real-time corrections via a WiFi or LAN connection; however, unlike RTK corrections, the user is not responsible for the maintaining the base station accuracy. The use of multiple reference stations reduces systematic errors that are commonly attributed to an increase in baseline distances. VRS alleviate atmospheric and satellite orbital errors based on observation data collected by multiple base stations within the reference station network, and reduced initialization time improves positional accuracy with extended baselines (Retscher 2002:41).

2.3.2 Ultra-Short Baseline (USBL) Positioning Standards for Geophysical Surveys

Irrespective of contemporary advancements in enhanced positional accuracy and modern components that acquire centimetre-level accuracy at the surface, satellite receivers are incapable of receiving electromagnetic navigation messages while underwater (Whitcomb et al. 1999:346; Kussat et al. 2005:153; Bahr 2009:23; Tan et al. 2009; Yan et al. 2015:809; Ebolese et al. 2018:325-330; Zhang et al. 2018:171-177). The chemical and physical properties of water prevent electromagnetic signal transmission for more than a few centimetres beneath the surface, therefore, requiring supplemental instrumentation for underwater positioning (Hunt et al. 1974; Stewart 1991:230-235; Whitcomb et al. 1999:346-353; Bulusu et al. 2001; Eustice et al. 2008:103; Kunz 2012:8; Jayasiri et al. 2016:1). BOEM, Historic England, and other institutions associated with geophysical and archaeological surveys specifically address this issue in their guidelines and recommend the use of an ultra-short baseline (USBL) acoustic ranging systems

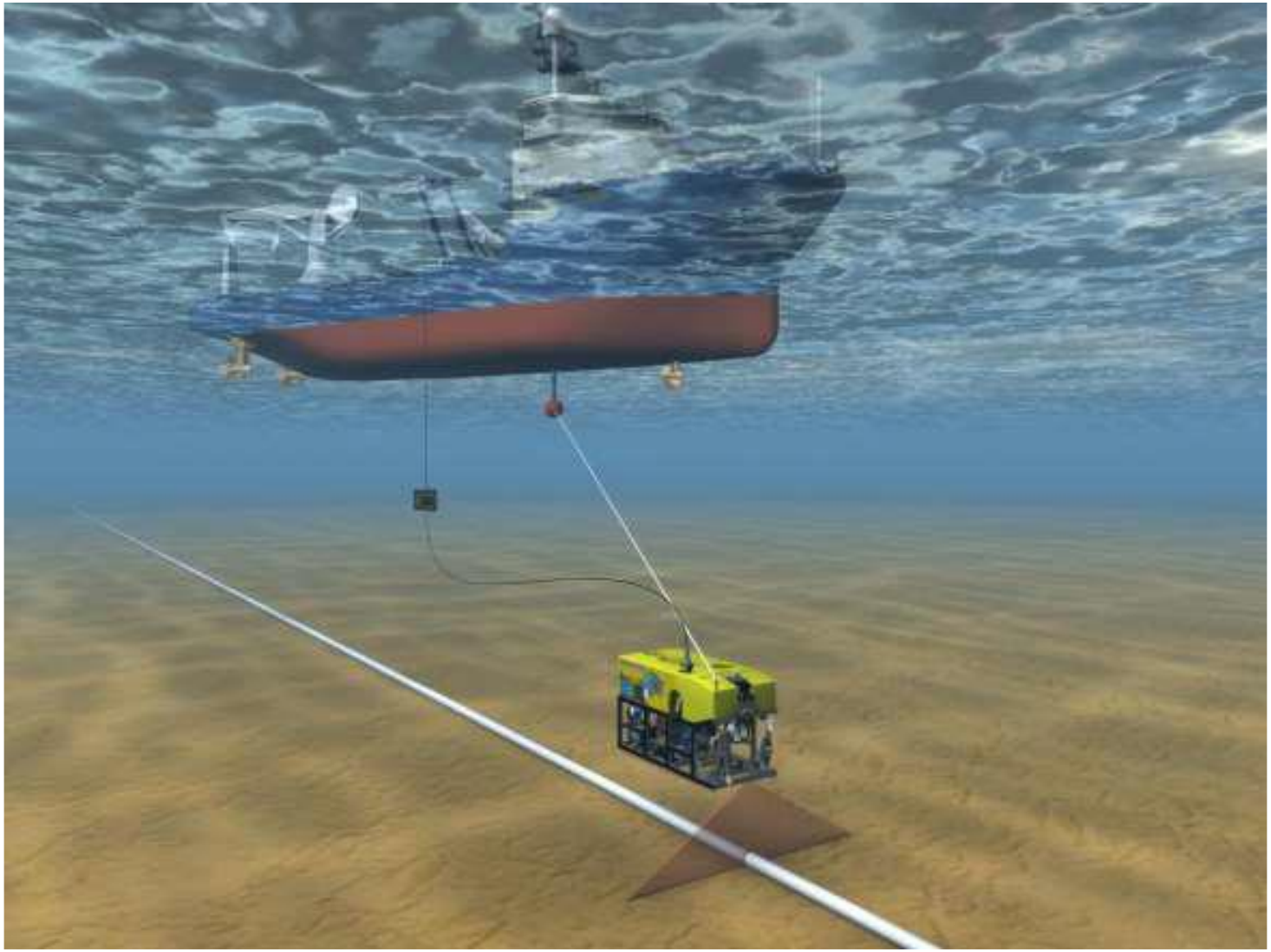


FIGURE 2-3: Illustration of a remotely-operated vehicle (ROV) conducting a pipeline survey while tracked by an USBL system. The white line between the vessel and ROV is representative of the two-way transmission of the acoustic ranging signal used to calculate the underwater position of the ROV (IMCA 2017:3).

for underwater positioning (Figure 2-3) (Plets et al. 2013:13; BOEM 2020a:7-8; BOEM 2020b:7). Although these institutions promote the use of USBL for underwater positioning of towed sensors and other equipment systems, their published guidelines do not provide specific details pertaining to USBL apart from the general description of the technology. A plausible explanation for this omission is to permit the geophysical surveyor some flexibility in determining what type of USBL system is applicable for a specific location and desired underwater positioning accuracy. Due to the absence of this information, this thesis refers to the International Marine Contractors Association (IMCA) *Guidance on Vessel USBL Systems for use in Offshore Survey, Positioning and DP Operations* for recommendations pertaining to USBL specifications, accuracy, function, and configurations (IMCA 2017). The IMCA and their published documents are internationally recognised and implemented throughout the world by geophysical surveyors and other marine-related industries. Additional information pertaining to USBL function from academic and professional studies are used as references for real-world examples of system performance and application.

Ultra-short baseline, and other acoustic time-of-flight (TOF) systems, have assisted offshore navigation and positioning for more than 40 years (Kinsey et al. 2006). The first USBL systems were used as relative positioning systems that operated in conjunction with other offshore short-range radio locational methods (Philip 2003a:18). Technological advances in geophysical surveying have increased technical specification and client expectations regarding underwater positioning capabilities of all sensors used for mapping the seafloor (Philip 2003a:18; Qiu et al. 2012:14; Morgado et al. 2013:142; Ai et al 2015:115; Jakuba et al. 2015; Mandić et al. 2016; Reis et al. 2016:1491; Dajun et al. 2017). Improved USBL design combined with high accuracy satellite navigation systems has increased its popularity for use on projects where other

types of acoustic ranging systems, such as long baseline (LBL), were commonly used (Alcocer et al. 2006; Gamroth et al. 2011:183; Yan et al. 2015:809-826; Batista 2016:1837-1855; Melo and Matos 2016:1-8). Larger systems such as LBL require the placement of seafloor beacons and complex calibration sequences; thus, resulting in the need for significantly increased operating costs and technical expertise (Collin et al. 2000; Gamroth et al. 2011:183; Almeida et al. 2016). Although LBL systems are capable of providing higher precision coordinate measurements, the requirements for successful LBL operation exceed the practicality and efficiency that USBL systems offer for shallow-water applications (Jaffree and Stokey 2005; Qiu et al. 2012:141; Morgado et al. 2010; Morgado et al. 2014:322-330; Campos et al. 2016:1; Reis et al. 2016:1491-1514; Dajun et al. 2017). Modern USBL systems in tandem configurations with high accuracy satellite positioning systems are capable of providing underwater positioning accuracy of just a few metres on the seafloor in depths that exceed 1000 m (IMCA 2017:1).

USBL usage for offshore operations evolved from the need for an underwater positioning system capable of integration with dynamic positioning (DP) systems designed to maintain a specified location above a point on the seafloor (IMCA 2017:3). This was accomplished by placing a transponder on the seafloor which communicated with the shipborne transducer which relayed relative measurements between the two sensors. The reader should note that the use of USBL predates the commercial availability of GPS navigation and positioning receivers; therefore, the measurements used were in X, Y, Z coordinates relative to the transponder position on the seafloor (Figure 2-4) (Enge et al. 1990). USBL continues to operate in this same way, but modern USBL units are capable of integration with high accuracy GPS receivers which provide latitude and longitude coordinates in addition to relative measurements (Orpen and Asheims 2002; Philip 2003b:10-12). In comparison to LBL, which uses multiple seafloor transponders to

calculate the geometric position (comparable to GPS position calculation) of an equipment system, such as an ROV, the USBL is much simpler in terms of setup but careful attention is required when calibrating USBL units (IMCA 2017:3). The use of a single transponder reduces geometric precision in terms of calculating underwater position, but modern USBL technology combined with a sturdy mounting solution and thorough calibration process has promoted USBL systems as the most frequently used type of underwater positioning system for shallow-water surveys.

USBL system specifications and acquirable accuracy pertains to the robustness of the system and the manner in which it is utilised during survey operations. Similar to GPS positioning systems, USBL underwater positional accuracy is dependent upon the quality of the acoustic ranging system and its arrangement on the survey platform. There are several manufacturers of USBL equipment and these companies produce acoustic ranging systems that are tailored to specific industries and operating environments. Manufacturers such as Applied Acoustics Engineering, iXblue, and Sonardyne are among the most well-known in the industry for producing high accuracy underwater positioning systems for a wide variety of applications. Determining what USBL system should be used for a particular survey is typically dependent upon manufacturer stated performance and operating depth. In terms of performance pertaining to positional accuracy, most manufacturers present performance ratings according to slant range. Slant range accuracy is a product of the accuracy of the pitch and roll sensors used to augment the system for vessel movement (IMCA 2017:7). USBL sensors that are permanently attached to a surveying vessel or platform generally have superior tilt sensors in comparison to portable USBL systems with internal tilt sensors. Portable USBL systems typically have less achievable

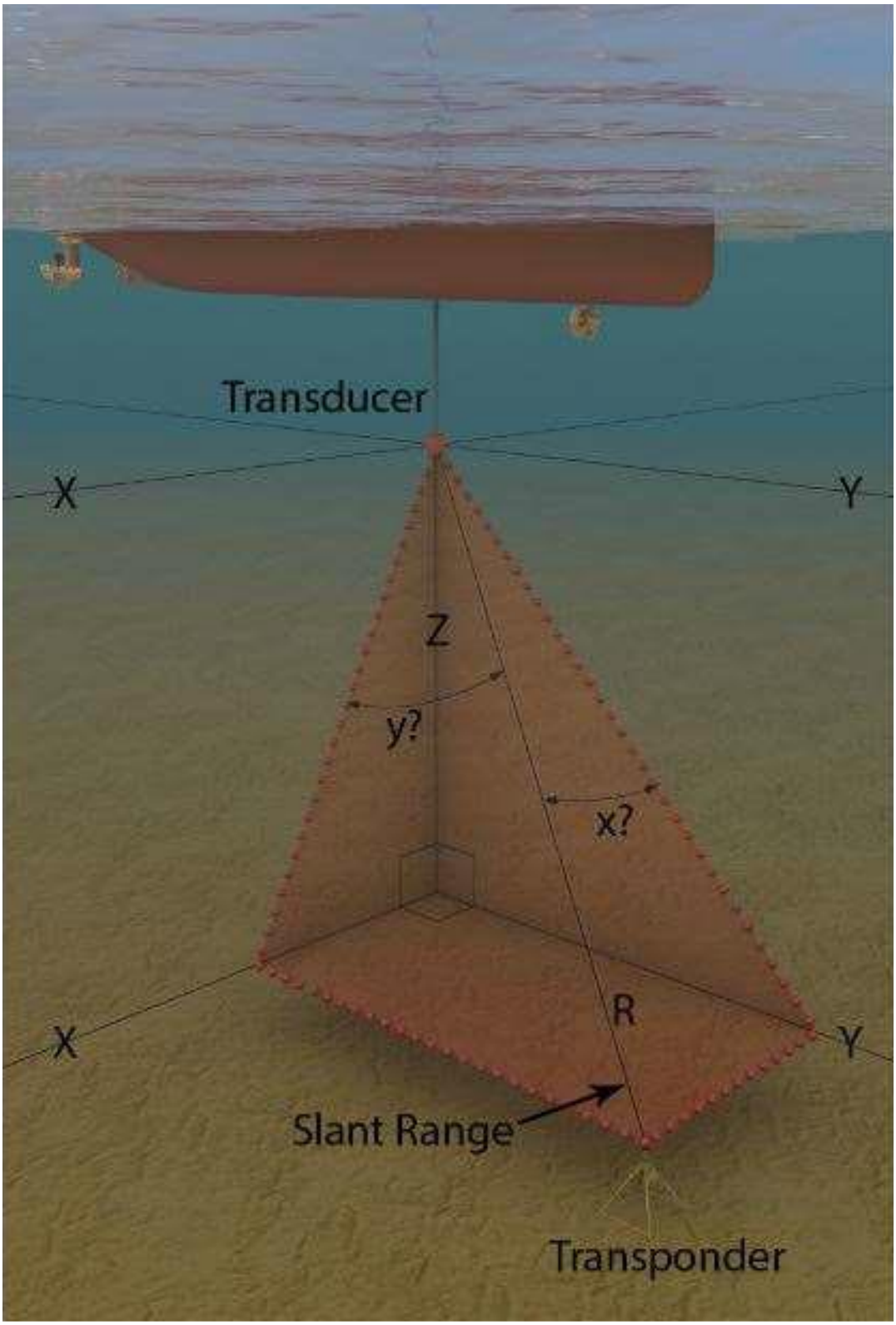


FIGURE 2-4: Illustration depicting USBL geometric positioning of a seafloor transponder (IMCA 2017:5).

accuracy in comparison to permanent vessel- mounted USBL units; however, permanent USBL systems are used for operations in water depths ranging from shallow depths to several thousand metres. If working on sites within typical scientific diving depths (≤ 30 m), geophysical and/or surveys which require diver investigations, archaeologists can rely on quality-made portable USBL units for underwater positioning and diver tracking. It must be noted that USBL system calculations of absolute positioning on the seafloor are directly dependent upon the accuracy of the integrated GPS navigation system (Orpen and Asheims 2002). Any errors in the satellite positioning are included in the USBL positioning uncertainty; therefore, it is good practice to maintain separate logs for each system. By doing so, any gross errors in underwater positioning can be narrowed to the system and environmental conditions at that time. This information is then transferable to an overall positioning log for the survey which can be used for post-survey analysis and in the future for anticipated error budgets as part of the survey proposal process.

The previous paragraph emphasises the importance of utilising quality USBL systems for performance and achievable positional accuracy; but, even the best USBL systems are subject to environmental conditions that affect acoustic signal transmission between the transducer and transponder. USBL systems exist in many different sensor arrangements; however, all require accurate timing calculations of sound signal transmission and reception for determining the slant range between the transducer and transponder (Figure 2-4) (Vickery 1998:5-17; Almeida et al. 2016). Similar to GPS positioning calculations, any variations in the timing measurement of the acoustic signal transmission will result in positional error. What are the variables that contribute to acoustic signal timing errors and how do they affect the signal? The answers to those questions are typically reserved for oceanographic research and not part of maritime archaeological study; however, instrumentation used for geophysical surveys requires a

fundamental understanding of this information and the ability to recognise their effects in real-time and post-survey data analysis. Oceanographic information pertaining to sound wave formation, transmission, and attenuation factors and variables in the marine environment are examined in the subsequent paragraph as they relate to USBL positioning and underwater acoustics in general.

2.3.3 Physical Properties and Characteristics of Underwater Sound

Underwater sound originates in the propagation medium (freshwater or seawater) in the form of longitudinal waves that move as a result of pressure changes created by compression and rarefaction (NOO 1999:1; Lurton 2010:14). A physical characteristic of a longitudinal sound wave is specific regions in which the particles contract (compression) and expand (rarefaction); thus, resulting in pressure fluctuations within the propagation medium and measured in microPascals (µPa) (Urick 2008; Lurton 2010:14). Sound wave frequency is generally defined as the number of wavelengths (crest to crest) passing a specific point at a one-second interval and measured in Hertz (Hz) (Lurton 2010:16). The signal frequency is caused by vibrations at the source, such as a sonar transducer which resonates at a specified rate to produce a precise signal frequency and expressed using the equation below (NOO 1999:1):

$$\lambda = \frac{C}{f}$$

where: λ *= wavelength (m)*
C = sound speed (m/s)
f = frequency (Hz)

In regards to underwater acoustic ranging equipment (and imaging systems), the source of the mechanical vibrations is the transducer which produces an active sound signal that is transmitted through the water column to a transponder unit. Acoustic signal transmission from the transducer

to the transponder and return signal is timed to calculate slant range (baseline); whilst, during the signal transmission in which internal and external variables contribute to timing miscalculations (changes in sound signal speed) thus producing underwater positioning uncertainty (Stewart 2014:20; Jimenez et al. 2016).

The underwater speed of sound is a function of three primary factors: temperature, salinity, and pressure (depth) (MacKenzie 1981:807-812; Munk et al. 1988:8-10; NOO 1999:2-3; Talley et al. 2011:50; Stewart 2014:35). Variability in these three principal influences result in fluctuations in the transmission rate of in-water sound signals which affect acoustic ranging and imaging system performance. The relationship between these factors is calculated using the following formula (Wilson 1960:1357):

$$C = 1449.2 + 4.623t - 0.0546t^2 + 1.391\,(S - 35) + 0.016d$$

where: c = sound velocity in metres per second (m/s)
d = depth (metres)
t = temperature (ºC)
S = salinity in parts per thousand (0/00)

The above equation has been used extensively throughout the world for calculating the underwater sound speed, especially by the U.S. Navy for its oceanographic research and acoustic systems development (NOO 1999; Stewart 2014:35). Additional underwater sound speed equations are currently in use which implement similar data for determining acoustic signal speed, such as (MacKenzie 1981; Munk et al. 1988:8-10; Stewart 2014:35):

$$C = 1448.96 + 4.591t - 0.05304t^2 + 0.0002374t^2 + 0.0160Z + (1.340 - 0.01025t)(S - 35) + 1.675 \times 10^{-7}Z^2 - 7.139 \times 10^{-13}tZ^3$$

where: C = sound velocity in metres per second (m/s)
t = temperature (ºC)
S = salinity in parts per thousand (0/00)
Z = depth (metres)

If calculating the in-water speed of sound using identical temperature, salinity, and depth input values, the difference in the acoustic signal velocity for each equation can be considered marginal for the average observer. Contrary to this observation, even the slightest difference in the m/s rate of signal speed translates to increased horizontal and vertical positioning uncertainty.

Oceanographic research generally attributes temperature as the prime influence affecting any marine or freshwater environment, and is typically the first observation of any underwater acoustics study, but why? As the thermodynamic property of water, temperature directly affects the molecular and atomic energy levels which determines water density (Talley et al. 2011:32). Temperature variations within the upper layers of oceans and freshwater systems are a product of solar radiation caused by geographical and/or seasonal sun and atmospheric conditions (Harrison and Larkin 1998; Stewart 2014:77). This is generally true for the majority of the ocean surface layers with some exceptions in areas of extensive rainfall and the presence of sea ice; whereas, these locations are susceptible to density variations caused by salinity (Leighton 1998:381). Ocean salinity is the aggregate sum of all dissolved solids introduced into the ocean through continental runoff via riverine systems and is directly proportional to chlorine amounts in a given location. Although the electrical conductivity of seawater is predominantly controlled by temperature (heat), salinity content does contribute through the presence or number of dissolved ions. The final major component contributing to underwater sound speed is pressure, which can also be described as depth. Seawater is a compressible medium, which means the molecules within seawater can be pushed together or spread apart depending on the pressure at a specific depth (Talley et al. 2011:39). As the water depth increases the surrounding pressure compresses the molecules more closely together; thus, increasing the density of seawater and slowing the speed of underwater sound.

The earliest studies of these effects on underwater sound speed transmission began during the late 1930s by the U.S. Naval Research Laboratory and the Woods Hole Oceanographic Institute (Herrick 1951:8-9; Hackmann 1979:256; Lasky 1976:2; Namoroto: 2000:110). Sound signal variations had been recorded in previous field examinations of earlier echo-ranging equipment, but the sources causing the changes in sound speed were unknown. The NRL and WHOI team documented water temperature changes and surface conditions contributed to sound speed fluctuations, and recognized the influences of temperature and pressure as sound speed gradients (Klein 1967:43-44). A sound speed gradient is defined as the increase or decrease of temperature/pressure as it travels from one location to surrounding areas. Underwater sound waves are vulnerable to three types of sound speed gradients: positive, negative, and isospeed. Depending on the type of sound speed gradient, the sound wave bends in accordance to the gradient extent and scale. Positive sound speed gradients occur when underwater sound velocity increases with pressure (depth), resulting in an upward bending ray path towards the minimum sound speed depth. Conversely, negative sound speed gradients force the ray path downwards towards the pressure level of minimum sound speed. Isospeed gradients do not affect the ray path which permits the sound wave to travel in a continuous straight line (Leighton 1998: 384-385; NOO 1999:6-7). Given that the ocean and most other bodies of water do not exist in a homogeneous state, underwater sound transmission propagates by way of curved trajectories.

In an effort to predict underwater sound speed at various depths, geophysical survey projects utilise sound velocity profilers (SVP) which provide underwater acoustic signal speed (Figure 2-5). SVPs are produced by a variety of manufacturers and are generally based on operational requirements and depth ratings. The SVPs units are equipped with specialised hardware and software systems which analyse the water temperature, salinity, and pressure at



FIGURE 2-5: Photograph of a CastAway SVP unit after collecting sound velocity data for a geophysical survey off the coast of Maryland, U.S.A., as part of an offshore windfarm project. The image shows the unit screen which displays a depth profile from the surface to 30 m, minimum and maximum sound speeds, and the average velocity. The green line on the display screen demonstrates the variation in sound speed at each depth increment. (Photo by author, 2021).

incremental depths then provide a data file which display the in-water speed of sound that can be uploaded to USBL, MBES, SBP, Ultra High Resolution Seismic (UHRS), and other onboard acoustic systems. The SVP data file adjusts the sensors and software systems for these acoustic units to the in-water speed of sound from the transducer to the seafloor (and below with SBP and UHRS) for precise timing calculations for accurate positioning and imaging resolution. SVP data is updated several times per day throughout the duration of geophysical surveys due to the dynamic nature of oceans, lakes, and rivers; however, the added benefit of modern SVP systems is the ease of use and data application to geophysical survey equipment.

In addition to recognising the environmental variables which contribute to variations in the speed of sound underwater, accurate USBL positioning requires a robust mounting system for survey deployment (IMCA 2017:10). For ocean-going geophysical survey vessels, permanent mounting solutions are available which undergo a verification process by the manufacturer to ensure that the USBL transducer is properly positioned underneath the vessel (through-hull) and with adequate depth beneath the bottom of the hull and away from propulsion systems that generate air bubbles for unobstructed signal transmission. A potentially problematic issue with permanently mounted USBL systems in a through-hull configuration is the inaccessibility for maintenance and/or repair in the event the transducer becomes encrusted with barnacles or damaged. Other variations of through-hull mounting solutions exist which enable the USBL transducer to be lowered and raised through a moonpool, which allows accessibility to the sonar array for maintenance. Another popular mounting solution are fixed rotating mounts which allow the USBL to be deployed over the side of the survey vessel (Figure 2-6). These are typically used on smaller to medium size geophysical surveying vessels and offer an easier installation option in comparison to through-hull configurations. Regardless of which type of mounting solution is



FIGURE 2-6: HAS pole-mount developed by Fugro and installed on the R/V *Westerly* for use on a geophysical survey off the coast of Maine, USA. The MBES, SBP, and USBL transducers were installed on this single pole mount configuration and capable of rotating in the water for sensor deployment and recovery with minimal effort. The survey crew measured the positional offsets of the sensor heads to the central reference point in the middle of the survey vessel. (Photo by author, 2021).

used, precise measurements are required from the USBL transducer to the central reference point, which is typically a GPS antenna arrangement (IMCA 2017:10). The measured offset between the transducer and the reference point are needed to ensure the highest possible positional accuracy and measurement precision for USBL datasets. A major component for geophysical survey vessel mobilisation is USBL calibration and the associated report which demonstrates the purported accuracy of the system and if it falls within survey specifications.

Given the accuracy, ease of use, and cost-effectiveness attributed to USBL units for shallow- and deep-water subsea positioning applications, it is easily discernible why institutions and agencies such as IHO, BOEM, Historic England, and others recommend this technology for underwater positioning. USBL technology is the obvious choice for supplementing underwater archaeological documentation methods based on its accuracy, adaptability, and efficiency. Information from the review of geophysical surveying guidelines and IMCA USBL specifications provides useful insight to the research questions raised in Section 1.2 (see pg. 35), specifically pertaining to the integration of DGPS or real-time error corrected GPS receivers with USBL underwater ranging systems for acquiring sub-metre underwater positional accuracy at general scientific diving depths. The IHO, BOEM, and Historic England guidelines do not provide best practices recommendations regarding archaeological documentation methods in support of geophysical surveying projects in the event such operations are required to supplement geophysical survey data. They did, however, offer the needed information to satisfy the second thesis research question pertaining to what types of equipment can be used for underwater positioning on geophysical surveys. How a coupled GPS/USBL system should be integrated with underwater archaeological documentation methods requires the review of commonly used data acquisition techniques and their positioning referencing strategies.

Understanding how specific archaeological data acquisition techniques are positionally referenced allows this research to move forward with developing an effective methodology which supplements those methods with an integrated GPS/USBL configuration.

2.4 Literature Gap Analysis

Section 2.4 provides a literature gap analysis of selected published references and resources used by this thesis. As part of this analysis, the author created TABLE 2-6 (see pgs. 95-98) which includes nearly 100 cited references with information pertaining to underwater positioning methods within the archaeological, hydrographic/oceanographic, and marine sciences disciplines. The cited references are presented in chronological order so that they reader can visualise technological developments and methodological improvements for underwater positioning, tracking, and localisation. To assist the reader, the author colour-coded table rows according to the type of technology/methodology used for calculating absolute geospatial data.

In review of the information presented in TABLE 2-6, there is a glaring omission of absolute geospatial information in modern digital photogrammetry surveys conducted by maritime archaeologists throughout the world starting in 2012 through the present day. The spatial control (if any) for these projects were relative measurements used to calculate site feature dimensions which are inapplicable for georeferencing or localising any ground control points within an established reference frame such as UTM, WGS84, NAD83, etc. There were some earlier archaeological studies which included underwater acoustic measuring devices, such as the SHARPS and HPASS systems, however these systems were not designed to provide absolute geospatial coordinate information, but rather as a digital means to replace measuring site features with fiberglass tapes (Broadwater 1992; Cantelas 1997; Green and Duncan 1998;

TABLE 2-6
LITEATURE GAP ANALYSIS

Reference	Year	Site	Environment	Depth (m)	Survey Technique/s	Positioning Technology	Discussion of Absolute Positional Accuracy
Hastings	1949	N/A	N/A	N/A	N/A	Raydist	20-ft at 25 Miles Distant / Linear Distance
Green	1973	Cape Andreas	Cyprus	< 50	Swimline	Transits, Sextant	Transits were ineffective, Sextant was preferred
Throckmorton et al.	1973	Battle of Lepanto	Mediterranean Sea	Surface	MAG, SSS, SBP	Transits	±400 m, locating general area of the site
Broadwater	1975	USS *Monitor*	Atlantic Ocean	Surface	MAG, SSS, Diver	Transits, Raydist	2 m (Raydist), linear data for general mapping
Arnold	1981	N/A	N/A	N/A	Aerial Photographic	Point Triangulation	None
Schurer & Linden	1984	*Tonquin*	Templar Channel, BC	Surface	SBP	Marinav Trisponder (micro)	3 m, 4-sec update rate from microwave stations
Rule	1989	Multiple Historic Wrecks	Various	< 30	Direct Survey Method	Reference Datum (Relative)	No absolute georeferencing / localisation
Franklin et al.	1991	Pensacola Shipwreck	Gulf of Mexico	< 10	MAG, SSS, Diver	Si-Tex LORAN C EZ-97	Accuracy = 0.1 - 0.25 nautical miles
Broadwater	1992	Yorktown	York River, VA	6	Acoustic Ranging X, Y, Z)	SHARPS (Relative)	No specific data other than identified errors
Arnold	1993	Navidad River Wreck	Matagorda Bay, TX	Surface	MAG, SSS	Trimble Handheld GPS	15m uncertainty, used for survey navigation
Lurton & Millard*	1994	Test Site	Deep Ocean	N/A	AUV	VLBL, GIB, GPS/GLONASS	30 m reported source error at 40-100 km range
Henderson & Burgess	1996	Crannog (NN 57705)	Lake of Menteith	7	Linear Distance	Total Station, Pole (8 m)	Use and accuracy of method limited by depth
Arnold	1996	*Belle*	Matagorda Bay, TX	Surface	MAG	Trimble DGPS (Satellite)	±3 m, 1 sec update, USCG error corrections
Cantelas	1997	*Queen Anne's Revenge*	Atlantic Ocean	8	Acoustic Ranging (X, Y, Z)	SHARPS (Relative)	Mentions discrepancies and difficulties in use
Smith & Kronen*	1997	Atlantic Ocean	Deep Ocean	N/A	AUV	Doppler Sonar, SBL, DGPS	SBL = 6-in (1σ), Doppler for AUV navigation
Green & Duncan	1998	Test Site	Bathers Bay, Australia	7	Acoustic Ranging (X, Y, Z)	HPASS (Relative)	X=23 mm, Y=36 mm, Z=45 mm
Vickery*	1998	N/A	Deep Ocean	N/A	Acoustic Positioning	LBL, SBL, USBL,	Frequency dependent, 0.01 - 5 m relative data
Alves et al.	1998	Historic Shipwreck	Aveiro Ria, Portugal	4	Direct Survey Method	Scale Bar (Relative)	No absolute georeferencing / localisation
Leonard et al.*	1998	Test Sites	Deep Ocean	N/A	AUV	LBL, USBL	Acoustic systems for AUV navigation
Watts & Mather	1998	CSS *North Carolina*	Cape Fear River, NC	< 10	Phase I, II, III Surveys	Baseline, Trilateration	No absolute georeferencing / localisation
DeAngelis & Whitney*	2000	N/A	N/A	N/A	AUV	INS, Doppler Sonar, GPS	No error data, study was for AUV navigation
Collin et al.*	2000	N/A	N/A	Surface	N/A	Inverted LBL, GPS	Data presented in hypothetical relative format
Yuh*	2000	N/A	N/A	N/A	AUV	INS, Doppler Sonar, GPS	Mentions USBL units, ±0.15 cm typical accuracy

Green & Souter	2002	HMS *Pandora* / Roman	Australia / Netherlands	30 / 6	Acoustic Ranging (X, Y, Z)	HPASS (Relative)	35 mm RMS error / 30 mm RMS error
Holt	2003	Test Site	Fort Bovisand	10	Fiberglass Tapes	GCP Network (Relative)	1σ - 25 mm error for up to 20 m measurements
Phillip*	2003a	Use and Calibration	Deep Ocean	Ocean	AUV, ROV	USBL, RTK-GPS	Accuracy = 10 cm, with Lat/Lon Data
Phillip*	2003b	Use and Calibration	Deep Ocean	Ocean	AUV, ROV	USBL, RTK-GPS	Accuracy =10 cm, with Lat/Lon Data
Holt	2004	*Mary Rose*	Portsmouth	10	ROV, Diver	LBL, GPS	Accuracy = 0.21 (2σ)
Thomson*	2004	U/W Localisation	Vancouver Island	60-130	AUV	VENUS cabled hydrophones	Accuracy = 40 cm (horizontal), 70 cm (vertical)
Caiti et al.*	2005	Test Site	Deep Ocean	150	AUV	GIB, DGPS	Accuracy data presented in relative XYZ format
Jaffre & Stokey*	2005	USBL Operation Study	Woods Hole	< 30	REMUS AUV	USBL (Relative)	USBL used for AUV docking
Kusat et al.*	2005	N/A	San Diego, CA	300	AUV	LBL, RTK-GPS	Transponder = 8 cm (2-σ), Ship = 10 cm (2-σ)
Alcocer et al*	2006	Test Site	Portugal	50	AUV, ROV	GIB, DGPS	Limited information for accuracy results
Chandrasekhar et al.*	2006	Senor Localisation	Deep Ocean	Ocean	AUV, ROV	Acoustic Network, GPS	Accuracy = 1 m at 0.5 km, 1 - 10 m at 3 x 4 km
Kinsey et al.*	2006	N/A	Deep Ocean	Ocean	AUV	LBL, GPS	12 kHz LBL Accuracy = 0.5 - 10 m (5-10 km)
Zhou et al*	2006	U/W Sensor Network	Deep Ocean	Ocean	AUV, ROV	LBL, GIB, DGPS	Error discussed in relative X,Y, Z, but
Collins & Baldock**	2007	Brittlestar Surveys	Purbeck MWR, Dorset	16 - 23	Drift Diver Survey	Buoyed GPS / Rec Computer	GPS accuracy = 10 m, no angle offset data
Drap et al.	2007	Pianosa	Pianosa Island, Italy	35	ROV / Photogrammetry	Sonardyne USBL, DGPS	ROV positioning tracked with DGPS / USBL
Eustice et al.*	2007	Atlantic Ocean	Deep Ocean	N/A	AUV	Doppler Sonar, GPS, USBL	USBL used as verifying positioning source
Jakuba et al.*	2008	Hydrographic Study	Gakkel Ridge, Artic	Below Ice	AUV	LBL, GPS	LBL positioning used for AUV navigation
Bahr*	2009	Oceanography	Lake Grey, ME	Surface	AUV, ASC	Acoustic modem, GPS	Accuracy varied according to instrumentation
Tan et al.*	2009	Test Site	Deep Ocean	Ocean	AUV, ROV	LBL, GPS	Accuracy = 0.05 - 0.4 m
Morgado et al.*	2010	TRIDENT Project	Lisbon	2.5	AUV, ASV	USBL, DGPS	Accuracy = 0.3 m, slant range 21.5 m
Gamroth et al.*	2011	N/A	N/A	30	Buoys	Inverted LBL, SPS-GPS	Receiver motion resolved to ±10 cm
Kebkal et al.*	2011	USBL Operation Study	Pool Testing	3.5 - 4.5	AUV	USBL, GPS	Accuracy = 1.5 mm (1σ)
Mahon et al.	2011	Pavlopetri	Mediterranean Sea	Surface	Stereo-Vision	Total Station, GPS Camera	GPS camera operated at surface
Aparicio et al.*	2012	Test Sites	Simulated Testing	N/A	AUV, ROV	Inverted LBL, GPS Omitted	Study was designed for relative positioning w/ LBL
Henderson et al.	2012	Pavlopetri	Mediterranean Sea	1-4	Sector Scan Sonar (SS)	Total Station, GPS	3.5-5 cm with total station, ±50 mm with SS/GPS
Kuch et al.**	2012	Test Site	Mediterranean Sea	N/A	Diver	Telit GM862 Handheld GPS	GPS accuracy = < 5 m, Overall = unquantifiable

Kunz*	2012	Test Sites	Deep Ocean	N/A	AUV	LBL, USBL, MBES, DGPS	Acoustic systems for AUV navigation
Mahiddine et al.	2012	Arles-Rhône 13 Wreck	Rhodano River, France	5-6	Digital Photogrammetry	No Observed Spatial Control	No absolute georeferencing / localisation
Qiu et al.*	2012	U/W Communication	Lab Study	N/A	AUV, ROV	USBL	USBL acoustic channel study, no POS data
Skarlatos et al.	2012	4th Century BC Wreck	Mazotos, Cyprus	45	Digital Photogrammetry	Scale Bar (Relative)	No absolute georeferencing / localisation
Westoby et al.	2012	N/A	N/A	Surface	Digital Photogrammetry	GCP Network, DGPS	Absolute positioning for terrestrial sites
Diamanti et al.	2013	Hellenistic Shipwreck	South Euboean Gulf	40-47	Digital Photogrammetry	GCP Network (Relative)	No absolute georeferencing / localisation
DeMarco et al.	2013	Diver Tracking	Indoor Diving Well	N/A	ROV	Forward-Looking Sonar	Used sonar to identify and track divers
Morgado et al.*	2013	USBL / INS Validation	Sesimbra, Portugal	2	AUV, ROV	USBL, INS, RTK-GPS	RTK Accuracy = < 4 cm, USBL = 1.3 - 2 m
Niedzwiedz & Schories	2013	Test Site	Baltic Sea	5-40	Diver, Scooter	Garmin 76csx Handheld	GPS = ±3-10 m, Overall error = unquantifiable
Packard et al.**	2013	Shark Survey	Cape Cod, MA	60	AUV	USBL, GPS, ADCP	Config. used to track transponders on sharks
Viola et al*	2013	NEMO Tower Install	Capo Passero	3500	ROV	USBL, DGPS	Accuracy on the seabed = 1 m
Gawlik	2014	Historical Shipwreck	Trondheim Harbor	60	ROV / Photogrammetry	GPS / IMU Camera	Each photo from ROV was given lat/lon data
McCarthy	2014	Aberlady Church Yard	East Lothian, Scotland	Surface	Digital Photogrammetry	Total Station, GPS	Absolute positioning for terrestrial sites
McCarthy & Benjamin	2014	Historic Wrecks	Baltic, North Sea	30	Digital Photogrammetry	No Observed Spatial Control	No absolute georeferencing / localisation
Morgado et al.*	2014	USBL / INS Validation	Lab Study	N/A	AUV, ROV	USBL, INS, RTK-GPS	Evaluation of coupled USBL / ISN system
Seddik et al.*	2014	U/W Localisation	Deep Ocean	Ocean	AUV	Doppler Velocity Log	Study focused on relative positioning for AUVs
Balletti et al.	2015	Cape Granitola, Italy	Mediterranean Sea	< 8	Digital Photogrammetry	GCP, RTK-GPS	Shallow water survey using RTK GPS with pole
Bianco et al.	2015	Baia	Naples, Italy	5	Digital Photogrammetry	Scale Bar (Relative)	No absolute georeferencing / localisation
Capra et al.	2015	Roman Amphora	Olbia, Italy	15	Digital Photogrammetry	Calibration Frame (Relative)	No absolute georeferencing / localisation
Choi & Choi*	2015	Shore-Based Test Site	Daejeon, Korea	N/A	AUV	IMU, USBL, DGPS	<1 m with combined inertial / acoustic setup
Diamanti & Vlachaki	2015	Multiple Sites	South Euboean Gulf	22-47	Digital Photogrammetry	Scale Bar (Relative)	No absolute georeferencing / localisation
Jakuba et al.*	2015	Deep AUV Navigation	Deep Ocean	Ocean	AUV, ROV	Inverted USBL	Improved relative accuracy, no POS data
Maas	2015	N/A	N/A	N/A	Digital Photogrammetry	No Observed Spatial Control	No absolute georeferencing / localisation
Munafò et al.*	2015	U/W Localisation	Sesimbra, Portugal	Ocean	AUV	GIB / DGPS Network	AUV navigation and localisation
Muzzupappa et al.	2015	ROV Site Maintenance	Deep Ocean	Ocean	ROV	USBL, IMU, GPS	AAE EasyTrack USBL unit

Van Damme	2015	Straatvaarder Wreck	Rotterdam	16-20	Digital Photogrammetry	No Observed Spatial Control	No absolute georeferencing / localisation
Viola et al*	2015	Observation Study	Capo Passero, Italy	N/A	KM3Net Telescope	Combined LBL / USBL, GPS	Accuracy = 10 cm
Yan et al.*	2015	UXO, Marine Bio	Simulated Testing	Ocean	AUV, ROV	Inverted LBL, GPS	Accuracy information presented in relative format
Ai et al.*	2016	Underwater Positioning	Deep Ocean	Ocean	AUV	USBL, FLS, DGPS	Accuracy = 0.98 m (1σ)
Almeida et al.*	2016	Test Site	Leixões, Portugal	N/A	Acoustic Navigation Buoy	LBL, DGPS	Accuracy = 0.6 m RMS
Brennan et al.	2016	Ancient Shipwrecks	Aegean / Black Seas	Ocean	SSS, MBES, ROV-Stereo	No Defined Spatial Control	SSS/MBES is likely localised, no info on ROV
Casella et al.	2016	Coral Reef Mapping	Moorea, Polynesia	Surface	Aerial Bathy / LiDAR	GCPs, Handheld GPS	Poor positioning data due to handheld GPS
Jayasiri et al.*	2016	Plume Boundary	Deep Ocean	Ocean	AUV	Inverted USBL, DGPS	USBL used for AUV navigation / localisation
Khan et al.*	2016	ASV Localisation Fleet	Pool Testing	3	AUV, ASV	Inverted LBL, DGPS	Suffered signal multipath issues due to pool walls
Majid & Arshad*	2016	Localisation Strategy	Deep Ocean	Ocean	ASV, AUV	Acoustic Hydrophone Array	AUV localisation using ASV as the sonar array
Mandić et al.	2016	U/W Object Tracking	Biograd na Moru	< 50	AUV	USBL, MBES, DGPS	Acuracy = 0.7 - 1.2 m (static and moving targets)
Melo & Matos*	2016	Hydrographic Study	Shallow	Surface	AUV	Inverted LBL, DGPS	Accuracy = 1.4 - 2.1 m RMS
Valente*	2016	Passive Acoustic Track	Leixões	< 10	ASV, AUV	Hydrophone on ASV	Accuracy between ASV, AUV = 1.39 m
Zhang et al.*	2016	Test Simulation	China	N/A	AUV	SINS, LBL	LBL positioning used for AUV navigation
Rodionov et al.*	2017	Test Site	Vladivostok	Nearshore	AUV	Acoustic Modem, DGPS	Limited information, states several centimetres
Aragón et al.	2018	Punic / Roman	Majorca, Spain	70	Digital Photogrammetry	Scale Bar, GCPS (Relative)	No absolute georeferencing / localisation
Beltrame & Costa	2018	Byzantine / Roman	Sicily	< 8	Digital Photogrammetry	Total Station, GCPs, RTK	Model Accuracy = 0.03-0.05 m, limited by depth
Pacheco-Ruiz et al.	2018	Early Bronze Age	Ropotamo, Black Sea	< 3	Digital Photogrammetry	Total Station, GCPs, RTK	Data is georeferenced, but focused on imagery

Notes:
No asterisk – Archaeology Study; * - Hydrographic / Oceanographic Study; ** - Marine Biology /Botany Study

Green – Land-based and/or surface positioning method; Purple – Buoyed/Floating GPS method for underwater positioning; Orange – Underwater acoustic method for underwater positioning (LBL, SBL, USBL, etc.); Red – No underwater absolute positional information for georeferencing and/or localisation of collected data; Blue – Water depth column

Green and Souter 2002). The report by Frank Cantelas (1997) described the difficulties in the use of the SHARPS system on the *Queen Anne's Revenge* wreck site located in Beaufort Inlet, North Carolina. Following the study conducted by Jeremy Green and Corioli Souter (2002) on the HMS *Pandora* and the Roman bridge sites, there is no more mention of either the SHARPS and HPASS acoustic measuring systems. It can be reasonably assumed this was due to the complicated nature of the equipment setup, calibration, operation, and post-processing needed to collect site feature measurements. In 2003, a study by Peter Holt demonstrated the measurement precision of fiberglass tape measurements over specific distances which rivalled that of the relative acoustic systems, SHARPS and HPASS. Obviously, the objectives of these studies were to present alternative methods of measuring site features using relative calculations; however, there is an absence of absolute geospatial information in these field projects which was carried over into archaeological projects utilising traditional surveying and digital photogrammetry techniques from the early 2000s to the present day.

The archaeological projects during the early 2000s to the present day which utilised digital photogrammetry were actively engaged in solely improving the visual quality of the data, which is important, but serves as incomplete dataset without the requisite absolute geospatial information to state where the acquired data is referenced in space. The capabilities for maritime archaeologists to georeference their collected datasets with absolute positional information were readily available throughout the world from the early 2000s to the present day; however, very few incorporated such data into their workflows, and those that did typically used shore-based positioning systems for shallow water sites in close proximity to land or it was used in conjunction with deep-water sites utilising ROV technology. But, why? This research attributes the lack of integration of underwater acoustic ranging and satellite positioning systems with

maritime archaeological survey operations is a result of the unfamiliarity with the technologies and unawareness of the IHO, BOEM, and Historic England spatial guidelines and best practices recommendations. The information presented in Sections 2.2 and 2.3 is generally unknown to maritime archaeologists from the student level to professional practitioner, and is evidenced in the selection of references presented in TABLE 2-6. This is possibly a result of this information not being included in academic curriculum, and a review of graduate-level textbooks from the 1990s through the present day, revealed an omission of LBL, SBL, USBL technology, regardless of the fact that USBL, created as a standalone dynamic positioning system, has been in continuous use since 1977 (Phillip 2003a; Green 2004; Bowens 2009; Babits and Van Tilburg 2013). As stated previously, there are some exceptions which reference deep-water archaeology with the use of acoustic pingers for tracking ROVs. This informational gap has resulted in a geospatial problem which is prevalent throughout the maritime archaeology discipline. This problem carries over into modern archaeological projects pertaining to offshore energy, increased marine infrastructure, and a growing global commercial shipping industry which can negatively affect underwater cultural heritage sites.

2.5 Literature Review Summary

The review of information pertaining to modern geophysical survey spatial standards and equipment systems contributed to this thesis by forming the technical and operational bases for the UALR methodology concept development and field application. In the introductory chapter of this thesis (see pg. 24), the author stated this research was designed for commercial geophysical surveying applications; therefore, the current regulations and guidelines under which geophysical surveys are conducted, likewise apply to this thesis. Because of this, the author heavily focused on geophysical surveying standards and requirements published by the IHO,

BOEM, and Historic England. Whilst the IHO standards provide a general set of spatial and resolution guidelines in accordance to water depth, BOEM and Historic England published materials are more concentrated on required positioning equipment systems, archaeological considerations for underwater cultural heritage, and best practices recommendations. In compliance with the underwater positioning requirements and equipment recommendations from BOEM and Historic England, the author performed a review of all available satellite positioning and underwater acoustic ranging systems which contributed to UALR methodology equipment selection (see Chapter 3, pgs. 102-155) (Plets et al. 2013; BOEM 2020a; BOEM 2020b). The following chapters which include UALR methodology research design (see pg. 102), field work case studies (see pg. 183), and the discussion of the case studies (see pg. 274), are grounded in the foundation based on information from the literature review chapter.

3.0 Materials and Methods

The development of the UALR methodology is based on the synthesis of research questions, review of relevant geophysical surveying standards, examination of modern technologies pertaining to satellite and underwater positioning systems, and a linear research design which was gradually refined through a series of field examinations for practical use as part of conventional maritime archaeological site documentation for supplementing geophysical survey datasets. Section 3 is divided into four main categories which examine details pertaining to all aspects of common offshore geophysical surveying operations and how the UALR methodology fits into that overall process, the UALR methodology's subsurface positioning data acquisition practices, spatial data analyses, and the manner in which the positioning information is applied to archaeological research and the protection of submerged cultural remains. The three primary categories are further dissected to provide the reader with useful insight to the inner workings of each process and how all of the equipment and techniques come together to form the overall UALR methodology.

3.1 Geophysical Survey Overview

Prior to examining the intricacies associated with the UALR methodology and how it supplements geophysical surveying activities in support of archaeological priorities, the following paragraphs provide information describing common commercial geophysical survey characteristics, equipment specifications, end products, and how that information is used. This information is included in Section 3.1 because this material is needed to develop the reader's understanding of all aspects pertaining to geophysical surveys and how submerged cultural resources are viewed throughout the entire process from the project beginning to the end. For the reader's clarification, this information is based on the author's professional experience as both an

archaeologist and geophysical surveyor. Details pertaining to particular project specifications are intentionally omitted due to stipulations of project nondisclosure agreements; however, the author provides generalised information so the reader can develop a working knowledge of how geophysical surveys are undertaken with a particular emphasis on archaeological considerations. The information pertaining to geophysical surveys provided in the following paragraphs permits the reader to better understand where the UALR methodology fits into the overall geophysical surveying process and why it is needed to improve archaeological spatial data acquisition in support of both geophysical survey and archaeological objectives.

Let us begin with an overall definition and description of a geophysical survey: what is it and what is the purpose? Using a term most maritime archaeologists are familiar with; a geophysical survey can be regarded as a much more sophisticated version of a typical marine remote sensing survey using equipment systems such as marine magnetometers, side scan sonars, and sub-bottom profilers. Within the last few decades these data acquisition systems have become common on most Phase I (or non-disturbance) archaeological surveys which provide researchers with basic information of any submerged cultural remains within a survey area. The data generated by marine remote sensing surveys typically includes two- and/or three-dimensional acoustic imagery and magnetic data which is then processed and used to plot and potentially identify submerged cultural remains. Geophysical surveys are conducted in a similar manner; however, the survey area, volumes of sensor data, the number and types of sensors, survey vessels, and number of onboard personnel are of a much larger scale. Geophysical survey objectives often include mapping large swaths of area for offshore wind turbine structures, drilling platforms, fibre optic cable and pipeline routes, and dredging operations. The legal and financial significance of these objectives require strict adherence to project specifications that are

well-beyond the typical permitting requirements (if any) for archaeological surveys like small marina construction or university field schools.

Submerged cultural materials are at the forefront of most geophysical surveys in which specified equipment requirements and operational parameters, such as survey line spacing, are utilised to ensure adequate detection probability. The same acoustic and magnetic sensor datasets used by geoscientists and marine construction firms to build offshore structures and corridors are used by project maritime archaeologists to identify and map potential submerged cultural remains. There is not a general consensus within geophysical surveying as to what constitutes an anomaly that could potentially be cultural remains; therefore, many projects will typically establish guidelines defining what should be considered an anomaly and marked for archaeological review. Similar to that of archaeological marine remote sensing surveys, the guidelines defining what anomalies should be reviewed take several factors into account such as geographic location leading to a higher probability of prehistoric/historic maritime navigation, previously discovered wreck sites within the vicinity of the survey area, submerged paleolandscape geological features, and the physical dimensions of a probable target. Depending on these factors, the project archaeologist may put forth the recommendations to establish an archaeological exclusion zone and/or more detailed site investigations to identify what the anomaly is and if it qualifies for protection under the preservation laws for that specific body of water. Regardless of whether an anomaly is confirmed as submerged cultural materials, there is a heavy emphasis in geophysical survey projects to perform data acquisition and site characteristic investigations in a timely and efficient manner to maintain the overall project schedule. Both project surveyors and archaeologists are on the clock to ensure all of the work is done as quickly

as possible to avoid any delays that can result in substantial legal and financial consequences in accordance to the agreed upon contractual and permitting documents.

Geophysical surveys use software programs such as HYPACK, Qinsy, CARIS, and a host of others for creating survey lines in which the vessel is to navigate during data acquisition. All data acquisition and satellite positioning systems are linked through these software programs in which the same positioning information is applied to each sensor. By doing so, data produced by each sensor can be used to verify the positions of both geological and cultural anomalies. The survey lines are evenly spaced (typically 15m) to allow magnetic sensor detection and to permit acoustic sensor overlap between parallel lines to ensure that the required coverage is achieved. The survey area length can extend dozens of kilometres offshore; whereas, the survey area width can vary from a few hundred metres to several kilometres. Using a 15m line spacing, it is easily discernible that large survey areas require a substantial amount of time and resources to adequately document the seafloor and underlying sediment; thus, maintaining the project schedule is of critical importance to the geophysical surveyors and client. In an effort to make sure that all systems acquire data within specific parameters, the geophysical survey vessel undergoes a mobilisation process and calibration test. The mobilisation process includes setting up the onboard data acquisition systems in the manner they will be utilised during the actual survey. After the completion of vessel mobilisation, the geophysical survey crew conducts a series of calibration tests to verify that the data acquisition systems are in working order. The calibration tests can vary from a few days to several weeks depending on the number of systems and if all function as required. Following the successful result of the calibration tests, the geophysical survey crew provides the project archaeologist and client with a mobilisation report

which provides documentation that all onboard systems are functioning within required specifications.

Geophysical survey data is collected, processed, checked, and re-checked to ensure 100 - 200% sensor data coverage as required by IHO order specifications (IHO 2020:12-13). If sensor data gaps are reported, the geophysical surveyor is required to re-run that area to fill in that particular gap. At times sensor data gaps are unavoidable due to the presence of fishing gear, steeply sloping bottom topography, and limited vessel manoeuvrability in confined bodies of water (for examples see Section 3.4, pg. 162); therefore, what can be done to fill in the data gap and satisfy archaeological requirements in the event that submerged cultural remains are suspected within the data gap? Realistically, there are only a few options available to fill in the sensor data gap which include:

1). Undertaking a diver and/or ROV site investigative survey to supplement available sensor datasets.

2). Altering the survey area to locations that allow full sensor data coverage.

3). Getting authorisation from the project archaeologist and/or client to solely rely on an incomplete dataset then clearing the area for ground disturbance.

Clearly, option three is the least favourable; however, the author has witnessed this option implemented more than the other mentioned possibilities. Option two is reasonable in that it can increase the likelihood of detecting submerged cultural materials with the required sensor resolution and coverage per IHO order specifications; yet, altering a cable or pipeline corridor may not be possible due to permitting requirements, environmental impact, legal issues, navigable channels, and many other preventative factors. Option one is the ideal course of action and the use of underwater acoustic tracking systems are proven to work in conjunction ROV surveys, but ROVs are not practical for reconnaissance or ground-truthing surveys in shallow

water locations with limited visibility preventing the use of photography or videography systems, in areas inundated with fishing gear due to the potential of a fouling hazard, and not cost- or time-efficient. The use of ROVs for offshore and deep-water segments of a geophysical survey is common practice where diving operations may not be feasible; nevertheless, trained archaeological divers represent the best possibility for identifying and mapping cultural materials in shallow water locations where geophysical survey sensors are not capable of producing full datasets which satisfy permitting requirements.

If certified archaeological divers are the best option for shallow water operations to supplement and/or verify incomplete sensor data, why are diver site investigations typically the last resort? The answers are:

1). There are no commonly used archaeological site recording methods that can provide absolute underwater spatial data compatible with geophysical surveying spatial requirements that are practical, efficient, impervious to water visibility, and capable of use in water depths ranging between 4 – 200m.

2). Nearly all archaeological site characterisation studies are performed using a desk-based analysis (DBA) of acquired sensor data, and archaeologists are rarely on-site to conduct in-person underwater investigative analysis and mapping. This practice is evidenced by the lack of follow-up archaeological diving operations during and/or after geophysical surveying operations, and the absence underwater site characterization studies carried about by archaeologists as part of the final reports filed with the permitting agencies.

If archaeological divers were equipped with an enhanced underwater positioning strategy to supplement various forms of site investigative practices, project archaeologists will have a more thorough analysis of specific anomalies identified as potential cultural materials. The ability to literally see and physically touch an anomaly is the best way to determine if in fact that object is manmade and undertake a cultural significance evaluation. A DBA can provide information that greatly contributes to a site characterisation study; however, for anomalies with inconclusive sensor datasets, a hands-on approach is the best course of action for verification. To undertake an

in-person archaeological site investigation, divers will need to use an applicable site recording methodology supplemented by an underwater positioning strategy for verifying or filling in geophysical sensor data gaps. This capability would be a valuable tool that archaeologists can use in the event additional site investigations are required for archaeological clearance and in the event follow-up missions are performed as part of more detailed cultural heritage assessments for protective status.

The UALR methodology was developed for supplementing archaeological site investigative practices by providing underwater positioning information on par with geophysical surveying spatial and equipment specifications. The UALR methodology does not require additional underwater positioning instrumentation beyond what is already onboard the geophysical survey vessel. In some cases, diving operations from the actual survey vessel may not be possible due to how the survey vessel is configured; however, a small support vessel could be used to deploy and recover divers during the archaeological site investigation. The only consideration would be ensuring clear line-of-sight between the transducer and transponder; therefore, the survey vessel will have to be in close proximity to the divers for uninterrupted acoustic signal transmission. Underwater communications between the divers and USBL operator can be facilitated by through-water acoustic systems for divers using SCUBA life-support equipment, or a hardwired configuration braided into the umbilical used for surface-supplied breathing gas. The UALR methodology provides archaeologists the means to undertake in-person site investigation surveys that are practical, time-efficient, and have the ability to confirm whether an anomaly retains cultural significance. This greatly benefits archaeological goals of preserving cultural materials within the survey area that would be at risk of damage or loss due to the construction process. Geophysical surveyors and their clients benefit from the

UALR methodology in that archaeological site characterisation studies of potentially significant cultural materials can be undertaken in a quick process that allows site clearance without having to assume the liability of damaging cultural materials in an area cleared by an archaeologist using a limited dataset to make that decision. The author believes using this method will facilitate increased cooperation between geophysical surveyors and archaeologists by allowing both to achieve their respective project goals such as maintaining the project schedule and reducing the likelihood submerged cultural resources are negatively impacted during construction processes.

3.2 Data Acquisition

The UALR methodology is firmly rooted in a fundamental concept which prioritises both archaeological concerns and geophysical surveying specifications; thus, implementing the best equipment and techniques from both disciplines for the purpose of achieving the mutually-shared goals of completing the project on time while protecting all known submerged cultural resources. The UALR methodology is a no-compromise solution that utilises real-time error-corrected satellite positioning which is coupled with an USBL acoustic ranging system to provide underwater positioning capabilities for supplementing conventional archaeological data acquisition methods. Global demands for offshore and inshore energy solutions, such as wind farms and their associated infrastructure, require intensive geophysical surveys while increasing the pressure for maritime archaeologists to accurately and efficiently document submerged cultural remains within areas potentially effected by development. Wind farms are often in shallow waters and relatively close to land, which is where most ships are lost. The UALR methodology offers maritime archaeologists an underwater positioning technique that is capable of application to nearly all systematically undertaken archaeological data collection methods

ranging from baseline surveys to digital photogrammetry. Site information collected using UALR-georeferenced archaeological data sampling methods can be used to fill in geophysical sensor data gaps and/or be used to provide necessary physical evidence to determine if an archaeological site is eligible for protective status while maintaining IHO, BOEM, Historic England, and other governing agency spatial specifications.

Geophysical surveyors and archaeologists must use the right tools for the job to achieve acceptable results. In regards to surface and underwater positioning, BOEM and Historic England explicitly state recommendations for differential-grade satellite navigation as the minimum requirement for vessel navigation, but prefer GPS systems with real-time error correction services which must be compatible with all onboard sensors; whilst, USBL acoustic ranging is the preferred method for underwater positioning (Plets et al. 2013; BOEM 2020a; BOEM 2020b). The combination of survey-grade satellite positioning and USBL acoustic ranging allows geophysical surveyors to achieve the required horizontal and vertical spatial accuracies while maintaining 95% measurement confidence for all onboard data acquisition sensors. Any underwater positioning method designed for supplementing archaeological data collection as part of geophysical surveys must operate within these spatial parameters and use the recommended equipment systems for compatibility. In accordance to these spatial and equipment specifications, this thesis established its UALR methodology research parameters based on published IHO, BOEM, and Historic England guidelines (Plets et al. 2013; BOEM 2020; IHO 2020). This decision was made in an effort to produce the UALR methodology for the purposes of supplementing conventional archaeological data acquisition techniques with underwater positioning information on par with geophysical survey requirements and conforming with the best commercial data acquisition practices.

The following subsections (3.2.1 – 3.2.4) provide information pertaining to both the satellite positioning and USBL acoustic systems used for the UALR methodology fieldwork examinations. In an effort to reduce overwhelming the reader with an abundance of information at one time, the author divided the delivery of the material pertaining to equipment specifications, setup/configuration, and operation into discrete subsections. Although the information is divided according to technology type and presented individually, the final UALR methodology process requires a tightly-coupled GPS/USBL arrangement for acquiring underwater positioning data. The subsections begin with Section 3.2.1, which provides specification and performance data pertaining to the satellite positioning instrumentation used for all UALR methodology fieldwork examinations. This is followed by Section 3.2.2, which discusses the setup and configuration of the satellite positioning equipment and operations used to acquire real-time satellite spatial data for vessel positioning and use with the USBL ranging system. Switching over to underwater acoustic technology, Section 3.2.3 provides specification and performance data for the USBL system used for this thesis. Section 3.2.4 presents the setup and configuration of the USBL system which includes how it is directly coupled to the satellite positioning system and the manner in which real-time underwater positioning data is acquired and prepared for post-processing. The information contained in these sections provides the reader with a complete diagnostic tool to re-test the implemented systems and configurations on other surveys and/or against presently available and/or future technologies.

3.2.1 Satellite Positioning Equipment Specifications

Geophysical surveying guidelines pertaining to satellite navigation require the positioning system to be of at least differential-grade (DGPS) and capable of integration with all onboard systems so that all data acquisition instrumentation use the same satellite positioning

system (Plets et al. 2013; BOEM 2020b). This requirement, combined with IHO order performance standards for satellite navigation equipment systems, contributed to the decision for this research to use Trimble satellite navigation equipment plus additional hardware and software systems which permitted real-time error correction capabilities via an Internet service provider. Case study research experimented with various Trimble system configurations and data acquisition methods (see Section 4.3.3, pg. 214); however, the refined UALR methodology satellite navigation equipment included the following hardware and software: Trimble SPS855 GNSS rover receiver, Trimble Zephyr Model 3 Rugged rover antenna, Trimble T10 tablet with Trimble SCS900 software, Acer Predator laptop computer, and Verizon MiFi wireless internet adapter for accessing real-time network (RTN) error corrections from virtual reference stations (VRS).

A Trimble SPS855 GNSS rover receiver served as the central hub for all satellite positioning hardware and software systems for UALR methodology development and field research. This particular GNSS receiver is commonplace throughout the world for civil construction projects, marine geophysical surveys, and other industries which require high-performance satellite positioning (Trimble 2021a:1). The purported horizontal and vertical positioning accuracies for the Trimble SPS855 receiver are directly related to the type of error correction service. The various types of accuracy grades and types of error correction services were previously discussed in Section 2.2 (see pg. 56); however, the Trimble SPS855 receiver is capable of achieving both differential- and survey-grade positional accuracy by means of user-defined error correction methods (Table 3-1). During the field examination phases for the UALR methodology testing and development, this research experimented with DGPS and RTN/VRS

TABLE 3-1
TRIMBLE SPS855 GNSS MODULAR RECEIVER ERROR CORRECTIONS AND PUBLISHED ACCURACY

Positioning Type	Horizontal Accuracy	Vertical Accuracy
SBAS (WAAS/EGNOS/MSAS)	± 0.50 m	± 0.85 m
Code Differential GPS (DGPS)	0.25 m + 1 ppm RMS	0.50 m + 1 ppm RMS
CenterPoint RTX	0.02 m RMS	0.05 m RMS
Location RTK (10/10) and (10/2)	(10/10 or 10/2) 0.01 m + 1 ppm RMS	(10/10) 0.01 cm +1 ppm RMS (10/2) 0.02 m + 1 ppm RMS
Real-Time Kinematic (RTK)	0.008 m + 1 ppm RMS	0.015 m + 1 ppm RMS
Virtual Reference Station (VRS)	0.008 m + 0.5 ppm RMS	0.015 m + 0.5 ppm RMS

Source: Trimble SPS855 Datasheet (Trimble 2021a:2).

error corrections. Although both methods are in compliance with IHO, BOEM, and Historic England geophysical surveying guidelines, this research preferred the use of RTN/VRS error corrections which were accessed using a mobile Wi-Fi internet adapter. Detailed information pertaining to the favoured use of RTN/VRS error corrections are reserved for later in this section.

The Trimble SPS855 receiver is capable of integrative communications with various electronic platforms such as laptop computers, tablets, and geophysical survey data acquisition instrumentation. Communication between external electronic instrumentation and the Trimble SPS855 receiver is imperative for receiving positioning information, updated error correction data for optimal positional accuracy, and satisfying the geophysical surveying requirement that all data acquisition systems operate using a single satellite receiver (Plets et al. 2013; BOEM 2020b). The Trimble SPS855 receiver is capable of using both wired and wireless communication; however, the type of communication method is dependent upon the required update rate for a particular data acquisition system and how the manufacturer designed its navigation communication (COM) port (Trimble 2021a:4). Wired COM port interfaces exist in a variety of formats such as RS-232 Serial, LEMO, and Local Area Network (LAN), which provide users the capability to connect the receiver to a variety of computer systems and topside processing units.

The Trimble SPS855 receiver wireless communication interfaces include an integrated radio receiver, Wi-Fi, and Bluetooth connections, which are generally used for accessing error correction services. In recent years, modern wireless communication systems have significantly improved to provide adequate bandwidth between GPS receivers and data acquisition systems equipped with wireless adapters; however, the author's professional experience as a geophysical surveyor contributed to the decision not to use wireless communications between the GPS

receiver, laptop computer, and USBL topside processing unit. The author observed on numerous occasions that the abundance of electronic equipment systems onboard geophysical survey vessels can result in electronic signal interference which can result in data gaps for navigation and positioning update intervals. For this thesis, the author used wired connections for communications between the Trimble SPS855 receiver, the Acer Predator laptop computer used for GPS data logging and monitoring, and the Applied Acoustics Engineering, Ltd. Alpha Portable Easytrak USBL system. Wireless communications for accessing RTN/VRS error correction services included a Wi-Fi link from a Verizon mobile internet adapter to the Trimble T10 tablet; whilst the tablet communicated the updated error correction data to the Trimble SPS855 receiver via a close-range Bluetooth connection. The smaller required signal bandwidth and proximity between sensors permitted the use of Wi-Fi and Bluetooth for communications between the mobile internet adaptor, tablet, and GPS receiver. A detailed description of the wired and wireless communication interfaces for equipment used for this thesis is provided in Section 3.2.2 (see pg. 107).

During the course of this thesis, the author utilised two Trimble rover antenna types as part of the fieldwork examinations. A Trimble GA530 was initially used in conjunction with the Trimble SPS855 receiver, but was later replaced with a Trimble Zephyr Model 3 Rugged rover antenna due to improved performance and satellite signal acquisition capabilities. The visual appearances and dimensions of the Trimble GA530 and Zephyr Model 3 are quite similar; however, the performance capabilities of the Zephyr Model 3 vastly outpace the GA530 and place it in the top tier of rover antennas produced for professional surveying applications (Trimble 2021b:1). According to the Trimble datasheet, the Zephyr Model 3 antenna is equipped

TABLE 3-2
TRIMBLE ZEPHYR MODEL 3 RUGGED ROVER ANTENNA SIGNAL TRACKING CAPABILITIES

GNSS Constellation	Administrator	Signal Frequency
GPS	United States of America	L1, L2, L5 *
GLONASS	Russia	L1, L2, L3 *
BeiDou	China	B1, B2, B3
Galileo	European Union	E1, E2, E5, E6
SBAS	Public and Private Sector	WAAS, EGNOS, QZSS, Gagan, MSAS, OmniSTAR, Trimble RTX

Source: Trimble Zephyr Model 3 Antennas Datasheet (Trimble 2021b:2).

Note: * The GPS and GLONASS L1 and L2 signals are not the same frequencies.

with the latest technological advancements to reduce signal multipath, and increase tracking capabilities in varying environments, while providing sub-millimetre phase centre stability and repeatability (Trimble 2021b:1). The signal tracking capabilities for the Zephyr Model 3 allow the use of various GNSS constellations and satellite-based augmentation systems (SBAS) for improved geometric and differential positioning (Table 3-2). Although the Zephyr Model 3 accepts differential error correction data, this particular antenna was specifically designed for optimal use with real-time kinematic (RTK) use. Although this research did not utilise a RTK base station, and instead used a real-time network of virtual reference stations (RTN/VRS), the Zephyr Model 3 antenna permitted sub-millimetre positional accuracy and use of the Trimble CenterPoint RTX online GPS data post-processing service.

Access to RTN/VRS error correction services was achieved using a Verizon mobile internet Wi-Fi adapter and Trimble T10 tablet equipped with SCS900 software. The use of a mobile internet Wi-Fi adapter was chosen as a comparable method to those used onboard geophysical surveying vessels for accessing error correction services. When operating at distances beyond shore-based RTK capabilities, geophysical survey vessels utilise satellite-based error corrections to supplement GPS navigation and positioning data. Based on the author's professional experience as a geophysical surveyor, it is common practice for satellite-based error corrections service utilised offshore to be likewise used for nearshore and inshore survey segments for the purpose of maintaining spatial data continuity. The satellite-based systems used to correct GPS navigation and positioning use comparable hardware and software to that of RTN/VRS error correction services; thus, contributing to the author's decision to utilise RTN/VRS for thesis fieldwork examinations.

While similar in many ways, RTN/VRS and satellite-based systems have distinct differences in terms of performance. With reference to error correction service estimated positional accuracies provided in Table 3-1 (see pg. 101), satellite-based error correction services (depending on the manufacturer/administrator) can produce horizontal positional accuracies that vary between 2 – 50 cm; whereas, vertical accuracies can vary from 5 – 85 cm. Satellite-based services, such as WAAS and EGNOS, are accessible to the general public but have a larger margin of error than that required for this thesis' research parameters and are limited for regional use. Subscription satellite-based services, such as Seastar produced by Fugro (see the following link https://www.fugro.com/our-services/marine-asset-integrity/satellite-positioning/seastar), offer high-accuracy error correction data for offshore use without requiring onshore base stations. Operational depths established by the University of Oxford limited all research examinations to inshore/nearshore archaeological sites; therefore, the author was not required to attain a subscription to an offshore satellite-based error correction service which instead permitted the use of RTN/VRS error corrections accessed via a mobile internet Wi-Fi adapter.

All fieldwork examinations took place in the United States and in relatively close proximity to virtual reference stations which were accessed via real-time networks. In the United States, RTN/VRS service providers vary according to state or region; whereas, some services are administered by state agencies and offered to the public free of charge, while other states utilise privately owned services which may charge a one-time fee or annual subscription for access. In North Carolina, where the majority of thesis fieldwork occurred, the author was required to pay a one-time fee of $500.00 USD to access the RTN/VRS error correction serviced administered by the North Carolina Geodetic Survey (NCGS). Accessing the NCGS RTN/VRS was achieved using the Trimble T10 tablet and Verizon Wi-Fi mobile adapter which utilises a 4G/5G cellular

signal for internet access. The use of a cellular signal for internet access limits its usage to inshore and nearshore locations or where cellular towers are available; but, for the purposes of this research, the use of a cellular Wi-Fi service was deemed applicable. The Trimble T10 tablet was designed for use with Wi-Fi, Bluetooth, and 2.4 GHz radio connections; thus, no additional adapters were required for accessing an internet service (Trimble 2021c:2). The Trimble T10 tablet operating software is Microsoft Windows 10 and utilises an Intel 6th Generation Core i7 processor, which is directly comparable to most high-performance laptop computer systems. The Trimble T10 tablet performance specifications, combined with Trimble SCS900 site controller software, allowed the author to achieve optimal GPS systems function while reducing onboard equipment space requirements. Typical geophysical survey vessels have enough onboard space for numerous computer systems; however, the 25-ft survey vessel used for this thesis research required careful planning in terms of available space. Due to the space limitations, the Trimble T10 tablet was an ideal choice for accessing the NCGS RTN/VRS error correction service.

The Trimble T10 tablet and Trimble SPS855 receiver were coupled using a Bluetooth wireless communication signal, thus allowing the receiver to obtain RTN/VRS error correction data. Monitoring the error-corrected data was achieved using an Acer Predator laptop computer which was connected to the Trimble SPS855 receiver via a local area network (LAN) cable. Using this setup, the Trimble SPS855 receiver functions are accessible via the laptop computer which permitted checking receiver specifications, changing configurations if required, monitoring all positional data in real-time, observations of which satellites were used to calculate receiver position, and activating/deactivating the data logging function. The data logging feature allows the storage and/or export of all recorded satellite positioning data in a variety of user-preferred file formats. Typically, data logging is activated throughout an entire survey and is

very useful during post-processing for rechecking datasets if an underwater positional anomaly is found. This allows the user to diagnose where the spatial error occurred and perhaps allow corrective measures for the post-processed results, if possible.

3.2.2 Satellite Equipment Configuration and Operation

The satellite positioning hardware and software systems described above function in a combined arrangement to provide survey-grade positioning information in compliance with geophysical survey spatial requirements. The following paragraphs provide step-by-step descriptions of the manner in which these systems were connected and configured for optimal performance during fieldwork examinations. In addition to text descriptions, the author provides the reader with visual aids which consist of flowcharts, photographs, and computer screen captures. This information is provided for the purposes of giving an in-depth presentation of how the satellite positioning hardware and software systems were combined so that it may be replicated for additional research and comparative analyses as future technologies become available for use. Although this thesis research was written for audiences with professional experience and technical expertise in geophysical surveying operations, the information in this section is presented using straightforward terms and analogous comparisons to help those with limited exposure to differential- and survey-grade satellite positioning systems.

Differential- and survey-grade satellite positioning systems are composed of multifaceted hardware and software arrangements which work in unison to produce high accuracy spatial information. The manner in which satellite positioning information is collected and communicated to survey instrumentation is similar to that of human anatomy. As previously mentioned, the Trimble SPS855 receiver served as the principal component (brain) to which all other satellite positioning instruments (limbs) were connected. Reciprocal communication



FIGURE 3-1: Satellite positioning hardware and software systems arrangement. (Photo by author, 2018).

between the receiver, antenna, and tablet was comparable to that of the central nervous system, in which sensory information was collected and transmitted to the receiver for data processing and dissemination to all connected UALR methodology instrumentation (Figure 3-1). This process was similar to the manner in which the human body receives and processes information that can affect motor skill function and performance. Although this comparative analogy between the UALR methodology satellite instrumentation and human anatomy is oversimplified, the reader should be able to follow the dynamic relationship of the satellite equipment components and how data is transferred back and forth between these instruments for optimal system performance and output to the connected underwater acoustic ranging unit. However, for reader clarification purposes, the data generated by the satellite instrumentation only provides positional information to be used to record surface vessel positioning and as a starting reference for the USBL ranging system.

The satellite navigation system components and their functions were discussed in Section 3.2.1, but how were these instruments physically connected and configured during UALR methodology fieldwork examinations? As with any type of geophysical or archaeological survey, where and the manner in which data acquisition systems are set up and configured determines their performance. Regardless of the purported performance specifications of any satellite positioning system, how users set up and configure the systems directly governs both data accuracy and precision; however, the setup processes for this thesis had a greater prominence on measurement precision and repeatability. The emphasis on precision and repeatable measurements for the setup and configuration processes for the selected satellite positioning system was based on the acknowledgement that these processes were under the author's control. The satellite system performance standards mentioned earlier in this writing were not under the

direct control of the author; but, rather under the influence of how the manufacturer designed the equipment and the construction materials.

The initial step in setting up the satellite positioning system was finding a location on the working platform with suitable room for establishing a workstation and within cable length of the antenna mounting location. Based on the author's professional experience, most geophysical survey vessels have a specific area designated for satellite positioning systems and associated computers for monitoring and data logging. However, for this thesis, the author utilised much smaller working platforms with limited available space, but the compact dimensions of the all UALR methodology hardware permitted its usage without encumbering other onboard systems and operations. Another consideration for this thesis was having adequate space to have both the satellite navigation equipment and USBL surface unit side-by-side so the topside operator could run both systems simultaneously. This is not a necessary requirement for a typical geophysical survey vessel, but worth considering in the event that the survey vessel is also used for follow-up archaeological documentation using the UALR methodology. Irrespective of the multitude of hypothetical ways to establish an onboard workstation, for the sake of ease of use and personnel requirements, both the satellite positioning system and USBL surface unit were set up in a side-by-side arrangement (Figure 3-2). The working platforms used for thesis fieldwork examinations permitted the use of a foldout table with adequate surface area for all equipment systems, yet small enough to work in a variety of locations with limited space. Regardless of the working platform, adequate space for the equipment systems is a necessity for efficient operations.

An efficient and reliable power source is an important, yet often overlooked consideration when establishing an onboard workstation. Most offshore geophysical survey vessels are equipped with onboard diesel-powered generators and electrical outlets for powering



FIGURE 3-2: UALR methodology satellite positioning and USBL acoustic ranging systems arrangement on a pier platform. The simulated workstation was beneficial in establishing equipment positioning for data acquisition on survey vessels with limited available space. (Photo by author, 2018).

electronic equipment. However, smaller survey vessels and other working platforms, such as those used for this thesis, required the use of a portable gasoline-powered generator and electronic power strip/surge protector with multiple outlets. The Honda 2000 portable generator used for this thesis was capable of efficiently and safely maintaining the electrical load required to operate all electronic systems. Given this generator uses a gasoline-powered engine, the author operated the generator in open, well-ventilated areas to prevent carbon monoxide poisoning, and similar considerations should be given to air intakes for air compressors in the event surface-supplied diving equipment is used for underwater archaeological documentation. Although this thesis did not conduct fieldwork examinations on archaeological sites which required the use of surface-supplied diving equipment, it is reasonably assumed that any diving operations working under US OSHA and UK HSB scientific diving legislation will require surface-supplied diving equipment. In this event, all consideration should be given to ensure the air intake systems are sufficiently distanced and upwind from all exhaust systems. The same considerations should be applied to small survey vessels with an enclosed cabin, or what the author refers to as a "survey shack." Carbon monoxide fumes can build up inside the confined space and cause serious medical issues for onboard personnel; therefore, the survey shack should be either well-ventilated or the hatch leading into the confined space be closed to limit the quantity of fumes entering this area. Regardless of the electronic power source, all care and consideration should be given to prevent fume inhalation, electrical shock, and tripping hazards.

As the central component for the satellite positioning system, the Trimble SPS855 receiver was the first piece of equipment set up in the workstation. The receiver was designed to accept both 7-pin Lemo and 26-pin adapters for a power source and communication ports with external devices (Figure 3-3). For this thesis, the author utilised a 26-pin Trimble 57168 Rev C



FIGURE 3-3: Rear view of the Trimble SPS855 GNSS receiver. The coaxial cable connection is the circular port on the left side. The 26-pin adapter port in located in the middle. The Lemo port is located on the right side. (Photograph by author, 2021).



FIGURE 3-4: The Trimble 57168 Rev C adapter with a power plug input, RS-232 serial com port, and LAN cable port. (Photograph by author, 2021).

adapter constructed with a DC power input and both RS-232 serial cable and local access network (LAN) ethernet cable communication ports (Figure 3-4). The 26-pin adapter was coupled to the receiver and secured using two thumb screws on either side of the connector. The RS-232 serial cable was routed and connected to the USBL surface unit and the LAN cable was routed and connected to the survey laptop to allow access to receiver functions, observing satellite positioning information, and monitoring real-time error correction services. It is of great importance for the user operator to be aware that if the power source plug is connected to a powered electrical outlet, the Trimble SPS855 receiver will POWER ON and the unit must be shut off prior to connecting the antenna cable; therefore, as a general rule of thumb, the author did not connect the power source plug until all cables were secured in their respective communication ports. Following the setup of the GPS receiver and laptop at the workstation, the Trimble Zephyr Model 3 rover antenna was connected to the receiver via a coaxial cable (Figure 3-5). The coaxial cable used for this thesis was manufactured by Trimble which ensured compatibility and optimal communication between the antenna and receiver. The antenna was attached to a lightweight and modular pole-mount system that was custom designed and fabricated by the author for this thesis. The coaxial cable is secured to the pole-mount using zip-ties to prevent snagging on other equipment and personnel. After the coaxial cable is connected to the antenna and receiver, both the receiver unit and laptop were powered ON to initialise the configuration process.

The Trimble SPS855 receiver functions and configuration settings were accessed by way of an Acer Predator 17 laptop computer which was connected to the receiver via a LAN ethernet cable (Figure 3-6). To access the receiver, the user opens an internet browser, enters the IP address for the Trimble SPS855 receiver, then logs into the receiver using the Trimble login tool.



FIGURE 3-5: Trimble coaxial cable for the Zephyr Model 3 rover antenna. (Photograph by author, 2021).

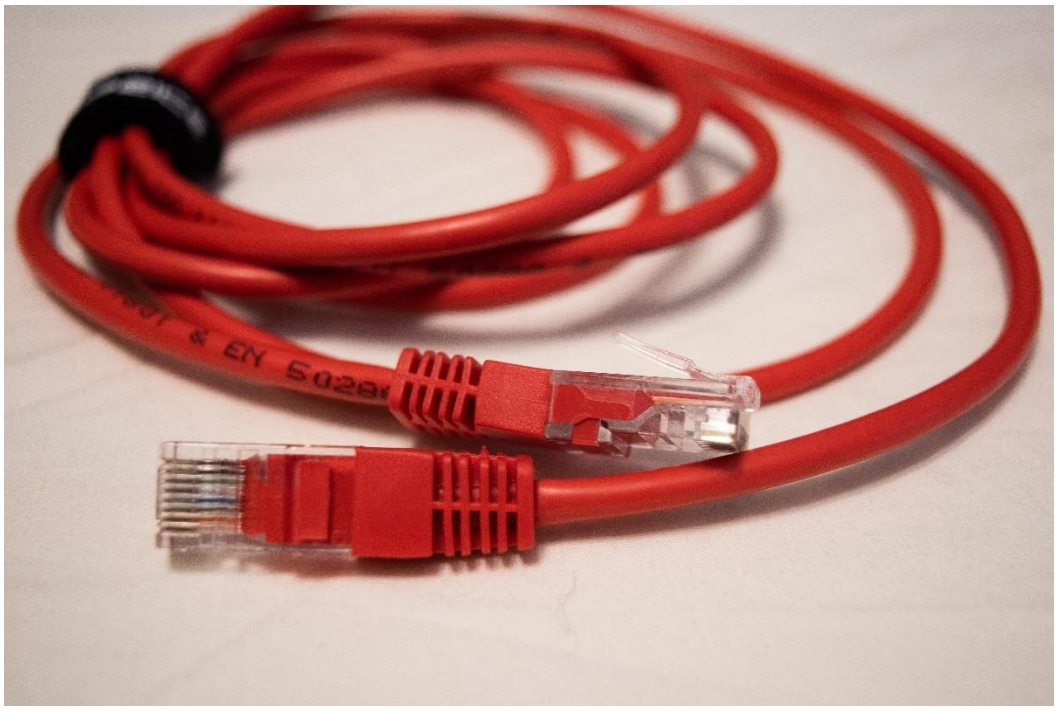


FIGURE 3-6: LAN cable used for connecting the Trimble SPS855 GNSS receiver to the laptop for system monitoring and activation receiver controls. (Photograph by author, 2021).

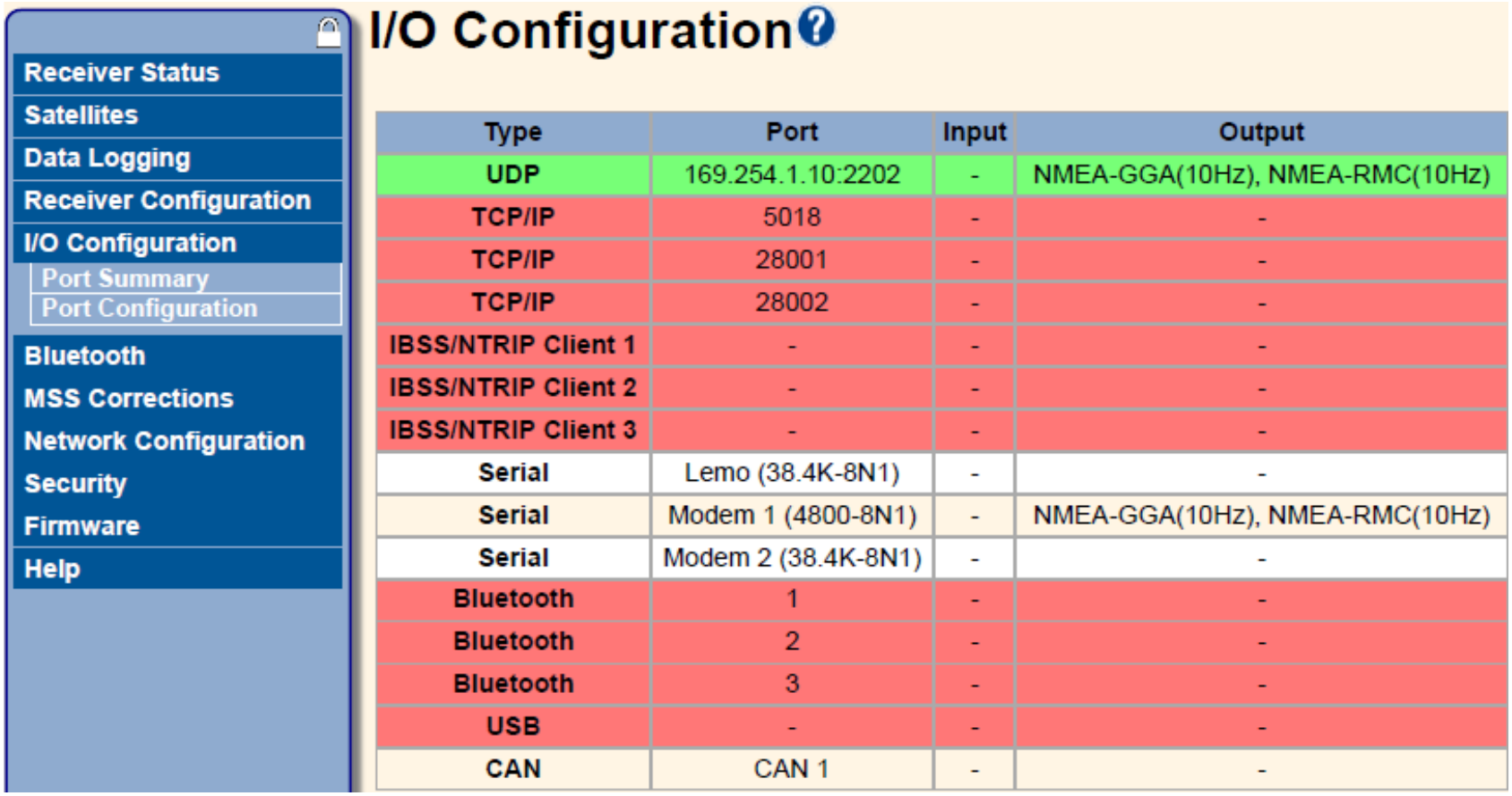
TABLE 3-3
DILUTION OF PRECISION VALUES

Value	Acceptable Usage
1	Optimal rating which provides the highest attainable confidence measurement. Data accuracy can be trusted for use for applications with the maximum precision requirements.
2 – 3	Positional accuracy in this DOP range can be trusted for mapping applications and surveying which do not require the maximum precision confidence values.
4 – 6	The least allowable DOP values acceptable for mapping operations.
7 – 8	Positional information within this range can be used; however, improved satellite geometry is required.
9 – 20	Low confidence data quality which may result in increased positional inaccuracy.
21 – 50	Ranging measurements within this range may be inaccurate by more than 45 m.

Source: Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA, USA. http://introgps.uga.edu/course/Dilution_of_Precision.html. (Accessed March 2020).

Located on the Trimble SPS855 receiver's home screen is a vertical toolbar with the following functions: Receiver Status, Satellites, Data Logging, Receiver Configuration, Input/Output (I/O) Configuration, Bluetooth, MSS Corrections, Network Configuration, Security, Firmware, and Help (Figure 3-7). For each fieldwork examination, the author ensured the appropriate configuration settings were in place prior to data acquisition. Observations of the GPS satellite positioning information were acquired using the Receiver Status tool which permitted the author to maintain real-time awareness of which satellites were used for calculating geometric position, monitoring the real-time error correction service, and various dilution of precision (DOP) degradation values. According to information provided in Table 3-3, DOP values range from 1-50; whereas, 1 is the optimal rating and 50 being the lowest. For professional surveying and mapping applications, the best DOP values range between 1-3 and any values outside of that range should not be used. For this thesis, DOP values never exceeded the 2 value which ensured survey-grade DOP for all satellite positioning information.

Additional configurations such as those for the receiver, I/O, and Bluetooth were configured for optimal use with the Trimble Zephyr Model 3 antenna, Trimble T10 tablet for access to RTN/VRS error correction services, and communication with the USBL surface unit. Under the Receiver Configuration tab, the user can adjust the receiver settings depending on the type of antenna being used, desired elevation mask for accepting GPS information from satellites above a specified angle above the horizon, and other basic functions. These types of settings are typically stated in the tender documents for geophysical survey specifications and can vary according to project and/or permitting agency. For this thesis, the author utilised a 10° elevation mask which ignored all positioning information from satellites beneath that threshold. By doing so, the likelihood of receiving positioning information which may have timing errors due to



Type	Port	Input	Output
UDP	169.254.1.10:2202	-	NMEA-GGA(10Hz), NMEA-RMC(10Hz)
TCP/IP	5018	-	-
TCP/IP	28001	-	-
TCP/IP	28002	-	-
IBSS/NTRIP Client 1	-	-	-
IBSS/NTRIP Client 2	-	-	-
IBSS/NTRIP Client 3	-	-	-
Serial	Lemo (38.4K-8N1)	-	-
Serial	Modem 1 (4800-8N1)	-	NMEA-GGA(10Hz), NMEA-RMC(10Hz)
Serial	Modem 2 (38.4K-8N1)	-	-
Bluetooth	1	-	-
Bluetooth	2	-	-
Bluetooth	3	-	-
USB	-	-	-
CAN	CAN 1	-	-

FIGURE 3-7: I/O Configuration Port Summary screen which shows which com ports are currently in use and the configuration settings for input and output message strings. (Image by author, 2021).

TABLE 3-4
NMEA-GGA DATA STRING EXAMPLE

$GPGGA,172814.0,3723.46587704,N,12202.26957864,W,2,6,1.2,18.893,M,-25.669,M,2.0,0031*4F

Field	Denotation
0	Message ID $GPGGA
1	UTC of Position Fix
2	Latitude
3	Direction of Latitude: N: North S: South
4	Longitude
5	Direction of Longitude: E: East S: West
6	GPS Quality Indicator: 0: Fix Not Valid 1: GPS Fix 2: Differential GPS Fix, OmniSTAR VBS 4: Real-Time Kinematic, Fixed Integers 5: Real-Time Kinematic, Float Integers, OmniSTAR XP/HP or Location RTK
7	Number of SVs in use, range from 00 to 24+
8	Horizontal Dilution of Precision (HDOP)
9	Orthometric Height (MSL reference)
10	M: Unit of measure for orthometric height is metres
11	Geoid Separation
12	M: Geoid separation measured in metres
13	Age of DGPS data record, Type 1 or Type 9. Null field when DGPS is not used.
14	Reference station ID, range 0000-4095. A null field when any reference station ID is selected and no corrections are received.
15	The checksum data, always begins with *

Source: https://www.trimble.com/oem_receiverhelp/v4.44/en/NMEA-0183messages_GGA.html. (Accessed 18 August 2018).

multipath and other local influences was eliminated; whilst, only positioning data from healthy satellites with clear line-of-sight to the GPS antenna were utilised to calculate the geometric position. The I/O configuration tool allowed the author to specifically tailor the type of satellite positioning information brought into the receiver and navigation output messages to the USBL surface unit (Figure 3-7) (Table 3-4). With reference to information provided in Table 3-4, the author set the outgoing navigation information to the USBL surface unit to use a NMEA-GGA message string with a 10 Hz update rate (10 times per second). The use of a 10 Hz update rate is 10 times faster than what is required by Historic England and BOEM geophysical survey equipment requirements; therefore, the positioning data was more detailed and with higher resolution for tracking (see pg. 120). RTN/VRS error correction services which increased positional accuracy and precision to levels that exceeded geophysical surveying spatial requirements were acquired using the Trimble T10 tablet. The tablet transmitted this information to the GPS receiver through a wireless Bluetooth connection. As a matter of security and privacy, details pertaining to the login process in which the author acquired RTN/VRS error corrections was intentionally omitted from this writing.

Following the completion of all satellite positioning equipment connections, all connected systems were powered ON for final configuration checks. Nearly all satellite positioning software systems use check boxes to activate and deactivate certain functions. In some cases, the configuration settings may not be saved from one project to another after powering down the satellite positioning system hardware. The author recommends users get into the best practices habit of creating configurations checklists prior to activating the Data Logging function. This helps ensure consistent performance and repeatability for all surveys. Once all configuration settings were verified, the author initialised the Data Logging function on the

Trimble SPS855 receiver and permitted continuous acquisition of satellite positioning information throughout the duration of each survey. In terms of survey operations, activating and subsequently deactivating the Data Logging function are the first and last actions taken during data acquisition. The satellite positioning information was stored inside the Trimble SPS855 receiver and later exported during post-processing using Trimble CenterPoint RTX.

3.2.3 Ultra-Short Baseline Equipment Specifications

The USBL system used for this thesis was the Applied Acoustics Engineering, Ltd. (AAE) Easytrak Alpha Portable model EZT-2665, used in conjunction with an AAE 1200 series transponder beacon and AAE ETM903C transducer (Figure 3-8). As required by thesis parameters which were based on geophysical surveying specifications published by BOEM, Historic England, and other associated institutions, this particular USBL unit satisfied all operational guidelines addressed earlier in this thesis (see pg. 38). In addition to the thesis parameters, this particular USBL unit was ideally suited for rapid use onboard small working platforms and was essentially a turn-key solution that did not require complex calibration processes. Although more robust systems are better suited for providing geophysical surveyors with underwater positioning information for towed sensors and other equipment, the USBL system used for this thesis proved to be a very accurate and precise tool that was both user-friendly and cost-effective.

Referring back to the previous discussion pertaining to an onboard workspace and the amount of available room to set up both satellite positioning and USBL systems, major considerations for selecting the AAE Easytrak Alpha Portable system were the relatively small dimensions (411 x 323 x 168mm), weight (6.0 kg), and construction design which included an integrated waterproof keyboard (QWERTY) and LCD display screen in a portable Pelican-style

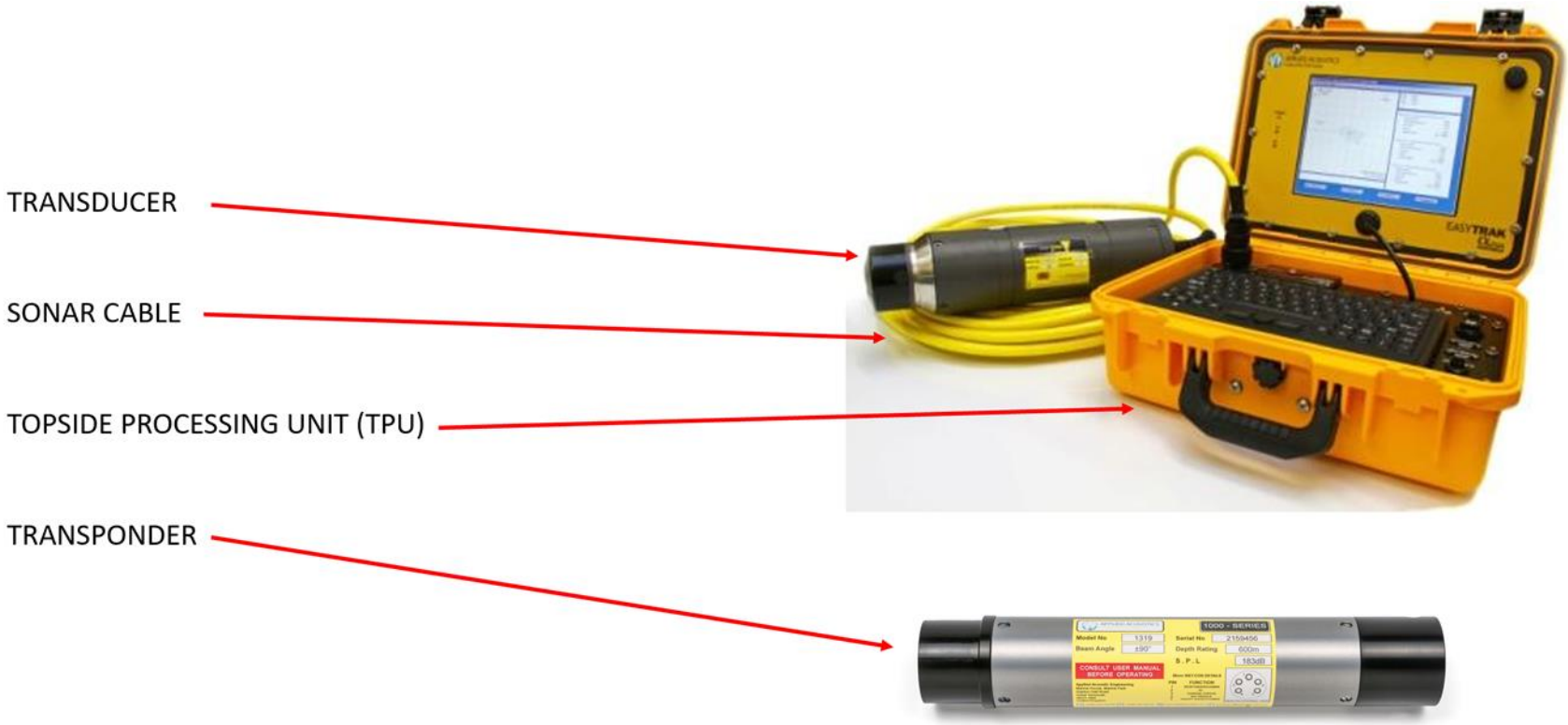


FIGURE 3-8: Applied Acoustics Easytrak Alpha Portable USBL topside processing unit and transducer (*top*), and 1200 series transponder (*bottom*). (Courtesy of Applied Acoustics Engineering, Ltd., 2015).

case (AAE 2021a:1). The AAE Easytrak Alpha Portable USBL is equipped with an internal battery power source which can be used to power both the unit and connected to the ETM903C transducer for at least two hours; however, given the author preferred the use of an external power supply provided by the same Honda 2000 generator used to power the satellite positioning systems.

The Easytrak Alpha Portable USBL console was designed for use with various communication ports for importing satellite positioning data, exporting underwater transponder information, and data exchange with other external devices. The Easytrak Alpha Portable USBL system was designed with an internal GPS receiver called the SiRF STAR III Chipset which is reported to have a positional accuracy of less than 5 m when utilising SBAS error correction services (AAE 2021a:2). This level of positional accuracy exceeds thesis spatial parameters, but the system can be utilised as a back-up in a worst-case scenario and simply requires the user to plug in the small GPS antenna provided by the manufacturer. The author did not utilise this GPS receiver for thesis field examinations, and instead connected the Trimble SPS855 GNSS receiver to the Easytrak Alpha Portable USBL console using a RS-232 serial connection. The connection of the Trimble SPS855 receiver to the Easytrak Alpha Portable USBL permitted the use of RTN/VRS error-corrected satellite positioning information to be used as the vessel reference point from which all other underwater ranging calculations were based. Other communication ports include an additional RS-232 data output port and universal serial bus (USB) port. The author did not use the data output serial port, but did use the USB port for an external mouse and also for transferring underwater positioning information to an external hard drive following the cessation of each surveying operation.

The Easytrak Alpha Portable system was designed for use with the ETM903C transducer which transmits and receives in-water acoustic signals for ranging calculations. The transducer is connected to the console by way of a 20 m polyurethane sheathed cable and pin connector. The exterior housing was constructed using PVC and has pre-cut grooves for attaching band-clamps as part of the mounting process. The transducer has a depth rating of 20 m, which means the transducer can be lowered to a depth of 20 m to clear the bottom hull of the survey vessel. As mentioned in Section 2, USBL units which do not require calibration, such as the Easytrak Alpha Portable, are less accurate when compared to more robust systems; however, the turn-key attributes of this system for shallow water diving operations more than offsets the need for more advanced USBL systems. While the Easytrak Alpha Portable is reported to have a slant range resolution of 10 cm and positional accuracy of 2.0º RMS / 3.5% of the slant range, this system is more than capable of producing highly accurate and precise underwater positional data which fall under IHO, BOEM, and Historic England spatial requirements (AAE 2021a:3). The overall design and dimensions of the ETM903C transducer allows easy transport between working platforms, and is small enough for the user to carry onboard commercial air transportation.

The underwater USBL transponder used for this thesis was the Applied Acoustics Engineering 1200A Series Micro Beacon. The 1200A beacon was specifically designed for shallow water operations which require diver and ROV tracking capabilities (Figures 3-9 – 3-10). This beacon is powered by an internal battery, which is rechargeable using a USB cable, that also serves as a communication cable to allow the user to undertake diagnostic evaluations of the beacon configuration settings using a laptop computer with the AAE Beacon Editor software. The battery has a reported operational life of 30 hours on a single charge, and only requires about 4 hours for a full recharge (AAE 2021b:2). The beacon is activated using a watertight connector



FIGURE 3-9: A diver entering the water with an AAE 1200 Series Micro Beacon attached to the air tanks. The use of the beacon allows topside dive supervisors to monitor where the diver is located and assist in navigating the divers to their targets. Photograph from the Applied Acoustics Engineering, LTD website at https://www.subseatechnologies.com/applied-acoustics/positioning-beacons/micro-beacons/. Accessed on 17 August 2021.



FIGURE 3-10: A small ROV equipped with the 1200 Series Micro Beacon for underwater tracking. Photograph from the Applied Acoustics Engineering, LTD website at https://www.subseatechnologies.com/applied-acoustics/positioning-beacons/micro-beacons/. Accessed on 17 August 2021.

plug which is screwed into the base. To deactivate the beacon, the user simply unscrews the connector. The 1200 Series Micro Beacon transmission frequency range is 21.5 – 30.5 kHz; whereas, the receiving frequency range is 16 – 26.5 kHz (AAE 2021b:2). The wide variance in transmission and receiving frequency ranges allows the beacon to be used with numerous USBL units which include iXblue, Kongsberg, Sonardyne, HiPAP, and GAPS systems. With regards to beacon dimensions, the 1200 Series Micro Beacon is lightweight and ideal for divers and ROV tracking. The beacon has an overall length of 248 mm, diameter of 52 mm, and in-water weight of 360 g (AAE 2021b:1). With a ±90º beam pattern and survival depth of 600 m, the 1200 Series Beacon was more than capable for shallow-water UALR methodology field examinations.

A critical component for successful utilisation of the AAE Easytrak Alpha Portable system was the development of the pole-mount used to affix the transducer to the working platform. During the period of time in which field examinations were conducted, no portable or adaptable USBL mounting systems were commercially available for small survey vessels. Even for large geophysical survey vessels, most USBL mounting solutions are custom made for that particular vessel and are permanently attached. The author recognised this issue early on during the initial research phase and determined the best course of action was designing and fabricating a pole-mount solution for fieldwork examinations. The pole-mount solution built by the author was composed of three sections: antenna pole, transducer bracket, and cleat mount (Figures 3-11 – 3-13). The antenna pole was constructed of rigid and lightweight aluminium which was threaded to accommodate a customised antenna mount on the top end and drilled to accept the transducer mount on the opposite end. The antenna pole was also cut into 1.5 m lengths for portability and threaded to permit the use of aluminium couplings depending on the needed height for the antenna and/or depth of the transducer. The transducer bracket was constructed



FIGURE 3-11: Aluminium antenna pole. Note the bottom right pole section is fitted with two 3/4-inch galvanized bolts for attaching the USBL transducer bracket. Each section was threaded to accommodate a pipe coupler which allowed the antenna pole to be the required height so the antenna could clear any obstructions and/or allowed the transducer adequate depth to clear the bottom of the working platform. (Photo by author, 2017).



FIGURE 3-12: Completed transducer bracket attached to the Applied Acoustics Engineering, LTD. ETM903C transducer. The band clamps are fastened through the transducer bracket and secured within the channels located on the transducer exterior housing. (Photo by author, 2017).



FIGURE 3-13: The cleat mount assembly underwent structural evaluations prior to use in thesis research case study fieldwork. In this photograph the pole mount is passed through the cleat mount sleeve and locked into place by the thumbscrews. (Photo by author, 2017).



FIGURE 3-14: The completed UALR methodology pole-mount solution composed of the transducer bracket, cleat mount, and pole assembly. The transducer and GPS antenna are in precise alignment at a 90º angle. Note: only a single pole section is demonstrated in this photograph. (Photo by author, 2017).

from steel and designed for use with the band clamp grooves present on the transducer exterior housing. The cleat mount was constructed using steel and can be used on a variety of cleat types or lashed due to the inverted hook design. The thumbscrews on the cleat mount sleeve allow the user to raise and/or lower the pole as needed to clear the bottom of the working platform. The most important design aspect of the pole-mount solution was the zero offset between the GPS antenna and transducer, which allowed both systems to be in perfect alignment and removed the possibility of introducing human measurement error into the spatial data information (FIGURE 3-14).

3.2.4 Ultra-Short Baseline Equipment Configuration and Operation

The acquisition of spatial data which satisfied geophysical surveying specifications required a positioning equipment configuration in accordance with the environmental and manmade conditions at each fieldwork examination site. Prior to undertaking data acquisition, the author performed a series of site assessments which documented observations of working conditions both above and below the water surface. This was an important initial step for every fieldwork examination in which the author was able to configure both GPS and USBL equipment settings and note any major discrepancies in the performance of the UALR methodology to determine if any issues were a result of naturally-occurring phenomena and/or operator error. The author created surface and subsurface observation forms which noted weather conditions, freshwater and/or marine environmental information pertaining to acoustic signal transmission, bottom sediment type, archaeological information regarding the structural aspects of the cultural remains, and analyses of marine life located within the site and surrounding area. Other observations such as surface water movement, site proximity to nearby shorelines, passing vessels, additional acoustic equipment in use, sudden and heavy precipitation, and others that

specifically influenced USBL equipment performance; thus, requiring documentation if these events occurred. Observational data was entered into an author-designed template and was continuously updated throughout each survey day for any variation that may have affected underwater acoustic performance.

The author described the AAE Easytrak Alpha Portable in Section 3.1.3 as a "turn-key solution" for USBL equipment which was both simple to set up and operate. Although most geophysical survey vessels are equipped with permanent or semi-permanent USBL equipment configurations, the USBL equipment used for this thesis was designed to be portable and transferable between any type of working platform. As a result, each fieldwork examination required the assembly and disassembly of all equipment systems; therefore, a specific process was developed for both consistency and optimal equipment performance. The setup and configuration processes described in the following paragraphs are presented in a step-by-step format for the reader to easily understand what actions were taken and why; furthermore, the entire process can also be replicated in the future for data analyses in comparable survey conditions or in the event other types of equipment are substituted for comparative studies. The setup and configuration processes described in the following paragraphs were developed as a result of the author's professional experience as a geophysical surveyor and experimentation using the pole-mount assembly specifically designed for use on small survey vessels and working platforms.

The initial step of the setup process was securing the ETM903C transducer in the transducer bracket. In most cases, this process can be performed prior to loading the equipment on the survey vessel and/or working platform. By doing so, this step assists in consolidating the equipment, but also provided a layer of protection to the transducer housing during all onboard

activities. The bracket was secured to the transducer by guiding two band clamps through the pre-cut holes in the transducer bracket arms which were lined up with the grooves on the housing exterior (Figure 3-15). Prior to tightening the band clamps, the author ensured the proper orientation of the transducer as per AAE recommendations. Following the proper transducer alignment process, the band clamps were hand-tightened with a screwdriver. The author elected not to use a power tool for this step to prevent overtightening the band clamps and possibly damaging the transducer housing. After the band clamps were properly tightened, the transducer and bracket were placed in a location that did not hinder onboard movement or other surveying operations.

The next phase consisted of setting up the cleat mount on the working platform. The initial action during this phase involved locating a mounting position on the working platform that was sufficiently distanced from the vessel's bilge outflow, diver entry points, ladder locations, and deck traffic. The mount was attached to the cleat by hooking the curved ends on the underside of a cleat and/or secured by way of lashing using appropriate line or ratchet straps; however, no matter the method of securing the cleat mount to the working platform, the cleat mount sleeve must be at a 90º angle to the water surface. After the cleat mount was secured to the working platform, the author attached the transducer bracket to the antenna pole and lowered it into the water to the appropriate depth using as many 1.5 m pole sections as required to clear the bottom of the hull. The top of the antenna pole was passed through the cleat mount sleeve and secured using two built-in thumbscrews. Additional 1.5 m antenna pole sections were added until the top of the pole cleared all vessel superstructure to allow clear line of sight for the antenna to orbiting satellites. Then the antenna was secured to the top of the antenna pole using a custom-made mount built by the author. Following the installation of the antenna pole, additional



FIGURE 3-15: An enhanced view of the transducer bracket and use of band clamps for securing the transducer within the bracket assembly. Note the channel grooves in the housing exterior to guide the band clamps and to prevent slippage. (Photo by author, 2017).

stay lines were attached to the entire pole-mount assembly to reinforce its rigidity and to prevent the possibility of working loose due to waves and vessel motion.

During all fieldwork examinations, the USBL console was setup adjacent to the GPS equipment so that the topside operator could simultaneously monitor both systems. Similar to the setup process of all GPS systems, the author connected all communication and power cables prior to powering on the USBL console. The ETM903C transducer was the first communications cable connected to the USBL console. This particular cable uses a pin connector with a locking mechanism to ensure the cable was secure in the console communications port throughout all survey operations. At this point, the author organized and stowed any excess cable in a location to reduce the possibility of a tripping hazard or entanglement with onboard cables, lines, and other equipment. For fieldwork examinations which utilised a small survey vessel with a T-top, the author secured and stored the excess cable on top of the T-top roof; whilst, other working platform setups required the author to use duct tape for securing cable to the deck to reduce the risks of tripping and entanglement. The next step in the configuration process was connecting the GPS RS-232 serial cable from the Trimble SPS855 receiver to the Data Input communication port. Lastly, the final step in the hardware configuration process involved connecting a portable mouse to the USB communication port. The AAE Easytrak Alpha Portable console is equipped with an integrated mouse which works well in confined locations; however, the author preferred the use of a portable mouse due to ergonomics. Following the connection of the power cable to the onboard power source, and communication cables to all hardware systems, the AAE Easytrak Alpha Portable was ready for use.

Powering on the AAE Easytrak Alpha Portable consisted on depressing the On/Off button located adjacent to the console keyboard. As with any computer operating system, there

was a software initialisation process which required about 15-20 seconds. During the console initialisation process, the author used this time to setup the AAE 1200 Series Mini Beacon. Prior to tightening the beacon connector, the author inspected the O-ring which ensured a watertight seal in the battery compartment. Following the inspection process and light application of food-grade silicone grease, the author activated the beacon by securing the connector using a handheld screwdriver. By this elapsed time, the AAE Easytrak Alpha Portable console had completed the initialisation process and the author was able to open the data acquisition software. Now that all GPS and USBL hardware and software systems were powered on, the author was able to observe satellite positioning information using the Trimble software program and confirm that information was successfully transferred to the AAE Easytrak Alpha Portable console. The screen displays the satellite positioning source and type of error corrections; however, this positioning information represents the survey vessel location. Upon confirming the GPS positioning systems were properly functioning, the author performed a preliminary communication test between the transducer and beacon. This was performed by activating the beacon function within the AAE software system in which the transducer began transmitting active acoustic ranging signals using the specific channel for the selected beacon. A line was secured to the beacon and it was then lowered over the side the farthest point on the working platform. The topside operator would then confirm if the transducer and beacon were successfully communicating underwater ranging information.

Configuring the AAE Easytrak Alpha Portable USBL settings was performed in the software program. Among the most important configuration settings for this thesis' fieldwork examinations were inputting the correct in-water speed of sound values and having a 1-second positioning update interval for improved performance and accuracy. The AAE Easytrak Alpha

Portable software was user-friendly and the screen display was not overwhelming for personnel with limited USBL experience. The toolbar and functions were easily discernible and did not require a sophisticated calibration process. With regards to the 1-second update interval, this can be checked by the diver due to an audible clicking noise every second and by the topside operator by way of observing continuous positioning updates. To deactivate the beacon, the topside operator clicks the beacon function and all communication between the transducer and beacon immediately ceases. The AAE Easytrak Alpha Portable system is capable of operating four separate beacons at a time; however, this thesis only required the use of a single beacon for fieldwork examinations. After all of the setup and configurations processes were completed and performance specifications verified, all systems were ready for UALR methodology data acquisition.

As the central component for the UALR methodology spatial data acquisition process for supplementing archaeological site documentation was the establishment of an effective control point network, this was the initial in-water action taken during all thesis field examinations. Fieldwork examinations used a variety of ground control points (GCPs) that ranged from steel rebar to coded targets constructed by the author which used waterproof ink printed onto weighted PVC plates. The steel rebar GCPs were used on sites with limited to zero visibility and no restrictions regarding driving them into the bottom sediment (Figure 3-16). The coded target GCPs were used on a field examination in which the author conducted a photogrammetric survey of a sunken vessel in the Florida Keys National Marine Sanctuary which prohibited bottom sediment disturbance; therefore, the GCPs were weighted to prevent unwanted movement (FIGURE 3-17). Regardless of which method used, the presence of a ground control network of static datum positions is



FIGURE 3-16: Steel rebar ground control points used for the establishing the spatial network on the WAL0004/WAL0006 site. (Photo by author, 2019).

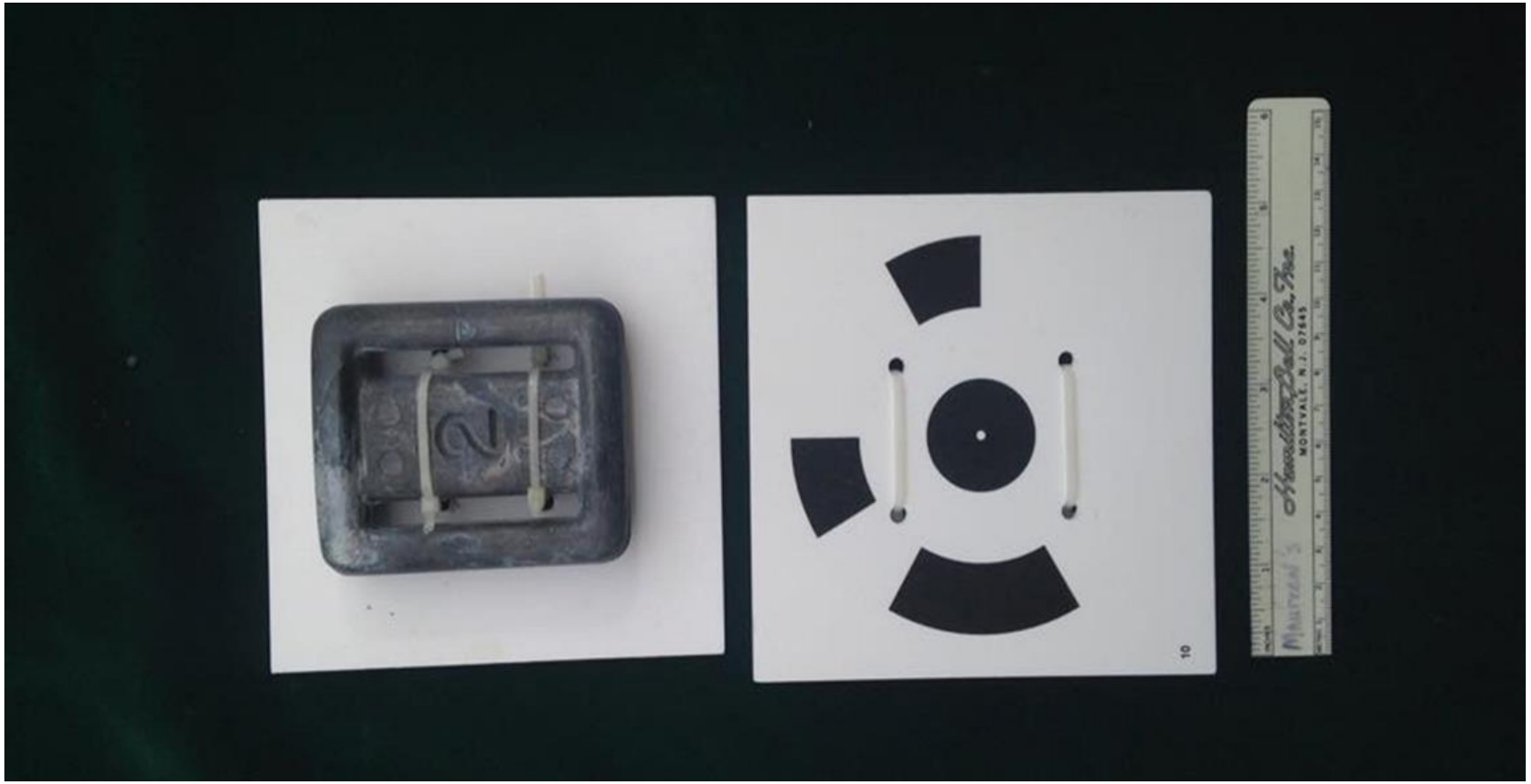


FIGURE 3-17: Ground control points using Agisoft Metashape coded designs. The coded targets were held in place on the seafloor by the 2 lbs. dive weight zip-tied to the underside. Each target was numerically labelled for assisting the diver in identifying which target position there were recording. The coded pattern is recognised by the Agisoft Metashape software and automatically loaded into the 3D model during processing. (Photo by author, 2017).

static datum positions is required for successful UALR methodology spatial data acquisition. If no control point network is established for the survey area, the archaeologist must determine the best course of action for creating the spatial network so that it is effective and discernible for all survey personnel. To assist personnel in navigating the ground control point network in zero visibility, the author installed transit lines between the datum positions with identification markers on the actual GCP, and using surface buoys so that the diver could easily surface swim to the buoy then descend to the datum position. This dramatically increased diver efficiency by reducing the risks of becoming disoriented and/or collecting data at the wrong location; whilst, maximising diving safety by reducing the required bottom time and life support resources for UALR methodology spatial data acquisition. However, in water depths that exceed 10 m, repeated ascents and descents using the surface buoys may contribute to diver equalisation issues; therefore, other means of diver navigation on site should be considered. Transit lines between GCP locations and diver communication systems offer a safe and reliable method of site navigation.

Following the establishment of a ground control network which encompasses all known site features, the next phase of the UALR methodology spatial data acquisition process was activating the transponder beacon and transferring it to the diver for transit to the initial datum position. The diver then confirmed with the topside operator that the beacon was activated by listening for the audible clicking sound indicating a positioning update interval. All field examinations for this thesis used Ocean Technology Systems (OTS) full-face masks with an OTS Aquacom MK2-DCI intercom system and waterproof earphone and microphone assemblies. This allowed constant communication between the topside operator and divers at all times which assisted in increasing efficiency and safety. Following the confirmation of signal

transmissions between the transducer and beacon, the diver descends to the first datum position. Upon arrival, the diver placed the beacon directly above the datum position then notified the topside operator to begin data acquisition. Following the confirmation that the diver was in position and ready for data acquisition, the topside operator activated the Data Record function on the AAE console software and began a five minutes long data acquisition period. The five minutes long data acquisition period with a one-second positioning update interval provided a minimum of 300 positional measurements for a datum location. The decision to use a five minutes long data acquisition period was based on the author's desire to achieve the highest possible accuracy based on the shallow nature of the case study sites, anticipated number of ground control points, and the available diving bottom time to remain within no-decompression limits. A shorter time period is perfectly acceptable, such as 30 seconds to one minute, and this is entirely site dependent and determined by collaboration with the survey party chief, survey boat captain, and project archaeologist. For this thesis, the number of positional measurements far exceeded the required number to achieve a 95% confidence measurement, and increased the positional accuracy of an averaged latitude and longitude coordinate assigned to a datum point. After the five minutes data acquisition period ended, the topside operator stopped the Data Record function, ensured the data was stored in the AAE console hard drive in .txt file format, then notified the diver to proceed to the next datum position. The process was repeated for however many GCPs were positioned throughout the survey area. After all of the GCPs were recorded, the diver returned to the working platform and the beacon was deactivated. Following the verification that all datum positions were recorded, the .txt files for each GCP were transferred to an external hard drive for data analysis and processing.

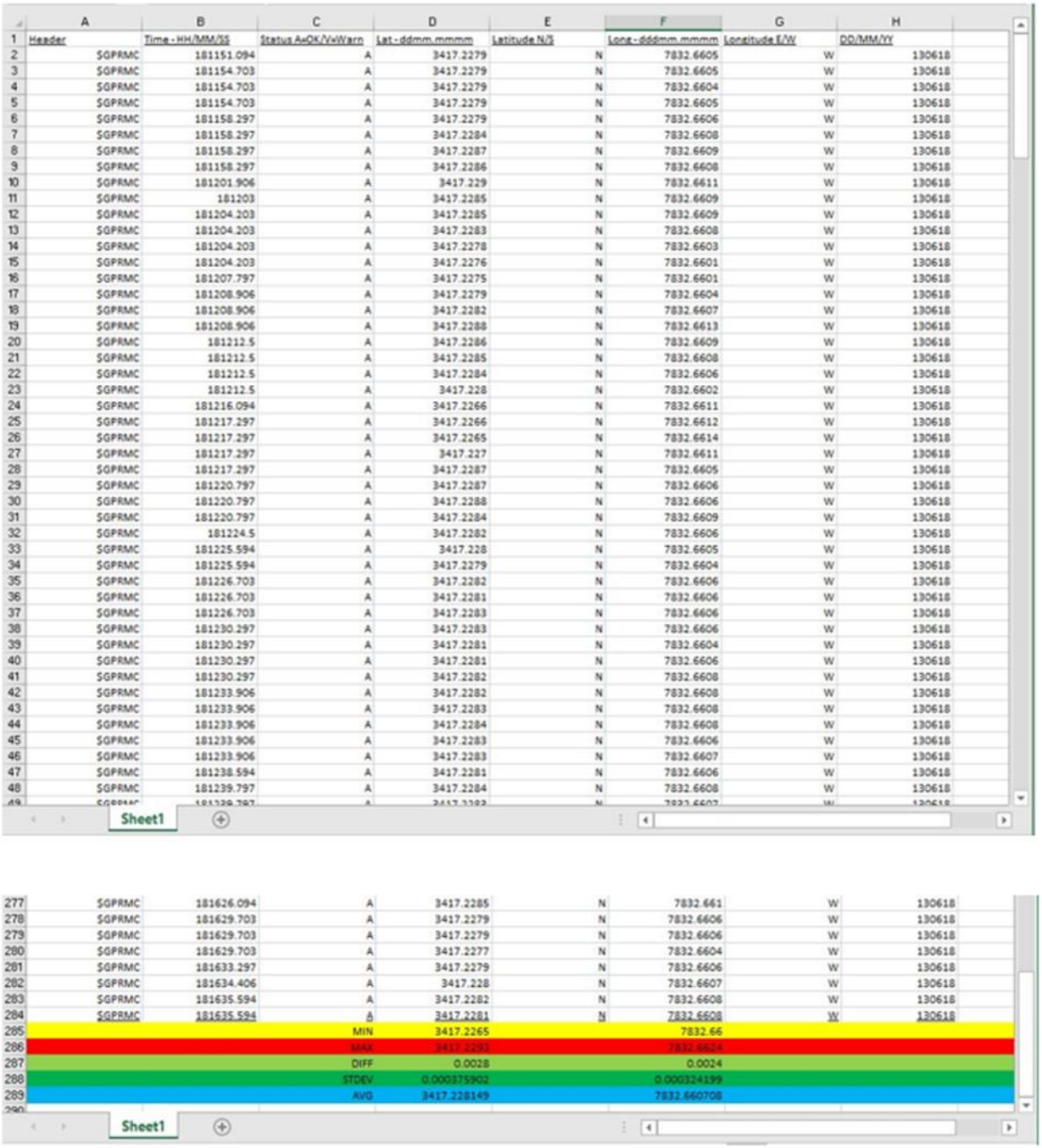
The UALR methodology data acquisition process described in the preceding paragraph is applicable for supplementing all traditional and modern optical archaeological site recording techniques with minimal variations. The application of a single spatial data acquisition method is beneficial in terms of efficiency, consistency, reliability, and familiarity. As described in the above paragraph, the actual UALR methodology data acquisition process was simple and efficient, requiring minimal physical exertion on behalf of the diver. The static placement of the USBL beacon over the datum position ensured the consistency of each positional measurement and the one-second update interval increased the number of measurements to provide a highly accurate averaged datum position. The GPS and USBL positioning systems produced reliable results that were both quantifiable and verifiable for use with other geophysical survey instrumentation; thus, providing the necessary underwater positional information for satisfying contractual specifications regarding submerged cultural resources. Finally, the familiarity of personnel using the UALR methodology on different sites only furthered data acquisition efficiency in which underwater spatial data collection only required a minimal amount of time and project resources.

3.3 Data Processing and Analysis

Underwater positioning data acquired by the AAE Easytrak Alpha Portable USBL system was processed using Microsoft Excel software. The spatial data .txt files saved on the AAE console were transferred to an external hard drive and immediately deleted from the console to prevent any possibility of accidentally combining information from different surveys. Additional copies of the spatial data .txt files were made and stored on other external hard drives for future use if the examined sites are revisited for future research. The .txt files were imported into a Microsoft Excel project named for the specific survey, and the comma-separated-value (CSV)

format allowed all information to be placed in specific columns and rows. The AAE data string provided ample amounts on information for review for each update interval and the author methodically inspected this data for obvious erroneous values that may skew the averaged latitude and longitude coordinates. The AAE data string was beneficial in this process by providing number-value indicators if the quality of the measurement was determined to be unhealthy. Following the initial data analysis, the author then focused on the latitude and longitude columns to determine the following information: minimum coordinate value, maximum coordinate value, the difference between the minimum and maximum values, the averaged coordinate value which was assigned to the specified datum position, and the two (2-σ) standard deviation value (Figure 3-18). These values were calculated using built-in formulae programmed into the Microsoft Excel software which greatly assisted in making short work of calculating this spatial information from over 300 measurements per datum position. The underwater positioning information was then readily available for application to other mapping software programs for producing georeferenced site maps, electronic navigation charts, 3D models, and geophysical survey navigation software.

The satellite positioning data collected by the Trimble SPS855 receiver was processed using the Trimble CenterPoint RTX online software program. This software is free to users with compatible GPS equipment systems and using an accepted file format. For this thesis' field examinations, the author transferred the satellite positioning information from the Trimble SPS855 receiver to an external hard drive for data processing and saving the information for future use. After the data transfer was completed, the author uploaded the raw satellite positioning information to the Trimble CenterPoint RTX online upload tool and submitted the file for processing. The actual data processing procedure was performed by Trimble and required



	A	B	C	D	E	F	G	H
1	Header	Time - HH/MM/SS	Status A=OK/V=Warn	Lat - ddmm.mmmm	Latitude N/S	Long - dddmm.mmmm	Longitude E/W	DD/MM/YY
2	$GPRMC	181151.094	A	3417.2279	N	7832.6605	W	130618
3	$GPRMC	181154.703	A	3417.2279	N	7832.6605	W	130618
4	$GPRMC	181154.703	A	3417.2279	N	7832.6604	W	130618
5	$GPRMC	181154.703	A	3417.2279	N	7832.6605	W	130618
6	$GPRMC	181158.297	A	3417.2279	N	7832.6606	W	130618
7	$GPRMC	181158.297	A	3417.2284	N	7832.6608	W	130618
8	$GPRMC	181158.297	A	3417.2287	N	7832.6609	W	130618
9	$GPRMC	181158.297	A	3417.2286	N	7832.6608	W	130618
10	$GPRMC	181201.906	A	3417.229	N	7832.6611	W	130618
11	$GPRMC	181203	A	3417.2285	N	7832.6609	W	130618
12	$GPRMC	181204.203	A	3417.2285	N	7832.6609	W	130618
13	$GPRMC	181204.203	A	3417.2283	N	7832.6608	W	130618
14	$GPRMC	181204.203	A	3417.2278	N	7832.6603	W	130618
15	$GPRMC	181204.203	A	3417.2276	N	7832.6601	W	130618
16	$GPRMC	181207.797	A	3417.2275	N	7832.6601	W	130618
17	$GPRMC	181208.906	A	3417.2279	N	7832.6604	W	130618
18	$GPRMC	181208.906	A	3417.2282	N	7832.6607	W	130618
19	$GPRMC	181208.906	A	3417.2288	N	7832.6613	W	130618
20	$GPRMC	181212.5	A	3417.2286	N	7832.6609	W	130618
21	$GPRMC	181212.5	A	3417.2285	N	7832.6608	W	130618
22	$GPRMC	181212.5	A	3417.2284	N	7832.6606	W	130618
23	$GPRMC	181212.5	A	3417.228	N	7832.6602	W	130618
24	$GPRMC	181216.094	A	3417.2266	N	7832.6611	W	130618
25	$GPRMC	181217.297	A	3417.2266	N	7832.6612	W	130618
26	$GPRMC	181217.297	A	3417.2265	N	7832.6614	W	130618
27	$GPRMC	181217.297	A	3417.227	N	7832.6611	W	130618
28	$GPRMC	181217.297	A	3417.2287	N	7832.6605	W	130618
29	$GPRMC	181220.797	A	3417.2287	N	7832.6606	W	130618
30	$GPRMC	181220.797	A	3417.2288	N	7832.6606	W	130618
31	$GPRMC	181220.797	A	3417.2284	N	7832.6609	W	130618
32	$GPRMC	181224.5	A	3417.2282	N	7832.6606	W	130618
33	$GPRMC	181225.594	A	3417.228	N	7832.6605	W	130618
34	$GPRMC	181225.594	A	3417.2279	N	7832.6604	W	130618
35	$GPRMC	181226.703	A	3417.2282	N	7832.6606	W	130618
36	$GPRMC	181226.703	A	3417.2281	N	7832.6606	W	130618
37	$GPRMC	181226.703	A	3417.2283	N	7832.6606	W	130618
38	$GPRMC	181230.297	A	3417.2283	N	7832.6606	W	130618
39	$GPRMC	181230.297	A	3417.2281	N	7832.6604	W	130618
40	$GPRMC	181230.297	A	3417.2281	N	7832.6606	W	130618
41	$GPRMC	181230.297	A	3417.2282	N	7832.6608	W	130618
42	$GPRMC	181233.906	A	3417.2282	N	7832.6608	W	130618
43	$GPRMC	181233.906	A	3417.2283	N	7832.6608	W	130618
44	$GPRMC	181233.906	A	3417.2284	N	7832.6608	W	130618
45	$GPRMC	181233.906	A	3417.2283	N	7832.6606	W	130618
46	$GPRMC	181233.906	A	3417.2283	N	7832.6607	W	130618
47	$GPRMC	181238.594	A	3417.2281	N	7832.6606	W	130618
48	$GPRMC	181239.797	A	3417.2284	N	7832.6608	W	130618
277	$GPRMC	181626.094	A	3417.2285	N	7832.661	W	130618
278	$GPRMC	181629.703	A	3417.2279	N	7832.6606	W	130618
279	$GPRMC	181629.703	A	3417.2279	N	7832.6606	W	130618
280	$GPRMC	181629.703	A	3417.2277	N	7832.6604	W	130618
281	$GPRMC	181633.297	A	3417.2279	N	7832.6606	W	130618
282	$GPRMC	181634.406	A	3417.228	N	7832.6607	W	130618
283	$GPRMC	181635.594	A	3417.2282	N	7832.6608	W	130618
284	$GPRMC	181635.594	A	3417.2281	N	7832.6608	W	130618
285			MIN	3417.2265		7832.66		
286			MAX	3417.2293		7832.6624		
287			DIFF	0.0028		0.0024		
288			STDEV	0.000375902		0.000324199		
289			AVG	3417.228149		7832.660708		

FIGURE 3-18: Screenshot computer image of the Microsoft Excel program used for post-processing acoustic data. Subsurface positioning data for each ground control point is processed using and relevant information is displayed in colour-coordinated schemes for easier identification. (Image by author, 2018).



Post-Processing Service Based on RTX Technology

TrimbleRTX.com

Contributor:	matthew@thompsonmaritimeconsulting.com
Reference Name:	24641600.T02
Upload Date:	06/09/2018 21:54:12 UTC
Report Time Frame:	
Start Time:	06/09/2018 15:42:45 UTC
End Time:	06/09/2018 18:32:00 UTC
Observation File Type(s):	T02
Observation File(s):	24641600.T02
Antenna:	
Name:	TRM55970.00 NONE
Height:	0.026 m
Reference:	Bottom of antenna mount
Receiver Name:	TRIMBLE SPS855
Coordinate Systems:	NAD83-2011 (Auto-detected) & ITRF2014
Tectonic Plate:	North America (Auto-detected)
Tectonic Plate Model:	MORVEL56
Processing Interval:	15 s

Statistics

# Total Obs	# Usable Obs	# Used Obs	Percent
678	678	678	100

Used Satellites

# Total Satellites:	16
GPS:	G01 G03 G06 G07 G08 G09 G11 G13 G17 G18 G19 G22 G23 G27 G28 G30

Processing Results

NAD83-2011 at Epoch 2010.0		
Coordinate	**Value**	**σ**
X	1047722.423 m	0.005 m
Y	-5170287.266 m	0.013 m
Z	3572784.291 m	0.010 m
Latitude	34° 17' 13.17895" N	0.005 m
Longitude	78° 32' 40.32406" W	0.004 m
El. Height	-17.468 m	0.016 m

ITRF2014 at Epoch 2018.44		
Coordinate	**Value**	**σ**
X	1047721.563 m	0.005 m
Y	-5170285.784 m	0.013 m
Z	3572784.167 m	0.010 m
Latitude	34° 17' 13.20532" N	0.005 m
Longitude	78° 32' 40.34552" W	0.004 m
El. Height	-18.879 m	0.016 m

Report Information

Trimble RTX Solution ID:	17636261
Solution Type:	Static
Software Version:	6.1.4.17185
Creation Date:	06/09/2018 21:54:35 UTC

Disclaimer

Trimble Navigation Limited does not guarantee availability, reliability, and performance of the current RTX Post-Processing service and accepts no legal liability arising from, or connected to, the use of information on this document or use of this service.

FIGURE 3-19: Trimble CenterPoint RTX Report example from the Lake Waccamaw Pier Evaluation survey. (Image by the author, 2018).

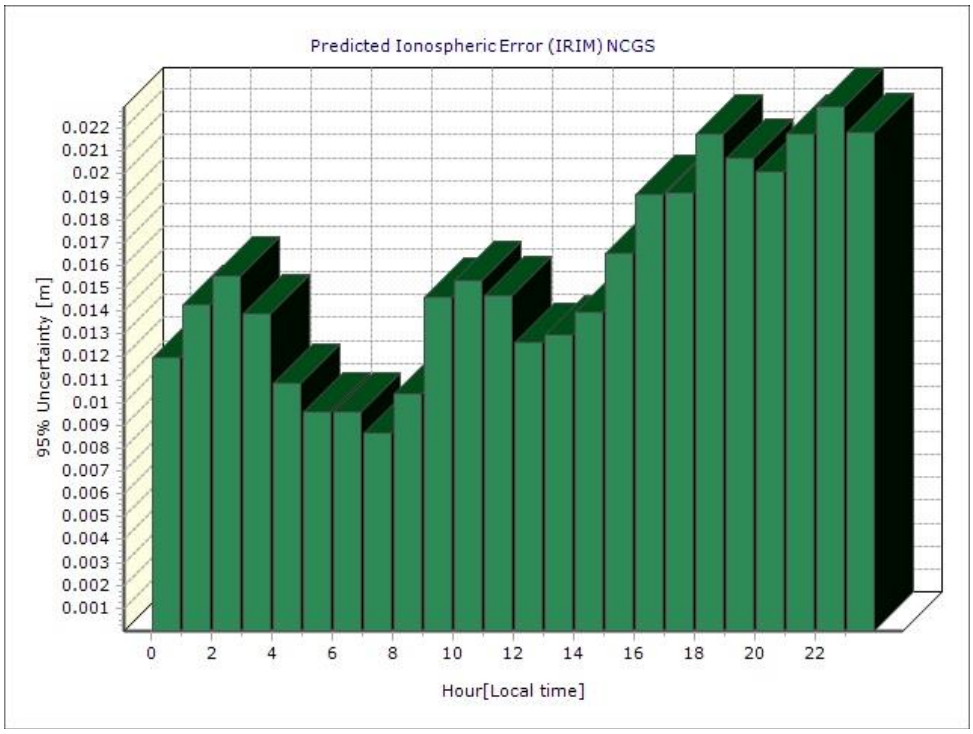


FIGURE 3-20: Predicted ionospheric error for 8 June 2018. Graph provided by the North Carolina Geodetic Survey. Accessed on 9 June 2018.

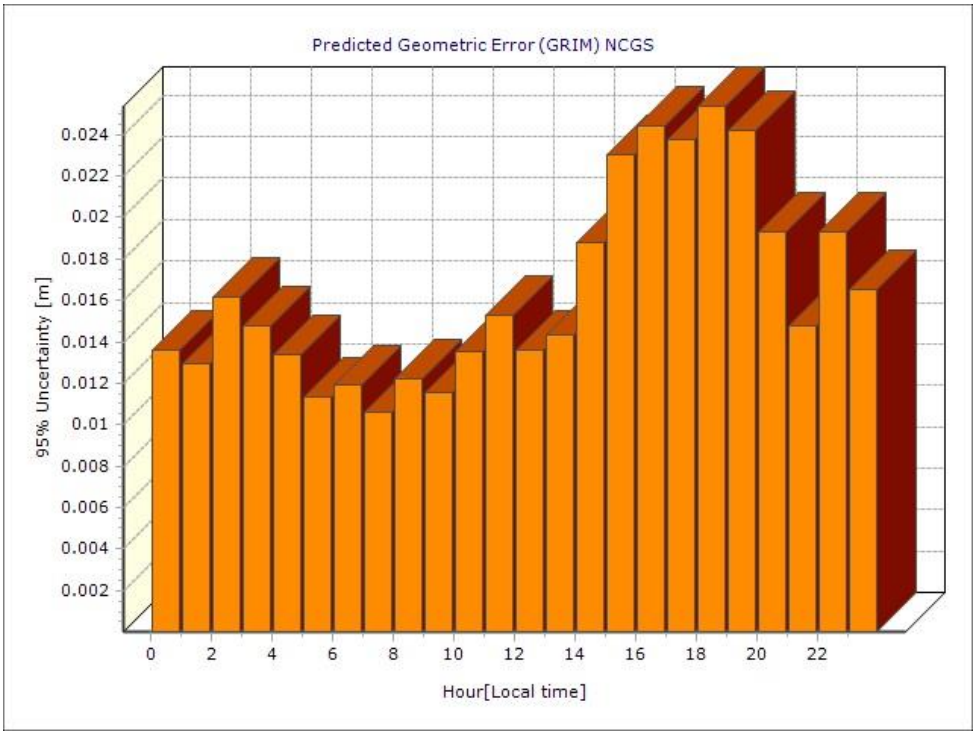


FIGURE 3-21: Predicted geometric error for 8 June 2018. Graph provided by the North Carolina Geodetic Survey. Accessed on 9 June 2018.

no further input from the author. Within the hour, Trimble emailed a report of the satellite positioning information in PDF format (Figure 3-19). The Trimble post-processing service report included all relevant information pertaining to which satellites were used to determine geometric position, the number of observations during the data acquisition process, the percentage of observations used to calculate the geometric position, and the processing results to one standard deviation. The reader should be aware this information pertains just to the GPS system and the values posted in the processing results do not represent the underwater positioning data. The purpose of post-processing the GPS data was to supplement the underwater spatial information if an erroneous dataset was discovered and to determine if that error was a result of an unhealthy satellite, an error with the USBL system, or an error induced by human factors.

Identifying erroneous GCP data is assisted by the use of Microsoft Excel software by examining the difference of the minimum and maximum coordinate values (Figure 3-18). There should be minimal differentiation between these values for a static position; therefore, if an exceedingly large difference value is observed, the reader can review the data and delete the erroneous data entry. If many erroneous data entries are observed, the user should refer to information, such as provided in Figures 3-20 – 3-21, and determine if the cause of the errors were a result of variables outside the user's control or introduced by a human mistake. Although this did not occur during fieldwork examinations, in the event a GPS-induced positioning error is identified during post-processing and data analysis, readers can access solar weather activity reports from www.gps.gov and the error correction service provider to determine the cause and the time period in which that solar weather activity affected the satellite positioning systems. As part of the satellite data analysis process, the author routinely downloaded all ionospheric data

information and predicted geometric errors from RTN/VRS error correction services and analysed the information for any irregularities (Figures 3-20 – 3-21).

3.4 UALR Methodology Application to Archaeological Data Collection Practices

The use of conventional archaeological data collection methods, and even modern digital photogrammetry techniques, have the connotation of being rudimentary when compared to the technologies used for geophysical surveying. The simplicity of commonly-used archaeological data collection practices such as baseline-offset, trilateration, grid squares, and other low-tech data acquisition techniques, allow their application in nearly all marine and freshwater environments that are accessible for scientific diving surveys (Green 2004; Smith 2006). The author's description of the above-mentioned data acquisition techniques as "simple" or 'fundamental" is not based on the necessary steps used to successfully carry out data collection but to describe the technological sophistication of the associated equipment systems. In fact, depending on the scope of a particular archaeological site, these "simplistic" methods are rather arduous depending on the materials used for constructing reference baselines or semi-permanent grid systems for feature documentation. Although these materials are often weighty to withstand environmental conditions and require a substantial amount of physical exertion for mobilisation/demobilisation, the technical sophistication of these systems is minimal and the relative accuracy is largely on part of the researcher. Though these methods do not independently produce underwater positioning values that are compatible with established global reference frames, they do require the use of datum positions for fiberglass tape measurements and optical data collection such as videography, photographic mosaicking, and photogrammetry.

In addressing a thesis research question raised in Section 1.2 (see pg. 35), are these basic archaeological documentation methods capable of integration with a coupled GPS/USBL

system? In Section 3.4, the above-mentioned conventional archaeological site recording methods are reviewed with specific attention to the positional referencing strategies used to document site features. The documentation methods discussed in this section were developed decades prior to the existence of GPS and USBL positioning systems; therefore, these recording techniques were designed using tape and/or optical measurements that were relative to a particular site; whilst, the conversion of those values to latitude and longitude coordinates were neither practical nor accurate in comparison to modern standards. While the presentation of relative measurements as the final positioning product and referenced to a centralised geographic coordinate may have been acceptable for most archaeological projects from the middle to the late 20th century, modern geophysical surveying guidelines utilise strict spatial tolerances for acquired datasets. The research aims in this section are to analyse the positioning referencing datum and the manner in which a USBL transponder can be affixed and/or held in a static position for underwater localisation.

Prior to the analysis of selected conventional archaeological data collection methods, there is an examination of various circumstances based on the author's real-world professional experiences which hypothetically should have warranted the application of archaeological site recording methods to supplement modern geophysical surveys had submerged cultural materials been identified or suspected within survey boundaries. The instrumentation used for geophysical surveys is technologically sophisticated and capable of highly accurate seafloor mapping; however, natural and manmade circumstances exist that can either reduce and/or prohibit their application. In the event a shipwreck or suspected paleo-landscape is discovered in a location in which these circumstances prevent the use of geophysical surveying instrumentation, archaeologists may be required to utilise alternative means of documenting these sites in

accordance to permitting and contractual specifications. Diver and ROV investigative surveys qualify as substitute non-disturbance methods that can be used to supplement geophysical survey datasets. There are an infinite number of circumstances that can contribute to the need for diver and/or ROV investigative surveys; yet, the most common situations observed by the author during geophysical surveying operations were steep variations in bottom topography, the presence of thermocline, fishing gear which posed entanglement risks to towed equipment, and the discovery of previously unknown archaeological sites that may be of cultural significance. Each circumstance presents its own set of challenges; however, such situations can prevent the acquisition of much-needed data used by archaeologists to clear an area for bottom sediment testing and cable/pipeline trenching operations.

Steep variations in bottom topography are a common issue facing geophysical surveys in which geophysical surveyors are required to ensure towed sensors remain at specified altitudes throughout data acquisition. Altitude specifications are typically applied to towed SSS and magnetic transverse gradiometer (TVG) systems in which they are required to collect data at a certain distance above the seafloor, and that height is determined by a percentage range of the water depth. As an example, the below equations demonstrate how to calculate sensor altitude range for 10 – 20% of the water depth of 50 m:

$$Minimum\ Range\ (m) = .10 \times 50$$

$$Minimum\ Range = 5\ m$$

$$Maximum\ Range\ (m) = .20 \times 50$$

$$Maximum\ Range = 10\ m$$

$$Sensor\ Altitude\ Range = 5 - 10\ m$$

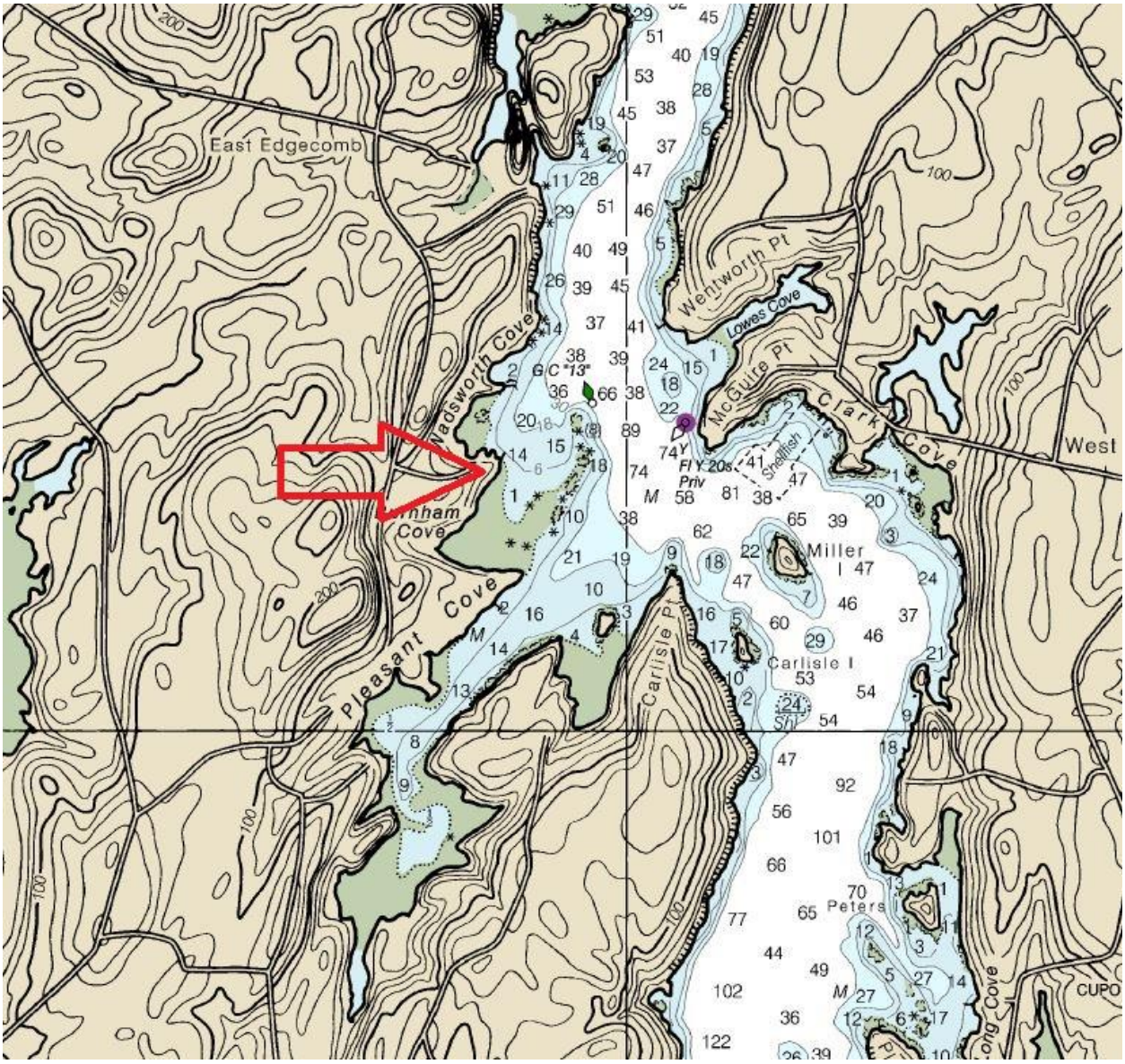


FIGURE 3-22: A topographic map displaying terrestrial contours and depth soundings (in ft.) of the Damariscotta River near East Boothbay, Maine, USA. The red arrow indicator is the terminal location of the marine geophysical survey for the New England Aqua Ventus windfarm project. The cable corridor leading from the deep river channel to the shore junction experiences steep variations in depth and minimal room for manoeuvrability, thus making it impossible to maintain specified towed sensor altitudes. No cultural materials were identified in this area; however, the geophysical surveyors were forced to rely on fixed sensors (MBES and SBP) for feature detection and bottom coverage. In the event submerged cultural resources were discovered in this area, a diver/ROV survey could be used to supplement fixed sensor data for feature identification and determining site extents. Chart from https://nauticalcharts.noaa.gov/charts/noaa-enc.html (accessed March 2021).

This altitude range is based on required survey line spacing and sensor detection coverage; whilst, geophysical surveyors maintain sensor altitude by adjusting the amount of cable out using onboard winches. If the acquired data is outside of the altitude specifications, the geophysical surveyor is obligated to rerun that portion of the line to ensure full coverage; however, this may not be possible in areas of steep bottom topography (Figure 3-22). If the seafloor has rapid changes in depth, the onboard winch systems may not be able to pay out or bring in cable fast enough so that the sensors remain within altitude specifications and/or prevent impacting the seafloor. Archaeologists participating in geophysical surveys require SSS and TVG data for the interpretation of possible cultural remains; however, the absence of these important datasets in an area containing suspected cultural material warrants diver and/or ROV mapping surveys. A trained archaeological diver, or observer in the event of an ROV survey, can effectively investigate and evaluate features on the seafloor to determine if they are manmade and relevant cultural significance.

A thermocline is another naturally-occurring phenomenon in which a distinct water layer of a differing temperature (usually colder) is present in the water column between the surface and seafloor; thus, changing the acoustic signal transmission speed from the surface to the seafloor, and vice-versa. The effects of temperature on the in-water speed of sound and sound speed gradients were previously discussed with temperature reported as having the greatest effect on underwater sound speed and signal path. Thermoclines affect all acoustic imaging and ranging systems, but its effects can be increasingly detrimental to SSS data records leading to the inability to effectively interpret seafloor features. When using a SSS system towed above a thermocline layer, the resultant imagery appears cloudy, hazy, or stretched which does not permit accurate feature interpretation or measurements during post-processing. An effective mitigation

technique is to lower the SSS towfish to a water depth below the thermocline layer and the imagery will become clearer. Unfortunately, this mitigation method is not always possible with geophysical surveys in which strict towed sensor altitudes are required. The bottom of the thermocline layer may be outside of the sensor altitude range or may extend to the seafloor. In these circumstances, the acquired SSS data (and other acoustic sensor information) may be insufficient for archaeological interpretation and require a diver/ROV survey if an area is suspected of having submerged cultural resources.

Manmade obstacles such as surface navigation aids and fishing gear pose entanglement risks to both fixed and towed sensors; whereas, fishing gear poses the greatest risk due to not being labelled on navigational charts and not always visible on the water surface. Fishing gear is the general term used to describe equipment used for lobster traps, crab pots, nets, and other tackle. This equipment is typically resting on the seafloor but marked at the surface using a buoy or series of buoys. The buoy line connected to the traps is typically the entanglement point for the towed sensors which can cause nightmarish problems including dragging towed equipment out of altitude specification, pulling towed sensors off the survey line, double-wrapping (intertwining) the sensor cables, and the worst being cable separation in which the sensors become physically detached (Figures 3-23 – 3-24). In addition to damaging, and possibly losing towed sensors, fishing gear entanglements also result in contributing to tense relationships (sometimes hostile) between geophysical surveyors and local fishermen (Bever 2021; Schreiber 2021; Wolfe 2021). In the plausible event that fishing gear is positioned inside the survey corridor and in the vicinity of submerged cultural resources, surveyors and archaeologists may elect to avoid the risk of entanglement with towed sensors and use diver/ROV mapping techniques to document the site. By doing so, the diver/ROV survey reduces the hazards to the



FIGURE 3-23: A lobster trap buoy entanglement with a side scan sonar cable. The entanglement was discovered when the USBL transponder beacon affixed to the sensor indicated a severe line deviation. (Image by author, 2021).



FIGURE 3-24: A lobster trap brought onboard after an entanglement with the TVG and buoy line. The appearance of the trap indicates it is derelict gear. Photograph by M. Thompson (2021).

towed survey equipment, fishing gear, personnel safety, and possibility of dragging gear across a culturally significant site.

The final circumstance in which archaeological diver/ROV mapping can supplement a geophysical survey is in the event of discovering an unknown shipwreck or previously-discovered site determined to be of substantial cultural significance. Determining cultural significance is the responsibility of the survey archaeologist and they make the necessary recommendations regarding the establishment of avoidance zones or if additional research is needed to satisfy permitting requirements. In the U.S., federal agencies and state historic preservation offices generally abide by Section 106 of the National Historic Preservation Act (NHPA), which lists specific criterion that an archaeological site must meet for protective status (NHPA 1966). Part of the Section 106 criterion requires the identification of the site and features within its extents; however, this is not always an easy task for maritime archaeologists surveying a submerged site. SSS and TVG data greatly contribute to identifying wreck site features such as hull composition, exposed framing or decking, the overall length and beam, and other characteristics which contribute to the documentation process. Sometimes geophysical survey data is not sufficient for satisfying Section 106 requirements and further archaeological investigations are required, especially on wrecks within survey corridors that have the potential for NRHP nominations. One such example is the Mardi Gras Shipwreck Site (16GM01) located off the coast of Louisiana in the Gulf of Mexico at a depth of 1220 m, and this wreck site was thoroughly mapped and excavated using ROV technology and tracked using LBL/USBL acoustic positioning (Ford et al. 2008). The vessel was initially discovered in 2007, during a geophysical survey for the Mardi Gras Pipeline System and analysis of vessel construction and artefacts determined the age to be circa 1815. The archaeological investigation satisfied NHPA

requirements and permitting guidelines from the Minerals Management Service (MMS) of the United States Department of the Interior, and subsequently added to the NRHP under Criterion D (Ford et al. 2008:2).

The previously-mentioned circumstances are but a few of numerous potential events that can lead to the need for supplemental diver and ROV operations for satisfying archaeological requirements as an integral part of a geophysical survey. In the event supplemental archaeological diving and/or ROV mapping is needed, what type of site mapping methods should be used? IHO, BOEM, and Historic England guidelines do not state specific archaeological documentation techniques to be used in conjunction with geophysical surveys; therefore, that decision is relegated to the project archaeologist. So, which archaeological site documentation methods can be used to supplement geophysical data? The author asserts that archaeologists can choose whichever method they prefer given the selected technique is applicable to site conditions and produces usable information that complements geophysical datasets. For the purposes of expediency, this thesis reviews three commonly-used archaeological documentation methods: baseline survey, grid survey, and digital photogrammetry. Archaeologists have likely used all three of these methods at some point in their careers and are familiar with how they work; therefore, the review of these methods simply focuses on aspects pertaining to positioning and datum referencing. Review of these referencing strategies provides the necessary information to determine if these methods are capable of integration with a coupled GPS/USBL system for underwater datum positioning and overall site georeferencing using an established reference frame.

3.4.1 Baseline Surveys

Baseline surveys are typically among the first taught to archaeological students at the undergraduate and graduate levels for detailed site documentation. They are typically easy to construct, simple to use, and generally have little impact or disturbance on the site; thus, making it ideal for phase one archaeological surveys. In terms of datum referencing and spatial control, baseline surveys can be used in conjunction with as many ground control points as required to achieve the desired geometric accuracy (Smith 2006:19). Determining the position of an object on the seafloor using a baseline survey with multiple datum points is comparable to using multiple GPS satellites to calculate a satellite receiver's location on the earth's surface. The more datum points to which an object is measured, the more geometrically accurate that object's position will be in relation to the overall site frame of reference. Measurements are typically recorded using fiberglass tapes, compasses, and dive slates in which a diver documents the distance and headings (azimuth and back azimuth) from the site feature to the datum position. The overall accuracy of the recorded measurements is dependent upon the structural integrity of the baseline system to prevent sagging and/or unwanted movement, the ability of the archaeologist to accurately and consistently use fiberglass tapes or other measurement devices, environmental conditions such as visibility and strong water movement, and the strategic placement of datum points to ensure the entire site falls within the survey extents.

Datum points are the critical component for baseline survey accuracy given they are the basis from which all measurements are recorded and spatially referenced. For baseline surveys, datum positions can include the zero and terminal ends of the baseline, and in some cases, multiple baselines are used on sites with features scattered across a large area. The materials used to construct the baseline system need to be robust so they do not sag or move throughout the

duration of the project. The author typically uses iron fence posts or rods driven into the bottom sediment in locations that do not disturb the site, and while the posts physically support the baseline, they also serve as datum positions. Depending on the intactness of the site, site features may also serve as datum positions if they are static and not likely to move during the course of the survey. Site feature datum can be parts of a wreck such as the keel or stempost, while artefact assemblages such as cannon and anchors offer immovable reference points which can be used in place of posts driven into the seafloor. The principal requirements for datum positions either driven into the seafloor or the use of existing site features are that they remain static throughout the duration of the survey, and measurements points are clearly identified and explained to diving personnel.

While the use of datum points greatly assists in calculating the geometric positions of site features within a survey area, all of the recorded measurements are relative to that particular site. For coastal sites in shallow water (4 m or less), past archaeological surveys utilised telescoping GPS antenna poles or shore-based total stations to determine the latitude and longitude coordinates of specific points within a specified reference frame (Bowens 2009:119-120; Gallou and Henderson 2012). In doing so, those surveys have the capability to accurately georeference the datum positions and all site features measured from those control points. The obvious limitations to this method include the proximity to shore in which a total station can be effectively used and the shallow operating water depth to keep a GPS antenna or reflective prism above the water surface. Since the 1990s, archaeologists borrowed a method commonly used by recreational divers for marking underwater positions which uses waterproofed GPS units equipped with a tethered floating antenna or the use of a handheld GPS receiver at the water surface which is connected to a line from the surface swimmer to the object on the seafloor

(Green 2004:57). As discussed earlier in this writing, the accuracy of these types of GPS units and data collection methods do not satisfy IHO, BOEM, or Historic England geophysical survey underwater positioning requirements. These institutions recommend the use of USBL acoustic ranging systems for underwater positioning, which are capable of integration with onboard GPS equipment while satisfying accuracy and measurement confidence guidelines. USBL acoustic ranging is the clear choice for acquiring the underwater coordinates for datum positions based on its ease of use, cost and time efficiency, compatibility with onboard survey instrumentation, and the high probability this type of equipment is already onboard or available for immediate use in the field.

If operating under IHO, BOEM, or Historic England guidelines, how can a coupled GPS/USBL system successfully integrate with baseline surveys for supplementing geophysical datasets? The USBL data collection process can be used in a similar manner to that of the shallow-water GPS antenna pole technique, in that the USBL transponder is placed directly over the datum position and held motionless throughout data acquisition. The USBL data acquisition process can be repeated for each datum position and record underwater positioning coordinates in user-defined reference frames such as UTM, WGS84, NAD83, etc. Additional information pertaining to acoustic signal strength is provided for each signal update and can be assessed in real-time or reviewed during post-processing. Unlike shore-based and floating underwater positioning methods, USBL is not limited by proximity to shore and capable of use by archaeological divers for shallow water environments and ROVs for deeper sites in which the use of divers is not practical. As with any acoustic ranging system, the use of USBL for underwater positioning requires the users to be acutely aware of the environmental conditions of the site and manmade factors which can affect two-way signal transmission. Many of the issues

affecting underwater sound transmission were previously reviewed in Section 2.2.2 (see pg. 73); however, ensuring visible line-of-sight from the USBL transducer to the transponder is necessary, especially on archaeological sites with sloping bottom topography, coral and other botanical life, marine life such as schools of fish, and wreck components with structural relief extending from the bottom sediment vertically into the water column.

The underwater positioning information produced by a coupled GPS/USBL system allows archaeological researchers to georeference all baseline survey data using quantifiable positional accuracy and measurement confidence that can be used for updating electronic navigation charts and future archaeological field research. Using the absolute-localised baseline as the reference point for all site feature positional computations, fiberglass tape measurements and compass headings are used to calculate the latitude and longitude coordinates for each point; whilst, such calculations can be performed using Microsoft Excel and do not require expensive and complex software programs. Although calculating site feature coordinates using distance and azimuth measurements is relatively simple and a common navigational practice, the latitude and longitude coordinates can be uploaded to archaeological mapping software programs such as AutoCAD, ArcGIS, Global Mapper, Google Earth, and other available systems. Beyond the use of latitude and longitude coordinates for electronic mapping purposes, the added versatility for incorporating a GPS/USBL system with baseline surveys are the capabilities to monitor unwanted datum point shifting that can induce measurement errors, the ability to rebuild the baseline in the exact position for subsequent fieldwork (if required), and the positional accuracy and measurement confidence for the overall baseline survey will be in compliance with geophysical survey requirements. Baseline surveys are among the most rudimentary and simple to use site documentation techniques, but offer exceptional mapping capabilities when properly

implemented. Baseline surveys combined with a coupled GPS/USBL system offer archaeologists an effective and efficient option for supplementing geophysical survey data to ensure the protection of submerged cultural resources.

3.4.2 Grid Surveys

Underwater excavations of submerged cultural resources are among the most complex and exhaustive practices in archaeological research. Archaeological excavation practices require the implementation of a spatial control system in which all site features are properly documented in the *X*/*Y*/*Z* axes. The excavation process is inherently destructive to the site due to ground disturbance which alters artefact physical and chemical conditions. The change in the physical and chemical properties of the archaeological site can restart or significantly increase the rate of deterioration, especially for site features which were preserved in anaerobic environments or concretions. Archaeological excavations which require the displacement or removal of artefacts run the risk of losing site feature context and the physical relationships of artefacts within the overall site. The spatial context between site features, both big and small, reveal significant information pertaining to the vessel and those who were onboard; therefore, the proper documentation of where these features are located within the overall context of the site cannot be overstated. Maintaining spatial control of a complex underwater archaeological excavation is not a simple endeavour and requires the use of a sophisticated control network which is why a grid system is typically used for such projects.

Grid systems are a common mapping tool for archaeological excavations on land and underwater. Archaeological sites of all shapes and sizes can be effectively mapped with a high degree of accuracy using grid systems, which is why this type of mapping strategy is essential for documenting excavations (Smith 2006:23). When compared to other low-tech archaeological

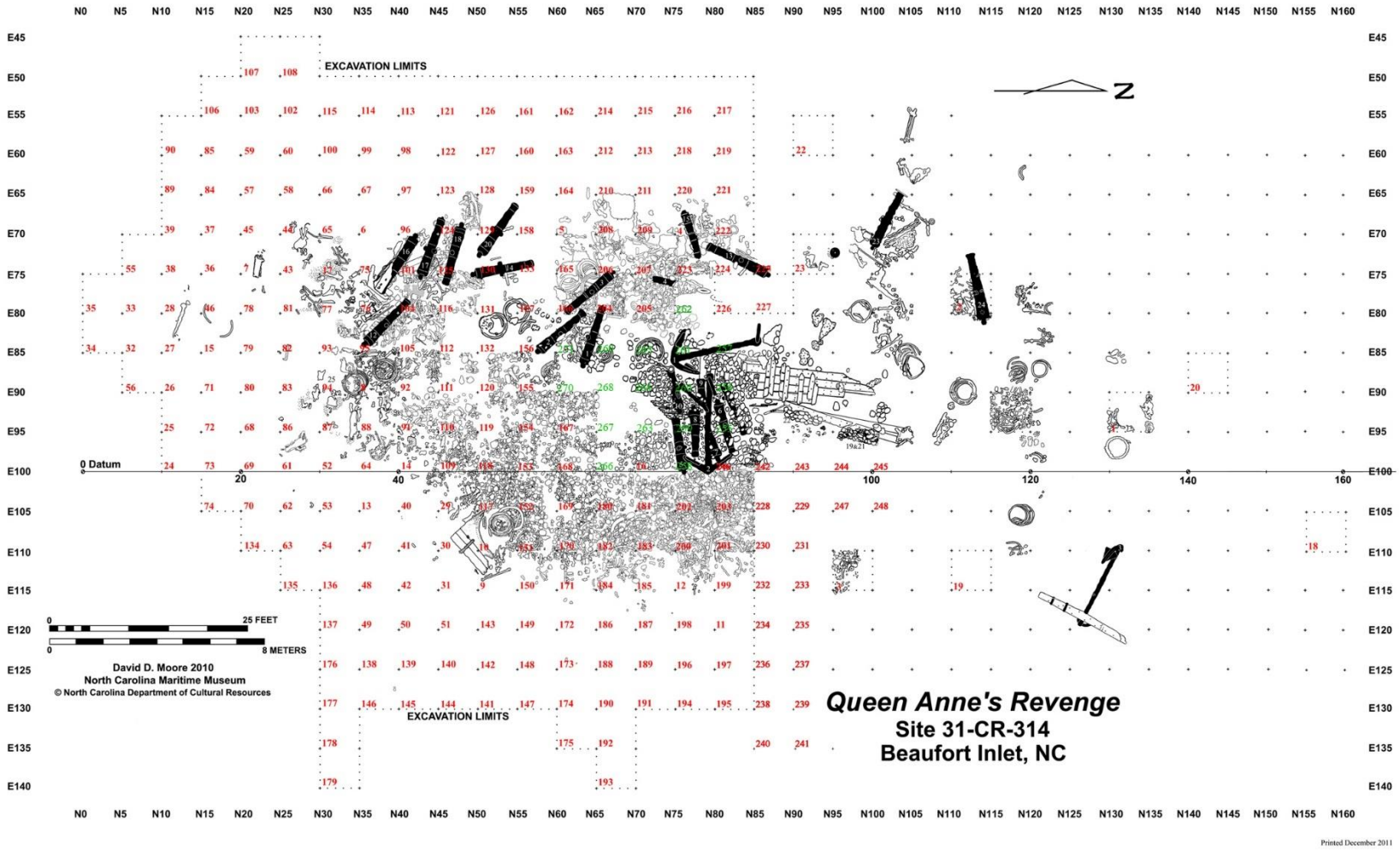


FIGURE 3-25: Illustrated site map of the *Queen Anne's Revenge* shipwreck site, located in Beaufort Inlet, North Carolina, USA. The author participated in a number of field seasons on this site in which portions of the wreck were systematically mapped and excavated using a grid system. The grids are numbered and referenced to permanent datum positions driven into the seafloor. These datum positions were used for multiple field seasons. The site map illustrations for each grid square are added as they are excavated. Site map courtesy the North Carolina Department of Natural and Cultural Resources. (Accessed June 2021).

mapping methods, grid systems do require more robust materials, time, personnel, and consideration for construction and maintenance. Over the course of his academic and professional careers, the author worked on dozens of projects which utilised grid systems for documenting excavation processes. Some grid systems were constructed using hastily-built intersecting baselines, while others used pre-constructed wooden or PVC squares which were then secured over sections of a site. The grid squares varied in size and were labelled using some form of an alphanumeric system and cardinal directions (Figure 3-25). Regardless of construction variations, grid surveys theoretically use similar measurement practices for the documentation and excavation of site features within each individual grid. The use of fiberglass tapes, plumb lines, levels, and digital cameras are commonly used to document the positions of site features within a grid. The grid system allows archaeologists to systematically record and excavate a site in manner which minimises the risk of losing valuable spatial information and site feature context.

Spatial data generated through grid surveys allow archaeologists to accurately map site features and document where specific artefacts were excavated using relative measurements in *X*/*Y*/*Z* format. Knowing where artefacts rest on the bottom is important in determining the context of the physical remains which ultimately contributes for the determination of site significance and if the remains are eligible for protective status. Although the relative measurements generated during the course of the grid survey have the potential to be both accurate and precise, these values are not easily transferable to established reference frames without some form of positioning supplementation. If a grid survey is conducted in shallow water (4 m or less) in close proximity to shore with a calm sea state, a total station can be used to provide latitude and longitude measurements for datum positions (Henderson and Burgess

1996:250; Henderson et al. 2011:208). For geophysical surveys beyond the effective range of total stations, or in nearshore locations with deep-water drop-offs such as the area shown in Figure 3-22 (see pg. 165), shore-based technologies cannot be used to accurately georeference the grid system within acceptable horizontal and vertical uncertainty values.

Grid survey datum positions exist in a variety of forms and the preference of which type to use is generally the decision of the project archaeologist; yet, the type of datum and how measurements are recorded should be discussed in pre-survey briefings with all diving personnel. In regards to grid survey datum configurations, the actual control point depends on the grid system construction. If a grid system is constructed using a series of overlapping baselines, the rods or posts used to construct those baselines can be used as the datum reference points; whereas, grids constructed from wooden or PVC frames may use a specific corner(s) of the frame. If using a coupled GPS/USBL system for underwater positioning, the USBL transponder can be held in a static position directly above the datum position for a specified time duration (same concept used for baseline surveys). Depending on grid construction materials, available time, and desired levels of spatial accuracy, archaeologists can choose which datum positions to georeference within the grid system. Obviously, georeferencing each corner of a grid system over a large survey area can become laborious and time-consuming; therefore, archaeologists must consider logistical concerns when deciding the spatial data acquisition method. Regardless of the time available for spatial data acquisition for each datum position, a coupled GPS/USBL system offers the most efficient and accurate results.

Grid survey deliverables are comparable to other low-tech survey practices such as baseline surveys; yet, have the capability to offer more accurate and precise site feature information. Georeferenced grid datasets are easily transferable to software programs for

generating overall site maps with localised datum points using latitude and longitude coordinates. In the event multiple field seasons are required for site feature mapping and artefact excavations, the georeferenced datum positions allow archaeologists to reconstruct the grid system in the exact position as used for prior fieldwork. This is important for many reasons, but most importantly in regards to accurate site mapping, latitude and longitude coordinates for datum positions greatly assist in ensuring the measurement confidence of the original grid system is maintained. During the grid reconstruction process, a diver can carry a USBL transponder and the topside USBL operator can "walk" the diver to the exact coordinates for setting up each datum position used for previous fieldwork. This is not to say that a grid system cannot be effectively reconstructed using fiberglass tape measurements and compass headings; however, human error and environmental conditions will cause variations where the grids are positioned. If a grid system is constructed from a central datum position and measured outward using fiberglass tapes and compass headings, the measurement error margin will grow larger as the distance from the datum point increases. This type of error, coupled with diver fatigue, air consumption, and bottom time can be problematic in terms overall survey accuracy and diving personnel safety. The use of a GPS/USBL system replaces the laborious tasks of divers orienting their position on the site in reference to a datum position, swimming a specified distance while following a compass heading, and driving a rod or stake at the position assumed to be a previous datum point without the capability of real-time verification. In many cases, the positional errors using fiberglass tape and compass measurements will not be known until all of the grid information is compiled onto the overall site map which can reveal significant data gaps. Using a GPS/USBL system reduces the amount of work and gear needed for divers to reconstruct the grid system, and do so with known positional accuracy and measurement confidence.

3.4.3 Digital Photogrammetry Surveys

Underwater digital photogrammetry is a popular archaeological data acquisition method currently in use throughout the world where water visibility is adequate for optical instrumentation such as digital single lens reflex (DSLR) cameras and videography systems. Photogrammetry is not a new method of archaeological site documentation; however, recent innovation in digital camera systems, user-friendly software, computer processing capabilities, and general interest in three-dimensional (3D) modelling as a terrestrial and underwater survey tool has contributed to the increase in its usage (Green 2004:165; Drap et al. 2007; Westoby et al. 2012:300-314; McCarthy 2014:175; Bianco et al. 2015:25-32; Eisenhofer at al. 2017:1-14). Photogrammetric models are routinely included in archaeological reports and uploaded for public viewing on selected websites such as Sketchfab and other similar sites.

Although modern digital photogrammetry produces useful deliverables such as computer-based 3D models in which site features can be examined from an office chair, physically reproduced using 3D printing technology, and applied to other graphics-based systems for animation, the photogrammetric method requires underwater positioning supplementation for georeferencing the dataset. Photogrammetric software, such as Agisoft Metashape, allow users to input ground control point coordinate information for identified targets during image processing; thus, allowing the entire dataset to be georeferenced (Agisoft 2021). This is a common practice for aerial and terrestrial surveys where latitude and longitude coordinates are easily collected and applied during the 3D model rendering process. Underwater photogrammetry requires additional equipment to produce similar results; however, underwater archaeological surveys using georeferenced photogrammetric data have been generally restricted to marine environments with optimal visibility and very shallow depths for allowing the camera system to operate at the

surface (Henderson et al. 2011:207-217). Photogrammetric surveys of archaeological sites in deeper locations have also included ground control points for use in georeferencing datasets using a relative coordinate system which only pertains to a particular site (Bianco et al. 2015:269-275; Capra et al. 2015:67-72; Diamanti and Vlachaki 2015:93-98; Casella et al. 2016:269-275). Although relative measurements have been submitted for both amateur and professional photogrammetric surveys of archaeological sites, the product deliverables should not be used for supplementing geophysical surveys if the photogrammetric data cannot be georeferenced using absolute coordinates within specified horizontal and vertical uncertainty requirements issued by IHO, BOEM, and Historic England.

Geophysical surveys require archaeologists use applicable methods that can supplement acquired datasets, and photogrammetry is an ideal non-disturbance site documentation method for sites environments adequate water visibility. Underwater photogrammetry does not require the use of baselines or grids as part of its spatial control; yet, most scientific research prefer the use of datum positions for desk-based analysis and measurements. Desk-based assessments which conduct site measurements of the dataset do require that archaeologists record the spacing between datum positions which can be recorded using *X*/*Y* measurements. It is noted that these measurements are relative to a particular site and cannot be transferred to an established reference frame without absolute underwater positioning. The inability for this method to independently produce latitude and longitude coordinates requires that it have a supplemental underwater positioning system to fill in the spatial data gap. Similar in regards to baseline and grid surveys, photogrammetric surveys can benefit from the use of a coupled GPS/USBL survey in which a diver holds a USBL transponder in a static position directly above a datum position for a specified time duration. The averaged coordinate values for each position can then be

uploaded into the photogrammetry processing software and applied to each recognised target. Following the generation of a georeferenced 3D model, the entire dataset can be exported to other software programs for further mapping and animation, or added to websites for general viewing.

4.0 Fieldwork Examinations

The application of the UALR methodology to existing traditional and modern optical archaeological site recording techniques required a series of fieldwork examinations. The research aims and objectives for each fieldwork examination varied in accordance to specific goals the author determined necessary at each phase for the UALR methodology development. The final UALR methodology was a linear development which spanned from the formulation of the research questions for this thesis, initial literature review, and various phases of fieldwork operations which resulted in a refined underwater positioning technique for supplementing archaeological site documentation practices in support of high-resolution geophysical surveys. The case studies examined in Section 4 were the real-world field testing of the equipment systems and data acquisition methods previously discussed in Section 3. The case studies were conducted in varying marine and freshwater environments, which offered specific challenges in site accessibility, underwater visibility, bottom sediment composition, size and type of cultural remains, and archaeological documentation methods. The case studies and their respective results demonstrated the UALR methodology as a viable underwater positioning solution for supplementing archaeological field documentation practices that independently lack subsurface localisation capabilities.

The fieldwork examinations discussed in Section 4 underwent a series planning and permitting processes prior to all survey activities. Fieldwork and diving operations planning were shared with the University of Oxford's Safety Office, and upon the safety recommendations of the university's diving supervisor, the author determined that all diving operations were to be conducted in shallow-water environments to reduce the risks of decompression illnesses and other diving-related injuries. In compliance with the university's diving safety recommendations,

the author pursued opportunities to conduct fieldwork examinations on archaeological sites that could potentially benefit from updated underwater positioning information while also providing applicable testing locations for the UALR methodology. In reference to hypothetical scenarios pertaining to the inability for geophysical survey sensors to collect full datasets, the case study locations offered similar challenges and can be considered realistic scenarios in which to test the UALR methodology. Although the fieldwork data sampling set was limited by operational depth requirements, the information garnered from these case studies are applicable to geophysical surveys. Furthermore, the author anticipates that the spatial requirements currently in place for geophysical surveys will gradually shift to all maritime archaeological field research in similar ways to that previous surveying methods and equipment; therefore, information from this thesis can be used as a pragmatic approach to solving the spatial problem and informational gaps currently present within the maritime archaeology field.

4.1 Rolesville Quarry Research Case Study (August 2016)

4.1.1 Introduction

The Rolesville Quarry case study was carried out during two separate field examinations for the purposes of analysing modern underwater digital photogrammetry equipment, acquisition methods, and post-processing software as an archaeological documentation method for supplementing high-resolution geophysical surveys. Modern digital photogrammetry and end products offer maritime archaeologists the ability to create detailed three-dimensional imagery of submerged sites, which in previous years would have required substantial amounts of time to produce similar results using manual approaches (Bass 1970; Green 2004:165, McCarthy 2014:175). As an evolutionary step in underwater archaeological data acquisition, digital photogrammetry offers maritime archaeologists with a cost-efficient and pragmatic method of high-resolution site documentation; however, the technology systems and acquisition method lack the capability to independently produce absolute underwater positioning information. As a consequence, non-georeferenced photogrammetric models, or any archaeological datasets without spatially-referenced datum, are not applicable for supplementing geophysical survey data.

The research aims for this particular case study were multifaceted and undertaken in successive order. The initial objective was to carry out a photogrammetric survey in a relatively controlled underwater environment; whereas, the secondary and tertiary goals were to observe specific spatial aspects upon which this thesis research could improve for potential use on geophysical surveys, then develop ideas for an underwater positioning technique to rectify the spatial issue. Ultimately, the secondary and tertiary goals for this case study evolved into the primary objectives for this thesis; however, at the time of this fieldwork in the Rolesville Quarry,

the UALR methodology concept had not yet been developed. The information gathered from this case study propelled this thesis research in the appropriate direction in terms of developing an applicable spatial data acquisition process that was both simplistic and transferable to all commonly used archaeological data collection practices.

4.1.2 Site Location and Background Information

The Rolesville quarry is the site of the Fantasy Lake Scuba Park, founded in the 1980s by Doye Sherrill for the purpose of creating an underwater environment to be exclusively enjoyed by recreational SCUBA divers (FLSP 2020). The quarry is composed of 52 acres of water with multiple diver access points for shoreline entry and is regarded as the largest SCUBA diving park on the east coast of the United States (Figure 4-1). Although the site is considered a confined body of water, the sheer size of the quarry does permit limited surface water movement due to wind and other local weather effects. Many objects were intentionally submerged in this quarry to give divers training experience by swimming through airplanes, buses, and other machinery. This location is regularly frequented by recreational, technical, law enforcement, and military divers for training. The author was familiar with the quarry following scientific diver training while a graduate student in the Program in Maritime Studies at East Carolina University.

The quarry was originally developed in the 1800s for mining stone for construction projects throughout North Carolina and neighbouring states (FLSP 2020). Mining operations immediately ceased in 1950, when digging activities struck a freshwater spring that flooded the entire quarry. The high rate at which the quarry flooded resulted in the loss of mining machinery, all of which currently reside in the same locations the day flooding began. These relics of the past are now visited by recreational SCUBA divers and used for training purposes. For those



FIGURE 4-1: Rolesville quarry site location. Positioned in the Piedmont region of North Carolina, USA, the Rolesville quarry offered an excellent controlled environment in which to perform a series of underwater photogrammetric surveys of various submerged objects. (Google Earth imagery modified by author, 2016).

willing to descend to 27.4 m, the cold spring water creates a cold, but high visibility freshwater environment, that is ideal for training in harsh conditions. Moving away from the spring water, water temperature increases and freshwater life is abundant on all submerged objects and platforms. In the shallower and warmer locations, water visibility is often less due to algae growth and other suspended particulate in the water column as a result of divers moving through these areas. The quarry is actively managed to ensure a natural underwater environment without the use of added chemicals that may negatively affect water quality and freshwater inhabitants.

In the weeks leading up to the initial fieldwork surveys, the author determined the Rolesville quarry as an ideal facility for evaluating modern digital photogrammetry practices for contemporary and future archaeological surveying applications. Although the quarry is not generally regarded as an archaeological site with significant cultural remains, this environment and available infrastructure provide an excellent evaluation facility in a semi-controlled setting. Submerged objects such as an airplane, bus, and other vehicles were targeted for photogrammetric surveys due to their dimensions, construction materials, depth, ambient lighting, and water clarity. These objects were located on the Fantasy Lake Scuba Park map (Figure 4-2), then added to the planned diving objectives for preliminary reconnaissance and photogrammetric surveying assessments.

4.1.3 Previous Archaeological Research Using Digital Photogrammetry

Prior to undertaking photogrammetric surveys at the Rolesville quarry, the author performed preliminary research pertaining to archaeological projects which incorporated photogrammetry as part of the data collection process. The aims for the initial research were to ascertain the current mindset regarding photogrammetry as a primary data collection method for archaeological applications, and also to evaluate what techniques and equipment systems were in

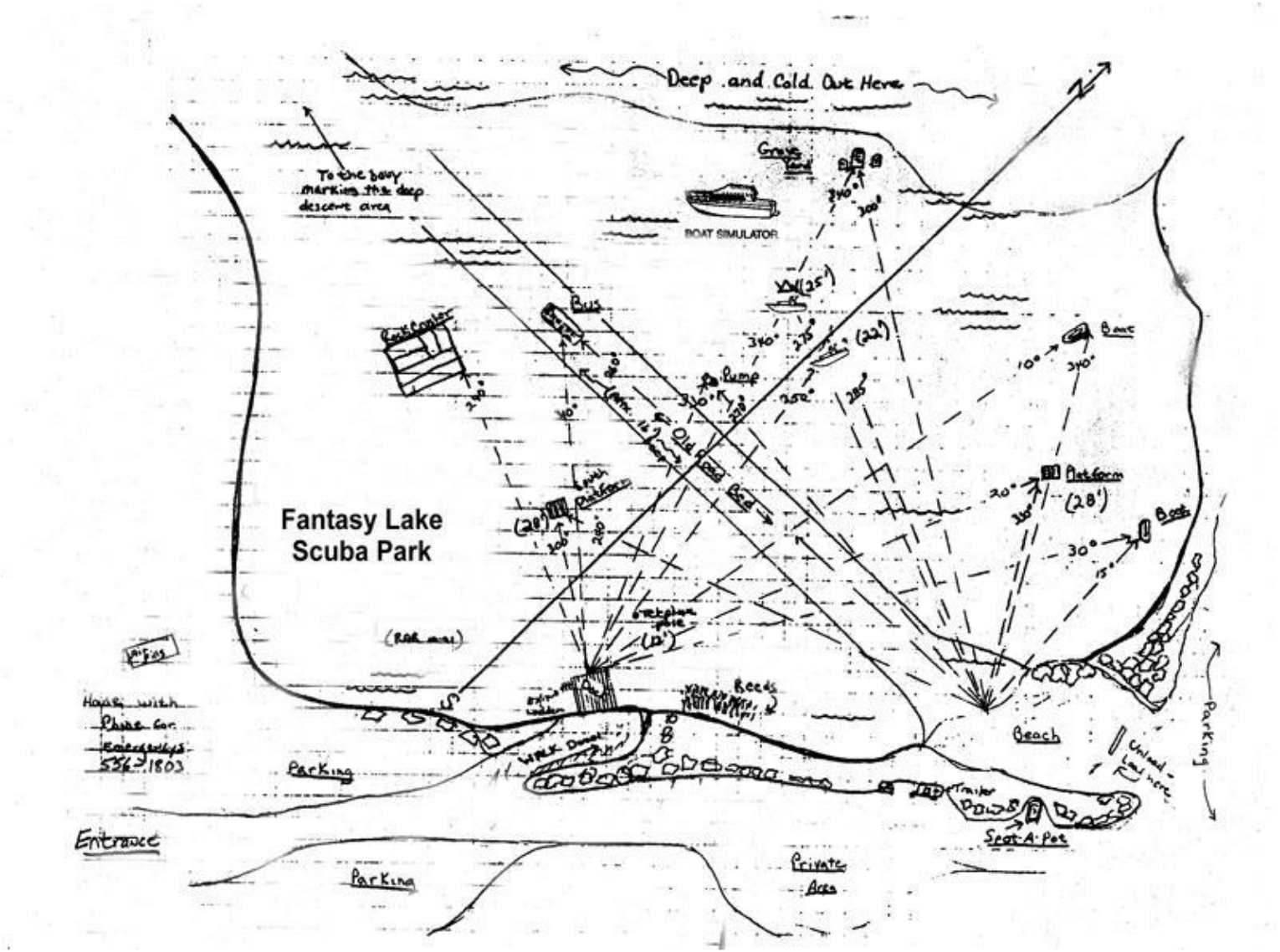


FIGURE 4-2: Fantasy Lake Scuba Park map. This illustrated map displays all underwater objects, depths, and compass bearings from shoreline entry locations. Illustration from https://www.fantasyscubapark.com/lake_map.htm. (Accessed on 2 August 2016).

common use. The author's professional experience in marine remote sensing and geophysical surveys contributed to the focus on spatial data inclusion as part of the three-dimensional (3D) image. Enhancing the visual quality of the 3D image was not within the scope of this research; however, careful attention was given to camera systems, post-processing software, and fieldwork techniques that increased the likelihood of optimal photogrammetric imaging results.

Manual forms of underwater archaeological documentation are inherently arduous, and nearly all field archaeologists have experienced such physically exhaustive surveys that extended over long durations of time. Furthering the complications associated with conventional archaeological data collection methods are the required equipment setup, manual documentation processes using fiberglass tapes and dive slates, and the eventual site breakdown. In a review of archaeological surveys which incorporated modern photogrammetry, nearly all cite the modern photogrammetric method as a much easier data collection technique that was less expensive and more time efficient (Drap et al. 2007; Skarlatos et al. 2012; Henderson et al. 2011:243; McCarthy 2014:175; Diamanti and Vlachaki 2015:93-94). The general consensus of the reviewed archaeological studies revealed a favourable view of digital photogrammetry and its results; however, there were noticeable omissions from most reports regarding underwater spatial control. Some authors address the spatial issue directly; whereas, others briefly mention a referencing system or the intentional omission thereof (Mahiddine et al. 2012; Skarlatos et al. 2012; Henderson et al. 2013:243-256; Gawlik 2014:3). The varied levels of spatial data and collection techniques indicate the absence of a consensus regarding the manner in which absolute spatial data is acquired for underwater photogrammetric data. In most cases, absolute spatial data was not included at all and in general most projects solely relied on the use of relative coordinates using *X, Y, Z* values. A shared characteristic among the majority of these non-

georeferenced photogrammetric surveys were the emphases on camera calibrations and image enhancements for improving the overall 3D image (Drap et al. 2007; Skarlatos et al. 2012).

The 2013 report of the Pavlopetri photogrammetry survey is an example of an archaeological project that prioritises absolute spatial data in conjunction with enhancing imaging results (Henderson et al. 2013:243-256). The Pavlopetri site is located off the coast of Laconia, Greece, and the objectives of this survey were to perform a photogrammetric survey which incorporated absolute positioning for georeferencing the 3D imagery. The photogrammetric survey was performed using an underwater camera system with an integrated GPS antenna and receiver unit. This unit was used at the water surface; therefore, the GPS antenna was not submerged, thus allowing the reception of satellite positioning information (Henderson et al. 2013:247). The shallow marine environment and clear water visibility at the Pavlopetri site permitted the use of the diver rig with successful results. In addition to the use of the diver rig with integrated GPS, underwater positioning of various control point locations was performed using a Total Station survey. The survey area's close proximity to the shoreline permitted the use of a Total Station, which is a commonly used land-surveying method (Henderson and Burgess 1996; Green 2004:42; Henderson et al. 2011). Using a prism pole, the divers were able to work in depths ± 4 m and the ranging information was then transferred to a computer program for plotting (Henderson et al. 2013:245). The marine environment at the Pavlopetri site is unique in that it is of shallow depth and water visibility permits the use of optical imagery and shore-based positioning techniques (Henderson et al. 2013:247). The survey team was successful in creating georeferenced photogrammetric imagery of site features; thus, implementing the photogrammetric method as a complete surveying technique.

The Pavlopetri survey design and equipment configuration were ideal given the site conditions and marine environment. For sites existing in similar circumstances, such methods and equipment setups can be used with effective results. For sites in deeper waters, or in marine environments that do not have clear visibility, these methods will not be effective in producing the same georeferenced imagery. The authors of the Pavlopetri survey acknowledged this fact in the results section of the report, stating that this system remains to be tested at greater depths and may require the integration of acoustic beacons for underwater positioning (Henderson et al. 2013:254). The mutually shared concerns regarding the acquisition of GPS coordinates on the seafloor and the solution involving underwater acoustic ranging systems reinforced the author's current research direction. Prior to developing a georeferencing methodology that utilises both GPS positioning and underwater acoustic ranging systems; however, the author planned two preliminary photogrammetric surveys at the Rolesville quarry for familiarization with contemporary data collection techniques, equipment, and identifying associated research complexities.

4.1.4 Archaeological Research Objectives

The research imperatives for the Rolesville quarry case study pertain to evaluating modern underwater photogrammetric data collection techniques, post-processing procedures, and end products for archaeological applications. This case study does not introduce new or novel approaches to underwater photogrammetry surveying practices, but rather serves as preliminary field evaluations of the method for the basis of improving the feasibility of acquiring absolute coordinates. Following the conclusion of the surveying operations, the author anticipated obtaining the requisite knowledge to develop theoretical, yet plausible approaches to subsurface

absolute positioning that are practical and efficient for archaeological applications to geophysical surveying operations.

4.1.5 Case Study Survey Equipment Setup and Configuration

The Rolesville quarry case study utilises photogrammetric hardware and software systems that are commonly available for archaeological applications. The camera system used for this case study is the Nikon D7100 Digital Single Lens Reflex (DSLR) equipped with a Nikkor 18-35 mm lens. The camera system is protected underwater by using an Ikelite underwater camera housing designed specifically for the Nikon D7100 DSLR camera. The Ikelike housing port housing port is also compatible with the Nikkor 18-35 mm lens. This equipment setup is rated for use in depths down to 200 m, well beyond average archaeological surveying activities. Given the shallow and relatively clear water of the Rolesville quarry, the author decided not to include artificial illumination sources (strobes, floods, etc.) and rely strictly on ambient light. For data processing, the author used Agisoft Metashape Professional installed on an Acer Predator 17 laptop computer. The underwater camera housing was fully assembled and tested prior to use at the Rolesville quarry case fieldwork case studies. For safe and effective use in an underwater environment, these systems require pre-diving function checks and maintenance. System settings and specific functions were chosen due to the environmental and site conditions; however, the reader should note that camera settings are subject to change to variable environmental influences.

Prior to donning diving gear, the author performed a “bubble test” to ensure the underwater housing was properly sealed. While holding the camera system underwater, the housing controls and knobs were activated to verify all were in their correct positions and ready for use. The diving protocol was designed to mimic a non-disturbance archaeological survey in

which the bottom sediment was not to be agitated through maintaining neutral buoyancy. Three dives were planned for each survey day, permitting one reconnaissance dive to ascertain site conditions, followed by two working dives. In between the working dives, the author planned to post-process photographs by converting them from RAW to TIFF format prior to processing in Agisoft Metashape Professional. This permitted the author to see any visible gaps in the data record that can be filled during the second working dive. Given that all dives performed at the Rolesville quarry were conducted under no decompression limits, the post-processing time in between working dives further decreased the likelihood of any diving-related illnesses.

4.1.6 Photogrammetry Data Acquisition Process and In-Field Analysis

Prior to performing the photogrammetric survey, the dive team conducted a reconnaissance dive to observe underwater conditions and determine if any reconfigurations to the photogrammetric equipment were required prior to surveying operations. The Nikon D7100 DSLR and Ikelite housing system were carried during the reconnaissance dive for evaluation and initial object photographs. Referring to the illustrated map provided by the diving facility, the author plotted the heading to the submerged airplane and proceeded to swim staying about 1 m above the bottom sediment (Figure 4-2). Although compact, the Ikelite housing is not streamlined; however, the neutral buoyancy did not negatively affect the transit swim from the shoreline to the submerged airplane. Following the inspection of the submerged airplane, the dive team returned to the shoreline to switch bottles and perform a post-dive review.

During the post-dive review, team members deliberated potential complexities regarding the target and its surrounding marine environment. Various subjects were raised ranging from ambient lighting to the optimal distance from the target during data collection; however, the most pressing concerns involved the exterior surface of the target and water turbidity (Figures 4-3 – 4-

4). A commonly understood issue regarding photogrammetry applications for both land-based and underwater surveys are the associated difficulties in point cloud generation on reflective surfaces and others with little differentiation for identifying point positions. This is sometimes mitigated through the use of control points or markers to assist in tying specific points; however, the author opted to not use such markers given the research objectives. The other issue regarding water turbidity is a common issue on many archaeological sites, specifically those located in inland waterways and nearshore sites. Water visibility was not the primary concern; however, the suspended particulate could result in producing erroneous points, thus requiring extended editing time during data post-processing. The concerns were noted, but ultimately determined outside of the scope of the research objectives.

The photogrammetric survey of the submerged airplane was performed in one dive, in which the author was able to collect over 350 images, with an estimated 70-80% image overlap. Each image was recorded in RAW file format and stored on an SD card that can be removed for uploading the images to the post-processing computer. Without the use of ground control points or a system of transit lines, the author performed a boustrophedonic surveying pattern, which resembles a mowing the lawn form, allowing total site coverage in a systematic arrangement. The bottom sediment surrounding the airplane was sandy and barren, with limited identifiable features absent of associated plane debris. All photographs were taken using the automatic camera functions as opposed to manual camera manipulation. The author's decision to use automatic processes was based on the realistic probability that mid-water column buoyancy control combined with camera manipulation could result in increased diver fatigue. The entire aircraft was surveyed in one dive, requiring about one hour of bottom time. Given that the depth of the site was less than 4 m, no diver decompression was required. Following image collection,



FIGURE 4-3: A RAW format image of the sunken plane nose section. The suspended particulate in the water column was due to a recent algae bloom in the quarry and the presence of recreational divers. (Photo by the author, 2016).

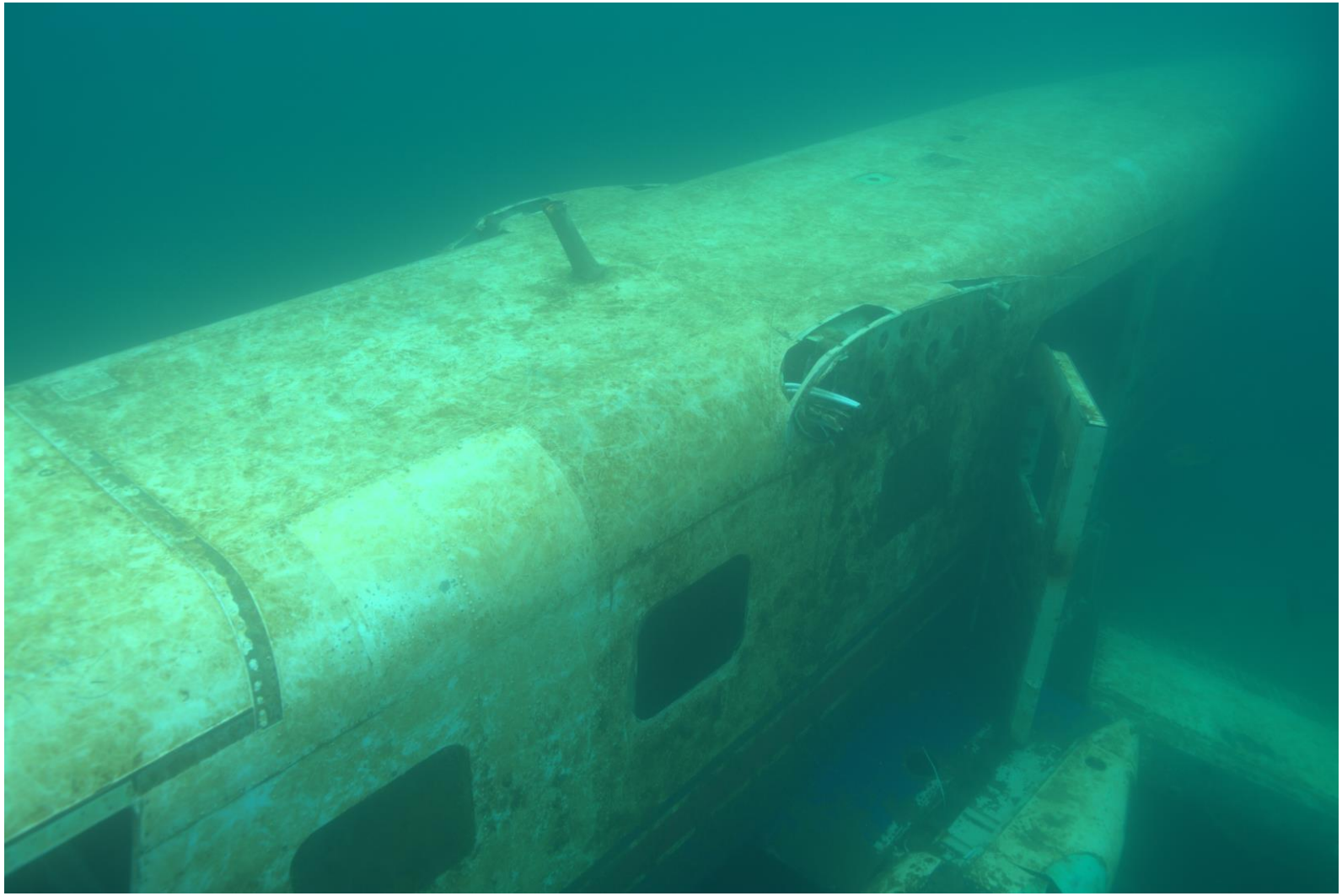


FIGURE 4-4: A RAW format image of the top of the plane fuselage. The suspended particulate in the water column decreased as the author moved higher in the water column which assisted in better image quality; however, the plane's highly reflective and light-coloured metallic surface was a subject of concern for point cloud generation during post-processing. (Photo by author, 2016).

the author returned to the shore to perform preliminary post-processing while preparing all SCUBA equipment for the second dive.

Immediately following the first dive, the author carefully removed the Nikon D7100 DSLR camera system from the Ikelite housing, then immediately resealed the housing to prevent any accidental water drippage that may damage the camera or cause a visual distortion into the dome port. The SD card was removed from the camera body and inserted in the Acer laptop. The 350 images were then uploaded to the Nikon ViewNX2 for file format conversion from RAW to TIFF. Referring to the Agisoft Metashape Professional manual, RAW files converted to TIFF format is the preferred file type for this software (Agisoft 2016). The file conversion process requires a few minutes, depending on the number of images, and users can save the converted TIFF files in a separate folder. Following the file format conversion, the TIFF images were then uploaded into the Agisoft Metashape Professional software. For a reduced interval period, the author opted to use a medium setting for point cloud generation. This allowed the author to quickly review a sparse point cloud to determine if any gaps in the data were present. As anticipated, most data gaps and erroneous points were located on the top surface of the fuselage, and additional imaging at that location was planned for the second dive. Other erroneous points, such as those caused by water turbidity, were noted and slated for deletion during the final editing process. Overall, the medium sparse point cloud clearly depicts the target with adequate points for a full photogrammetric image.

The third, and final dive for this case study, was focused on filling in data gaps on the upper fuselage for the final imaging process. Utilising the boustrophedonic pattern used for the initial survey scan, the author traversed the upper portions of the fuselage and collected additional images with 70-80% overlap. The camera settings and configuration for the second

dive remained unchanged for the purpose of maintaining similar image quality and ease of use during mid-water data collection. Following completion of the third dive, the Nikon D7100 DSLR camera was removed from the Ikelite housing, disassembled, and packed for transport. All images from the second dive were uploaded to the laptop computer for safekeeping prior to post-processing. The Ikelite housing was allowed to air dry during diving equipment breakdown, then stored in its protective case for transport.

4.1.7 Post-Fieldwork Analysis

The final data post-processing procedure mirrored the steps undertaken during the fieldwork operations. Changes in the point cloud generation process involved producing a higher density image for further post-processing into a complete 3D model (Figure 4-5). In terms of analysing the Rolesville quarry fieldwork, the photogrammetric equipment and associated support systems offered a very fast method of underwater data collection and produces quality visual imagery for archaeological interpretation. The compact nature of the equipment was not unwieldy or cumbersome when compared to traditional photogrammetric methods used in past decades. Photogrammetry serves as a beneficial tool for archaeological site documentation in marine environments that permit the use of optical sensors; however, where there is limited or no visibility, manual site recording methods remain vital for archaeological applications.

For this survey, the author replicated actions of some previous archaeological surveys by not establishing a ground control network or marker system used for aligning photographs during post-processing. The author asserts, however, that static ground control positions are imperative if such imaging methods are used, specifically in terms of site recording. A spatial control network is required for surveying applications, and considerations regarding the type of control point system should be based on the operating environment. The marine environment at the

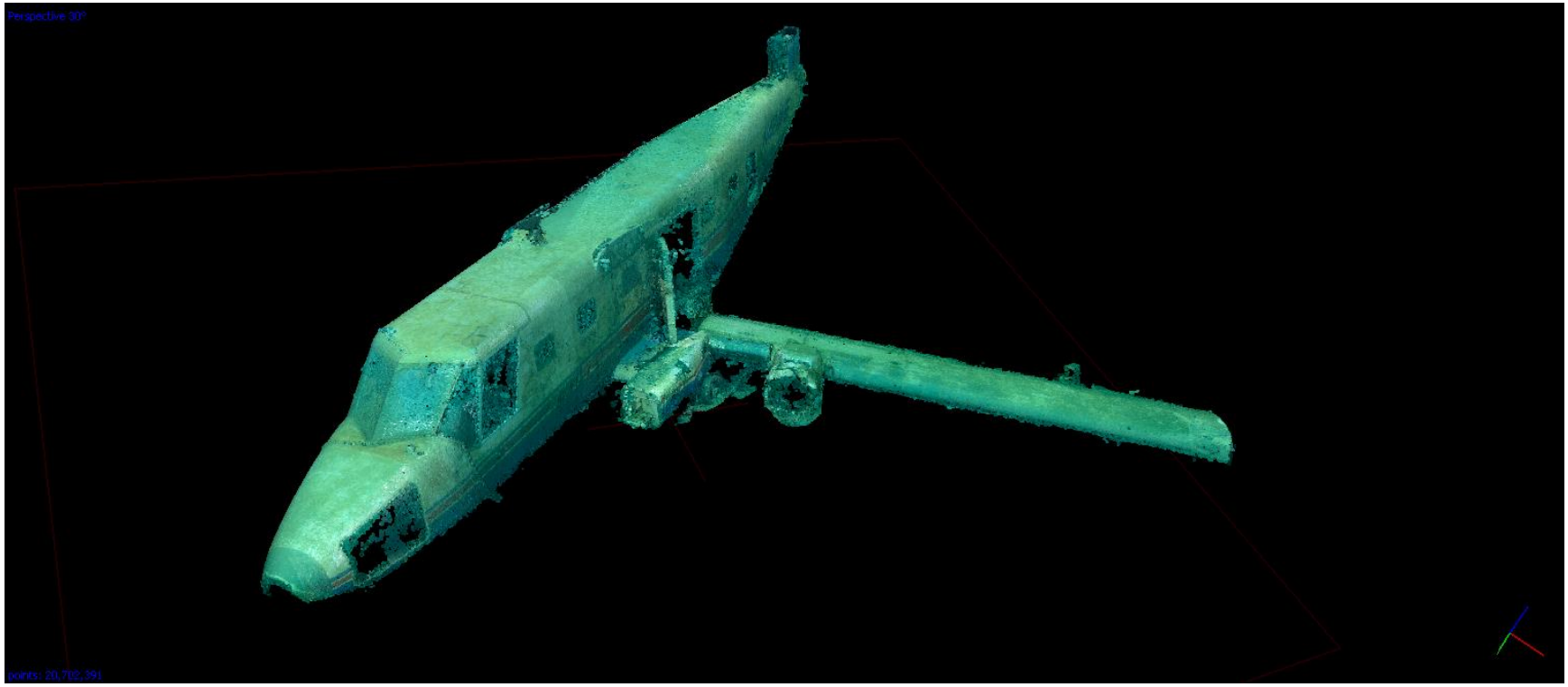


FIGURE 4-5: Edited photogrammetric image using a high point cloud density. The surrounding bottom sediment was removed during the editing process so that only visible points were that belonging to the subject (plane). (Image by author, 2016).

Rolesville quarry could support the use of coded targets recognizable by Agisoft Metashape Professional software; however, the manner of their deployment throughout the site was yet to be determined beyond the general acceptance they should be placed at the site extents and included in the processed image, which was not performed during this case study. The Agisoft Metashape Professional software is capable of accepting absolute coordinate values, in which users can manually enter the information for each target location.

4.1.8 Conclusion and Research Direction

The Rolesville quarry survey served as the initial research case study in which the author performed a basic photogrammetric survey of a sunken airplane. The information gathered during this case study did not focus on the 3D image itself, but rather on the data collection process, associated equipment, and what supplemental measures would be required for georeferencing photogrammetric data with absolute coordinate values. The research focus at this phase was determining the best type of equipment for seafloor target localisation, and specific systems that could provide absolute positioning at the survey-grade level. This preliminary case study directly benefitted in directing research avenues through the identification of specific shortcomings pertaining to digital photogrammetry and potential mitigation solutions that could be potentially used for archaeological applications on high-resolution geophysical surveys to supplement other sensor data.

4.2 Marker 39 Wreck Site Research Case Study (June 2017)

4.2.1 Introduction

The Marker 39 wreck site case study was the initial fieldwork evaluation of the Underwater Acoustic Localization and Referencing (UALR) methodology, which was developed for the purposes of georeferencing subsurface archaeological datasets for supplementing high-resolution geophysical surveys. The fieldwork was undertaken in June 2017, in which researchers performed a georeferenced photogrammetric survey of the Marker 39 wreck remains located near Molasses Reefer in the Florida Keys National Marine Sanctuary (FKNMS) at Key Largo, Florida, USA (Figures 4-6 − 4-7). The wreck was believed to be a wooden barge that sank in 7.6 m of water sometime in the early 20th century (NOAA 2009). The wreck site retains minimal cultural significance, yet offers an excellent testing location for developing new methodologies for archaeological applications. The purpose of the fieldwork was to assess the practicality and efficiency of the UALR method as a subsurface positioning technique designed to provide absolute positional values for ground control point networks.

The requirement for absolute spatial information for archaeological datasets pertains to the enhancement of data collection methodologies which traditionally relied on the use of relative measurements (*X*, *Y*, *Z*) for mapping artefact assemblages and overall site extents (Mahiddine et al. 2012; Skarlatos et al. 2012). As part of the technological evolution for archaeological data collection techniques, the UALR methodology was designed to supplement both traditional and modern digital site recording processes by providing absolute spatial information in which researchers can georeference underwater datasets. Information gathered

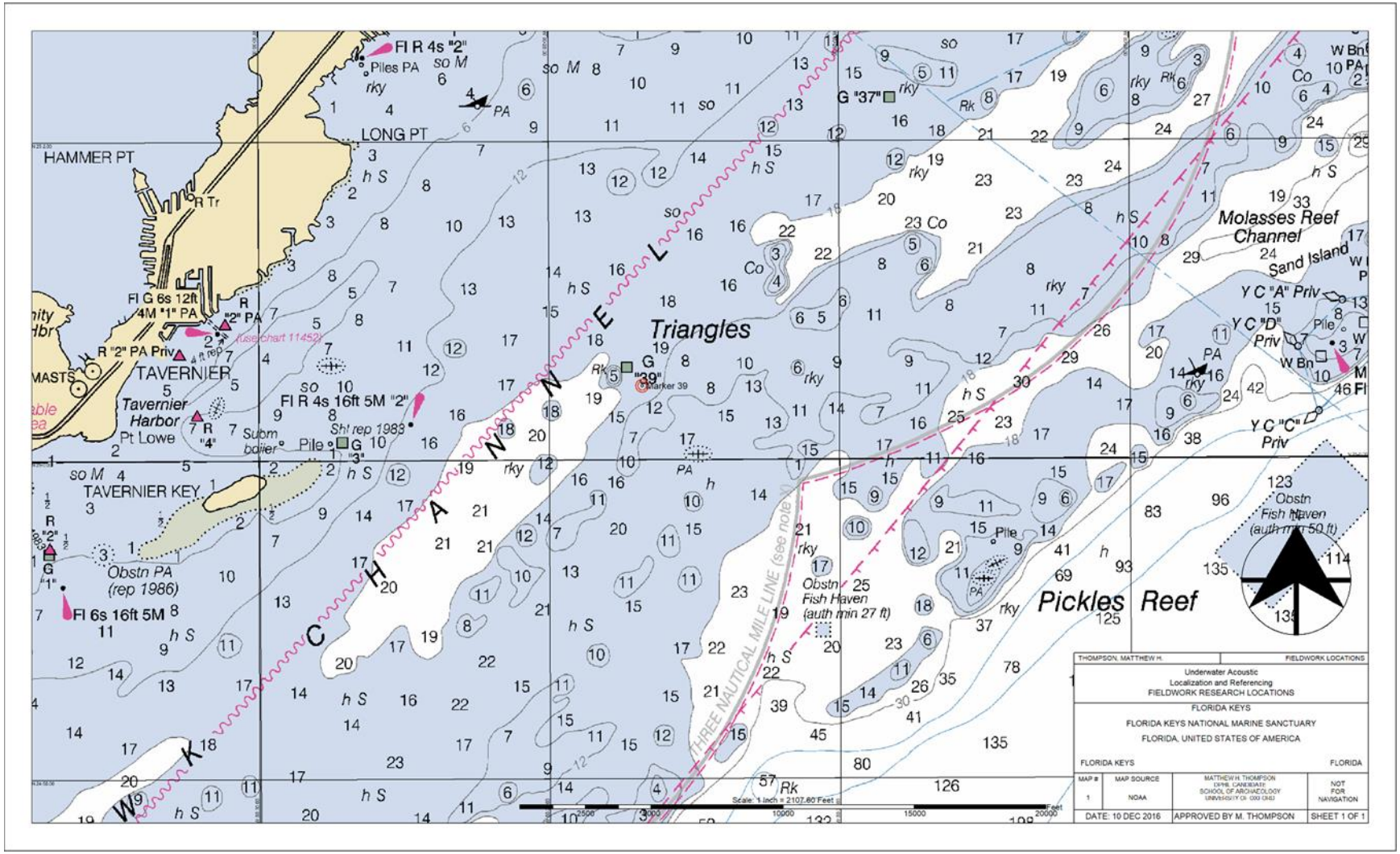


FIGURE 4-6: Project location is indicated by the red target icon and Marker 39 designation in the centre of the map. Map produced by author, 2016).

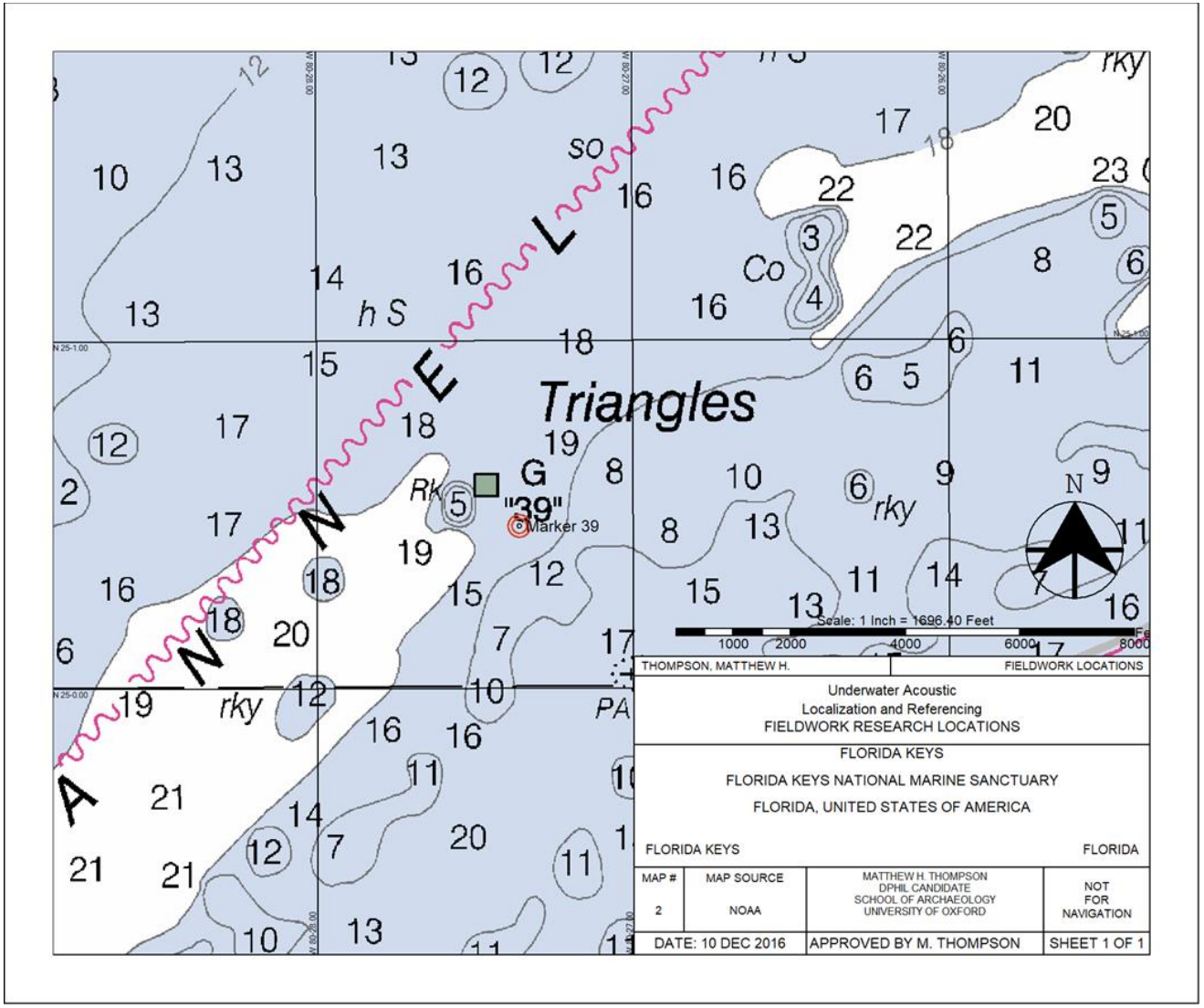


FIGURE 4-7: Enhanced project location image. The site location is marked with a red target icon and Marker 39 designation. Map produced by author, 2016).

throughout the Marker 39 wreck site case study was used for evaluating the UALR methodology's practicality and efficiency for archaeological applications as required for supplementing geophysical survey datasets. Being the first case study focused on equipment evaluation, the Marker 39 wreck site survey provided gainful insight for refining the UALR methodology as a robust process for acquiring absolute spatial information in support of both traditional and modern digital archaeological data collection techniques.

4.2.2 UALR Methodology Concept Phase Development

The preliminary fieldwork case study at the Rolesville quarry provided gainful insight pertaining to modern digital photogrammetric techniques and data processing, specifically in terms of practical and efficient approaches to underwater point positioning. Following the Rolesville quarry evaluation and the identification of a lack of absolute underwater positional information, the author pursued research avenues pertaining to underwater acoustic ranging systems with operational functions compatible with archaeological data collection methods. Evaluations of various acoustic ranging systems currently in use with the offshore energy and defence industries led to the decision to incorporate ultra-short baseline (USBL) acoustic ranging for coupling with a survey-grade GPS receiver (Philip 2003a:18; Qiu et al. 2012:14; Morgado et al. 2013:142; Ai et al 2015:115; Jakuba et al. 2015; Mandić et al. 2016; Reis et al. 2016:1491; Dajun et al. 2017). USBL ranging calculations are a function of timed sound signal transmissions from a transducer mounted on the surveying vessel to a transponder located on the seafloor (Vickery 1998:5-17; Almeida et al. 2016). The sound signal undergoes an interrogation process to confirm the right signal was received, then the transponder transmits a return signal to the transducer (Vickery 1998; Philip 2003a:20; Aparicio et al. 2012; Melo and Matos 2016:1). The two-way time of travel of the acoustic signals are calculated for determining the slant range

between the transducer and transponder. Modern USBL systems are capable of coupling with GPS receivers; therefore, allowing ranging measurements to be converted to absolute coordinates compatible with most global reference frames (Audric 2004:786-788; Kinsey et al. 2006:5).

4.2.3 Marker 39 Wreck Site Case Study Equipment and Research Design

The fundamental basis for the UALR methodology was for acquiring absolute coordinates while underwater; therefore, requiring an assemblage of instrumentation working in tandem for achieving that purpose. For this research case study, the author elected to use a Trimble SPS855 GNSS receiver and Trimble GA530 rover antenna for satellite positioning. As a dual-frequency system, the SPS855 receiver and GA530 antenna eliminate ionospheric error sources; however, tropospheric and signal multipath errors would remain if error correction services were not used. For this fieldwork, the author enabled the wide-area augmentation system (WAAS) function provided by the FAA to provide differential error corrections for allowing sub-metre positional accuracy at the GPS level.

The Trimble SPS855 receiver was coupled with an Applied Acoustics Engineering, Ltd. Easytrak Alpha Portable USBL ranging system. The Easytrak unit was connected to the Trimble SPS855 receiver via a RS-232 serial cable; therefore, applying absolute coordinates to underwater acoustic ranging calculations. The coupling of the GPS receiver and USBL unit form the fundamental basis of the UALR methodology through the capability of acquiring absolute positional values in an underwater environment. At the time of the Marker 39 survey, the Easytrak system only displayed absolute coordinates in Universal Transverse Mercator (UTM) format. UTM coordinates are commonplace for archaeological projects; however, conversions to other formats are possible through online programs. Subsequent case study surveys are recorded in North American Datum 1983 (NAD83)-2011 and International Terrestrial Reference Frame

(ITRF)-2014, made possible through a software update provided by Applied Acoustics Engineering, Ltd. For the Marker 39 research case study, all coordinate format conversions were performed using the Montana State University online conversion tool available at http://www.rcn.montana.edu/resources/converter.aspx (Last access on 30 June 2017).

The coupled GPS and USBL systems were capable of providing absolute coordinates for underwater positions, but the manner in which the data was collected required thorough planning while maintaining environmental and archaeological considerations. The Marker 39 wreck site is located within the Florida Keys National Marine Sanctuary (FKNMS), under the jurisdiction of the National Oceanic and Atmospheric Administration (NOAA) Office of National Marine Sanctuaries (ONMS); therefore, all archaeological surveying activities require prior approval. As part of the approved permit for the Marker 39 wreck case study (FKNMS-2017-008), the author was required to provide an archaeological survey design which prevents any type of disturbance to the marine environment or submerged cultural remains. In addition to maintaining the integrity of the Marker 39 wreck remains and the surrounding marine environment, the UALR methodology was required to be in compliance with the Florida Division of Historical Resources Performance Standards for Submerged Remote Sensing Surveys, available review at the online at https://dos.myflorida.com/media/31390/remote_surveys.pdf (Last access on 1 June 2017). The UALR methodology equipment and data collection process used for the Marker 39 research case study satisfied all NOAA and Florida Division of Historic Resources requirements; however, the permitting requirements did not provide any reference to spatial data metric guidelines or underwater positioning equipment specifications.

The Marker 39 wreck site research case study fieldwork design was composed of a digital photogrammetric survey supplemented by UALR absolute spatial data collection. The

photogrammetry survey fieldwork equipment includes: a Nikon D7100 DSLR camera, Nikkor 18-35 mm lens, Ikelite underwater housing, and ten coded 12.7 cm x 12.7 cm polyvinyl chloride (PVC) ground control points with 0.9 kg weights (Figure 3-17, pg. 153). Following the review of previous archaeological surveys at the Marker 39 wreck site, the author was confident that the use of weighted PVC plates with coded Agisoft Metashape target designs would serve as the optimal ground control point network for this specific marine environment. Each target was recognized by Agisoft Metashape then subsequently numerically organized during image post-processing. As a marine environment with reported excellent water visibility and sandy bottom sediment, the weighted PVC ground control points offer the best semi-permanent spatial network that was easily deployed without any form of disturbance. The ground control point network design was created to encompass wreck site extents, and also allow placement on sections of the wreck without any damage to the physical remains. This removes the need to attach identifier tags to the wooden structure that can negatively impact upon site preservation. As a semi-permanent ground control point network, the coded targets are strategically placed and remain untouched throughout the duration of the survey. Following all image collection and the acquisition of spatial data, the coded targets were removed from the site with no adverse effects to cultural remains and the marine environment.

Spatial data for each ground control point location was acquired by placing the USBL transponder directly on top of the coded target with the position recorded as a waypoint. Communication between the diver and sonar operator was facilitated through the use of an underwater acoustic communications unit, in which the diver informs the sonar operator when to record each ground control point position. For the Marker 39 wreck case study, each ground control point location was documented using single-point positioning. The author surmised the

lack of measurement accuracy and precision were partially alleviated through the use of a higher quantity of ground control points; yet, calculating measurement precision using a single value is neither quantifiable nor does it satisfy IHO guidelines which state the need for 95% measurement confidence. Undoubtedly, an increased number of ground control points increases site georeferencing capabilities; however, the manner in which the absolute coordinates for each ground control point are rectified may require probable estimation. A comparable analogy could be the configuration of site map illustrations in which measurement errors result in site feature spatial discrepancies that require alignment through probable estimation. Similarly, georeferenced photogrammetric imagery can be aligned using ground control points assigned absolute coordinate values acquired using single-point positioning. The use of single-point positioning is not ideal and will require further refinement for future case study research.

4.2.4 Fieldwork and Data Analyses

The Marker 39 wreck research case study was scheduled for 12-16 June 2017, with three days reserved for survey fieldwork. The reserved dates for field research were established for anticipated inclement weather which is common for the southeastern United States during warmer seasons. The project commenced on the morning of 12 June, in which the author departed North Carolina for the Marina Del Mar Resort and Marina located in Key Largo, Florida. This resort was chosen as the field research base of operations due to the capability to house both the dive team, diving equipment, and onsite marina for docking the working platform. In addition to the provided amenities, the physical distance between the resort and the Marker 39 wreck site was roughly 9.6 km, thus increasing efficiency in terms of time and fuel resources. NOAA FKNMS permitting guidelines require that all archaeological surveying activities were to take place between one hour before sunrise and one hour after sunset;

therefore, the short travel time between the marina and site offered ample time to conduct fieldwork activities.

Following the arrival at the Marina Del Mar facility in the evening of 12 June, the author launched and docked the working platform in preparation for surveying operations. The Trimble SPS855 GPS receiver, Trimble GA530 antenna, Applied Acoustics Engineering, Ltd. Easytrak Alpha Portable USBL, and 1200 series transponder were connected to electric outlets for charging the respective batteries for surveying work scheduled for the following day. The transducer bracket, cleat mount, and pole mount systems were assembled and prepped for pre-survey evaluations. After meticulous evaluations ensuring that all surveying instrumentation was in working order, the equipment was then broken down for transport to the working platform for the upcoming surveys. Due to inclement weather, surveying operations at the Marker 39 wreck site began on the morning of 14 June, in which the survey team departed the Marina Del Mar Resort at 0700 hours.

After arriving at the site GPS coordinates provided by NOAA, the Marker 39 wreck position was verified using the onboard Humminbird 1198c side imaging system. Determining where the physical wreck remains were located was not a difficult process at this site due to the shallow water and water clarity. Shortly following the anchoring of the working platform upwind of the Marker 39 site, the survey team commenced setting up all positioning instrumentation and prepped diving gear for an initial site reconnaissance (Figures 4-8 – 4-10). The objectives for the initial dive were to examine the Marker 39 wreck site, note dominant site features and to assess the local marine environment and site conditions. The Marker 39 wreck examination was



FIGURE 4-8: The pole mount assembly during UALR data collection at the Marker 39 wreck site. The assembly provided flawless performance and demonstrated the assembly's efficiency and ease of use. (Photo by author, 2017).

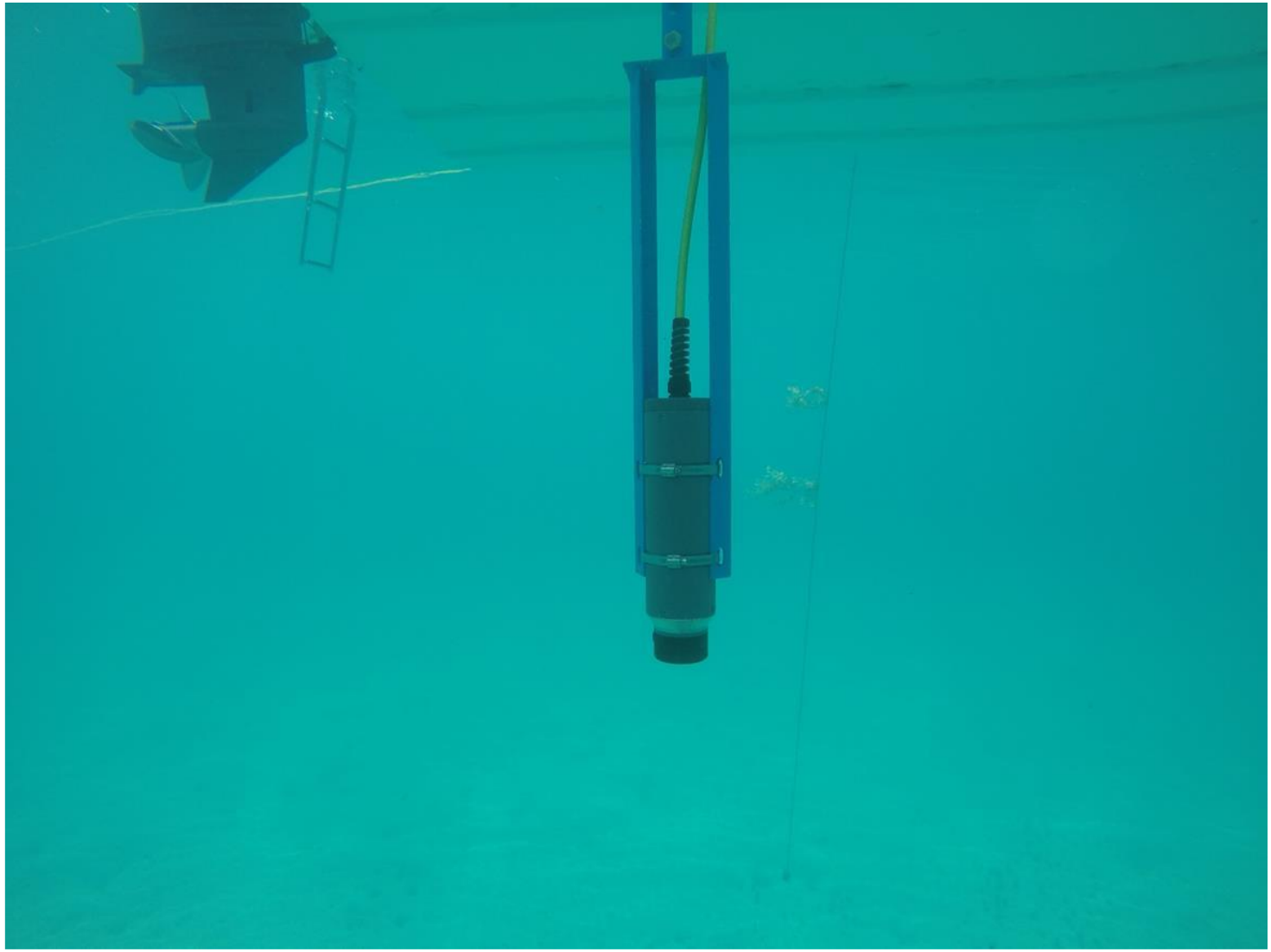


FIGURE 4-9: The Applied Acoustics Engineering, Ltd. Easytrak USBL transducer deployed in the author-designed bracket device during marker 39 project fieldwork. The transducer bracket secured the USBL transducer to the pole which allowed zero offset calculations. (Photo by author, 2017).

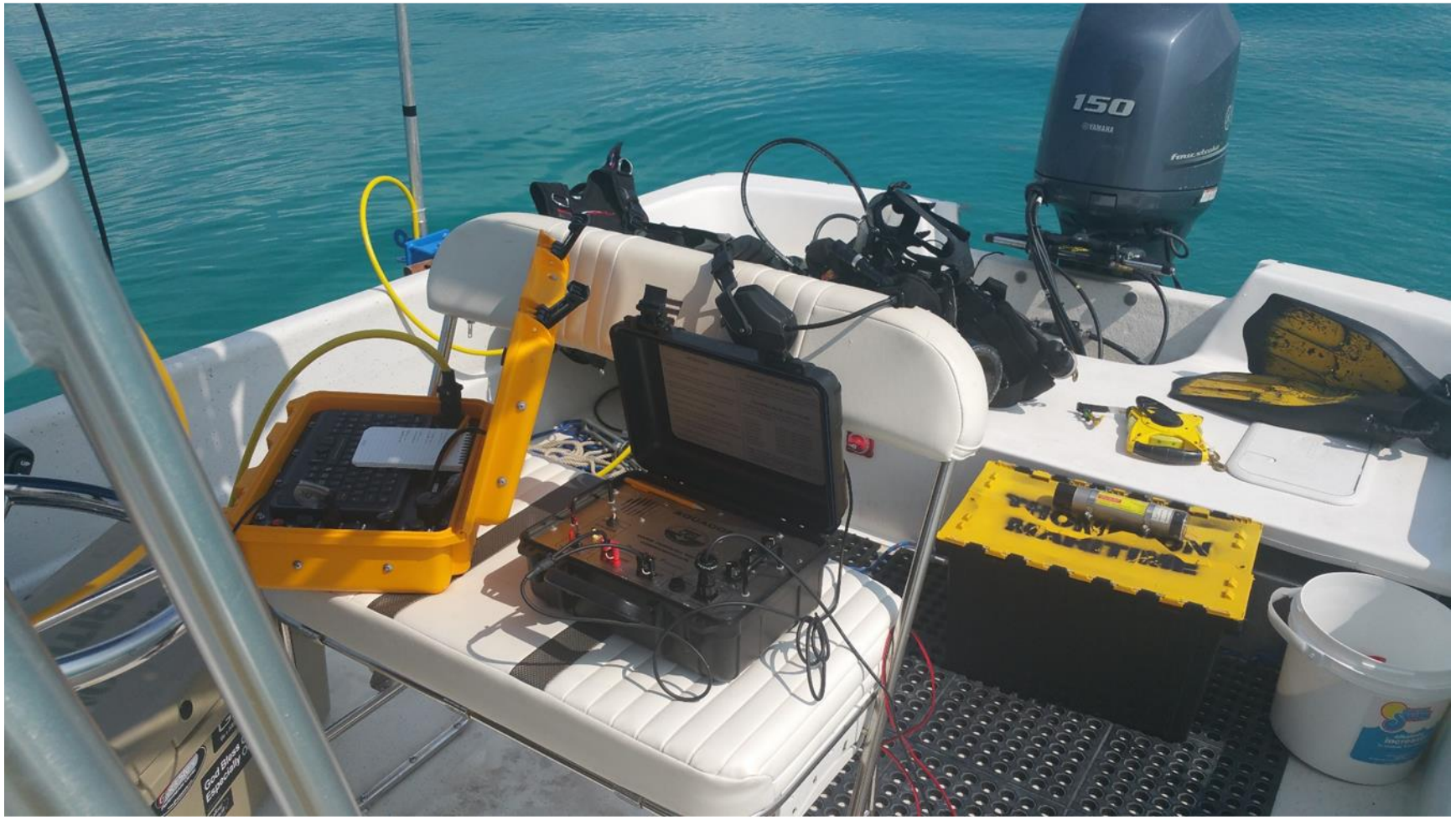


FIGURE 4-10: USBL and underwater communication equipment setup for UALR methodology data collection on the Marker 39 wreck site. (Photo by author, 2017).

performed to determine if the site had experienced any noticeable changes since the previous archaeological surveys conducted by NOAA and affiliated institutions (NOAA 2001). The identification of predominant site features was useful for site orientation, specifically during photogrammetric data collection in which a diver records still imagery with a 70-80% overlap. Having visual indicators of where a diver was positioned above or beside the object being recorded increases the probability of achieving successful image overlap which in turn assist point could generation as part of data post-processing. The marine environment assessment inspects the plant and animal life present at the site to determine if their presence can interfere with the photogrammetric data collection or underwater acoustic signal transmission. The reconnaissance dive identified many species of coral; however, the most problematic for photogrammetric surveying are fan corals which are in constant motion due to water movement. An assessment of both static and dynamic marine species determined that high-angle imagery would reduce the negative effects caused by objects in motion. It should be noted that any blurred images can be removed prior to data post-processing.

The second series of dives involved establishing the ground control network to encompass site extents and for placing a limited number of coded targets on the Marker 39 wreck structure to assist photograph alignment as part of the process in developing a three-dimensional point cloud. The coded targets were lowered to the seafloor using a perforated plastic bucket that was weighted on the bottom to prevent upending and dumping the ground control points. A single diver travelled with the bucket to provide additional balance and to ensure it was not placed on sensitive cultural remains or marine plant life. Divers distributed nine ground control points to throughout the site; four representing the corners of the site extents, and the remaining five placed within the confines of the ‘survey box’. The bottom sediment surrounding the Marker

39 structural remains was sandy, which offered optimal stability for the coded targets. The dive weight zip-tied to the underside of each PVC target prevented unwanted movement. Impressed with the manner in which the coded targets functioned in this marine environment, the author determined that all ground control points would remain in place for all photogrammetric operations for this case study and only removed at the conclusion of all fieldwork activities. The use of the ground control point network was a marked improvement over the previous photogrammetry survey conducted at the Rolesville Quarry, in which no spatial reference system was in place. The use of coded ground control points as a spatial referencing system at the time of the Marker 39 survey was not a new process and had been used in previous archaeological surveys utilising photogrammetric data acquisition (Bianco et al. 2015:269-275; Capra et al. 2015:67-72; Diamanti et al. 2015:93-98; Casella et al. 2016:269-275). The differentiation between the Marker 39 survey and previous projects was this case study's use of the UALR methodology which utilised a GPS/USBL coupled system to provide underwater positioning data for each ground control point location. Previous surveys either relied on relative coordinates derived from tape measurements/scale bars, acquired absolute coordinates using a shore-based total station and prism for shallow sites, or used an integrated GPS camera system which provided latitude and longitude coordinates for each image but forced the user to remain at the water surface for GPS signal transmission (Henderson et al. 2013:243-256).

Stemming from the establishment of the ground control point network, the next phase of the Marker 39 survey was to acquire absolute spatial coordinates of each coded target position. Using the coupled GPS and USBL systems, the diver and sonar operator worked in unison to collect absolute coordinates for all nine ground control positions. Communication between the diver and sonar operator was facilitated through the use of an Ocean Technology Systems

underwater acoustic communication system. Using a single-point positioning method, the diver swam to each coded target, notified the sonar operator to mark the waypoint, then repeated the process for all remaining ground control points. The photogrammetric survey was carried out using a Nikon D7100 DSLR camera, Nikkor 18-35 mm lens, and Ikelite underwater housing. The diver re-utilised a boustrophedonic surveying pattern to ensure total site coverage. More than 600 photographs were taken using 90º, 45º, and sediment-level angles in effort to fully canvass the entire Marker 39 wreck site. As a rectangular-shaped wooden barge with limited structural relief and ample water visibility, photographic data collection was not difficult and achieved in less than 90 minutes of bottom time. The shallow operating depth at this location permitted the use of standard diving equipment and practices for safe and efficient data collection. Following the photogrammetric survey of the Marker 39 wreck site, divers ensured the ground control point network had not shifted due to water movement or unintentional diver contact by using fiberglass tape measurements between specified points. Upon returning to the Marina Del Mar resort, all equipment was completely disassembled and cleaned using freshwater. Air cylinders were refilled and other diving equipment prepared for the next survey day.

Post-processing the photogrammetric data was identical to the methods described for the Rolesville quarry research case study. All photographs were analysed for blurs or marine life that may potentially hinder the photograph alignment or point cloud generation processes. The photographs underwent a format conversion process from RAW to TIFF, which was better suited for post-processing in Agisoft Metashape software (Figure 4-11). The photogrammetric model was created using a high-density point cloud in which the entire Marker 39 wreck site was clearly identifiable with all nine ground control points recognized by the Agisoft Metashape

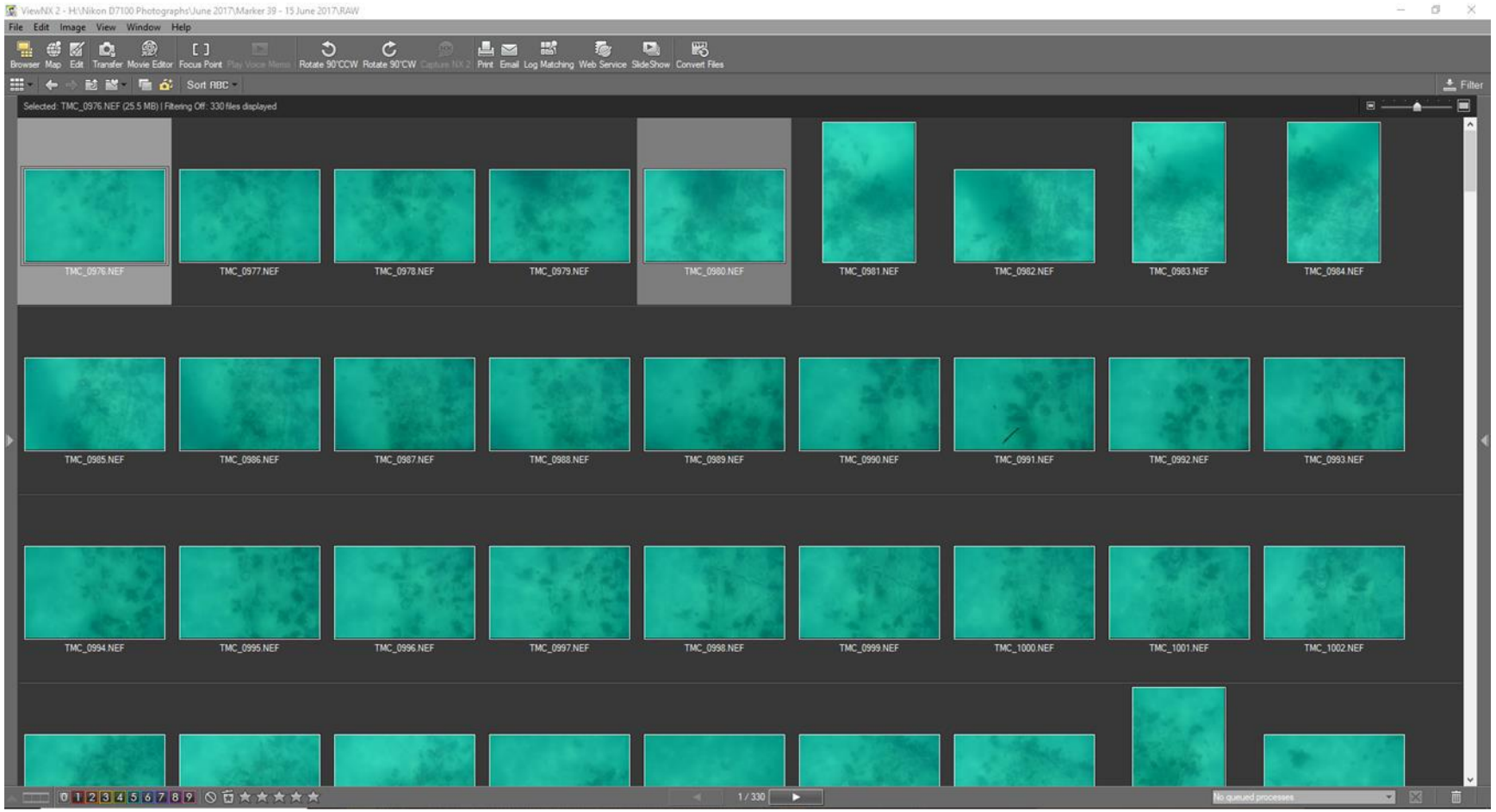


FIGURE 4-11: Computer screen image of Marker 39 photogrammetric images unloaded to the Nikon ViewNX2 software for file format conversion from RAW to TIFF. Note the author did not alter the image other than the file format conversion. The UALR research was not designed to enhance the graphical appearance of photogrammetric imagery. (Image by author, 2017).

software. The spatial data collected during this day was discovered to have a few discrepancies, most likely attributed to communication error between the diver and sonar operator. Although the data was retained for further analysis, it was not applied to the 14 June photogrammetric model. The decision was made to re-survey the Marker 39 site the following morning (15 June) using the same equipment and fieldwork techniques.

The subsequent survey at the Marker 39 site on 15 June offered better surface and marine environment conditions. The sea state on this day was relatively flat, thus increasing underwater visibility and improved photogrammetric data collection capabilities. The initial dives were undertaken to confirm the ground control point network was intact and that no coded targets had moved overnight. Impressively, none of the targets had shifted due to water movement but did require light hand-fanning to remove some sand from the top surface. Divers performed a quick visual assessment of the Marker 39 physical remains and determined that the site was in the same condition as the previous day. Given the local cloud cover during the morning hours, the author elected to undertake the second photogrammetric survey of the Marker 39 site prior to spatial data collection. Excessive sunlight, combined with water rippling effects, are problematic for underwater photogrammetric data collection. The decision to move forward with the photogrammetric survey was beneficial to the overall image quality, thus contributing to a better three-dimensional site model.

Spatial data collection for the 15 June survey was more successful following a change in communication protocols between divers and the sonar operator. Through-water communication systems are sometimes susceptible to muffling a diver's voice based on microphone placement within the full-face mask. This, combined with improper use of the Push-To-Talk (PTT) button can result in fragmented sentences that are easily misinterpreted. The same single-point

TABLE 4-1
MARKER 39 WRECK SITE COORDINATE INFORMATION IN UTM, WGS84, AND X/Y FORMAT

GCP	UTM	WGS84 LAT/LON	X/Y
1	554917.6mE, 2765905.5mN	25.007653 N, -080.455746 W	836403.657, 245402.918
2	554910.3mE, 2765915.0mN	25.007739 N, -080.455818 W	836379.699, 245434.076
3	554890.8mE, 2765922.3mN	25.007806 N, -080.456011 W	836315.700, 245458.169
4	554912.4mE, 2765902.8mN	25.007629 N, -080.455798 W	836386.591, 245394.127
5	554903.1mE, 2765913.0mN	25.007721 N, -080.455889 W	836356.069, 245427.440
6	554887.8mE, 2765929.4mN	25.00787 N, -080.4560408 W	836305.855, 245481.388
7	554903.6mE, 2765901.9mN	25.007621 N, -080.455885 W	836357.710, 245391.104
8	554892.6mE, 2765914.7mN	25.007737 N, -080.455993 W	836321.608, 245433.116
9	554881.0mE, 2765923.5mN	25.007817 N, -080.456108 W	836283.537, 245462.037

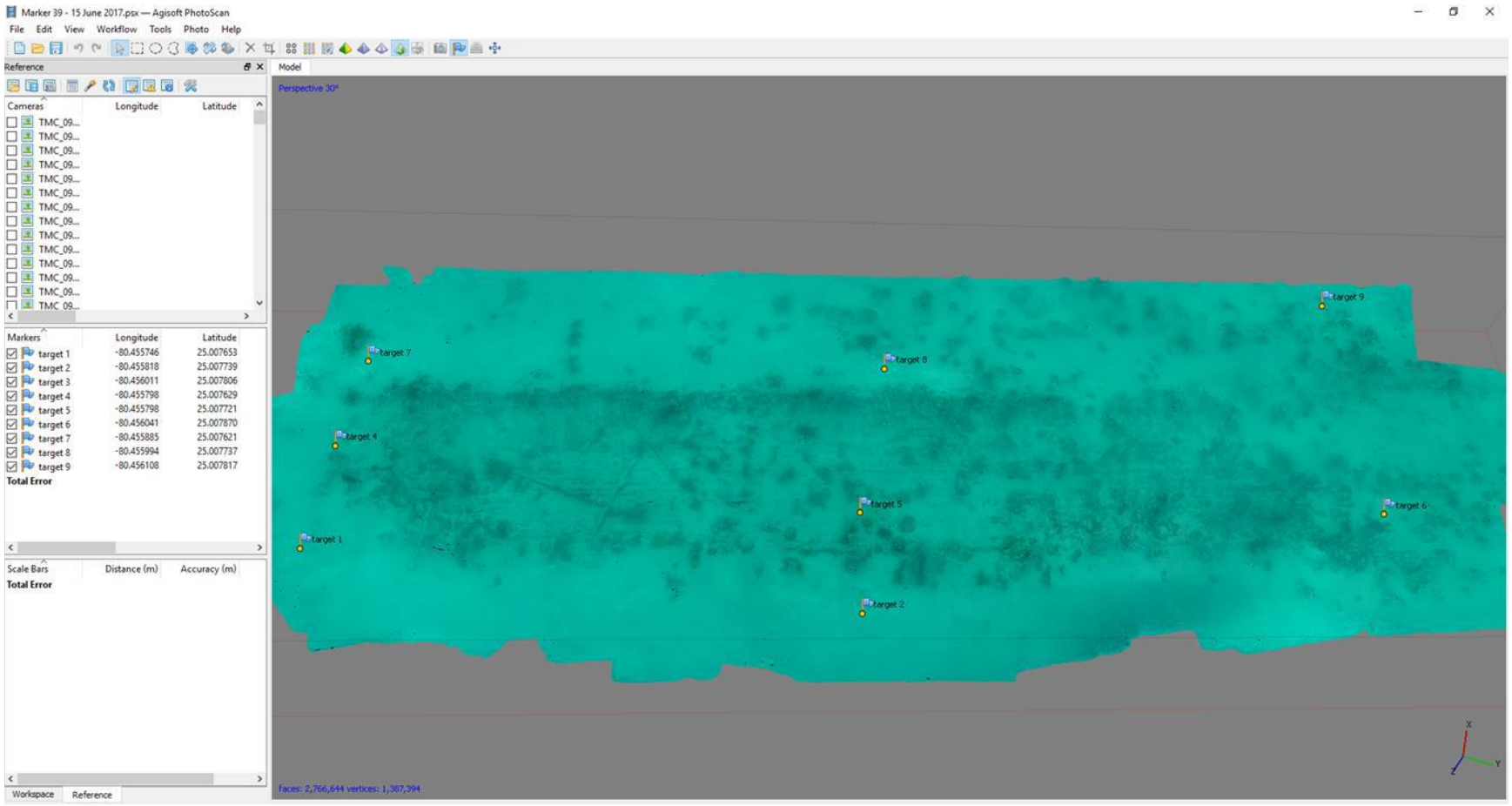


FIGURE 4-12: The Marker 39 site photogrammetric model with ground control points marked as targets. Each target is provided latitude and longitude coordinates then manually input the Agisoft Metashape software program (left side of screen). The coordinates were converted from UTM to decimal degrees format as required by the software. (Image by author, 2017).



FIGURE 4-13: Google Earth satellite mage of the Marker 39 wreck site with an overlay of the ground control point positions. The ground control points fully encompass the entirety of the site and can be used to mark the known extents for the establishment of an avoidance zone. (Image by author, 2017).

positioning technique was used for absolute coordinate data collection for each ground control point location. The information was stored on the USBL console then exported to an external hard drive. Photogrammetric data post-processing was undertaken in a similar method to the previous day; however, improved communications between the sonar operator and divers resulted in improved spatial datasets that were capable for use for georeferencing the Marker 39 photogrammetric model. The absolute coordinates were recorded in UTM format, then converted to NAD-83 in a decimal-degrees format for manual input into the Agisoft Metashape software and Google Earth (Table 4-1) (Figures 4-12 – 4-13). Each coded target was assigned absolute coordinates for both latitude and longitude. The Agisoft Metashape software calculated the positional error of the coded targets using the user-input absolute coordinate values. The software calculated the 15 June photogrammetric survey and UALR methodology supplementation to retain a positional accuracy of 1.1 m. Although this positional accuracy value for this case study fell within geophysical survey underwater positioning requirements published by the IHO, BOEM, and Historic England, the measurement confidence level of 95% was not achieved using single-point positioning (see Sections 2.2 and 2.3).

4.2.5 Case Study Survey Conclusion and UALR Methodology Research Direction

The Marker 39 wreck research case study demonstrated the practicality and efficiency using the UALR methodology as a supplemental technique for spatial data acquisition as required for photogrammetric surveying applications. The Marker 39 wreck research case study demonstrated the acquisition of absolute positioning coordinates with differential-grade spatial accuracy on a wreck site beyond the capabilities of most shore-based positioning equipment and techniques. Although the Marker 39 case study was considered a successful application of the UALR methodology, the author recognised significant shortcomings regarding data collection

equipment and techniques which required refinement prior to the next series of research case studies. The primary limitations for the UALR methodology at this time were the inability to acquire survey-grade underwater positional accuracy using the WAAS differential-positioning service, and the incapacity to achieve the required 95% measurement confidence through the implementation of single-point positioning.

4.3 Lake Waccamaw Pier Evaluations (April/June 2018)

4.3.1 Introduction

The Lake Waccamaw Pier Evaluations were carried out in April and June 2018 in preparation for succeeding research case studies in Florida and North Carolina. Lake Waccamaw was selected based on availability and the potential of future case study research performed in this particular water body. The shallow, freshwater environment facilitated testing without requiring diving equipment, a certified dive team, or surveying permits/authorisation at the local or state agency levels. The equipment and data collection assessments conducted during this period represent the final phase of the UALR methodology concept development.

4.3.2 Research Context

Following the analyses of the Marker 39 wreck case study, the author identified limitations in terms of satellite positional accuracy and data collection procedures which required refining prior to the next series of fieldwork surveys. During the Marker 39 case study fieldwork, the author noted that satellite positional accuracy at the GPS receiver level was ± 0.8 m using a Trimble SPS855 receiver, Trimble GA530 rover antenna, and GPS standard positioning service with WAAS differential error corrections. While sub-meter (differential-grade) positional accuracy may satisfy permitting requirements for some cultural resource management programs, the absolute spatial requirements established for this thesis research pursued underwater positioning accuracy that meet and/or exceed IHO, BOEM, and Historic England spatial guidelines. Single-point positioning, as used during the Marker 39 wreck research case study, was determined to be an ineffective data collection practice for UALR methodology applications. The use of a single measurement for a ground control point position does not factor

in probable variables that permanently or temporarily contribute to timing/ranging errors, thus resulting in less accurate subsurface localisation when compared to other methods such as time-window averaging. The research aims were to determine if recently acquired GPS hardware and software systems significantly improve satellite positional accuracy to survey-grade values (≤ 5 cm at the receiver level) and dilution of precision (≤ 2.0).

4.3.3 UALR Methodology Updated Hardware and Software Systems

Improving positional accuracy at the GPS receiver level for UALR applications required the addition of various hardware and software systems for acquiring error correction services. Following electronic communications with geospatial technology experts, the author determined the use of a real-time network (RTN) which incorporated virtual reference stations (VRS) as the preferred error correction service for satisfying the research aims. Throughout the United States, United Kingdom, Europe, and other coastal nations, public and private sector reference stations exist for providing error correction data for improving satellite positional accuracy (Chen et al. 2011:1; Donahue et al. 2013:6-7). For the research case studies at Lake Waccamaw, and other locations throughout North Carolina, the network of virtual reference stations are maintained by the North Carolina Geodetic Survey (NCGS) (Figure 4-14). Accessing the NCGS RTN/VRS required additional hardware and software systems compatible with the Trimble SPS855 receiver which included: a Trimble T10 Site Tablet with SC900 software, Zephyr Model 3 rover antenna (added for June 2018 evaluations), and mobile WiFi adapter. The Trimble T10 Site tablet and SC900 software are common pieces of surveying equipment routinely seen on construction sites, which allows users to maintain spatial control throughout a work site. The tablet is equipped to accept Wi-Fi, thus allowing the use of a mobile Wi-Fi adapter to access the internet and RTN/VRS error correction data stream. The tablet is connected to the Trimble SPS855 receiver

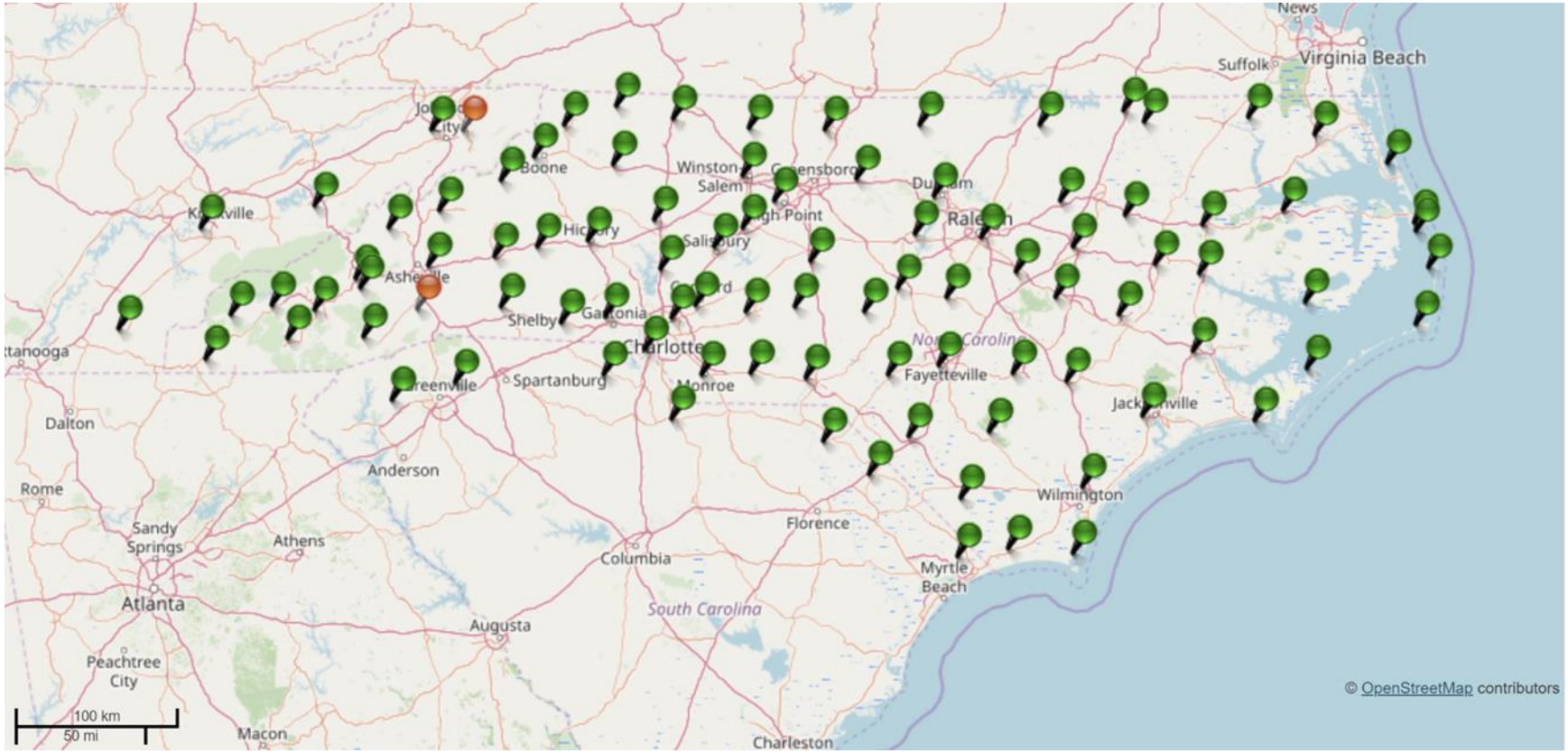


FIGURE 4-14: North Carolina Geodetic Survey sensor map indicating where all virtual reference stations are located throughout the state. Green indicates an active and healthy reference site, where as orange indicates the data should not be used. Image from http://rtn.nc.gov/Map/SensorMap.aspx. (Accessed 6 April 2018).

via Bluetooth connection, and all spatial controls and error correction data can be viewed on the tablet or dedicated laptop used to monitor GPS activity. The Trimble Zephyr Model 3 rover antenna was acquired to replace the GA530 antenna given its incompatibility with the Trimble CenterPoint RTX post-processing service.

4.3.4 Pier Evaluation #1 and Analysis (April 2018)

The initial Lake Waccamaw Pier Evaluation began on 16 April 2018, and consisted of a basic assessment of updated satellite positioning instrumentation and software for enhancing the spatial accuracy of the UALR methodology. The research aims for this evaluation were to ascertain the highest attainable positional accuracy at the GPS receiver level, and establish an equipment configuration that was acceptable for archaeological surveying applications on a variety of working platforms. The initial pier evaluation independently investigated the updated satellite positioning system arrangement as a focused assessment of the GPS equipment performance prior to coupling with the USBL console.

The pier structure used as the working platform during the Lake Waccamaw evaluations offered a static position on which to examine updated satellite positioning hardware and software systems in a semi-controlled environment. The stationary capabilities of the structure allowed the assessment of satellite positioning system performance in optimal conditions absent of continuous movements experienced on floating platforms. Adding to the advantages of testing the satellite positioning system arrangement on a stable working platform, the nearest NCGS virtual reference station site is located in Whiteville, North Carolina, at a distance of 15.6 km. The short baseline distance between the reference station and evaluation site permitted a young error correction age, thus increasing the likelihood of mitigating tropospheric weather conditions that potentially affected satellite signal transmission.



FIGURE 4-15: The cleat mount lashed to a deck-mounted cleat. Note the cleat mount arms do not reach the deck cleat; therefore, requiring the arm loops be lashed to the deck cleat. (Photograph by author, 2018).



FIGURE 4-16: The antenna extended to full height allowing the Trimble GA530 antenna full visibility to orbiting satellites above the user-defined elevation mask of 10º above the horizon. The rigid aluminum pole construction provided excellent stability on a static working platform (Photograph by author, 2018).

The 16 April pier evaluation commenced with the transportation of all satellite positioning equipment to the farthest end of the pier. This pier is equipped with boat cleats which allowed the use of the cleat mount designed and fabricated by the author; however, the distance of the cleat from the edge of the structure required lashing the mount to the cleat as opposed to utilising the arms underneath the cleat ends (Figure 4-15). The distance between the pier edge and cleat also required the use of an aluminium pipe positioned underneath the cleat mount to ensure the pole mount rested at a 90º vertical angle. After confirming the cleat mount's stability to withstand the weight of the pole mount, the author inserted a lower section of the pole through the cleat mount sleeve until the base of the pole rested on the lake bottom. The reason for allowing the pole to rest on the lake bottom was to simulate the counterweight of the transducer and bracket. Attaching additional pole sections without any form of counterweight could result in warping the pole or excessive unwanted movement. Prior to attaching the additional pole sections, the author attached the Trimble GA530 antenna and coaxial cable. The author extended the pole 4.5 m above the top of the pier deck to increase antenna visibility to orbiting satellites (Figure 4-16).

Following the cleat mount and pole setup, the author configured the satellite positioning systems arrangement under the pier shelter. Using a small table, the various hardware systems were arranged in a manner that permitted the monitoring of all equipment to ensure that all systems maintained an operational status. Throughout the duration of the satellite positioning systems evaluation, the Trimble SPS855 Receiver Status application displayed positional error estimates (1-σ) at: easting 0.04 m, northing 0.05 m, vertical 0.01 m (Figure 4-17). Position, horizontal, vertical, and timing dilutions of precision values never exceeded 1.8, which was below the research requirements for maintaining survey-grade accuracy and precision. In

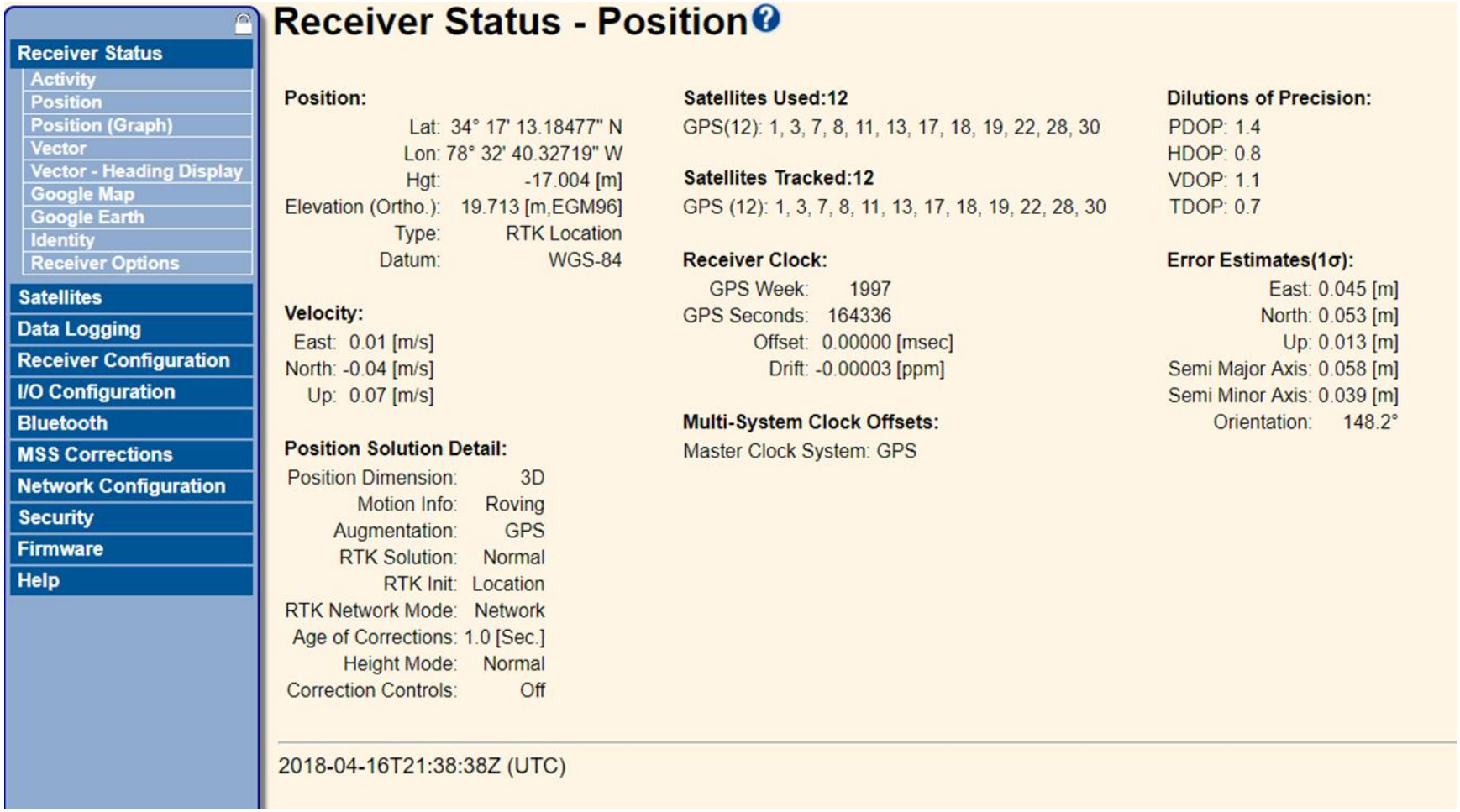


FIGURE 4-17: The Trimble SPS855 receiver status display. This screenshot was taken during the 16 April 2018 pier evaluation which indicated horizontal positional accuracies of 5 cm or less and with dilutions of precision of 1.4 or less. The information in the receiver status is updated in real-time to provide the user with updated satellite positional information. (Image by author, 2018).

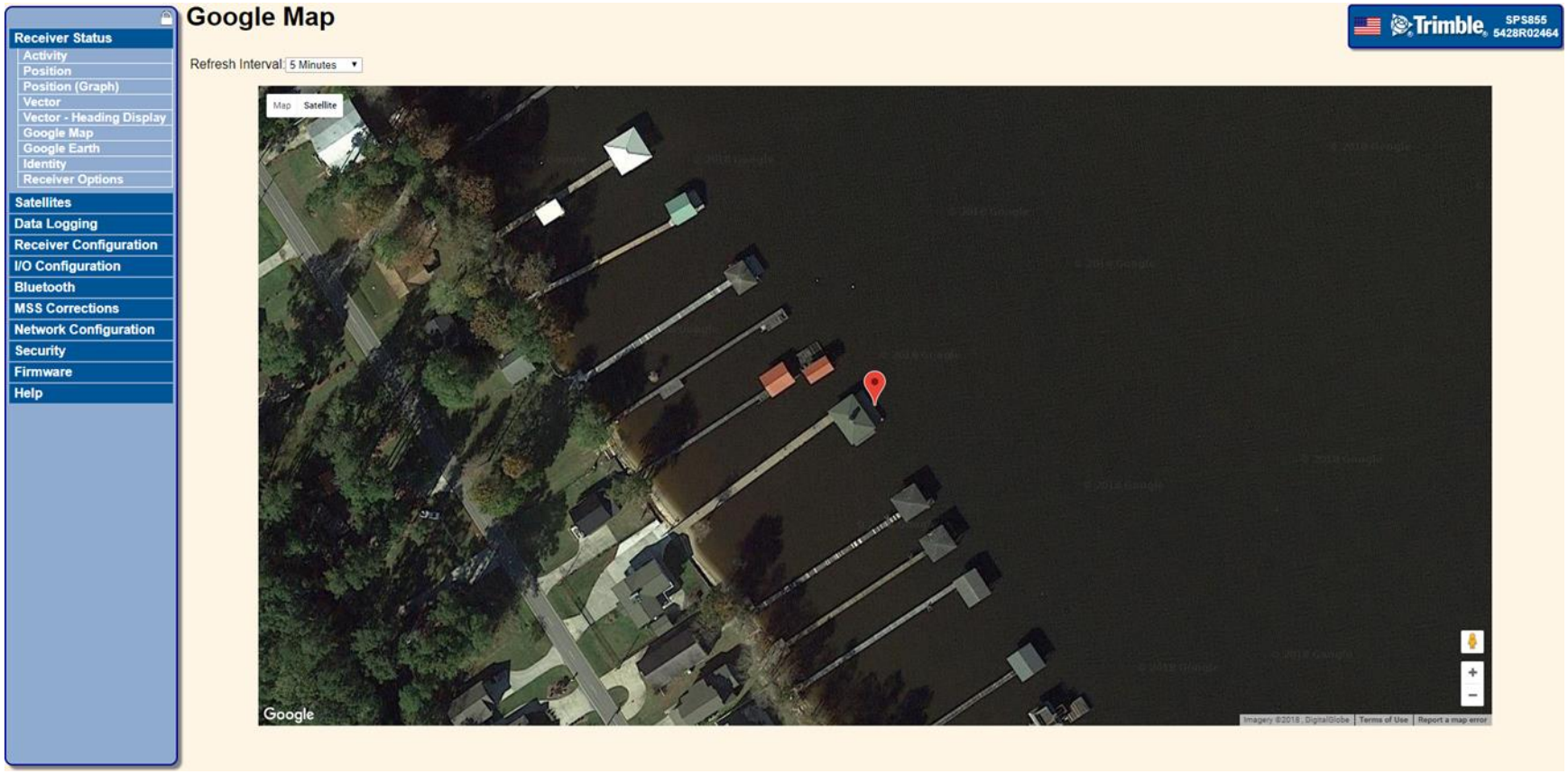


FIGURE 4-18: The Trimble software allows users connected to the internet to view where they are located through Google Earth imagery. The red indicator in the middle of the image indicates where the GA530 antenna was located during the equipment evaluations. (Image by author, 2018).

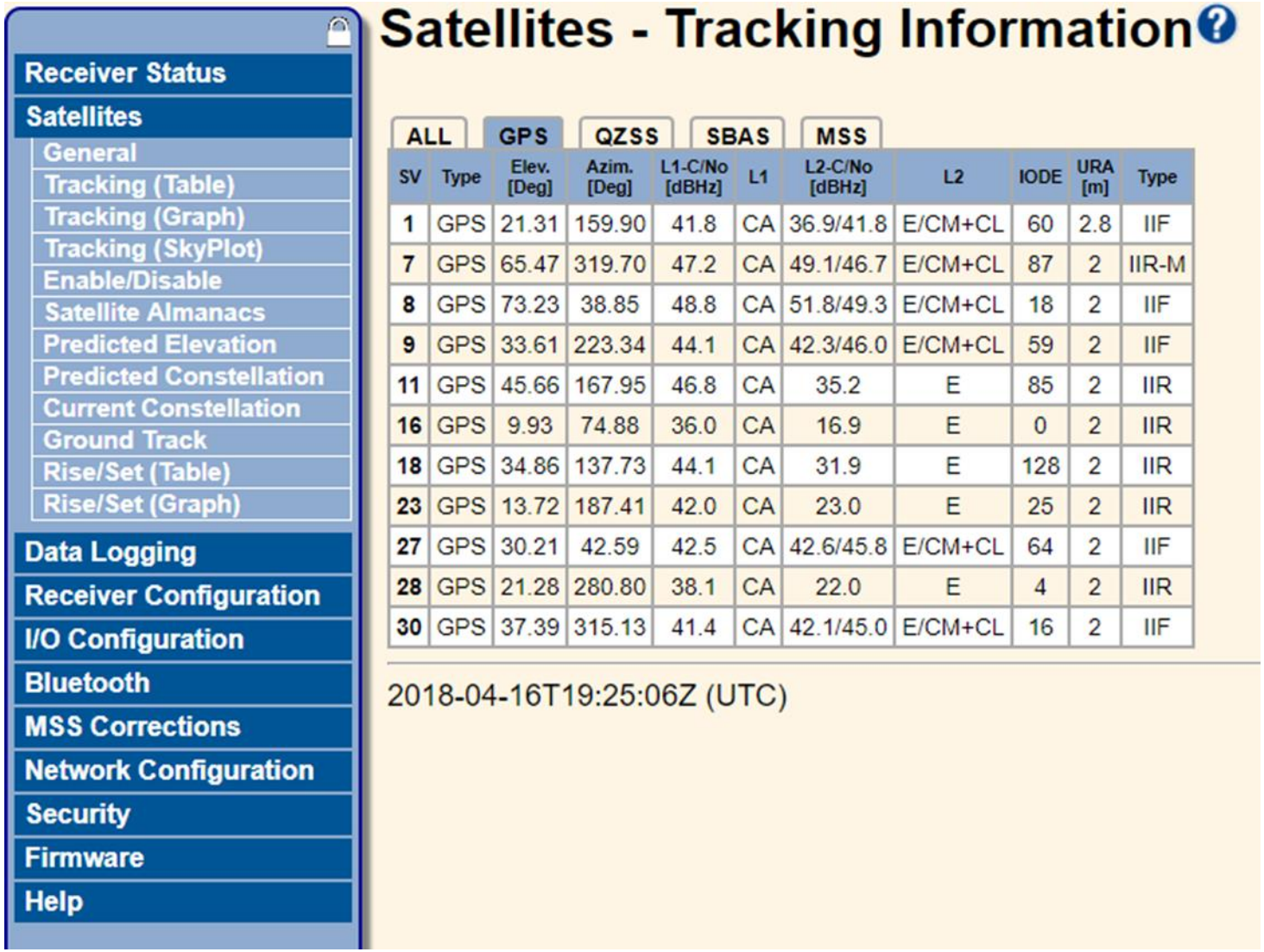


FIGURE 4-19: Satellite tracking information which provides users with GPS frequencies, elevations above the horizon, bearing, and satellite type. (Photograph by author, 2018).

addition to monitoring positional information and error correction data, the author maintained documentation pertaining to which orbiting satellites were visible during the equipment evaluations. It should be noted, that Trimble calculates the positional error estimated based on 1σ values, and as a result, to achieve the required 95% confidence estimate, the displayed values need to be doubled to equal 2σ. In additional to calculating position and accuracy estimates, the Trimble SPS855 software permits users to "see" where they are located on a Google Earth image review, which satellites were present during survey operations, their status (health), signal transmission type, elevation above the horizon, and azimuth (Figures 4-18 – 4-19).

The 16 April equipment evaluation determined that the hardware and software upgrades were successful in reducing satellite positional error estimations from an average of 0.8 m to an average of 5 cm or less. Known limitations for the satellite positioning systems arrangement at this phase pertained to the use of the Trimble CenterPoint RTX-PP service, which was unable to post-process the satellite data log file due to the incompatibility of the Trimble GA530 rover antenna. The GA530 antenna was not capable of accepting certain navigation data required for CenterPoint RTX post-processing; therefore, the acquisition of a compatible replacement rover antenna was the immediate research focus. Within a week, the author acquired a Trimble Zephyr Model 3 rover antenna which was purported as compatible with all hardware and software systems used for UALR methodology research. Although the positional accuracy and dilution of precision values were within the desired survey-grade standards, the author decided to conduct further pier evaluations for assessing the Zephyr 3 antenna, performance of the coupled satellite and USBL positioning systems, and revised data collection practices.

4.3.5 Pier Evaluation #2 and Analysis (June 2018)

The second series of Lake Waccamaw Pier Evaluations occurred on 8, 9, and 13 June 2018, using the same testing location in an effort to replicate the 16 April equipment assessment. The 8 and 9 June evaluations were focused on examining the satellite positional accuracy and dilution of precision values utilising the Trimble Zephyr 3 rover antenna. The Zephyr 3 is a more enhanced antenna system when compared to the GA530, and permits the use of the Trimble CenterPoint RTX post-processing service. The 13 June evaluation assessed the satellite and USBL positioning systems in tandem operation, while the time-window averaging data collection method was used to acquire underwater absolute coordinates. To simulate a ground control network, the author utilised 1.5 m iron fence posts driven into the lake bottom which offered static positions to which the USBL transponder was attached during the data collection process. The satellite positioning hardware and software systems were configured in the same arrangement as the 16 April evaluation and connected to the USBL console via a RS-232 serial cable. For the 13 June evaluation, the USBL transducer and bracket were attached to the bottom end of the pole for underwater signal transmission.

The utilisation of the Zephyr 3 antenna permitted the use of the Trimble CenterPoint RTX post-processing service available at https://trimblertx.com/UploadForm.aspx (last access on 13 June 2020). The service is free for all users with compatible hardware systems and a variety of data log formats. Following surveying activities for each day, the author uploaded the satellite data log to the CenterPoint RTX website, following which the service produced a detailed PDF report displaying relevant satellite navigation information (Figures 4-20 – 4-21). Comparative analyses of the processed results indicate minimal antenna movement due to it being fixed in a static position; however, these types of results are not anticipated on floating working platforms



Post-Processing Service Based on RTX Technology

TrimbleRTX.com

Contributor:	matthew@thompsonmaritimeconsulting.com
Reference Name:	24641590.T02
Upload Date:	06/08/2018 21:17:12 UTC
Report Time Frame:	
Start Time:	06/08/2018 17:33:30 UTC
End Time:	06/08/2018 19:37:00 UTC
Observation File Type(s):	T02
Observation File(s):	24641590.T02
Antenna:	
Name:	TRM55970.00 NONE
Height:	0.026 m
Reference:	Bottom of antenna mount
Receiver Name:	TRIMBLE SPS855
Coordinate Systems:	NAD83-2011 (Auto-detected) & ITRF2014
Tectonic Plate:	North America (Auto-detected)
Tectonic Plate Model:	MORVEL56
Processing Interval:	15 s

Statistics

# Total Obs	# Usable Obs	# Used Obs	Percent
495	495	495	100

Used Satellites

# Total Satellites:	13
GPS:	G01 G03 G06 G07 G08 G11 G13 G17 G18 G19 G22 G28 G30

Processing Results

NAD83-2011 at Epoch 2010.0		
Coordinate	**Value**	**σ**
X	1047722.360 m	0.006 m
Y	-5170287.362 m	0.013 m
Z	3572784.265 m	0.010 m
Latitude	34° 17' 13.17676" N	0.005 m
Longitude	78° 32' 40.32721" W	0.005 m
El. Height	-17.416 m	0.016 m

ITRF2014 at Epoch 2018.43		
Coordinate	**Value**	**σ**
X	1047721.500 m	0.006 m
Y	-5170285.880 m	0.013 m
Z	3572784.141 m	0.010 m
Latitude	34° 17' 13.20313" N	0.005 m
Longitude	78° 32' 40.34867" W	0.005 m
El. Height	-18.827 m	0.016 m

Report Information

Trimble RTX Solution ID:	17623657
Solution Type:	Static
Software Version:	6.1.4.17185
Creation Date:	06/08/2018 21:17:33 UTC

Disclaimer

Trimble Navigation Limited does not guarantee availability, reliability, and performance of the current RTX Post-Processing service and accepts no legal liability arising from, or connected to, the use of information on this document or use of this service.

FIGURE 4-20: 8 June 2018 Trimble CenterPoint RTX Report. Received on same day via email.

Post-Processing Service Based on RTX Technology

TrimbleRTX.com

Contributor:	matthew@thompsonmaritimeconsulting.com
Reference Name:	24641600.T02
Upload Date:	06/09/2018 21:54:12 UTC
Report Time Frame:	
Start Time:	06/09/2018 15:42:45 UTC
End Time:	06/09/2018 18:32:00 UTC
Observation File Type(s):	T02
Observation File(s):	24641600.T02
Antenna:	
Name:	TRM55970.00 NONE
Height:	0.026 m
Reference:	Bottom of antenna mount
Receiver Name:	TRIMBLE SPS855
Coordinate Systems:	NAD83-2011 (Auto-detected) & ITRF2014
Tectonic Plate:	North America (Auto-detected)
Tectonic Plate Model:	MORVEL56
Processing Interval:	15 s

Statistics

# Total Obs	# Usable Obs	# Used Obs	Percent
678	678	678	100

Used Satellites

# Total Satellites:	16
GPS:	G01 G03 G06 G07 G08 G09 G11 G13 G17 G18 G19 G22 G23 G27 G28 G30

Processing Results

NAD83-2011 at Epoch 2010.0		
Coordinate	**Value**	**σ**
X	1047722.423 m	0.005 m
Y	-5170287.266 m	0.013 m
Z	3572784.291 m	0.010 m
Latitude	34° 17' 13.17895" N	0.005 m
Longitude	78° 32' 40.32406" W	0.004 m
El. Height	-17.468 m	0.016 m

ITRF2014 at Epoch 2018.44		
Coordinate	**Value**	**σ**
X	1047721.563 m	0.005 m
Y	-5170285.784 m	0.013 m
Z	3572784.167 m	0.010 m
Latitude	34° 17' 13.20532" N	0.005 m
Longitude	78° 32' 40.34552" W	0.004 m
El. Height	-18.879 m	0.016 m

Report Information

Trimble RTX Solution ID:	17636261
Solution Type:	Static
Software Version:	6.1.4.17185
Creation Date:	06/09/2018 21:54:35 UTC

Disclaimer

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FIGURE 4-21: 9 June 2018 Trimble CenterPoint RTX Report. Received on same day via email.

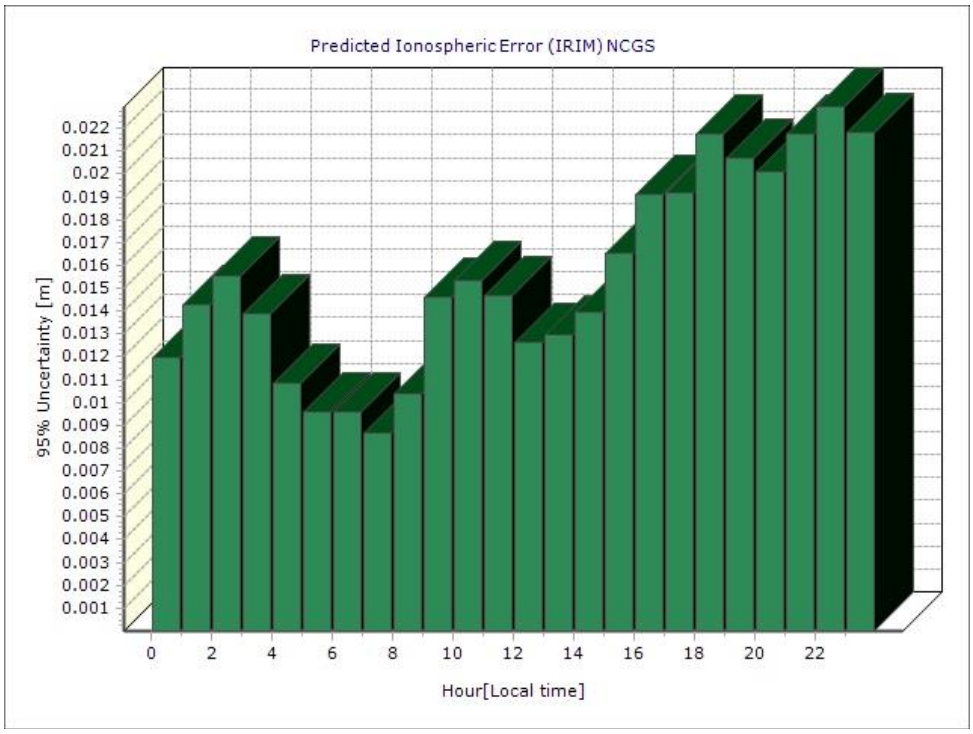


FIGURE 4-22: Predicted ionospheric error for 8 June 2018. Graph provided by the North Carolina Geodetic Survey. Accessed on 9 June 2018.

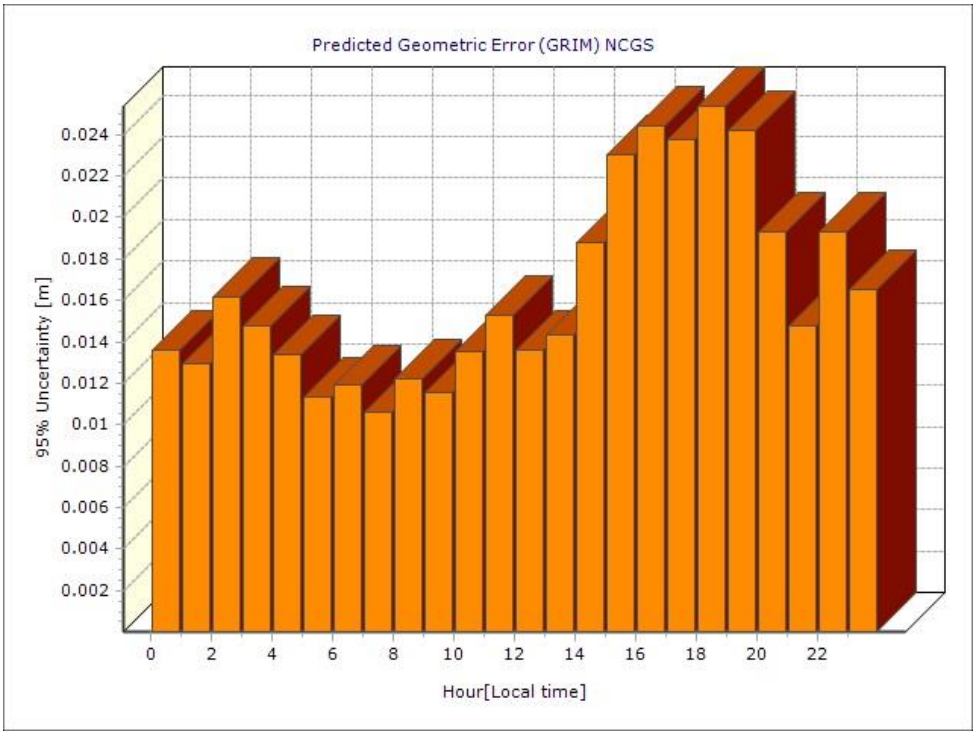


FIGURE 4-23: Predicted geometric error for 8 June 2018. Graph provided by the North Carolina Geodetic Survey. Accessed on 9 June 2018.



FIGURE 4-24: Predicted ionospheric error for 9 June 2018. Graph provided by the North Carolina Geodetic Survey. Accessed on 10 June 2018.

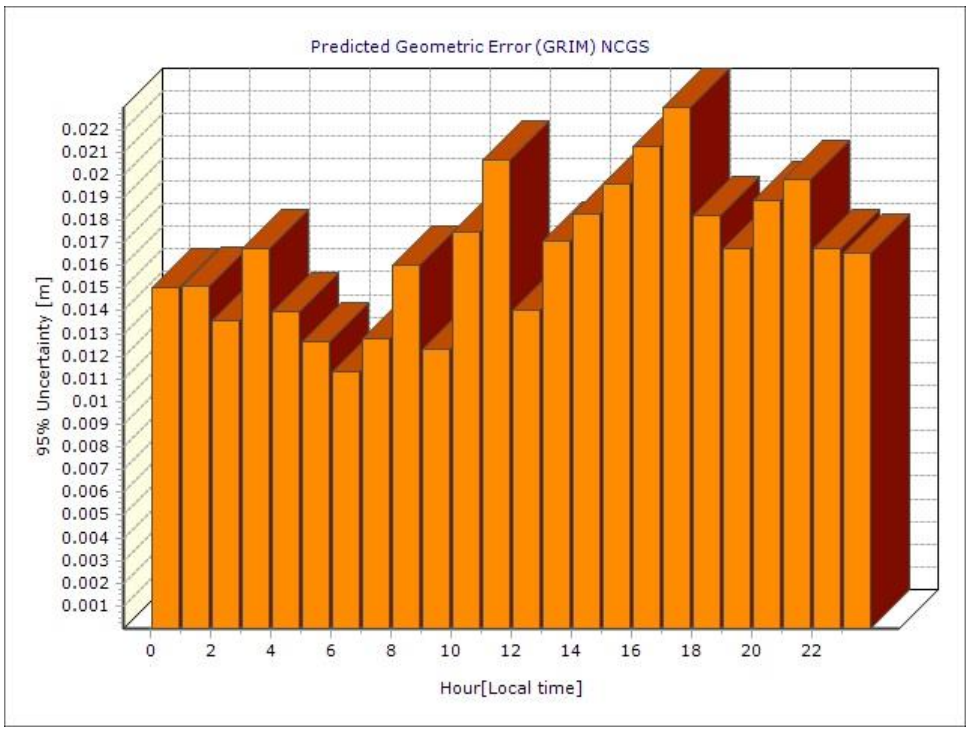


FIGURE 4-25: Predicted ionospheric error for 9 June 2018. Graph provided by the North Carolina Geodetic Survey. Accessed on 10 June 2018.

TABLE 4-2
GROUND CONTROL POINT DATA FOR THE 13 JUNE 2018 PIER EVALUATION

GCP	Minimum	Maximum	Average	1- σ	2- σ
1	34.28710833 N 78.54433333 W	34.287155 N 78.54437333 W	34.28713582 N 78.54434514 W	62.3 mm 54.0 mm	125.3 mm 108.1 mm
2	34.28700333 N 78.54429833 W	34.28715833 N 78.5446 W	34.28710667 N 78.54437578 W	239.0 mm* 401.7 mm*	478.1 mm* 803.4 mm*
3	34.286995 N 78.54426 W	34.28701 N 78.54426667 W	34.28700445 N 78.54426554 W	16.5 mm 11.9 mm	32.9 mm 23.9 mm
4	34.28696 N 78.54426333 W	34.28698333 N 78.54427167 W	34.28697156 N 78.54426745 W	57.8 mm 16.1 mm	115.8 mm 32.3 mm
5	34.28684 N 78.54420833 W	34.28685667 N 78.54422333 W	34.28684788 N 78.54421765 W	28.1 mm 20.1 mm	56.2 mm 40.2 mm

Notes: * GCP 2 data suffered from temporary inadequate underwater signal transmission believed to be associated with the very shallow operational depth (< 1 m).



FIGURE 4-26: Google Earth satellite image of the pier evaluations area. In this image, the averaged ground control point positions and location of the antenna/transducer pole are labelled. (Image by author, 2018).

that are susceptible to water movement. In addition to reviewing the 8-9 June 2018 CenterPoint RTX reports, the author examined predicted ionospheric and geometric error data for each survey day provided by the North Carolina Geodetic Survey (Figures 4-22 – 4-25). The author recommends reviewing the error data reports if erroneous positional data is collected during the surveying process, because otherwise it is not necessarily required for spatial data analyses as part of examining the underwater positioning control point information. It is not obligated for each survey day unless documentation protocols warrant such reports. In doing so, the author elected to forgo the inclusion of the NCGS predicted ionospheric and geometric error reports for the 13 June evaluation.

The 13 June evaluation was characterised as the synthesis of research and equipment acquisition for the establishing the final UALR methodology concept. During this assessment, all positioning systems were assembled for UALR methodology application for georeferencing a simulated ground control point network constructed of 1.5 m fence posts. The USBL transponder was attached to each ground control point location, which permitted the author to return to the USBL console to activate the Data Record function for a 5-minute interval. Using a 1-second update rate, over 300 absolute positioning measurements were collected for each ground control point location using the $GPRMC data string format. Following data collection of the simulated ground control point network, the author exported the data to an external hard drive for post-processing in Microsoft Excel. The Microsoft Excel program was used to calculate each ground control point minimum and maximum coordinates, the difference between the min. and max. coordinates, the average position which was assigned as the target location for each point, and standard deviations from the averaged position (1-σ for 68% and 2-σ for a 95% confidence levels) (Table 4-2) (Figure 4-26).

4.3.6 Survey Findings

The results of the Lake Waccamaw Pier Evaluations revealed the updated satellite positioning systems and time-window averaging greatly increased the effectiveness of the UALR methodology for georeferencing underwater ground control point positions. When compared to time-window averaging, single-point positioning used for the Marker 39 wreck site was determined to be inferior due to a lesser measurement confidence level and the inability to reliably test data results. Time-window averaging, as used in this case study, allows the user to acquire a sub-metre underwater positional accuracy with a 95% confidence levels as published in IHO, BOEM, and Historic England geophysical surveying guidelines. The use of the UALR methodology and time-window averaging process allowed to calculate averaged ground control point coordinates to the millimetre level; whereas, the overall positional accuracy was calculated to be 10 cm or less. This level of positional accuracy was impressive given the extremely shallow working conditions. While the use of 5-minute data collection intervals was beyond the required time for acquiring a viable sample set, processed datasets indicated the UALR methodology concept was a practical and accurate means of georeferencing archaeological datasets in support of geophysical surveying operations. As the final phase of UALR methodology concept development, future case study research involved testing the described equipment and data collection practices in real-world environments on submerged cultural sites.

4.4 Lake Waccamaw Prehistoric Canoes Case Study (June/July 2019)

4.4.1 Introduction

Cultural resource management surveys constitute the majority of contemporary archaeological projects on both land and underwater sites. Powerful storms and manmade events require the assessment of newly discovered sites, but also create circumstances in which known archaeological sites are re-evaluated as part of damage assessments and/or site formation process appraisals. The Lake Waccamaw Prehistoric Canoes research case study aided in the assessment of undocumented prehistoric canoes, fragments, and the re-evaluation of two previously documented canoes (WAL0004/WAL0006) currently undergoing in situ preservation (NCUAB 2001, 2010). The case study research design was originally intended to survey WAL0004 and WAL0006 as part of a post-hurricane assessment (Florence, September 2018); however, local residents discovered undocumented canoes in the vicinity of Big Creek, a waterway that serves as the primary water source for Lake Waccamaw. At least one intact canoe was uncovered, but was subsequently "lost", according to state authorities who questioned the individual responsible for moving the canoe (Nathan Henry 2019, pers. comm.).

The disappearance of submerged cultural materials, especially intact canoes which can yield useful information of past human lifeways, compelled the author to redesign the research case study objectives to performing a reassessment survey of the WAL0004/WAL0006 site and the inclusion of an emergency survey of the area surrounding the mouth of Big Creek for additional submerged cultural resources (Figure 4-27). The research aims were: to identify the locations of the WAL0004/WAL0006 canoes, assess their current condition and structural integrity, create a simulated avoidance zone using the UALR methodology, and repeat the process for additional canoe remains found in the Big Creek vicinity. The author coordinated and

maintained constant communications with the Lake Waccamaw State Park and the North Carolina Underwater Archaeology Branch throughout the project duration. The outcomes of the Lake Waccamaw Prehistoric Canoes research case study survey resulted in the creation of a simulated avoidance zone for the WAL0004/WAL0006 preservation site, updated absolute coordinates for both canoes for site files and upcoming extraction for laboratory conservation, and the rescue of an intact prehistoric canoe and additional canoe fragments for conservation and subsequent display at the University of North Carolina at Pembroke and other local museums.

4.4.2 Lake Waccamaw Emergency Cultural Resources Survey

On 18 June 2019, the author commenced an emergency archaeological survey for the documentation of submerged cultural resources reported in the vicinity of the mouth of Big Creek. Recent storm flooding resulted in massive sediment displacement which revealed previously buried canoe remains; thus, subjecting them to enhanced decomposition and tampering. The author's familiarity with the area greatly assisted in determining the manner in which the survey was to be conducted in a safe and efficient manner. The shallow water and sand bottom sediment prevented the use of side scan sonar for a wide area survey, which limited the author to performing a walking survey in a linear pattern.

Initial observations of the survey area indicated the presence of a large sandbar formed at the mouth of Big Creek upon which local residents began stacking natural wood debris. The author identified a canoe fragment that had washed onto the sandbar and was partially exposed above the waterline (Figure 4-28). Although the fragment had been removed from its original context, the author obtained satellite positioning coordinates for documentative purposes and re-submerged the canoe fragment to prevent rapid drying and decomposition. After resuming the walking survey, the author discovered a large prehistoric canoe fragment which consisted of an



FIGURE 4-27: Google Earth satellite image of Lake Waccamaw. The WAL0004/WAL0006 and Big Creek survey locations are indicated using white boxes. (Image by author, 2019).

end section and roughly 1.4 m of hull (Figure 4-29). The canoe fragment was discovered in less than 1 m of water and photographed using a Nikon D810 DSLR and Nauticam underwater housing. In addition to the photographic documentation and basic dimension measurements, the author acquired satellite positioning coordinates to return to the fragment in the event of extraction for conservation. Other smaller canoe fragments were discovered, documented, and photographed as part of the walking survey. Following the walking survey, the author uploaded all photographs and field notes then emailed the data to the North Carolina Underwater Archaeology Branch.

4.4.3 WAL0004/WAL0006 Survey and UALR Methodology Application

The post-hurricane assessment of WAL0004 and WAL0006 began on 18 June 2019, the same day as the emergency survey at the mouth of Big Creek. While en route to Big Creek to perform the emergency survey, the author performed preliminary site reconnaissance using a vessel-mounted Humminbird 1198c side-imaging sonar system. The Humminbird 1198c was designed as a high-resolution acoustic imaging system for fishermen, but has been routinely utilised by search and rescue units for recovering drowning victims and other submerged objects. Following the arrival at the pre-entered GPS coordinates, the author began traversing the area using compass bearings for maintaining survey lanes. Within a few minutes, the outline of one canoe was visible on the bottom; however, this was concerning given that two canoes were placed at this location for in situ conservation. Although the emergency survey was given priority at this time, the author updated the WAL0004/WAL0006 site coordinates for more thorough side scan sonar and diver surveys in the near future.

On 20 June 2019, a side scan sonar survey was undertaken of a grid area the author



FIGURE 4-28: Exposed canoe fragment on a sandbar just outside of the mouth at Big Creek. (Photo by author, 2019).



FIGURE 4-29: Submerged canoe fragment discovered during the emergency survey. The author discovered the fragment while performing a walking survey in the vicinity of the sandbar. (Photo by author, 2019).

determined as the area of potential effect (APE) for the WAL0004/WAL0006 site. The objectives of the side scan sonar survey were to confirm the location of both canoes and identify storm debris that has or may negatively impact the prehistoric canoes. The side scan sonar survey was performed using a Klein 3900 side scan sonar unit, Trimble SPS855 using RTN/VRS error correction services identical to UALR methodology specifications, and a 7.6 m Carolina Skiff centre console. The survey vessel was outfitted for single-person surveying operations using dual monitors, and a waterproof keyboard, while the Klein 3900 side scan sonar was configured in a hip-mounted arrangement allowing ease of deployment and recovery. The water depth in the survey area varied between 1.5 – 2 m; therefore, requiring close survey lane spacing of 15 m and sonar range for overlapping acoustic imaging and improved target positioning. For the initial search the author utilised a 455 kHz frequency for general imaging; however, if a potential target was located, the target was resurveyed using a 900 kHz frequency to provide improved image resolution to assist in possible identification. The result of the side scan sonar confirmed the location of the WAL0004/WAL0006 site at 34º 17.33712 N; 078º 31.827914 W, and no storm debris was identified within potential impact range.

Following the side scan sonar survey of the WAL0004/WAL0006 site and surrounding area, the author processed the raw data using SonarWiz post-processing software. Similar in regards to the Humminbird acoustic imagery, only one canoe was visible on the sonar record. The author conjectured the probability that the second canoe was buried in the muddy bottom sediment adjacent to the visible canoe. Following the sonar data analysis, the author determined that a diver survey was needed prior to UALR methodology mapping and georeferencing. In July 2019, the author constructed ground control points using iron stakes equipped with surface markers made from neon green foam (Figure 4-30). On 12 July 2019, the author identified the



FIGURE 4-30: Ground control points used for the establishing the spatial network on the WAL0004/WAL0006 site. (Photo by author, 2019).



FIGURE 4-31: Ground control point surface marker located adjacent to the dive flag. (Photo by author, 2019).

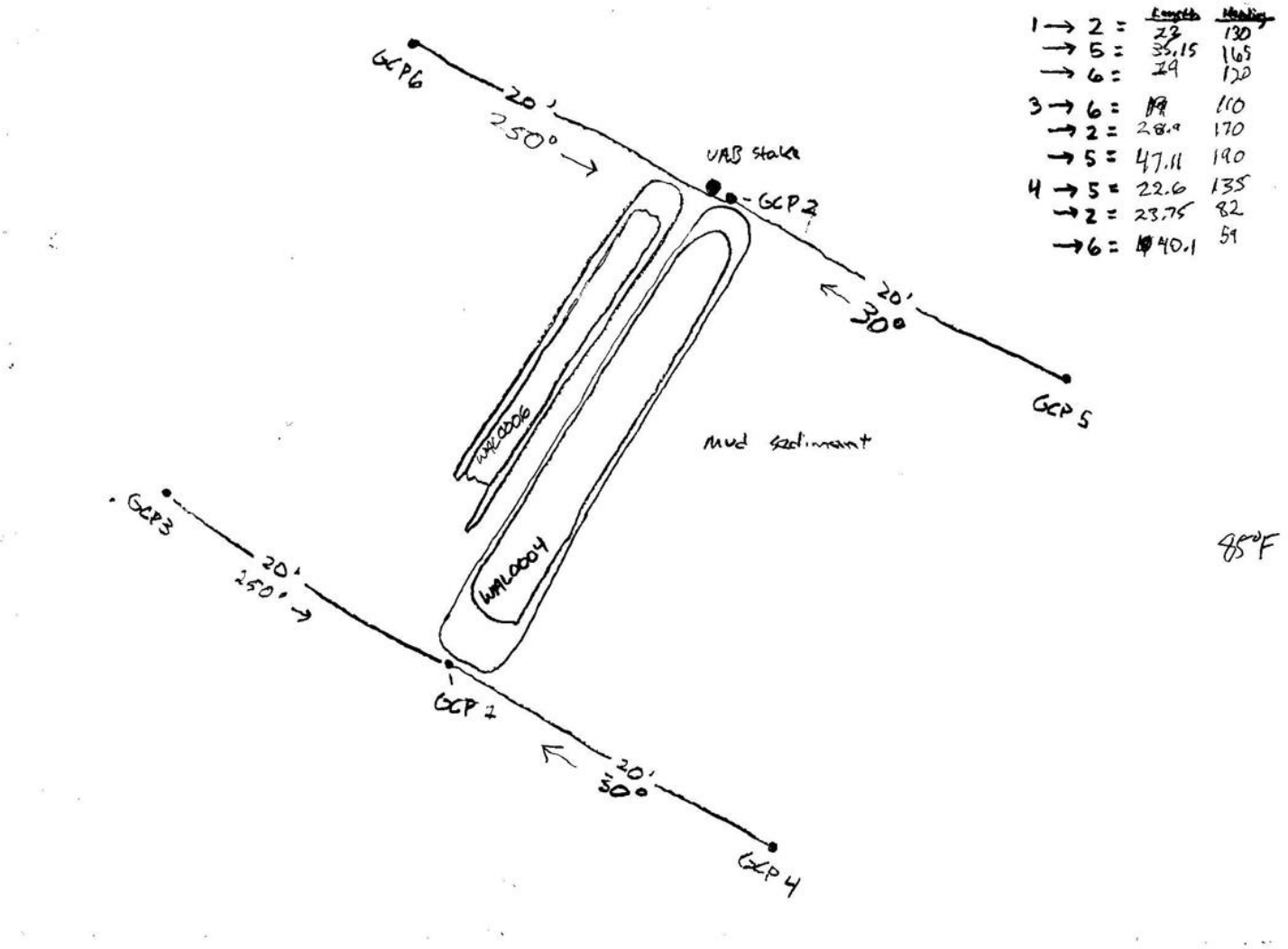


FIGURE 4-32: Sketched site map displaying the WAL0004/WAL0006 site, ground control point locations, tape measurements between trilaterated points, and compass bearings. (Image by author, 2019).



FIGURE 4-33: UALR methodology data collection equipment positioned on the working platform forward of the helm. Shade was provided by a portable beach umbrella. (Photograph by author, 2019).

locations of both canoes, and as previously assumed, the "missing" canoe was buried adjacent to the canoe visible on the sonar record. Subsequent to identifying both canoe positions, the author commenced establishing a ground control point network to encompass the site. Ground control points 1 and 2 were located on opposite ends of WAL0004 due to this canoe being intact and extending 6.7 m (Note: WAL0006 is a large canoe fragment in which one end was broken from the main section). The ground control network was established using six steel rods with attached surface markers for identification and fieldwork efficiency, and the dive flag/buoy was moored at the site to warn passing boaters and thus increasing safety for divers while working underwater (Figure 4-31).

The UALR methodology data collection process commenced on 14 July 2019, and required a total of 70 minutes to perform underwater trilateration measurements of each ground control point position which included both tape measurements and bearings. Each ground control point position was measured in reference to two other datum positions, and the information recorded on a dive slate (Figure 4-32). UALR methodology data collection was performed using the process described in the 2018 Lake Waccamaw Pier Evaluations (see pgs. 224-243), and successfully collected absolute spatial information for each ground control point position (Figure 4-33). Following the UALR methodology data collection procedure, the raw data was processed using Microsoft Excel software in which the author produced spatial information that included: minimum coordinate value, maximum coordinate value, the difference in the minimum and maximum values, the averaged position coordinates, one standard deviation, and two standard deviations (Table 4-3). The averaged latitude and longitude value for each ground control point was then used to plot the avoidance zone (Figures 4-34 – 4-35).

TABLE 4-3
GROUND CONTROL POINT INFORMATION

GCP	Minimum	Maximum	Average	1- σ	2- σ
1	34.28900167 N 78.53042833 W	34.28945667 N 78.53074167 W	34.28925739 N 78.53060518 W	0.156 m 0.945 m	0.312 m 1.890 m
2	34.28892667 N 78.53042667 W	34.289325 N 78.53074667 W	34.28901444 N 78.53063961 W	0.865 m 0.547 m	1.731 m 1.095 m
3	34.28897833 N 78.53053333 W	34.28935833 N 78.53070167 W	34.28913559 N 78.53062237 W	0.126 m 0.474 m	0.252 m 0.948 m
4	34.28891333 N 78.530205 W	34.289155 N 78.53073667 W	34.28900682 N 78.53044739 W	0.788 m 0.195 m	1.577 m 0.391 m
5	34.28885833 N 78.53027667 W	34.28913667 N 78.53081 W	34.28890444 N 78.53051594 W	0.335 m 0.962 m	0.671 m 1.925 m
6	34.289215 N 78.530095 W	34.28950333 N 78.53061333 W	34.28944647 N 78.53039524 W	0.5136 m 0.9121 m	1.027 m 1.824 m



FIGURE 4-34: The WAL0004/WAL0006 survey location is indicated by the yellow box. (Image by author, 2019).

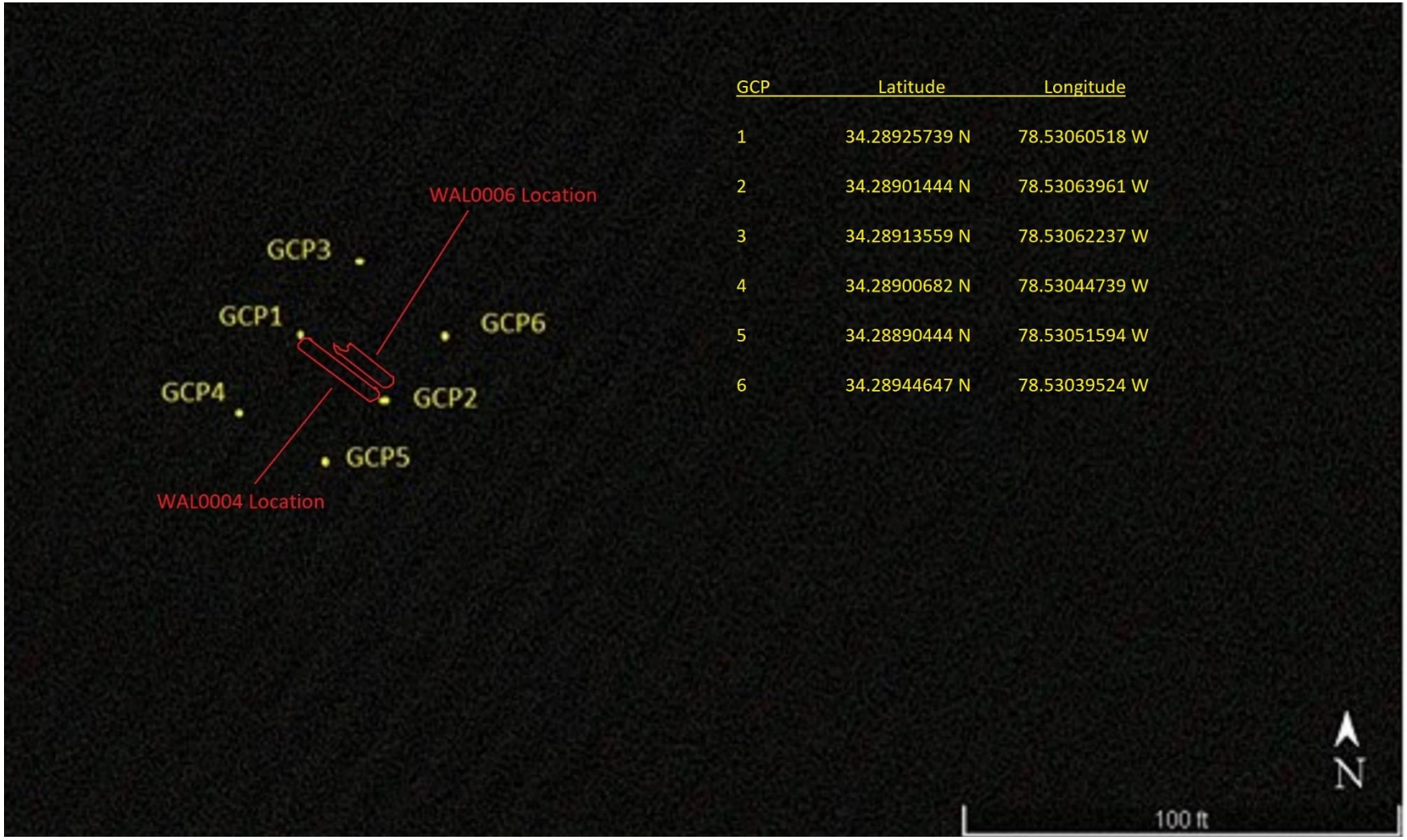


FIGURE 4-35: Google Earth enhanced satellite image of the WAL0004/WAL0006 survey area. Plotted ground control point locations are indicated in yellow. The perimeter of the ground control point locations can be used to establish an avoidance zone and for *in situ* monitoring. (Image by author, 2019).

4.4.4 Survey Analysis and Conclusion

The Lake Waccamaw Prehistoric Canoes Case Study served as a real-life cultural resource management survey of endangered cultural remains. Although the UALR methodology data collection and post-processing procedures were limited to the WAL0004/WAL0006 site, the emergency survey at the mouth of Big Creek emphasised the importance of preserving submerged cultural resources in an environment that subjects cultural materials to rapid deterioration and/or illegal salvage. Apart from thesis objectives pertaining to using the UALR method for geophysical surveying operations, this case study demonstrated the necessity for archaeological surveys to utilise data collection methodologies that are time efficient and accurate. The Trimble SPS855 receiver, Trimble Zephyr 3 rover antenna, Trimble site tablet, RTN/VRS error correction data, and AAE EasyTrak USBL system were capable of producing survey-grade positional accuracy with 95% measurement confidence which satisfies geophysical surveying spatial guidelines.

The Lake Waccamaw Prehistoric Canoes survey determined the UALR methodology to be an effective and efficient method of georeferencing submerged cultural remains. While the general location of WAL0004 and WAL0006 was known, that position was represented by a single latitude and longitude value. Those original coordinates were acquired at the surface without a specific on-site reference point. An iron stake that had previously been driven to into the sediment at the site was not designated as a datum position, but rather a ferrous object to assist in relocating the site with a magnetometer. The advantages of the UALR methodology for this type of cultural resources survey is the ability to georeference a ground control network within a short period of time which can be utilised as an avoidance zone, while also allowing researchers the ability to know site extents within a known underwater positional accuracy and

measurement confidence values. Furthermore, this case study demonstrated the ease of use in which the UALR methodology was applied to a baseline-type survey in a zero-visibility underwater environment which is common throughout the world in nearshore and riverine locations. These types of underwater conditions are prevalent in locations where submerged cables and pipelines are connected to shore-based junctions. These junction areas are part of geophysical survey corridors which require data acquisition by either onboard sensors and/or diver documentation. The results of this case study indicate in the event diver site reconnaissance and mapping is required for supplementing geophysical survey sensor data, the UALR methodology is an accurate and efficient underwater positioning technique which can be used to provide spatial data for archaeological data collection practices.

4.5 Rose Hill Wreck Site Case Study (August 2019)

4.5.1 Introduction

The Rose Hill wreck site survey was the second post-hurricane assessment of coastal North Carolina submerged cultural remains using the UALR methodology and served as the final case study for this thesis research project. The Rose Hill wreck remains indicate that the vessel was an early-18th century sloop and was considered North Carolina's oldest known shipwreck site until the discovery of the Queen Anne's Revenge in Beaufort Inlet (Wilde-Ramsing et al. 1992:13). The wreck site was discovered in the Northeast Cape Fear River near Castle Hayne, North Carolina, by local recreational divers and reported to the North Carolina Underwater Archaeology Branch (UAB), who in 1992, conducted an archaeological survey of the site (Figure 4-36). Recent Hurricanes Matthew (2016) and Florence (2018) subjected the region to record-level flooding which undoubtedly impacted submerged cultural remains. In addition to storm flooding, the riverbank adjacent to the wreck site has experienced significant modification due to residential development.

The research objectives for this case study included performing a post-hurricane and post-construction survey of the site, then develop an avoidance zone by way of establishing a ground control point network utilising absolute spatial data acquired through the implementation of the UALR methodology. The Northeast Cape Fear River environmental conditions at the Rose Hill wreck site are not favourable for novice divers due to the rapid tidal current and zero visibility. This case study demonstrated the adaptability, but most importantly, the efficiency and accuracy of the UALR methodology in adverse underwater conditions such as those commonly found in tidal riverine environments.

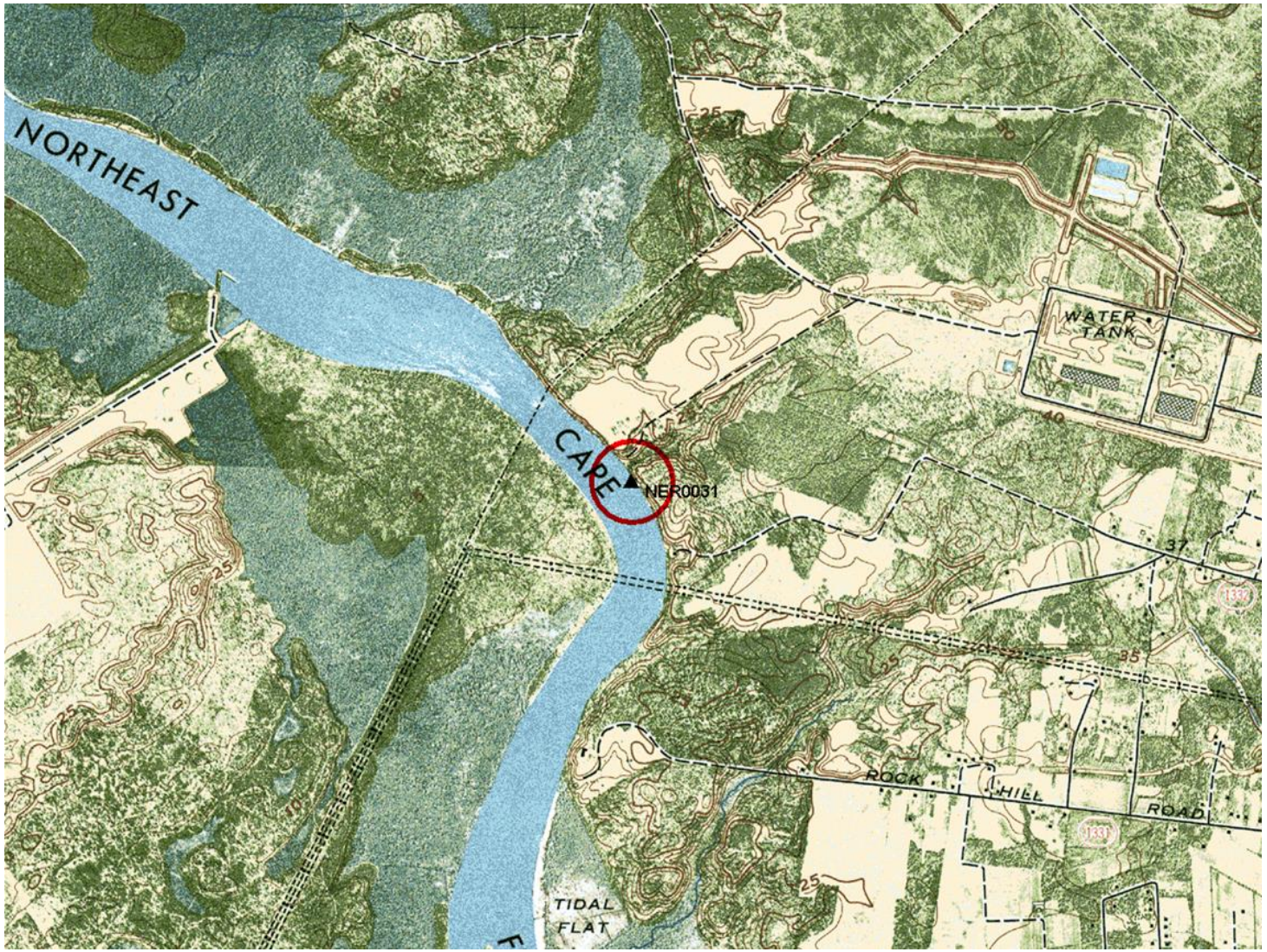


FIGURE 4-36: Topographic map of the Northeast Cape Fear River which indicates the position of the Rose Hill wreck site in UTM coordinates near Castle Hayne, North Carolina, USA. Image courtesy of the North Carolina Underwater Archaeology Branch. Accessed on 13 August 2019.

4.5.2 Survey Assessment and UALR Methodology Application

Fieldwork at the Rose Hill wreck site began in the morning of 27 August 2019, when the author arrived at the boat landing adjacent to the site. In addition to the boat ramp, it was noted that a pedestrian walkway and floating dock had been constructed along the riverbank. The location of the floating dock and two spuds driven into the bottom sediment were initial causes for concern given the proximity to the estimated position of the Rose Hill wreck remains based on the 1992 survey site map created by the North Carolina Underwater Archaeology Branch (Figure 4-38) (Wilde-Ramsing et al. 1992:31). An accurate determination of where the site was located based on previous transit lines was ineffective based on the drastic riverbank modifications; therefore, the author determined the only way to confirm the wreck location and extents was by diver reconnaissance. Although the floating dock was a cause for alarm, its proximity to the site served as an ideal working platform. Following a brief shoreline assessment, the author initiated the assembly of all UALR methodology equipment.

Using the same equipment configuration as the Lake Waccamaw Pier Evaluations and Prehistoric Canoes research case studies, the author utilised a small fold-out table to serve as the central hub for all positioning systems (Figure 4-38). The floating dock presented a stable working platform which experienced minimal movement when compared to positional shifting of a moored vessel. The floating dock was also outfitted with boat cleats which permitted the author to affix the cleat and pole mounts. In addition to the UALR methodology positioning systems, the use of underwater acoustic communications was an operational imperative; therefore, the central hub also served as the communication centre between topside and diving personnel.

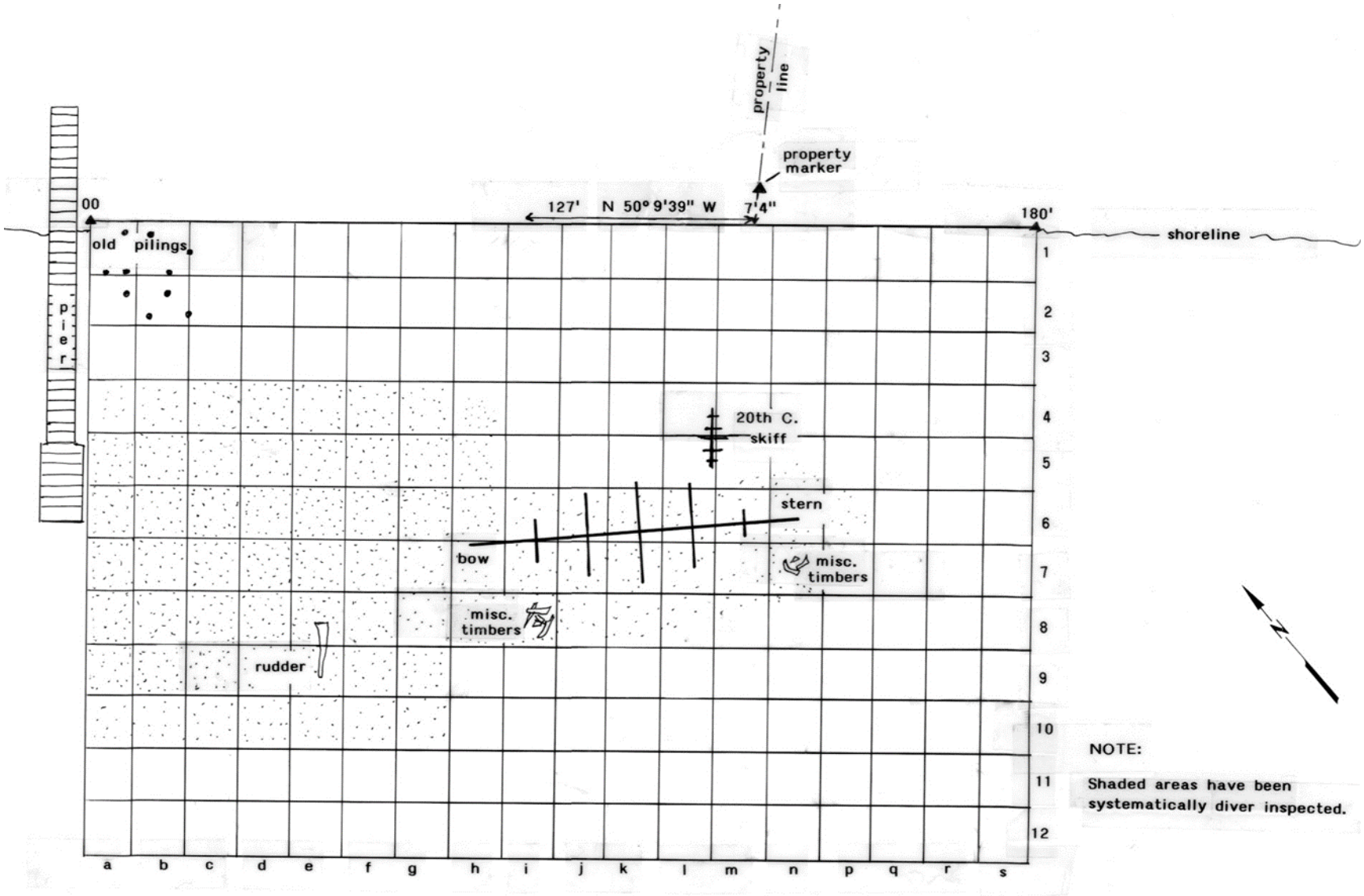


FIGURE 4-37: Site map included in the 1992 UAB survey indicating the position of the Rose Hill wreck in relation to the shoreline and GE pier. Illustration courtesy of the North Carolina Underwater Archaeology Branch. Accessed 10 August 2019.



FIGURE 4-38: UALR methodology underwater positioning systems arranged on the fold-out table on the floating dock. This area served as the central hub for all surveying operations on this day. (Photo by author, 2019).

Prior to the first dive, the author carried out a pre-survey briefing with the UAB staff and volunteer personnel for the purpose of explaining the research aims, planned survey methods, the desired data results, and the manner in which absolute spatial data will greatly assist in situ preservation management plans for the Rose Hill wreck site. Nearly all diving personnel involved with this particular survey had extensive experience diving on the Rose Hill wreck site; therefore, that level of expertise and familiarity with working on this site expedited the pre-survey briefing. Following the briefing, the author and a UAB staff member performed the initial dive reconnaissance to determine where the Rose Hill wreck remains were located and site extents. The Rose Hill wreck remains lie parallel to the riverbank, which has previously allowed divers the ability to quickly locate the wreck site. Using this information, the author and UAB staff diver entered the Northeast Cape Fear River at the boat ramp and proceeded into the river perpendicular to the outgoing tidal current. Although visibility was severely limited and a strong current present during tidal cycles, divers were able to orient themselves using either an underwater compass and/or water flow direction. Within a few minutes of initiating the dive, the divers located the wreck site and set up fiberglass tapes for on-site transit.

The initial dive assessment indicated that the wreck site has suffered increased deterioration, most likely due to storm flooding and the deposition of natural debris. The UAB staff diver noted a change in specific site features that were undoubtedly repositioned since the previous UAB site assessment a few years prior. The most prevalent site feature was the ballast pile, which included various pieces of wooden vessel remains. At the downriver extent of the ballast pile, the author noted the outermost floating dock spud was driven into the bottom sediment less than 1 m from the ballast stones. The probability the spud installation process damaged Rose Hill wreck remains is likely, but could not be determined during this survey.

Verification of wreck remains in this location requires a bottom sediment disturbance permit and extended survey time, both of which were not available for this case study.

Following the conclusion of the first dive, the author consulted with the UAB staff to use the ballast pile as the basis upon which to establish the ground control point network. Using the same steel rods as those on the Lake Waccamaw Prehistoric Canoes case study, the author and UAB staff commenced building the ground control network in a similar block pattern used for the Prehistoric Canoes survey. The ground control point network consisted of six targets; two control points were positioned at the ballast pile linear extents, whereas, the additional points were driven 9 m to either side of those initial control points maintaining a 90º offset to the ballast pile. Constructing the ground control point network required considerable caution not to foul the fiberglass tapes on natural debris, and the associated weight with the steel rods and tools increased the physical exertion in the unrelenting tidal current. Surface markers were attached to each ground control point; however, the rapid water movement prevented the markers from reaching the water surface with some exception during slack tide.

Subsequent to establishing the ground control network, the author powered up all UALR methodology positioning systems and underwater acoustic communication equipment. The author acted as the sonar operator throughout the data collection process and UAB staff alternated carrying the USBL transponder to each ground control point location. Satellite error correction data was provided by the North Carolina Geodetic Survey (NCGS) RTN/VRS service via mobile WIFI. For surveying operations in this region of North Carolina, the author connected to the NCGS reference station in Castle Hayne identified using the station code NCCH, which was located 7.8 km from the Rose Hill wreck site. The short baseline distance between the NCGS reference station and survey location increased the real-time positional accuracy and

dilution of precision of satellite data. Given the physical location of the Trimble Zephyr 3 rover antenna in relation to the riverbank, the author noted the possibility of limited satellite visibility due to tall trees lining the shoreline. Real-time monitoring of orbiting satellites and geometric dilution of precision values of 1.6 and lower indicated adequate satellite visibility. Throughout surveying operations, satellite data logging was activated for post-processing using Trimble CenterPoint RTX for post-survey analysis.

Utilising the research standard 5-minute data collection interval period, the underwater acoustic data logging process extended for a total of one hour and twenty-six minutes (1:26). A few ground control points were allocated more time due to garbled underwater acoustic communication between the sonar operator and diver. While this may have increased the total diving bottom time, it similarly increased the number of measurements to be calculated for an averaged ground control point position. Given the shallow operational depth at the Rose Hill wreck site, all divers remained within no-decompression limits which greatly reduced the possibility of any diving related illness or injuries. Despite the unfavourable diving conditions at the Rose Hill wreck site, the UALR methodology was demonstrated as a streamlined and efficient means of acquiring subsurface spatial data otherwise not possible using traditional methods.

During the initial data collection process of GCP 1, the author noticed major fluctuations in acoustic ranging information. Initially, the author checked to see if the acoustic signal was blocked by the floating dock spud but then noticed the USBL console was operating on a low battery. This power resulted in weakened acoustic signal transmission, which negatively affected underwater acoustic ranging calculations. Using a Honda 2000 portable generator, the author activated the external power source and acoustic signal transmission and ranging calculations

were immediately corrected. In spite of this, the author decided to recollect the spatial data at this location using an additional 5-minute interval. The inclusion of this information is an important reminder regarding the need to constantly monitor all underwater positioning systems to ensure optimal signal transmission and reception which directly affects the quality of spatial data. Calculating the potential error of the weakened acoustic signal was not possible; however, it can be assumed the margin of error would very likely have been outside the established spatial data parameters for this thesis. Following the data collection process, the ground control network was disassembled and transported back to the boat ramp. Underwater positioning equipment was quickly broken down and stowed for transport. At the conclusion of the fieldwork survey, the total time on the Rose Hill site was less than 10 hours, in which all UALR methodology procedures were performed using a relaxed, yet constant pace. UAB staff and volunteer personnel had no prior experience using the UALR methodology or associated positioning systems preceding this case study research; however, the simplistic and efficient methodology design was easily understood while providing quality spatial information.

4.5.3 UALR Spatial Data Processing and Analysis

Data post-processing was carried out the following day, in which the author produced results comparable to that of the Lake Waccamaw Pier Evaluations and Prehistoric Canoes case studies (Figures 4-39 – 4-41). The averaged absolute coordinates for each ground control point position were documented and emailed to the UAB for updating the Rose Hill wreck (NER0031) site file and for future preservation efforts at this location (Table 4-4) (Figure 4-42). The survey-grade absolute spatial data can be used for establishing an effective avoidance zone in an effort to prevent incidents similar to that of the floating dock spud driven in close proximity to vessel remains. According to conversations with the residential developer, additional marine



Post-Processing Service Based on RTX Technology

TrimbleRTX.com

Contributor:	matthew@thompsonmaritimeconsulting.com
Reference Name:	24642390.T02
Upload Date:	08/30/2019 15:33:52 UTC
Report Time Frame:	
Start Time:	08/27/2019 20:05:00 UTC
End Time:	08/27/2019 21:42:30 UTC
Observation File Type(s):	T02
Observation File(s):	24642390.T02
Antenna:	
Name:	TRM55970.00 NONE
Height:	0.001 m
Reference:	Bottom of antenna mount
Receiver Name:	TRIMBLE SPS855
Coordinate Systems:	NAD83-2011 (Auto-detected) & ITRF2014
Tectonic Plate:	North America (Auto-detected)
Tectonic Plate Model:	MORVEL56
Processing Interval:	15 s

Statistics

# Total Obs	# Usable Obs	# Used Obs	Percent
391	391	391	100

Used Satellites

# Total Satellites:	9
GPS:	G02 G05 G10 G13 G15 G20 G21 G24 G29

Processing Results

NAD83-2011 at Epoch 2010.0		
Coordinate	**Value**	**σ**
X	1100530.294 m	0.007 m
Y	-5157245.572 m	0.014 m
Z	3575707.144 m	0.014 m
Latitude	34° 19' 8.37115" N	0.009 m
Longitude	77° 57' 14.56843" W	0.006 m
El. Height	-33.840 m	0.019 m

ITRF2014 at Epoch 2019.65		
Coordinate	**Value**	**σ**
X	1100529.416 m	0.007 m
Y	-5157244.091 m	0.014 m
Z	3575707.025 m	0.014 m
Latitude	34° 19' 8.39783" N	0.009 m
Longitude	77° 57' 14.58995" W	0.006 m
El. Height	-35.256 m	0.019 m

Report Information

Trimble RTX Solution ID:	21763072
Solution Type:	Static
Software Version:	6.1.4.17185
Creation Date:	08/30/2019 15:34:00 UTC

FIGURE 4-39: Trimble CenterPoint RTX post-processing report for satellite data during the Rose Hill wreck survey. Using the floating dock as the working platform greatly assisted in reducing point shifting when compared to a moored vessel that is susceptible to wind and water movement. Report received on the same day via email.

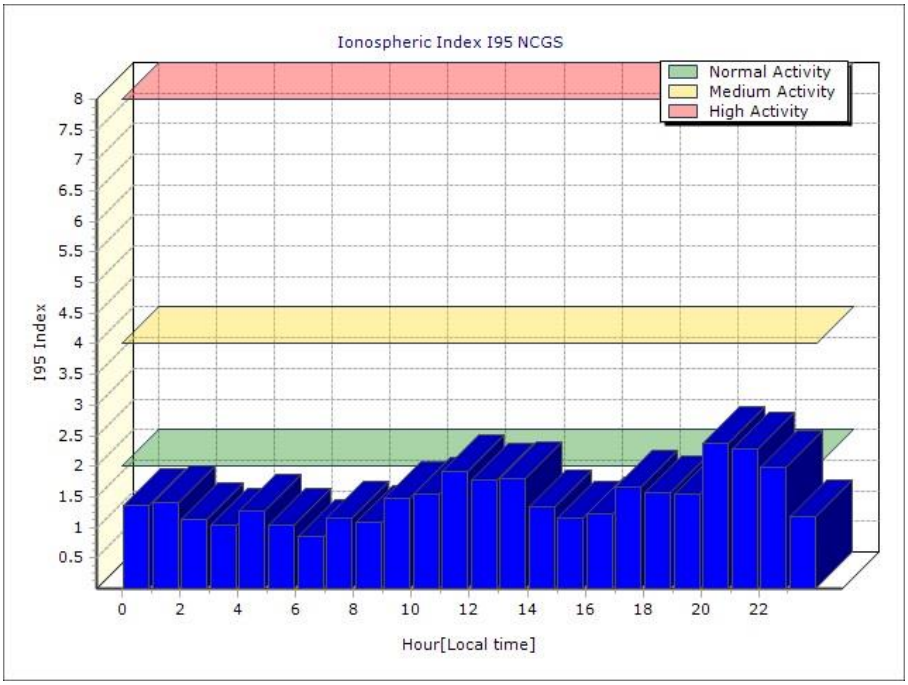


FIGURE 4-40: Ionospheric Index for the Rose Hill wreck survey day (27 August 2019). The chart was provided by the North Carolina Geodetic Survey which is used for determining anticipated inaccuracies in positional accuracy caused by environmental factors. Accessed on 28 August 2019.

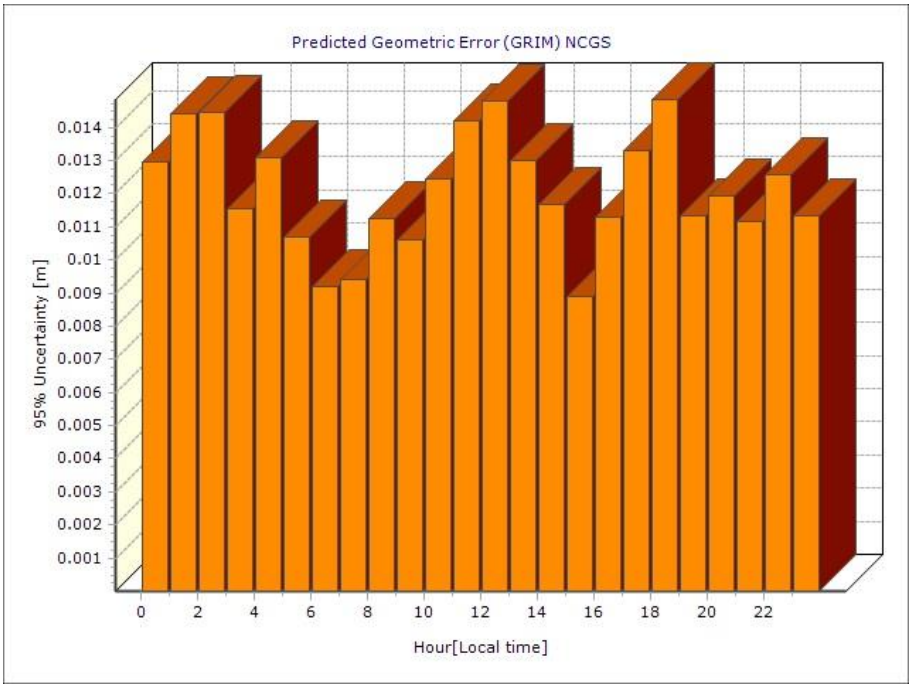


FIGURE 4-41: Predicted geometric error as reported by the North Carolina Geodetic Survey on 27 August 2019. Accessed on 28 August 2019.

TABLE 4-4
GROUND CONTROL POINT INFORMATION

GCP	Minimum	Maximum	Average	1- σ	2- σ
1	34.31901667 N 77.95402667 W	34.31906 N 77.95407333 W	34.31904393 N 77.95405647 W	0.583 m 0.635 m	1.166 m 1.270 m
2	34.31897667 N 77.95387833 W	34.31899833 N 77.95397167 W	34.31898944 N 77.95390384 W	0.318 m 0.729 m	0.636 m 1.458 m
3	34.31899 N 77.954065 W	34.31899833 N 77.95407833 W	34.31899565 N 77.95407203 W	0.123 m 0.183 m	0.246 m 0.366 m
4	34.31908833 N 77.95405833 W	34.31911 N 77.954095 W	34.31909268 N 77.95406642 W	0.355 m 0.432 m	0.710 m 0.864 m
5	34.31898667 N 77.95389667 W	34.31905833 N 77.95385333 W	34.319022 N 77.95386852 W	0.890 m* 0.601 m*	1.781 m* 1.202 m*
6	34.31676833 N 77.953835 W	34.31907167 N 77.95810667 W	34.3190438 N 77.95387887 W	1.733 m* 3.108 m*	3.466 m* 6.217 m*

Notes: * GCP 5 and 6 datasets suffered due to weak signal transmission as a result of a low internal battery. The topside console was connected to external power during the data acquisition process, but the principal investigator elected to continue data collection to demonstrate the effects.

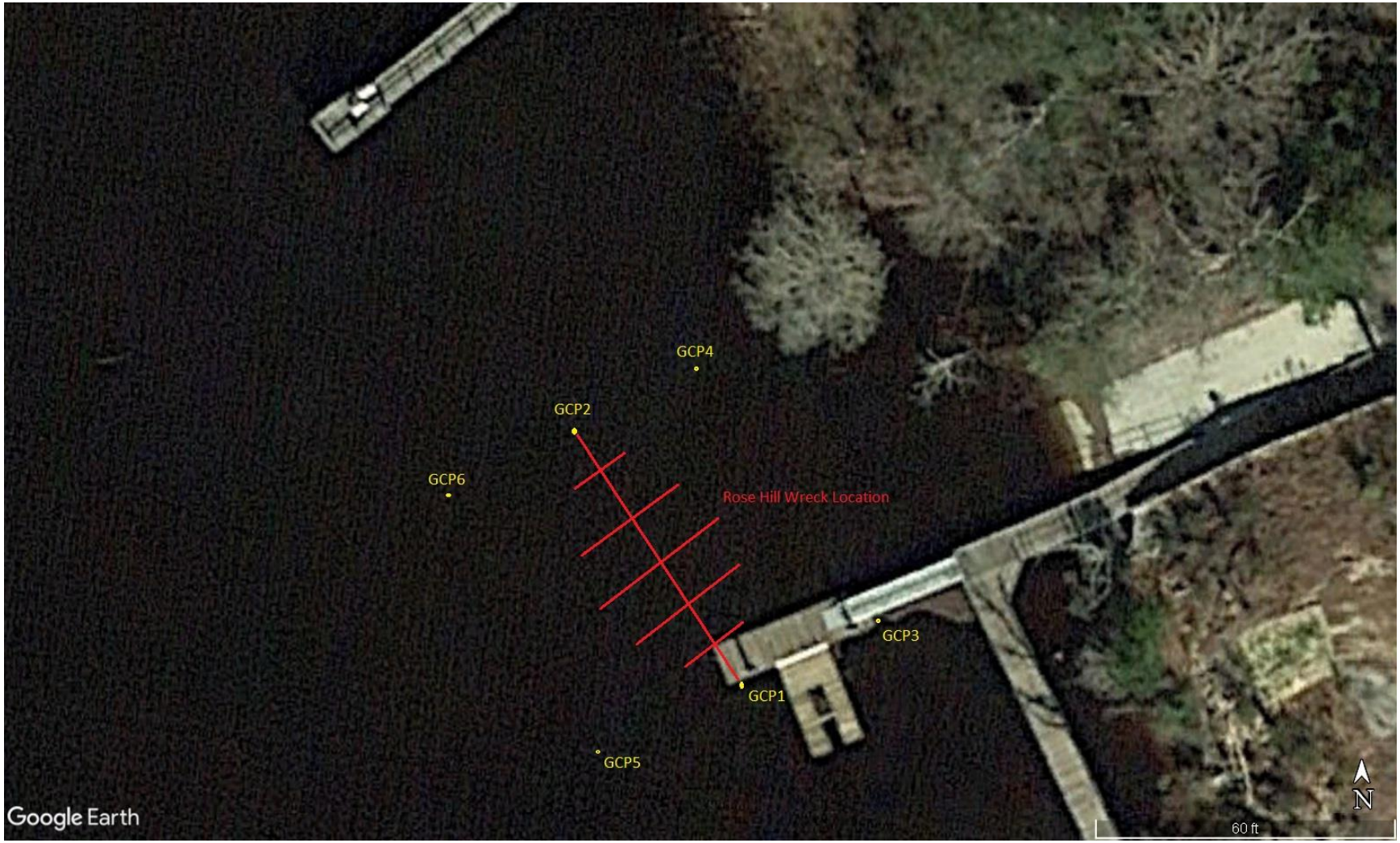


FIGURE 4-42: The Rose Hill wreck site case study area located in the Northeast Cape Fear River. The red shipwreck indication displays the lengthwise extent of the ballast pile. The ground control point locations are displayed in yellow. As discovered during this case study, the current floating dock structure sits directly above the wreck site. (Image by author, 2019).

construction was planned at this location and the updated absolute coordinate information of the vessel remains will greatly assist in ensuring protective measures for preserving the Rose Hill wreck site for continued archaeological research (Burrows Smith 2019, pers. comm.).

4.5.4 Survey Discussion and Conclusion

The Rose Hill wreck (NER0031) is one of North Carolina's most significant shipwreck sites and has offered substantial information pertaining to ship construction technology; yet, much is still to be learned through the continued examination of its physical remains (Wilde-Ramsing et al. 1992). The riverine conditions at the Rose Hill site make it a somewhat challenging wreck for quick documentation; however, this location and wreck site offered a great opportunity to demonstrate the UALR methodology in a real-world environment consistent with most coastal riverine sites commonly found throughout the world. Low visibility and high-speed water movement are surveying conditions archaeologists are routinely subjected to; thus, a method requiring streamlined equipment systems and minimal diver physical exertion is ideal. As the final case study for this thesis, the Rose Hill wreck site survey demonstrated the successful use of the UALR methodology in austere conditions, while providing subsurface absolute positioning information that was both accurate and precise.

The information gathered during this survey will contribute to the continued preservation of the Rose Hill wreck site and serves as a prime example of the manner in which the UALR methodology can be used in conjunction with previous survey information, while offering updated spatial data sets for present and future archaeological research. As the final case study for this thesis research, this field examination verifies the application of the UALR methodology alongside traditional archaeological site documentation techniques. It demonstrated that such techniques can be used to supplement geophysical surveying operations. The efficient acquisition

of accurate spatial information in a volatile underwater working environment using the UALR methodology only furthers the concept of its incorporation into high-resolution geophysical surveys by allowing archaeologists the ability to ground truth specific targets determined to be possible cultural remains.

5.0 Discussion

The objectives of this chapter are to recount information pertaining to the thesis research context and questions, UALR methodology development, case studies and their outcomes, and unexpected findings that the author asserts can contribute to improving archaeological science through the application of the UALR methodology to underwater site documentation. As stated throughout this thesis, the UALR methodology was developed in response to the author's observation of a spatial data problem within traditional and optical archaeological site documentation methods if used as part of geophysical surveying operations. The circumstances in which additional archaeological data collection may be required include surveying in locations which limit the use of towed acoustic and magnetic sensors due to shoreline geography, steep-sloping bottom sediment topography, obstructions such as fishing gear, and follow-up archaeological significance investigations of vessel remains and/or paleolandscapes suspected of having underwater cultural heritage. In the event a site requires additional archaeological investigations, archaeologists and other trained personnel need to include absolute spatial data information that can be collected in accordance to geophysical surveying standards and using recommended underwater positioning equipment (Plets et al. 2013; BOEM 2020a, BOEM 2020b, IHO 2020). The UALR methodology is an underwater positioning solution for these types of supplemental archaeological site investigations.

The following subsections examine specific aspects of the UALR methodology as they relate to addressing the research questions raised in Section 1.2. Section 5.1 provides a concise review of the thesis context and the research questions which were posed in direct response to the spatial problem facing current maritime archaeological fieldwork practices. This subsection reviews the information previously discussed in Sections 1.1 and 1.2; however, the re-

examination of this material with a newly-developed perspective on underwater positioning complexities can assist the reader in recognising that there is a spatial problem within the archaeological community and the results contained within this thesis, offer a way for this to be ameliorated. Section 5.2 is the discussion of fieldwork case study results and the manner in which they directed the development of the refined UALR methodology. The information contained within Section 5.2 is presented in a direct format which examines any identified shortcomings in the development and implementation of the methodology and what corrective measures were taken. Section 5.2 concludes with the final prognosis as to whether the UALR methodology is applicable to geophysical surveying activities and what improvements should be considered in the future. This chapter also includes Section 5.3, which discusses the unanticipated findings of this thesis research that specifically pertains to creating general awareness of the spatial problem within maritime archaeological research and how the UALR methodology can be adapted from geophysical surveying applications to universal archaeological use.

5.1 Thesis Context and Research Questions Redux

Chapter 5, as a whole, was written to provide an in-depth discussion of all aspects of this thesis and its contributions to archaeological science; however, without examination of the circumstances which prompted the undertaking of this thesis, the words contained within these pages do not adequately describe the intuitive characteristics of the UALR methodology and how the use of absolute underwater positioning coordinates can hypothetically change archaeological site documentation practices. However, by no means does Section 5.1 once more delve into the complexities of underwater positioning; given, this subject has been thoroughly covered elsewhere in this thesis. Nonetheless, certain points are revisited for reminding the reader of why

this thesis was necessary for improving data collection practices in regards to the need for absolute underwater positioning information for all archaeological datasets. Pursuant to revisiting specific details which set the stage for identifying the spatial problem within maritime archaeological field practices and research, the thesis research questions are once again presented for the purposes of exhibiting how this thesis perceived the spatial problem and the planned course of action to solve that issue.

In review of the spatial problem affecting underwater site documentation, subsurface absolute positioning and its associated complexities are not circumscribed to purely maritime archaeological surveying and data collection practices. The issues we experience in maritime archaeology are shared by most marine sciences and industries which require accurate absolute underwater mapping capabilities (Collins and Baldock 2007:115-118; Niedzwiedz and Schories 2013:155-194). The defence and offshore energy sectors were among the first to tackle the spatial problem by coupling satellite positioning receivers with underwater acoustic ranging systems for vessel positioning, equipment location, and other subsurface tasks (Parthiot and Denis 1993; Singh et al. 1996:59-64; Opderbecke 1997:721-726; Smith and Kronen 1997; Pevronnet et al. 1998:1721-1727; Audric 2004:786-788; Jalying et al. 2004:173-190; Kinsey et al. 2006). As a result of the longstanding and routine use of these technologies, institutions such as the IHO, BOEM, IMCA, and a host of others, now mandate the implementation of specific underwater positioning parameters according to water depth, provide satellite navigation and underwater acoustic ranging equipment requirements, and best practices recommendations for geophysical surveying operations (Plets et al. 2013, IMCA 2017, BOEM 2020b, IHO 2020). Coupled GPS and USBL systems are commonly found onboard all geophysical surveying vessels, and are typically used to calculate the underwater positional layback of towed sensors

such as side scan sonars and transverse gradiometers. This type of underwater positioning equipment arrangement has a proven track record which contributes to the reason why USBL is one of only three generally approved methods for subsurface ranging applications for geophysical surveys and other commercial projects (DNV-GL 2016:106; Fugro 2017; Moran 2021:17-19).

So, where does archaeology fit into this situation? Governing bodies throughout the world have implemented legislation designed to protect underwater cultural heritage and most require geophysical surveying operations to go through a permitting and review process to ensure no cultural sites are inadvertently disturbed. Adherence to permitting regulations is often reviewed by a project archaeologist and the permitting agency in charge, in which collected sensor data is examined for any sign of submerged cultural remains. As discussed in Section 3.4 (see pg. 162), there are a number of reasons in which geophysical survey sensor data may be insufficient for determining if an object is cultural material and/or its level of cultural significance. In effort to fill in this informational gap, an archaeologist may be required to conduct an additional investigation to determine if the object is in fact manmade and if it retains some sort of cultural significance. If this situation occurs within scientific diving depths approved by the permitting agency, an archaeologist can dive on the site and use a variety of site recording methods.

Which site documentation method is used directly depends on the water depth, physical conditions of the marine environment, and available resources at the disposal of the archaeologist. For nearshore surveys in water depths of 4 m or less, the use of a shore-based total station can be used in conjunction with traditional site documentation methods to provide absolute positioning coordinates for datum locations (Green 2004:42). GPS-integrated digital

cameras can be used for shallow-water sites with clear visibility for producing georeferenced images, such as those used for the Pavlopetri survey; however, this type of system is limited for use at the water surface (Henderson et al. 2013:243-256). For deep-water sites that exceed scientific diving depth limitations, ROVs equipped with underwater acoustic tracking systems can provide georeferenced imagery and supplemental sensor data for identifying cultural remains, such as demonstrated on recent archaeological projects on Roman ships in the Black Sea (Pacheco-Ruiz et al. 2018:120-129; Pacheco-Ruiz et al. 2019). But what of the intermediate diving depths that are beyond the operational capabilities of shore-based positioning practices and too shallow for ROV use? These depths can be range between 5 – 100 m, but this may also vary according to scientific diving regulations administered by the permitting agency, such as those published by the U.S. Occupational Safety and Health Administration (OSHA) which limit surface-supplied diving to 220 feet of seawater (FSW) (OSHA 2021). At these intermediate depths, how can archaeologists georeference their datasets by localising ground control point positions using absolute spatial information in accordance with geophysical surveying underwater positioning requirements? For archaeological clearance of a cable route or wind turbine platform, additional archaeological investigations should be able to provide absolute georeferenced data in the form of illustrated site maps, three-dimensional photogrammetric imagery (if possible), and provide coordinates of the site extents in latitude and longitude coordinates for the establishment of an avoidance zone. By doing so, archaeologists fill in the sensor data gaps with supplemental information which assists in the future preservation of the site by informing the geophysical surveyor and permitting agency exactly where cultural materials are located using an established global reference frame.

Circling back to the question from the previous paragraph, how do archaeologists acquire absolute spatial information in these intermediate depths to supplement geophysical surveys? Traditional archaeological and digital photogrammetric data acquisition methods lack the capability to independently produce absolute underwater spatial data, and earlier methods of underwater positioning, such as the floating GPS, are not applicable for use on modern geophysical surveys because they do not satisfy the requisite positioning and equipment specifications (Plets et al. 2013; BOEM 2020b, IHO 2020). The margin of positional uncertainty of a handheld GPS can vary between 3 – 5 m based on its construction components; thus, far exceeding the possibility of acquiring the minimum total horizontal uncertainty (THU) requirement for the least stringent IHO Order 2 (20 m + 10% of the water depth), nor is it possible to calculate the measurement confidence to the required 95% level (Hall et al. 2008; Hussein 2016:162-174; IHO 2020:27). In no capacity is this type of underwater positioning method allowed for geophysical surveying or commercial applications, and the author questions its applicability for use in archaeological surveys and excavations undertaken as part of research projects, given the prominence and proven records of other underwater positioning systems, such as USBL acoustic ranging systems, as presented in this thesis.

In the past, archaeological projects in the intermediate zone relied on the use of a centralised GPS position or transit line intersection over a wreck site for determining a general site location (Wilde-Ramsing 1992). That may be a perfectly acceptable method for relocating a site for recreational diving purposes; however, this is not applicable for modern geophysical surveys or commercial projects. Additionally, past projects may provide a centralised GPS position for the wreck site then include datasets which include relative positioning measurements presented in *X/Y* format. It is possible to convert relative measurements to absolute coordinates,

but the accuracy and measurement precision of the centralised coordinate may be unknown or not documented during the data collection process; thus, the converted values will have an unknown margin of uncertainty and measurement confidence. The author is also aware of a theoretical concept to merge bathymetric and photogrammetric datasets by matching prominent features; however, the accuracy and precision of such overlays is directly dependent on the quality and calibration settings of the data acquisition instruments, pixel resolution and size, appearance of the processed bathymetric and photogrammetric imagery, and the interpretation of the computer graphics technician. Is this a plausible method of georeferencing photogrammetric datasets; absolutely, but only in areas where optical methods can be used to record submerged cultural remains. This may be possible in many places throughout the Mediterranean Sea and other locations with low water turbidity, but nearly impossible for some coastal regions and inland waterways of the United States which have large amounts of suspended particulate in the water column. In regard to geophysical surveying standards, matching bathymetric data with photogrammetry imagery does not satisfy the IHO, BOEM, and Historic England spatial guidelines by providing a 95% measurement confidence level; therefore, the data matching process should not be approved for geophysical surveying applications (Plets et al. 2013; BOEM 2020a, BOEM 2020b, IHO 2020). So, what other known methods currently exist that can provide underwater positioning information that can satisfy geophysical surveying requirements? The short answer is: none. This lack of a standardised underwater positioning practice for maritime archaeological site documentation of the intermediate scientific diving depth range has resulted in what the author refers to as the spatial problem.

Traditional archaeological site recording techniques and digital photogrammetry are vital assets to documenting underwater cultural heritage; yet, the inability for these methods to

produce independent positioning information limits their usefulness for geophysical surveying. Determining if integrated conventional techniques are capable for use in verifying or filling in data gaps from onboard/towed geophysical sensors required a multi-tiered research question. The overall thesis objective was broken down into three discrete, yet associated research questions pertaining to:

1). conventional archaeological data collection methods and the feasibility of underwater positioning equipment integration

2). the preferred underwater positioning system for supplementing commonly-used archaeological data collection techniques

3). and the development of a spatial data acquisition strategy which maximises the performance of the underwater positioning system

The UALR methodology was specifically designed satisfy the above questions by supplementing conventional and digital optical archaeological site recording practices; whilst, using underwater positioning technologies and a data acquisition process which satisfies IHO, BOEM, and Historic England geophysical surveying guidelines.

5.2 UALR Methodology Research Design Fieldwork Review

Following the initial thesis case study at the Rolesville Quarry (pg. 185), the author's research of the spatial problem regarding the inability for traditional archaeological data collection methods to be used in support of geophysical surveys, spurred the momentum to investigate pragmatic solutions. The results of the photogrammetric survey at the Rolesville Quarry site provided the author with an adequate working knowledge as to what would be required to georeference the three-dimensional imagery using absolute coordinates. Although photogrammetry is a trending data acquisition method within the archaeological community, it is restricted to underwater environments with adequate visibility to permit three-dimensional point

cloud generation. The final product of the Rolesville Quarry case study was a detailed three-dimensional model of a sunken airplane. The model was sufficient for identifying what the survey subject was and also additional features that can be used to determine how it was used during its period of operation. While the model was visually appealing, the author determined it was an incomplete dataset simply because there was no spatial information to determine where this sunken airplane was located in space. The Rolesville Quarry case study demonstrated that while this method is certainly capable of documenting archaeological sites with great detail and its end products are useful for interpretational analyses, the absence of underwater positional information determined the photogrammetry survey to be inadequate as a primary data acquisition method. The final product has an incomplete dataset. The result of the Rolesville Quarry case study was not data on a spreadsheet, but the realisation of the need for a supplemental underwater positioning technique impervious of water depth and location, capable of use with both old and new archaeological data collection methods, and able to satisfy stringent geophysical survey spatial standards currently in use throughout the world.

During the preliminary research phase, the author examined various technologies used for underwater navigation and tracking which included both acoustic and inertial motions systems. The author's experience as a professional archaeologist and geophysical surveyor greatly contributed to the decision to primarily focus on the use of underwater acoustics for subsurface positioning. Following the literature review and recommendations from institutions such as BOEM, Historic England, IMCA, and USACE, the author determined USBL ranging systems to be the best suited for supplementing archaeological research as part of geophysical survey operations. In most cases, geophysical survey vessels have USBL equipment onboard for tracking towed acoustic/magnetic sensors, which are likely to be readily available for use in the

event additional archaeological investigations are required. As discussed in Section 3, through consultation with numerous companies, the author decided to use the Easytrak Alpha Portable USBL system produced by Applied Acoustic Engineering, Ltd. (AAE). This system was compatible with the author's Trimble SPS855 satellite positioning receiver, and served as a vital component for UALR methodology development. Of course, other underwater acoustic ranging systems can be used; however, the Easytrak Alpha Portable was the ideal choice for this research and its case studies.

Acquisition of applicable instrumentation was but one part of developing the UALR methodology; which required the design of associated hardware and fieldwork practices to utilise the full potential of both satellite positioning and USBL systems. Although the Trimble SPS855 satellite receiver and AAE Easytrak Alpha Portable USBL system are readily available on the commercial market for purchase, vessel mounting hardware that accommodated both systems operating in unison was virtually non-existent. Research parameters dictated that the GPS antenna and USBL transducer be perfectly in line with a zero offset, which removed the need to calculate the distance between both sensors and unavoidable measurement error. Bearing this in mind, the author designed a pole mounting system which accommodated the GPS antenna at the top of an aluminium pole above the water surface, while the lower extremity was attached to the transducer. The GPS was attached to the pole through the development of a pipe cap with an appropriately sized bolt, and the transducer was attached to the pole by way of an author-designed bracket. Attaching the pole to the working platform required the design and fabrication of the cleat mount, which demonstrated its versatility during case study fieldwork by its use on a variety of working platforms that ranged from an outboard skiff to a floating dock. The combination of off-the-shelf instrumentation, coalesced with a custom-fabricated mounting

solution, resulted in the successful application of both positioning systems with optimal outcomes for each case study.

The development of the UALR methodology data collection procedure, and subsequent information processing, was a linear concept which evolved through case study fieldwork. The use of a ground control network is a commonly used technique for archaeological surveying practices; however, the manner in which subsurface absolute spatial data was collected at each reference point required thorough consideration. Obviously, using a higher number of control points on site greatly contributes to the overall survey accuracy, but if the collected measurements are plagued with egregious margins of positional error, the effectiveness of the survey is diminished. The Marker 39 case study (pg. 202) demonstrated the first successful use of the UALR methodology in an open water setting. The observed positional accuracy of the satellite receiver (0.8 m), and photogrammetric model targets calculated by Agisoft Metashape (± 1.1 m) resulted in an absolute georeferenced three-dimensional image of a shipwreck site. The use of differential-grade satellite positioning combined with a single-point positioning acquisition technique provided underwater positional accuracy within geophysical surveying requirements; however, the author determined that the single-point positioning acquisition technique did not provide an adequate measurement confidence.

Unsatisfied with the positional accuracy and measurement confidence results of the Marker 39 survey, the author reformulated the UALR methodology data collection process to include RTN/VRS error correction services through the addition of enhanced Trimble satellite positioning hardware and software systems. While the Marker 39 retained acceptable horizontal positional uncertainty, the author realised the improved potential of the UALR methodology if using improved satellite error correction services and a better data acquisition technique. In

addition to the improved satellite positioning system arrangement, the author further refined the UALR methodology data collection process by utilising time-window averaging rather than single-point positioning. The time-window averaging process calculates the mean position of logged absolute coordinates collected over a user-specified time period. The author configured the USBL system to have a one second update rate over the data collection period of five minutes; therefore, permitting the acquisition of at least 300 absolute coordinate measurements. The upgraded UALR methodology, equipment, and data acquisition process was examined as part of the Lake Waccamaw Pier Evaluations. The purposes of these evaluations were to test the new equipment and data collection process prior to fieldwork on actual archaeological sites. The improved satellite positioning system, combined with the refined data collection method, produced less than 5 cm positional accuracy and survey-grade dilution of precision 1.8 or less (see Table 3-3. Dilution of Precision Values, pg. 129). Given USBL underwater positional accuracy is based on uploaded GPS positioning data, increasing the positional accuracy and dilution of precision at the GPS level directly improved USBL performance.

The results of the Lake Waccamaw Prehistoric Canoes case study demonstrated the effectiveness of the UALR methodology in a shallow freshwater environment in support of a typical baseline survey with georeferenced datum positions (pg. 244). The limited underwater visibility in Lake Waccamaw prevented the use of photogrammetric surveying techniques; therefore, the author was obligated to utilise a non-optical style survey. In the event additional archaeological investigations are required as part of a geophysical survey, a baseline survey will be one of the “go-to” methods based on its efficiency and accuracy, if properly implemented. It works in adverse underwater environments and is not limited by visibility like photogrammetry and other optical data acquisition methods. The application of the UALR methodology to the

baseline survey by georeferencing each datum position proved to be an effective measure in creating an effective avoidance zone surrounding both prehistoric canoes. Regardless of the shallow freshwater environment, the satellite positioning values were ± 5 cm at the receiver level, and each ground control point location was given an averaged latitude and longitude coordinate value at the mm-level. The averaged waypoints for each datum position were provided to the North Carolina Underwater Archaeology Branch for continued *in situ* monitoring and the planned excavations of both canoes in the near future. As a real-world case study, the collection of this underwater positioning information demonstrates the effectiveness and efficiency of the UALR methodology. The same process can be used for sites with a water depth range from 5 – 100 m, and provide permitting agencies the same underwater spatial information which can be used for *in situ* monitoring, establishing avoidance zones, and better understanding site formation processes.

The Rose Hill Wreck Site case study was the final fieldwork examination analysing the UALR methodology in a real-world environment on a protected archaeological site of significant cultural heritage (pg. 259). The location of the site in the Northeast Cape Fear River is notoriously difficult to work in due to zero water visibility and a very swift tidal cycle. As one of the most important wrecks within North Carolina, the cultural importance of this particular wreck is vital for understanding some aspects of human life during the middle to late 18th century. Unfortunately, the location of this wreck is in close proximity to modern residential development and is at risk of damage due to shoreline construction and the launching of recreational vessels at an adjoining boat ramp. The placement of the ground control points was based on identifying the extents of the ballast pile and measured offsets to ensure the entire site was included in the survey area. The sloping bottom topography of the riverine environment and

the large accumulation of natural debris created a unique challenge in ensuring acoustic signal transmission from the USBL transducer to the beacon at each ground control point location. This was resolved by using a floating dock located literally above the wreck site location which allowed clear line of sight from the transducer to each ground control point marker.

In a somewhat incongruous course of events at the Rose Hill site, the floating dock structure which represents the greatest threat to the wreck site, served as the best possible working platform for conducting the case study. The floating dock was a stable platform from which all equipment systems were affixed and diving operations were launched during the case study. The USBL data results of the UALR methodology data acquisition survey demonstrated that the floating dock structure was in fact built over a portion of the wreck site and the outermost spud was likely driven through vessel remains. It can also be reasonably assumed that the installation process of the floating dock and nearby structures have directly and indirectly damaged the physical remains. The averaged waypoint positions for each ground control point were provided to the North Carolina Underwater Archaeology Branch for establishing a much-needed avoidance zone to prevent further damage to the Rose Hill wreck site. As a listed site on the National Register of Historic Places, this site is to be afforded protections at both the state and federal levels. Now that the site has an adequate avoidance zone which uses absolute coordinate positions, if enforced, the likelihood of further damage is significantly decreased. In regards to the effectiveness of the UALR methodology in application to a baseline study in a riverine environment, the analysed GPS and USBL datasets demonstrated the UALR methodology provided survey-grade positional accuracy and measurement confidence in accordance to geophysical survey standards. Conducting a case study in this particular

environment was not an easy undertaking; however, the UALR methodology performed to desired expectations while maintaining optimal efficiency.

5.3 UALR Methodology Application for General Archaeological Use

Throughout the course of this thesis, the advantages of the UALR methodology and the use of absolute underwater positioning information for general maritime archaeological research became readily apparent. Although the UALR methodology progressed as a bespoke underwater positioning technique for geophysical surveying operations and commercial archaeology, this thesis determines that it is not limited to just that specialized niche within the archaeological community. The realisation of the UALR methodology's applicability to numerous forms of underwater archaeological research was an ancillary by-product; yet, there is the possibility that this research offers a more long-lasting benefit by bringing awareness to the spatial problem and improving data collection processes to resolve that oversight.

Survey-grade positional accuracy and repeated measurement precision were important factors when developing the UALR methodology design, but regardless of its performance, the method can be used on nearly all archaeological projects and for users with varying technical backgrounds. The very best manufactured technologies are only as effective as the people operating them, and if the systems are exceedingly complex, the likelihood of user error is increased. Bearing this in mind, the UALR methodology data collection process is a simplified scheme which limits diver and sonar operator responsibilities to a manageable level that even inexperienced users can quickly learn without requiring in-depth training courses. This ease of operation was made possible through the use of the AAE Easytrak Alpha Portable USBL system which comes with a user manual that provided step-by-step instructions and required no sensor calibration. Other acoustic ranging systems, such as LBL, are increasingly complex; thus,

requiring substantial financial resources and technical expertise for operation. In addition to the cost and complexity of LBL systems, such instrumentation is not practical for 'run of the mill' or even professional archaeological surveys in shallow water depths. The AAE Easytrak Alpha Portable system and 1200 series acoustic beacon are rated for operations to a depth of 600 m, exceeding normal archaeological diving requirements. Although USBL acoustic ranging was the preferred system for this thesis, users may substitute that type of system for LBL ranging if working in extreme depths for increased positional accuracy and precision measurements. The convenience and adaptability of the UALR methodology is what makes it engaging for general maritime archaeological use.

The UALR methodology data collection process design permits its use as a supplemental application to existing archaeological site documentation practices. Its usability on a wide variety of existing archaeological data collection methods is attributed to the streamlined equipment systems required for absolute spatial information acquisition. Conventional and modern digital data collection practices routinely use datum points that serve as the basis for all relative measurements taken on a particular site. The UALR methodology is applicable to these type of surveying practices by georeferencing the datum positions with absolute coordinates; therefore, allowing tape/heading measurements to be converted to latitude and longitude values. A significant advantage for documenting site features with absolute coordinate data is the capability to upload that information to GIS databases for mapping, predictive modelling, and other related applications. Current and future archaeological projects will rely on GIS mapping systems; thus, requiring absolute spatial information of submerged sites. In an effort for maritime archaeological fieldwork practices to adapt to an ever-changing technological world, all data collection methods must be able to provide survey results compatible with electronic databases.

The UALR methodology is capable of bringing traditional archaeological surveying methods into the modern age by allowing the acquisition of absolute spatial data for reference points that can be used in conjunction with relative site measurements. Equally, the UALR methodology can supplement modern optical data collection methods, such as photogrammetry and laser scanning, by georeferencing ground control points, as demonstrated in the Marker 39 case study. The usability and adaptability of the UALR methodology to existing archaeological data collection practices greatly increases their effectiveness by providing the needed absolute spatial data.

6.0 Conclusion and The Future of Underwater Positioning for Archaeological Research

6.1 Thesis Conclusion

The UALR methodology was specifically designed for the purpose of contributing absolute coordinate data to conventional and modern optical techniques; thus, allowing their usage for consideration as primary surveying techniques in compliance with geophysical surveying spatial requirements. In this era of rapid innovation, modern archaeological practises should be capable of adapting to digital interfaces or suffer the consequences of irrelevancy. Traditional, modern optical imaging, and other data collection practises must include absolute positioning information for consideration as primary surveying techniques. All contemporary end products generated through relative positioning measurements should be considered immaterial if presented as the final products of a survey.

The UALR methodology provides archaeologists with an option to supplement their surveys with absolute underwater positioning information. Although the UALR methodology was designed with geophysical surveying standards as the performance requirements, can it be used for general maritime archaeological use? Traditional site documentation practices developed decades ago continue as primary data collection methods which utilise relative spatial information. The application of shore-based positioning systems and supplementary marine remote sensing surveys can provide absolute positional data, but are limited in their use based on site location, project funding, and availability of trained personnel. Modern digital photogrammetry suffers under similar circumstances in that it solely provides an imagery record, with only relative positioning measurements based on site-specific scale bars. As mentioned in Section 3.4 (pg. 162), few archaeological projects attempt to georeference the photogrammetric imagery, and the instrumentation used for those surveys were limited to shallow and clear-water

environments (Henderson et al. 2011:207-217). Apart from those notable exceptions, the majority of maritime archaeological site documentation is without absolute positioning information, thus resulting in a spatial problem which directly influences our effectiveness in producing quality data for cultural resources interpretation and preservation. The absolute coordinate information is capable of updating custodial agency archaeological site files as the spatial data becomes available. Additionally, this type of spatial information is vital for updating GIS databases for continued research and added to electronic navigation charts to warn both commercial and recreational boaters that a protected site is in a specified location. Ultimately, absolute positioning information increases the effectiveness of submerged cultural resources management plans in terms of bolstering the capabilities of custodial agency resources.

In this thesis, the UALR methodology was presented as a supplemental technique for acquiring underwater positioning data in the event additional archaeological investigations are required as part of geophysical surveying operations. The technical feasibility of using the UALR methodology in conjunction with conventional and photogrammetric data acquisition practices is ideal for both archaeologists and geophysical surveyors in terms of equipment and dataset compatibility. Now, archaeological site documentations using both traditional measurement-based surveys and photogrammetry techniques can be performed using survey-grade positional accuracy and measurement precision in accordance with geophysical survey underwater positioning requirements (Green 2004; Smith 2006). The UALR methodology bridges that spatial gap between archaeologists and geophysical surveyors by now allowing both parties to conduct underwater surveying operations using the same absolute coordinate system.

6.2 The Future of Underwater Positioning for Archaeological Research

As the final section of this thesis, the author addresses a series of issues pertaining to the spatial problem within the maritime archaeology community. The subject matter raised in this section is presented in a Question & Answer (Q&A) format which the author believes is the best approach. The direct line of questioning and similarly straightforward answers strike at the core of what the author considers as the prevailing causes for the spatial problem within the maritime archaeology community. Although this information may be considered by some readers as outside the scope of this thesis, the author asserts that this research and the development of the UALR methodology could serve as the starting point for effectuating a change in mindset regarding underwater spatial information within maritime archaeological research. This may be the end of this thesis research, but it should be the beginning of how we as maritime archaeologists approach spatial information as part of our work for interpreting and preserving the past.

We can begin the discussion by examining the prevailing issue; why is the spatial problem absent from general maritime archaeology discussion? Surely, field archaeologists record where their projects take place; however, there seems to be an omission of spatial data information beyond the usual archaeological site indicator overlaid a regional map, or an overall site map which may include prominent site features and a scale bar. As part of the detailed literature review for this thesis of maritime archaeological journals, publications and project websites very few projects were revealed that have a dedicated focus on producing absolute spatial information (see Table 2-6, pg. 95). Those that do have an interest in absolute underwater positioning data are typically deep-water archaeological projects which utilise ROV instruments equipped with underwater acoustic ranging systems and highly-specialised camera systems for

site investigations (Caiti et al. 2010:261-265; Gambogi et al. 2010:257-260). Perhaps the technological sophistication and associated costs of such equipment is considered beyond the resources of the average maritime archaeological project, and therefore the idea of enhanced spatial information is regarded as data reserved for "high-end" or commercially funded archaeological research. While this may have been the case in the previous two decades, satellite positioning and underwater acoustic ranging systems are currently accessible throughout the world and should not be restricted to high-profile projects. A thorough investigation into the commercial availability of technology to provide accurate underwater spatial information and their applicability to the issues under consideration in this thesis revealed a range of readily available solutions from diver positioning systems to equipment used for positioning underwater equipment in the deepest reaches of the oceans (i.e. Blueprint Subsea at https://www.blueprintsubsea.com/divernav/index.php, Subsea Technologies, Inc. at https://www.subseatechnologies.com/, and AAE technologies, Ltd. at https://www.aaetechnologiesgroup.com/applied-acoustics/). The resources and information for including underwater positioning information is readily available for all maritime archaeologists to incorporate into their research.

In addressing why we do not typically see detailed absolute underwater spatial information in most maritime archaeology reports and publications, we have to ask ourselves if this information is indeed important for interpreting past human lifeways and needed for site preservation? Of course, this information is vital to our understanding of the past and site maintenance plans which may include *in situ* monitoring, complex excavations of cultural materials, and preserving sites for future research using improved equipment and methods. As part of those plans, archaeologists should be able to determine site extents with a high degree of

positional accuracy and measurement precision. This ensures the establishment of an avoidance zone is based on ground control points using an established reference frame, such as NAD83, WGS84, or whatever geodetic system is used for that particular region. By doing so, in the event of manmade intervention within close proximity of the archaeological site, the managers of that project will have documented latitude and longitude coordinates of the avoidance zone that are compatible with their onboard navigation systems. Transit lines and tape measurements from a centralised point do not work in these circumstances, and many culturally significant sites have been damaged or destroyed because the avoidance zone was not properly established to include all site extents, such as the Rose Hill wreck site used as a case study for this thesis (see pg. 259). Absolute underwater positioning coordinates offer the best opportunity for custodial agencies to implement preservation strategies for keeping archaeological sites intact, but this type of information is also important in understanding the site formation process. Knowing how a site is decomposing, the shifting of artefacts and other site features, and if external influences are negatively affecting the disposition of cultural materials are vital for all maintenance plans. All of this hinges on accurate underwater positioning information.

Would the publication of detailed spatial information for archaeological sites usher in the possibility of increased treasure hunting activities and increasing the rate of destruction for underwater cultural heritage (Hawkes-Reynolds 2019)? This is a realistic concern that should be considered given the cultural importance of particular sites, especially those that may have valuable cargo. There is the possibility that the custodial agency can maintain a discrete set of underwater positioning coordinates for particular sites, while publishing information which includes spatial information with a much larger margin of error. Similarly, if a culturally significant site is discovered or is suspected of having valuable cargo, an established avoidance

zone should be actively enforced until the conclusion of all archaeological research and placed under a continued protective status. This does not guarantee that the site will not be negatively impacted through potential treasure hunting activities; however, the protection of a wreck site is directly dependent upon the resources of the custodial agency. Another realistic aspect archaeologists need to consider is that no matter the lengths at which we go to conceal the location of archaeological sites, experienced and savvy treasure hunters already know where to look.

In regards to the general absence of absolute underwater positioning information within maritime archaeological research, what type of image are we presenting of ourselves to related disciplines, specifically to the geophysical surveying industry with whom we work side by side? Based on the author's experience as both a professional archaeologist and geophysical surveyor onboard offshore surveying projects, the general impression of archaeologists associated with geophysical surveys has been that of mixed reviews. Archaeologists are frequently regarded as "obstacles" due to delays in interpreting and analysing targets, determining cultural significance, and providing archaeological clearance to the survey area. It is the opinion of the author that some of these delays are generally caused by the archaeologist's indecision as to what an object is, and that they do not want to incur potential liability for damaging underwater cultural heritage. The extended periods of time required for the archaeologist to determine if a site should be further investigated or not, results in growing frustration and operating costs for the geophysical surveyors and their clients.

Does the maritime archaeology community, specifically the commercial sector which participates in offshore projects, have a professional obligation to adapt our practices to maintain a pace in accordance with other marine industries? Absolutely. If maritime archaeologists are

required by legislation to serve important roles within offshore projects, we should be required to operate under the same spatial standards and data acquisition practices as the geophysical surveyors. Furthermore, archaeologists who are registered members of professional organisations are often required as part of their membership duties to adhere to a code of ethics and professional standards which actively promote continuing education and training using the latest technologies and methods within their respective specialisations. For example, in the United Kingdom, the Chartered Institute for Archaeologists (CIfA) provide its members with the *Code of conduct: professional ethics in archaeology* publication which explicitly requires its members to adhere to the following principles and associated rules:

> Principle 1, Rule 1.5:
>
> *A member shall not undertake archaeological work for which they are not adequately qualified. A member shall have regard to their skills, proficiencies and capabilities and to the maintenance and enhancement of these through appropriate training and learning experiences. A voting member shall ensure that they carry out a minimum of 50 hours of continual professional development activity in any two-year period and shall be able to provide evidence of this to the Institute on request and according to such procedures required by the Board of Directors. A member shall inform current or prospective employers or clients of inadequacies in their qualifications for any work which may be proposed; they may of course seek to minimise such inadequacies by acquiring additional expertise, by seeking the advice or involvement of associates or consultants, or by arranging for modifications of the work involved; similar considerations apply where a member, during the course of a project, encounters problems which lie beyond their competence at that time. They should ensure in all cases that adequate support, whether of advice, personnel or facilities, has been arranged for any historic environment project in which they may become involved* (CIfA 2021:4.
>
> Principle 1, Rule 1.15:
>
> *A member shall work towards the development and continuous improvement of the profession by contributing to, and challenging, existing knowledge and professional practice where appropriate, by devising and validating new techniques, by ensuring that others benefit from the member's own experience and knowledge and by using their best endeavours to foster a culture of continuous professional development and career progression* (CIfA 2021:5).

Principle 3, Rule 3.3:

> *The member shall keep themselves informed about developments in their field or fields of specialisation* (CIfA 2021a:6).

In addition to the CIfA code of ethics, this organisation also provides it members with numerous professional standards and guidance publications which pertain to both terrestrial and maritime archaeological projects which are available online to the public using the provided link (https://www.archaeologists.net/codes/cifa). As part of these standards and guidance publications, the CIfA recognises that professional archaeology work is continuously evolving, and encourages its members to participate in updating the CIfA standards to modern specifications (CIfA 2020:3). Furthermore, the CIfA standards and guidance publications apply to both professional and unpaid (volunteer) archaeologists, and as members of the CIfA, are obligated to meet these standards (CIfA 2020:3). In the United States, the Register of Professional Archaeologists (RPA) operate under similar criteria in which they publish *The Register Code of Conduct* and *Standards of Research Performance* that state the requirements for professional behaviour and methods (https://rpanet.org/code-and-standards) (RPA 2021a; RPA 2021b). Similar to the CIfA, the RPA code of conduct include specific rules pertaining to the archaeologist's professional responsibilities:

Code 2.1-b:

> *Stay informed and knowledgeable about developments in her/his field or fields of specialization* (RPA 2021a:2).

Code 3.1-c:

> *Recommend to employers or clients the employment of other archaeologists or other expert consultants upon encountering archaeological problems beyond her/his own competence* (RPA 2021a:2).

The UALR methodology presented in this thesis is an example of an effort to modernise and improve traditional archaeological and digital photogrammetric methods to professional surveying standards, and done in the same spirit as required by both the CIfA and RPA organizations. This method can potentially allow project archaeologists another option for additional site investigations for the purposes of analysing targets for cultural significance and authorising route clearance. Using this method, archaeologists can also conduct thorough follow-up site investigations and provide detailed datasets using the same coordinate reference system as geophysical surveyors. There will be no more guesswork in determining if a particular site feature is the same as that depicted in sonar imagery; whilst, the latitude and longitude coordinates will provide that verification with an overall positional accuracy of 1 m or less. It is these types of efforts that will increase maritime archaeologists' capabilities as a critical part of geophysical surveys, and by doing so, improve our standing throughout the offshore industry and further our objectives for preserving underwater cultural heritage.

In regards to general maritime archaeology and the use of absolute underwater positioning, should the entire discipline use absolute underwater coordinates, and if so, to what level of spatial standards? Georeferencing archaeological data, whether they are illustrated site maps or three-dimensional photogrammetric models, should have absolute spatial information to a known margin of positional accuracy and measurement precision. This thesis discussed the many benefits of absolute positioning information for geophysical surveys, establishing avoidance zones, better understanding of site formation processes, documenting excavations, and others; but, is it necessary for all maritime archaeology? If the maritime archaeology community, as a whole, wants to continue as a scientific discipline, it has no choice but to implement absolute spatial standards for fieldwork research. We cannot pride ourselves on incomplete

research. Absolute spatial information should be required for all archaeological projects operating under permits issued by custodial agencies for fieldwork on protected underwater cultural heritage sites.

Perceptibly, most archaeologists place some level of significance on spatial information, though it may be relegated to where site features are located and their dimensions. For many projects and permitting authorities, tape measurements, site illustrations, and photographs of wreck sites with a centralised GPS point may satisfy survey requirements; however, that approach to site documentation and mapping has resulted in the damage and loss of many significant wreck sites such as the CSS *North Carolina* (Watts 1999), the Hilton Bridge Wreck (Watts 1994), and the Rose Hill wreck site (Wilde-Ramsing 1992). These wrecks sites were damaged and destroyed by marine construction activities that did have underwater positioning information of the site extents; thus, the dragging and placement of construction equipment on the bottom inadvertently impacted each of the vessel remains. These types of accidents are avoidable using updated underwater positioning systems and techniques, but only if absolute spatial information for entire site extents is provided to marine construction firms and enforced by custodial agencies. That stated, is it possible for the maritime archaeological community to establish commonly accepted spatial requirements for surveying activities that can be adopted by all permitting agencies, academic institutions, and private sector archaeologists? The establishment of a discipline-wide set of spatial data requirements is theoretically plausible; however, this would entail a massive undertaking of cooperation between multiple entities. As with many of the technologies currently used for maritime archaeology research, such as side scan sonars, magnetometers, etc., the author expects that the spatial standards that currently exist

within geophysical surveying guidelines will eventually trickle down to general use. It is simply a matter of time and the desire for archaeologists to improve their research capabilities.

Despite the assumption that implementing a standardised set of absolute spatial guidelines for maritime archaeology research would be an arduous task, we should review the manner in which terrestrial archaeologists incorporated satellite positioning information into their fieldwork methodologies. Our terrestrial counterparts quickly adopted satellite positioning technology and professional surveying practices over two decades ago, for the purpose of improving their research capabilities and data results (Barratt et al. 2000:133-143; Goossens et al. 2006:745-755). This change was not necessarily facilitated just by the accessibility of the positioning equipment, but the awareness that such information was necessary if they wanted to better protect cultural heritage. Today, we see the use of CAD and GIS software programs for archaeological mapping and planning activities, and all of this is made possible through the application of absolute positioning. The use of absolute positioning and these software programs are commonplace, and more importantly, required for terrestrial projects operating under commercial and scientific permits. Of course, this change in archaeological practice took time and considerable effort from terrestrial archaeologists, but what reasons exist that would prevent maritime archaeology from following a similar developmental path? The only difference is the working environment and the associated complexities with underwater positioning; yet, this thesis demonstrated they are easily overcome using the proper equipment and data acquisition methods in accordance with specific guidelines.

It is an understatement to say that this thesis advocates the importance of absolute spatial information for maritime archaeology for all levels of fieldwork; yet, what strategies could be used to promote the inclusion of this type of data for general use? The author asserts the answer

is simple, and the same answer as to why absolute spatial information is generally absent from maritime archaeological reports: awareness. The lack of awareness of the spatial problem directly contributes to why it has not been solved despite the availability and proven record of underwater acoustic positioning technologies. In fact, the author would further the argument by stating most graduate-level maritime archaeological students do not know that such technology exists, or are unfamiliar with how it works. This is easily solved by incorporating existing and developing underwater positioning technologies into academic curricula, and it should be taught in conjunction with other field research methods and the description of what equipment is used for data acquisition. In doing so, new maritime archaeologists are made aware the technologies exist and can devise ways to maximise their use for the creation of optimal datasets. This does not necessarily mean academic institutions are required to keep USBL equipment as part of their inventory and provide hands-on instruction; however, by simply introducing the students to literature and reports which utilised this technology, academic programs can facilitate an understanding of how USBL works and how the students can benefit from its use.

Subsurface positioning and target localisation will undoubtedly improve with the development of newer underwater acoustic ranging systems and enhanced satellite navigation. Maritime archaeology currently exists in an exciting period of rapid innovation which certainly outpaces our abilities to modify field surveying techniques; however, archaeological science should always be accepting of newer systems that better our capabilities in interpreting past human lifeways. The author encourages archaeologists to explore acoustic ranging technologies and other underwater positioning systems currently in use, and others currently under development for the offshore energy and defence industries. All relevant and capable systems are generally designed for use by those specific sectors; therefore, maintaining an awareness of what

technologies are commonly in use by these groups will be beneficial for adapting those systems for archaeological research aims. Maintaining working relationships with the energy and defence sectors, including the manufacturers of their equipment, is the best way forward in possibly developing dedicated underwater positioning systems that are both pragmatic for archaeological surveying and financially permissible for all levels of maritime archaeology research.

The USBL system used for this thesis is readily available for hire on a daily, weekly, or monthly basis as required for a project schedule; however, this thesis demonstrated the efficiency in which absolute underwater positioning data was acquired therefore limiting the amount of time a project needs that equipment on site. By doing so, the underwater positioning equipment can be rented at a cost that is comparatively less than digital total stations, side scan sonar, marine magnetometers, and other data acquisition systems commonly used for maritime archaeological research. Rental companies are located throughout the world, who regularly supply geophysical surveying firms with these types of underwater positioning systems can be found using an internet search based on the area of operation. The barriers of adoption of underwater positioning systems for general maritime archaeological use are virtually non-existent in modern times. This thesis recognises the importance of archaeological diving investigations in support of geophysical surveys and marine infrastructure; however, the prior methods used to calculate underwater positioning for supplementing underwater data were limited by proximity to shoreline, working depth, water visibility, and accuracy. The UALR methodology solves the underwater spatial problem by using the right equipment and a systematic approach which is simple, replicable, adaptable, and not limited to only technical experts. Through the publication of this research, and other projects which utilise absolute positioning for underwater datasets, the author anticipates a gradual paradigm shift with a greater

focus on spatial issues. This trend will allow us as a science and professional industry to continue upwards and strive for the next step on our ladder of excellence. The archaeological community should always be accepting of new ideas, technologies, and practices in effort to better ourselves for preserving the past for the future.

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Appendix I

IHO Standards for Hydrographic Surveys

INTERNATIONAL HYDROGRAPHIC ORGANIZATION



IHO STANDARDS FOR HYDROGRAPHIC SURVEYS

6th Edition

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Note: Annexes B, C and D will be removed from this document when the information contained in them is fully included in IHO Publication C-13, *Manual on Hydrography*

PREFACE

This Publication (S-44) defines the standard applicable to hydrographic surveys and takes its place amongst the other International Hydrographic Organization (IHO) publications, designed to improve the safety of navigation, knowledge and protection of the marine environment.

Formal discussions on establishing standards for hydrographic surveys began at the 7th International Hydrographic Conference (IHC) in 1957. The 1st edition of S-44 entitled "Accuracy Standards Recommended for Hydrographic Surveys" was published in January 1968. Since then, the IHO has endeavoured to update this standard regularly to keep pace with the existing technologies and methods. Four successive editions have thus been released since the 1968 original issue: the 2nd edition was published in 1982, the 3rd in 1987, the 4th in 1998, and finally, the 5th edition in 2008. The point of these being to maintain continuity of the original idea throughout successive changes.

By Circular Letter (CL) 68/2016 of 20 December 2016, the IHO established a Hydrographic Surveys Project Team (HSPT) tasked with updating the standard and in its CL 26/2017 further defined the composition of the team. The HSPT tasks consist of three goals: firstly, evaluate the 5th edition of the standard; secondly, prepare an S-44 6th edition; and finally, if necessary, set up a permanent Working Group tasked with addressing all hydrographic surveys concerns. The HSPT team was comprised of representatives from the IHO Member States, observers from international organisations (IFHS and FIG), other expert contributors, and the Secretariat of the IHO.

Hydrographic technologies and requirements are continually evolving, as is the expanding community of users. While hydrographers logically follow these changes, the S-44 standard needs to continue to evolve in order to remain the international reference for hydrographic surveys.

In the creation of this new edition, the IHO Hydrographic Surveys Project Team liaised with the hydrographic community and received input from IHO stakeholders (including industry). This input was crucial to express the needs of the community and drive the updates of this edition, while remaining committed to the IHO mandate.

INTRODUCTION

This publication aims to provide a set of standards for hydrographic surveys primarily used to compile navigational charts essential for the safety of navigation, knowledge and the protection of the marine environment. It specifies the **minimum standards** to be achieved based on the intended use. Where and when necessary, hydrographic offices or organisations are encouraged to define more stringent or specific requirements as national or regional realisations of the standard. This publication does not contain procedures for setting up equipment, conducting the survey, or for processing the resultant data. IHO Publication C-13, *Manual on Hydrography*, should be consulted for information on those topics (downloadable from the IHO homepage: www.iho.int).

In this edition, a new, more stringent Exclusive Order has been introduced. The use of Exclusive Order should be limited to areas with exceptional conditions and specific requirements. The other orders for safety of navigation surveys have kept the same names, but their interpretation has changed from the previous edition due to the introduction of the bathymetric coverage concept. Special Order now explicitly requires full bathymetric coverage. Furthermore, the orders have been divided into requirements above and below the vertical datum.

This edition aims to encourage the use of S-44 for purposes beyond the safety of navigation. It introduces the concept of a Matrix of parameters and data types to define realisations of survey standards and specifications. This Matrix alone is not a standard. It should be considered as a reference to specifying dedicated surveys, as appropriate, and to provide a tool for a broader classification of surveys. It is, by design, expandable and can evolve in future S-44 versions. Annex A provides guidance on how the Matrix can be used for specification and classification of surveys.

S-44 vocabulary has been revised in order to more closely align with references typically used in metrology (e.g. Guide to the expression of uncertainty in measurement). Horizontal positioning standards for aids to navigation have been revised and standards on their vertical positioning have been added. Emphasis has been placed upon the main components of hydrographic surveys while being technology independent.

While the hydrographic surveyor may have some flexibility on how to conduct survey operations, it remains the decision of the responsible authority on whether the standard has been achieved. Furthermore, the surveyor is an essential component of the survey process and must possess sufficient knowledge and experience to be able to operate the system to the required standard. Measuring this can be difficult, although surveying qualifications may be a basis in making this assessment. Available education in this field is (amongst others) Category A and/or B educational programme formed by International Board on Standards of Competence for Hydrographic Surveyors and Nautical Cartographers (IBSC), International Hydrographic Organization (IHO), International Federation of Surveyors (FIG), International Cartographic Association (ICA).

The information contained in annexes B, C, and D provide some guidance on quality control, data processing, and considerations for gridded bathymetry. These Annexes are not an integral part of the S-44 Standards and will be removed when the information therein is fully incorporated into IHO Publication C-13, *Manual on Hydrography*.

Note: The publication of this new edition of the standard does not invalidate surveys, or the safety of navigation products based on surveys conducted in accordance with previous editions.

GLOSSARY

Note: The terms defined below are those that are most relevant to this publication. A much larger selection of terms is defined in IHO Special Publication S-32 (Hydrographic Dictionary) and should be consulted if the required term is not listed here. If a term listed below has a different definition in S-32, the definition given below should be used in relation to these standards.

For the purpose of this Publication the words:

must: indicates a mandatory requirement; **should**:

indicates a recommended requirement; **may**:

indicates an optional requirement;

Terms that are only used within the Annexes are not included in this Glossary; these are defined within the Annexes.

Bathymetric coverage: Extent to which an area has been surveyed using a systematic method of measuring the depth and is based on the combination of the survey pattern and the theoretical area of detection of the survey instrumentation.

Confidence level: Probability that the true value of a measurement will lie within the specified uncertainty from the measured value.

Correction: Compensation applied to data to adjust for an estimated systematic effect.

Error: Difference between a measured value and the correct or true value. Errors can be categorised as systematic or random errors.

Feature: Any object, whether natural or manmade, which is distinct from the surrounding area.

Feature detection: Ability of a system to detect features of a defined size.

Feature search: Extent to which an area has been surveyed using a systematic method of identifying features.

Metadata: Data describing a data set and its usage.

Random error: Noise within a measurement caused by factors which vary between measurements and cannot be controlled but can be quantified by statistical means.

Reduced depth: Observed depth including all corrections related to the survey, post processing, and reduction to the appropriate vertical datum.

Significant Feature: Feature that poses a potential danger to navigation or object one would expect to see depicted on a nautical chart or product.

Systematic error: Component of measurement error that remains constant or varies in a predictable manner.

Total horizontal uncertainty (THU): Component of total propagated uncertainty (TPU) calculated in the horizontal dimension. THU is a two-dimensional quantity with all contributing horizontal measurement uncertainties included.

Total propagated uncertainty (TPU): Three dimensional uncertainty with all contributing measurement uncertainties included.

Total vertical uncertainty (TVU): Component of total propagated uncertainty (TPU) calculated in the vertical dimension. TVU is a one-dimensional quantity with all contributing vertical measurement uncertainties included.

Uncertainty: Estimate characterising the range of values within which the true value of a measurement is expected to lie as defined within a particular confidence level. It is expressed as a positive value.

Underkeel Clearance: Distance between the lowest point of the ship's hull and the seabed, riverbed, etc.

CHAPTER 1 CLASSIFICATION OF SAFETY OF NAVIGATION SURVEYS

1.1 Introduction

This chapter describes the orders of safety of navigation surveys which are considered acceptable by hydrographic offices or authorities to generate navigational products and services that allow surface vessels to navigate safely. As requirements vary with water depth, geophysical properties, and expected shipping types, five different orders of survey are defined; each designed to cater to a range of needs.

The five orders are described below along with a description of the intended area(s) of usage. The minimum standards required to achieve each order (Table 1 and Table 2) along with a new tool for enhancing and customising these orders (Specification Matrix) is presented in Chapter 7.

The hydrographic offices or authorities responsible for acquiring surveys should select the order of survey that is most appropriate for the requirements for safety of navigation in the area. A single order may not be appropriate for the entire area to be surveyed and, in these cases, the different orders should be explicitly defined through the survey area. For example, in an area traversed by Very Large Crude Carriers (VLCCs) and expected to be deeper than 40 metres, an Order 1a survey may have been specified. However, if the surveyor discovers shoals of less than 40 metres depth, then it may be more appropriate to survey these shoals and surrounding areas to Special Order or even Exclusive Order in some limited circumstances.

To be fully compliant with an S-44 Order, a hydrographic survey must comply with **all** bathymetric and feature detection requirements (Table 1) for that order and with all the other requirements (Table 2) for the same order, where applicable. Additionally, the tables must be read in conjunction with the detailed text in the following chapters. The challenge presented by each order, in particular Special and Exclusive Orders, is establishing the appropriate survey methodology to achieve the specified standards.

To ensure surveys are systematic, even where bathymetric coverage is specified at less than 100%, the horizontal distance between registered positions of depths should be no greater than 3 times the depth or 25 metres, whichever is greater.

1.2 Order 2

This is the least stringent order and is intended for areas where the depth of water is such that a general depiction of the bottom is considered adequate. As a minimum, an evenly distributed bathymetric coverage of 5% is required for the survey area. It is recommended that Order 2 surveys are conducted in areas which are deeper than 200 metres. Once the water depth exceeds 200 metres, the existence of features that are large enough to impact on surface navigation and yet still remain undetected by an Order 2 survey is considered to be unlikely.

1.3 Order 1b

This order is intended for areas where the types of surface vessels expected to transit the area is such that a general depiction of the bottom is considered adequate. As a minimum, an evenly distributed bathymetric coverage of 5% is required for the survey area. Thismeans

some features will not be detected, although the distance between areas of bathymetric coverage will limit the size of those features. This order of survey is only recommended where underkeel clearance is considered not to be an issue. An example would be an area where the bottom characteristics are such that the likelihood of there being a feature on the bottom that will endanger the type of surface vessel expected to navigate the area is low.

1.4 Order 1a

This order is intended for areas where features on the bottom may become a concern for the type of surface traffic expected to transit the area but where the underkeel clearance is considered not to be critical. A 100% feature search is required in order to detect features of a specified size. Bathymetric coverage less than or equal to 100% is appropriate as long as the least depths over all significant features are obtained and the bathymetry provides an adequate depiction of the nature of the bottom topography. Underkeel clearance becomes less critical as depth increases, so the size of the feature to be detected increases with depth in areas where the water depth is greater than 40 metres. Examples of areas that may require Order 1a surveys are coastal waters, harbours, berthing areas, fairways and channels.

1.5 Special Order

This order is intended for those areas where underkeel clearance is critical. Therefore, 100% feature search and 100% bathymetric coverage are required and the size of the features to be detected by this search is deliberately more demanding than for Order 1a. Examples of areas that may require Special Order surveys are: berthing areas, harbours, and critical areas of fairways and shipping channels.

1.6 Exclusive Order

Exclusive Order hydrographic surveys are an extension of IHO Special Order with more stringent uncertainty and data coverage requirements. Their use is intended to be restricted to shallow water areas (harbours, berthing areas and critical areas of fairways and channels) where there is an exceptional and optimal use of the water column and where specific critical areas with minimum underkeel clearance and bottom characteristics are potentially hazardous to vessels. For this order, a 200% feature search and a 200% bathymetric coverage are required. The size of features to be detected is deliberately more demanding than for Special Order.

CHAPTER 2 HORIZONTAL AND VERTICAL POSITIONING

2.1 Introduction

Positioning is a fundamental part for every survey operation. The hydrographer must consider the geodetic reference frame, horizontal and vertical reference systems, their connections to other systems in use (e.g. land survey datums), as well as the uncertainty inherent within associated measurements.

In this standard, position and its uncertainty refer to the horizontal component of the sounding or feature, while the depth and its uncertainty refers to the vertical component of the same sounding or feature.

2.2 Geodetic Reference Frame

Positions should be referenced to a geodetic reference frame, which can be the realisation of either a global (e.g. ITRF2018, WGS84(G1762)) or a regional (e.g. ETRS89, NAD83) reference frame and their later iterations. As there are frequent updates to geodetic reference frames, it is essential that the epoch is recorded for surveys with low positioning uncertainty.

Since positions are most often referenced in a compound coordinate reference system/frame such as geodetic, geopotential, and height reference system/frame, they can be separated into horizontal and vertical components.

2.3 Horizontal Reference System

If horizontal positions are referenced to a local datum, the name and epoch of the datum should be specified and the datum should be tied to a realisation of a global (e.g. ITRF2018, WGS84(G1762)) or a regional (e.g. ETRS89, NAD83) reference frame and their later iterations. Transformations between reference frames/epochs should be taken into account, especially for surveys with low uncertainty.

2.4 Vertical Reference System

If the vertical component of the positions is referenced to a local vertical datum, the name and epoch of the datum should be specified. The vertical component of the positions (e.g. depths, drying heights) should be referenced to a vertical reference frame that is suitable for the data type and intended use. This vertical reference frame may be based on tidal observations (e.g. LAT, MWL, etc), on a physical model (i.e. geoid) or a reference ellipsoid.

2.5 Chart and Land Survey Vertical Datum Connections

In order for bathymetric data to be correctly and fully utilised, chart and land survey vertical datum connections or relationships must be clearly determined and described. The IHO Resolution on Datums and Benchmarks, Resolution 3/1919, as amended, resolves practices which, where applicable, should be followed in the determination of these vertical datum connections.

This essential resolution 3/1919, as amended, is available in the IHO Publication M-3, Resolutions of the International Hydrographic Organization, which is downloadable from the IHO homepage www.iho.int.

2.6 Uncertainties

This standard addresses total propagated uncertainty (TPU) by the two components; total horizontal uncertainty (THU) and total vertical uncertainty (TVU). The TVU and THU values must be understood as an interval of ± the stated value.

A statistical method, combining all uncertainty sources for determining both the horizontal and the vertical positioning uncertainty should be adopted to obtain THU and TVU respectively. The uncertainties at the 95% confidence level must be recorded with the survey data.

The ability of the survey system should be demonstrated by *a priori* uncertainty calculations (THU and TVU). These calculations are predictive and must be calculated for the survey system as a whole, including all instrument, measurement, and environmental uncertainty sources. This estimation should be updated during the survey to reflect changes from environmental conditions such as wind, waves, etc. in order to make appropriate changes to survey parameters.

Final uncertainty values for the survey may consist of an *a priori* and *a posteriori* calculation, explicitly empirical values (e.g. based on standard deviation of vertical depths alone), or some combination of the aforementioned values. The metadata should include a description of the uncertainty type and the uncertainty(s) achieved.

Within this standard, for ease of use, allowable horizontal uncertainty is assumed to be equal in both dimensions. Therefore, assuming a normal distribution of error, the position uncertainty is expressed as a single number.

2.7 Confidence Level

In this standard the term confidence level is not the strict statistical definition, but is equivalent to the terms "level of confidence" or "coverage probability" as discussed in the *Guide to the Expression of Uncertainty in Measurement*, JCGM 100:2008, section 6.2.2.

It must be noted that confidence levels (e.g. 95%) depend on the assumed statistical distribution of the data and are calculated differently for one-dimensional (1D) and two- dimensional (2D) quantities. In the context of this standard, which assumes normal distribution of error, the 95% confidence level for 1D quantities (e.g. depth) is defined as 1.96 x standard deviation, and the 95% confidence level for 2D quantities (e.g. position) is defined as 2.45 x standard deviation.

CHAPTER 3 DEPTH, BATHYMETRIC COVERAGE, FEATURES, AND NATURE OF THE BOTTOM

3.1 Introduction

The navigation of surface vessels requires accurate knowledge of depth and features. Where underkeel clearance is potentially an issue, bathymetric coverage must be at least 100%, feature detection must be appropriate, and depth uncertainties must be tightly controlled and understood.

For customisation or enhancement of safety of navigation survey orders or other applications, survey criteria may be specified by selecting required criteria values from the Matrix (See section 7.5 and Annex A).

3.2 Depth

3.2.1 Depth Measurement

Depths are to be understood as reduced depths within a well-defined vertical reference frame. The depth of a feature is expressed as the minimum depth of that feature.

In waters with very high turbidity, e.g. estuaries, this minimum depth may be determined on the basis of sediment concentrations in the water.

Under exceptional circumstances, for safety of navigation purposes, the use of a high precision method (e.g. mechanical sweep) that the hydrographic office or authority deems able to confirm the safe depth in an area, or over a feature / wreck, can be used to certify a safe depth. In this case, the uncertainty of the vertical measurement will define the survey order to be quoted.

3.2.2 Drying Heights

In areas with larger tidal ranges where the drying zone is sometimes navigable during high tide, elevations within the drying zone also need to be thoroughly surveyed. Depending on the situation and available equipment, the drying heights may either be surveyed bathymetrically or topographically. However, regardless of the survey method, maximum uncertainties shall not exceed those specified for the submerged area outside of the drying zone.

3.2.3 Maximum Allowable Vertical Uncertainty

Recognising that there are both depth-dependent and depth-independent error sources that affect the measurements of depths, the formula below is used to compute the maximum allowable vertical measurement uncertainty.

The parameters “a” and “b”, together with the depth “d”, have to be introduced into the formula below in order to calculate the maximum allowable TVU:

$$\boldsymbol{TVU_{max}(d)} = \sqrt{\boldsymbol{a^2} + (\boldsymbol{b} \times \boldsymbol{d})^2}$$

Where

a represents that portion of the uncertainty that does not vary with the depth

b is a coefficient which represents that portion of the uncertainty that varies with the depth

d is the depth

Table 1 specifies the parameters "a" and "b" to compute the maximum allowable TVU of reduced depths for each survey order. The total vertical uncertainties of depth measurements calculated with a 95 % confidence level must not exceed this value.

3.3 Feature Detection

Minimum standards for feature detection are specified in Table 1. A cubic feature is used as a basic shape reference for a system feature detection ability and implies a symmetrical 3-D shape of six equal square sides.

In assessing a survey system's feature detection ability, the entire survey system, including equipment, methodologies, procedures, and personnel, must be assessed. It is the responsibility of the hydrographic office or authority that is gathering the data to assess the capability of any proposed survey systems to detect significant features.

Specified feature detection abilities are not implicit determinations of what constitutes a hazard to navigation. In some cases, significant features smaller than the defined sizes specified in Table 1 can be classifiedas hazards to navigation. It may therefore be deemed necessary by the hydrographic office or authority to detect smaller significant features in order to minimise the risk of undetected hazards to navigation. However, no single survey system can guarantee detection of all features. If there is a concern that hazards to navigation may exist within an area that may not be detected by the survey system, consideration should be given to use an alternative survey system.

3.4 Feature Search

Minimum standards for Feature Search are specified in Table 1.

For Order 1a, a 100% feature search may be achieved with a survey system that does not measure depth. Under those circumstances, least depth measurements from an independent bathymetric system will be required for any detected significant feature. Whenever possible, it is recommended to conduct a 100% feature search in conjunction with 100% bathymetric coverage.

A feature search greater than or equal to 100% must be planned and conducted with the intent of detecting all features of the sizes specified in this standard. Where more than 100% feature search is required, including 200% for Exclusive Order, it may be accomplished by adequately overlapping collection or by acquiring more than one independent dataset within a survey.

3.5 Bathymetric Coverage

The concept of bathymetric coverage was introduced in this edition of S-44, in order to make the standard technology independent. Acquisition of bathymetric coverage requires use of a sensor that measures and records depths. Table 1 specifies the minimum bathymetric coverage to be achieved by each survey order.

3.5.1 100% Bathymetric Coverage

A 100% bathymetric coverage should be interpreted as "full" bathymetric coverage. 100% bathymetric coverage does not guarantee continuous depth measurements, since the depth measurements are discrete and based on the inherent physical and survey instrumentation limitations.

3.5.2 Less than 100% Bathymetric Coverage

Bathymetric coverage of less than 100% must follow a systematic survey pattern to maximise uniform distribution of depth data across the survey area and must not be lower than 5%. Additionally, the nature of the bottom (e.g. roughness, type, slope) and the requirements for safety of surface navigation in the area must be taken into account early and often to determine whether the survey pattern should be adapted to meet the requirements for safety of navigation in the area, while still fulfilling the minimum requirements according to Table 1. To ensure surveys are performed systematically where bathymetric coverage is specified at less than 100%, the horizontal distance between registered positions of depths should be no greater than 3 times the average depth or 25 metres, whichever is greater.

For Order 1a, bathymetric coverage less than or equal to 100% is appropriate as long as the least depths over all significant features are obtained and the bathymetry provides an adequate depiction of the nature of the bottom topography. The system independent parameter bathymetric coverage (expressed in percentage) is used for all Orders. In the 5th edition, line spacing was used as the parameter for Order 2 and 1b. In transition from line spacing to an extent in percentage for bathymetric coverage, a single beam with 8-12° beam width was used as a realistic reference, with an inter-line spacing of 3-4 times water depths[1]. 5% is therefore the appropriate value for the Order 2 and 1b bathymetric coverage requirement.

3.5.3 Greater than 100% Bathymetric Coverage

Greater than 100% bathymetric coverage, including 200% for Exclusive Order, may be accomplished by adequately overlapping collection or by acquiring more than one independent dataset within a survey.

3.6 Hazards to Navigation

Hydrographic offices and authorities must consider the expected local traffic (e.g. draught of vessels) as well as general configuration of depths when assessing hazards to navigation.

Sufficient data must be acquired over features that are potential hazards to navigation (e.g. wreck or other obstructions) to ensure the least depth and position are adequately determined

[1] Example: For a singlebeam echosounder with an 8° beam width, considering a line spacing of 3-times depth for the main lines and 10 times the main line spacing for the cross lines, according to the formula, the bathymetric coverage is: % coverage

= surveyed area / total area = (footprint diameter*total line length) / total area = 2*tan (8°/2)*(1/3+1/(3*10)) = 0.051 = 5.1%

This formula is provided as an example and does not constitute part of this standard.

by appropriate methods, while meeting the minimum requirements of the appropriate order in Table 1.

Given current ship specifications, features with least depths deeper than 40m would not likely constitute a hazard to surface navigation. However, this statement should be constantly re- evaluated based on local circumstances and their potential changes.

The hydrographic office or authority, responsible for survey quality, may define a depth limit beyond which a detailed bottom investigation, and thus an examination of features, is not required.

3.7 Charted Object Confirmation / Disproval

For an object which has previously been recorded/presented in a chart, document, electronic publication, or database, it is recommended to confirm or disprove the existence of those charted objects such as rocks, wrecks, obstructions, aids to navigation, and doubtful data. Findings should be addressed in the report of survey.

Doubtful data includes, but is not limited to, data which are usually denoted on charts by PA (Position Approximate), PD (Position Doubtful), ED (Existence Doubtful), SD (Sounding Doubtful), or as "reported danger". Charted objects should be confirmed or disproved relative to their charted position.

No empirical formula for defining the search area can cover all situations. For object confirmation or disproval it is recommended that the search radius should be at least 3 times the estimated position uncertainty of the reported hazard. If a charted object is not located or indicated within the search radius, the charted object can then be recommended as disproved.

It is the responsibility of the hydrographic office or authority which is gathering the data to assess whether the charted object has been sufficiently disproved before removing it from the chart.

3.8 Nature of the Bottom

The nature of the bottom should be determined in potential anchorage areas, other critical areas, and in areas where bottom conditions are suspected to have significant influence on required feature detection. Bottom Characterisation Methods include: physical sampling (PHY) with visual (VIS) and / or laboratory (LAB) analysis, inference technique (INF) from other sensors (e.g. backscatter or reflectivity), or inference technique with physical ground truth sampling (INF w/ GT) and visual (VIS) and / or laboratory (LAB) analysis.

Bottom Sampling Frequency may be at a spacing sufficient for the intended product (e.g. chart), seabed geology, and as required to ground truth any inference technique. Bottom sampling for ground truth of inference technique does not require a regular sampling pattern, or distances. An average value, or maximum value, for the distance between samples can be used. If bottom sampling has been performed in specific areas, such as anchorage or other areas of interest of the surveyed area, the limits for the sampling area should be recorded.

There are currently no IHO safety of navigation standards for bottom characterisation methods or bottom sample frequencies. However, the Matrix may be used to task and classify any such work performed. What is appropriate for these parameters varies greatly based on the

nature and configuration of the bottom as well as the intended use of the area. The surveyor should exercise judgement in determining appropriate bottom characterisation methods and bottom sample frequency to adequately characterise the area.

CHAPTER 4 WATER LEVELS AND FLOW

4.1 Introduction

In this chapter, water levels are considered in the context of supporting the vertical solution of depth measurements, rather than water level measurements as a discrete dataset to define tidal harmonics etc, which are covered within other IHO documents. Tides and other changes in water levels which impact the TVU of depth data must be considered for any hydrographic survey regardless of the technology used to conduct the survey. Flow observations will often be required to support safe navigation, and when specified in the survey requirement, those observations must meet the parameters presented in this standard.

For requirements to clearly determine chart and land survey vertical datum connections, or relationships, see section 2.5.

4.2 Water Level (Tidal) Predictions

Water level observations may be required to facilitate generation and maintenance of tidal prediction models and the production of Tide Tables. Water level observations should cover as long a period as possible and preferably not less than 30 days.

4.3 Reductions for Water Level Observations

Whenever surveyed/predicted water levels or tides are used to reduce soundings to a datum, allowance shall be made in the TVU calculations for the uncertainty of the values. Observed values are preferred over predicted.

4.4 Water Flow (Tidal Stream and Current) Observations

The speed and direction of water flows (tidal streams and currents) which may exceed 0.5 knots should be observed in key areas, if not already defined. For example, at the entrances to harbours and channels, at any change in direction of a channel, in anchorages, and adjacent to wharf areas. It is also recommended to measure coastal and offshore streams and currents when they are of sufficient strength to affect surface navigation.

The water flow (tidal stream and current) at each position should be measured at depths sufficient to meet the requirements of normal surface navigation in the survey area. In the case of tidal streams, simultaneous observations of tidal height and meteorological conditions should be made. It is recommended that the period of observation be at least 30 days.

The speed and direction of the water flow (tidal stream and current) must be measured at 95% confidence level as defined in Table 2. Where there is reason to believe that other factors (e.g. seasonal river discharge) influence the water flows, measurements should be made to cover the entire period of variability.

CHAPTER 5 SURVEYS ABOVE THE VERTICAL DATUM

5.1 Introduction

Surveys above the vertical datum are necessary for safe and efficient navigation and mooring. Topographic and geodetic measurements that are of specific importance for navigation are presented in the following sections. Their corresponding allowable uncertainties (THU and TVU as applicable) are defined in Table 2.

Additional information such as drawings or photographs of these features should be captured where possible to support the measurement.

For Chart and Land Survey Vertical Datum Connection requirements see section 2.5.

5.2 Fixed Aids and Topographic Features Significant to Navigation

Fixed aids to navigation include, but are not limited to: beacons, day marks, range markers, and lighthouses.

Topographic features significant to navigation are conspicuous features, landmarks, and objects which assist mooring, docking, and manoeuvring in confined spaces and / or provide some aid in navigation.

Conspicuous features which provide some aid in navigation without being a dedicated aid to navigation may include, but are not limited to, conspicuous natural features, cultural features, and landmarks such as: chimneys, flare stacks, hill or mountain tops, masts, monuments, towers, refineries, religious buildings, silos, single buildings, tanks, tank farms, towers, and windmills. Features of this type may be both significant to navigation and less significant to navigation (section 5.5) depending on the feature's individual characteristics and surroundings.

Essential harbour, mooring, and docking features include, but are not limited to: groins, moles, wharfs (quays), piers (jetties), mooring dolphins, piles, bollards, slipways, docks, lock gates, and breakwaters.

Allowable THU and TVU for the positioning of these fixed aids and features significant to navigation are presented in Table 2.

One may consider drying features (including rocks) which are positioned by topographic means to be topographic features significant to navigation. Regardless of the positioning methodology, maximum allowable uncertainties for drying features shall not exceed those specified in this standard for the adjacent permanently submerged features (unless a different order of survey has intentionally been specified by the commissioning authority).

5.3 Floating Objects and Aids to Navigation

Floating objects and aids to navigation include, but are not limited to: buoys, articulated beacons, fish farms, and floating docks.For floating objects, the surveyed position uncertainty should be significantly lower than the sway (object's allowed movement). Sway due to currents, wind, and water level must be taken into account when computing the mean position of these objects.

Allowable THU for the positioning of these objects are presented in Table 2. Allowable TVU is not applicable to these measurements.

5.4 Coastline

IHO S-32, *IHO Hydrographic Dictionary*, generally defines coastline or shoreline as the line where shore and water meet. IHO S-4, *Regulations of the IHO for International (INT) Charts and Chart Specification of the IHO*, describes it more specifically as high water mark, or the line of mean water level where there is no appreciable tide or change in water level. The coastline may also be defined as the low water line. Allowable THU for the positioning of these objects are presented in Table 2. Allowable TVU is not applied to these measurements within this standard.

5.5 Features Less Significant to Navigation

Features less significant to navigation are non-conspicuous features which provide context and additional information, but are not likely to aid navigation. As stated in section 5.2, topographic features of the same type may be both conspicuous / significant to navigation and less conspicuous / less significant to navigation depending on the feature's individual characteristics and surroundings. Topographic features less significant to navigation may include, but are not limited to non-conspicuous landmarks such as: chimneys, flare stacks, hill or mountain tops, masts, monuments, towers, refineries, religious buildings, silos, single buildings, tanks, tank farms, and windmills.

Allowable THU and TVU for the positioning of these objects are presented in Table 2.

5.6 Overhead Clearances, Range Line and Sector Lights Heights

Overhead obstructions such as bridges and cables may pose a hazard to navigation. Range line and sector light heights may be of use for determining distance from shore. Allowable THU and TVU for the positioning of overhead clearances (including associated horizontal clearances), range line and sector light heights are presented in Table 2.

5.7 Angular Measurements

Angular measurements include, but are not limited to: limits of sectors and arcs of visibility of lights, alignments of leading lights and clearing lights, directions for passing off-lying dangers, and alignment of recommended tracks. Allowable THU for the measurement of these angles is presented in Table 2. Allowable TVU is not applicable to these measurements.

CHAPTER 6 METADATA

6.1 Introduction

Metadata is fundamental to ensure that survey data is correctly understood and utilised as required for chart production or other purposes. This Standard identifies the minimum metadata that is to be provided with hydrographic surveys conducted for safety of navigation. Where additional metadata is available this should be included to enhance the value of the survey data for other uses. Examples of metadata include overall quality, data set title, source, positional uncertainty, and ownership.

6.2 Metadata Content

Metadata can be provided in any format such as in the Report of Survey, or embedded within a specific metadata file. The chosen format should support discovery, clarity of understanding, and software compatibility. Each hydrographic office or authority may adopt metadata requirements beyond that specified here and should develop and document a list of additional metadata used for their survey data. The table below should be seen as a schema, and not a final data model.

Metadata should be comprehensive, but should include, as a minimum, information on:

Category or Group	**Description**
Survey Type	e.g. safety of navigation, passage, reconnaissance/sketch, examination
Technique of vertical / depth measurement	e.g. echo-sounder, side scan sonar, multi-beam, diver, lead-line, wire-drag, photogrammetry, satellite derived bathymetry, lidar
Order of survey achieved	In accordance with S-44
Horizontal and vertical datum and separation models used	Including ties to a geodetic reference frame based on ITRS (e.g. WGS84) and epoch information, if a local datum or realisation is used
Uncertainties achieved (at 95% Confidence Level)	For both horizontal and vertical components: THU and TVU
Feature detection ability	In metres
Feature search	% of survey area searched
Bathymetric coverage	% of survey area covered
Survey date range	Survey's start and end dates
Survey undertaken by	Surveyor, survey company, survey authority
Data ownership	e.g. funding body, government
Grid attributes	Where a grid is the deliverable (i.e. resolution, method, underlying data density, uncertainty)

Category or Group	**Description**
Data density	Description of average or range of density of source data (e.g. number of accepted points per surface unit)
Usage constraints	e.g. none, classified, not for navigation, or restricted

Metadata should preferably be an integral part of the digital survey record and conform to the "IHO S-100 Discovery Metadata Standard", when this is adopted. Prior to the adoption of S- 100, ISO 19115 can be used as a model for the Metadata. If this is not feasible, similar information should be included in the documentation of a survey.

CHAPTER 7 TABLES AND SPECIFICATION MATRIX

7.1 Introduction

As in previous editions, this edition of S-44 presents key elements of safety of navigation survey specifications in table format. This edition has two Tables (1 and 2) and provides a new specification Matrix for added flexibility for other types of hydrographic surveys carried out for purposes beyond safety of navigation. The new Matrix allows for customisation and enhancement of safety of navigation survey standards.

7.2 Safety of Navigation Standards

Minimum bathymetry standards are defined in Table 1. Other minimum standards for positioning and water flow measurements are defined in Table 2. Both tables must be read in conjunction with the detailed text in this document.

As stated above, all standards defined in Table 1 and Table 2 are included in the specification Matrix within ranges of specification values which are available to enhance and customise safety of navigation surveys. Although the Matrix is available for this purpose, its usage will not reduce the minimum standards defined for safety of navigation survey orders. See Annex A for guidance on how to use the Specification Matrix.

7.2.1 Bathymetry Standards

Table 1 defines minimum bathymetry standards for safety of navigation surveys. The standards are intended to be purpose specific but technology independent in design. The order achieved for bathymetry data (Table 1) may be assessed independently of order achieved for other positioning data (Table 2), so as not to unnecessarily degrade the representation of quality of bathymetry in nautical charts and products. Table 1 follows.

7.2.2 Other Positioning Standards, Tidal Stream and Currents

Table 2 defines minimum navigational aid, structural, and topographic positioning standards for safety of navigation surveys above the vertical datum. It also includes minimum standards for angular measurement in relation to range lines, sectors lights, and similar aids to navigation used on an established course or heading. Finally, requirements are set for direction and speed measurements for tidal stream and current. These standards only apply where such measurements are required for the survey. Table 2 follows.

7.3 TABLE 1 - Minimum Bathymetry Standards for Safety of Navigation Hydrographic Surveys

To be read in conjunction with the full text set out in this document, m = metres, all uncertainties at 95% confidence level, * = Matrix Reference.

Reference	Criteria	Order 2	Order 1b	Order 1a	Special Order	Exclusive Order
Chapter 1	**Area description** (Generally)	Areas where a general description of the sea floor is considered adequate.	Areas where underkeel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas where underkeel clearance is considered not to be critical but features of concern to surface shipping may exist.	Areas where underkeel clearance is critical	Areas where there is strict minimum underkeel clearance and manoeuvrability criteria
Section 2.6	**Depth THU** [m] + [% of Depth]	20 m + 10% of depth *Ba5, Bb2	5 m + 5% of depth *Ba8, Bb3	5 m + 5% of depth *Ba8, Bb3	2 m *Ba9	1 m *Ba10
Section 2.6 Section 3.2 Section 3.2.3	**Depth TVU** (a) [m] and (b)	a = 1.0 m b = 0.023 *Bc7, Bd4	a = 0.5 m b = 0.013 *Bc8, Bd6	a = 0.5 m b = 0.013 *Bc8, Bd6	a = 0.25 m b = 0.0075 *Bc10, Bd8	a = 0.15 m b = 0.0075 *Bc12, Bd8
Section 3.3	**Feature Detection** [m] or [% of Depth]	Not Specified	Not Specified	Cubic features > 2 m, in depths down to 40 m; 10% of depth beyond 40 m *Be5, Bf3 beyond 40m	Cubic features > 1 m *Be6	Cubic features > 0.5 m *Be9
Section 3.4	**Feature Search** [%]	Recommended but Not Required	Recommended but Not Required	100% *Bg9	100% *Bg9	200% *Bg12
Section 3.5	**Bathymetric Coverage** [%]	5% *Bh3	5% *Bh3	≤ 100% *≤ Bh9	100% *Bh9	200% *Bh12

7.4 TABLE 2 - Other Minimum Standards for Safety of Navigation Surveys

To be read in conjunction with the full text set out in this document. Standards for Table 2 data types only apply where such measurements are required for the survey.

m = metres. All uncertainties at 95% confidence level. * = Matrix Reference.

Reference	Criteria	Uncertainty Type	Order 2	Order 1b	Order 1a	Special Order	Exclusive Order
Section 5.2	**Fixed Objects, Aids, Features Above the Vertical Reference Significant to Navigation**	THU [m]	5 m *Pa4	2 m *Pa6	2 m *Pa6	2 m *Pa6	1 m *Pa7
		TVU [m]	2 m *Pb2	2 m *Pb2	1 m *Pb3	0.5 m *Pb4	0.25 m *Pb5
Section 5.3	**Floating Objects and Aids to Navigation**	THU [m]	20 m *Pc2	10 m *Pc3	10 m *Pc3	10 m *Pc3	5 m *Pc4
Section 5.4	**Coastline** (high, low, MWL water lines, etc)	THU [m]	10 m *Pd2	10 m *Pd2	10 m *Pd2	10 m *Pd2	5 m *Pd3
Section 5.5	**Features Above the Vertical Reference Less Significant to Navigation**	THU [m]	20 m *Pe2	20 m *Pe2	20 m *Pe2	10 m *Pe3	5 m *Pe4
		TVU [m]	3 m *Pf1	2 m *Pf2	1 m *Pf3	0.5 m *Pf4	0.3 m *Pf5
Section 5.6	**Overhead Clearances and Range Line, Sector Light Heights**	THU [m]	10 m *Pg1	10 m *Pg1	5 m *Pg2	2 m *Pg3	1 m *Pg4
		TVU [m]	3 m *Ph1	2 m *Ph2	1 m *Ph3	0.5 m *Ph4	0.3 m *Ph5
Section 5.7	**Angular Measurements**	[degrees]	0.5 degrees *Pi4				
Section 4.4	**Water Flow Direction**	[degrees]	10 degrees *Wa1				
Section 4.4	**Water Flow Speed**	[knots]	0.1 knots *Wb5				

7.5 Matrix Description

The Specification Matrix provides a range of selectable criteria for bathymetric parameters and other data types collected, reported, and delivered as part of a hydrographic survey. It is introduced to allow flexibility and customisation in the tasking and assessing of hydrographic surveys, accommodation of new and emerging technologies, and inclusion of hydrographic surveys conducted for purposes other than safety of navigation. By design, it is expandable and can evolve in future S-44 editions. The Matrix can be used both as a tool when specifying a survey, but also as a tool for classification of data after a completed survey.

It is important to note that the Matrix alone does not define any standards for hydrographic survey. Safety of navigation survey standards (as defined in Table 1 and Table 2) are referenced to the Matrix criteria and the Matrix can be used to customise and enhance these minimum standards. Standards for surveys conducted for purposes other than safety of navigation (e.g. geophysical, oil and gas, dredging, and geotechnical) are not currently defined in this document. However, the range of accuracies presented in the Matrix was designed to accommodate these surveys and to provide a common framework for tasking and assessing hydrographic surveys in general.

Additionally, with the emergence of new nautical products and associated specifications / data models (e.g. Electronic Nautical Charts (ENC) and S-101 ENC Product Specification), additional types of information will be available to the mariner. The Matrix can be used to help define and categorise the increasing variety of data that will be used in these evolving products.

See Annex A for guidance and additional information on how to use the Specification Matrix.

7.6 MATRIX

Matrix for Hydrographic Surveys. To be read in conjunction with the full text set out in this document, m = metres, all uncertainties at 95% confidence level.

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
B	**BATHYMETRY**														
a	**Depth** THU [m]	500	200	100	50	20	15	10	5	2	1	0.5	0.35	0.1	0.05
b	**Depth** THU [% of depth]	20	10	5	2	1	0.5	0.25	0.1						
c	**Depth** TVU "a" [m]	100	50	25	10	5	2	1	0.5	0.3	0.25	0.2	0.15	0.1	0.05
d	**Depth** TVU "b" Note 1	0.20	0.10	0.05	0.023	0.02	0.013	0.01	0.0075	0.004	0.002				
e	**Feature Detection** [m]	50	20	10	5	2	1	0.75	0.7	0.5	0.3	0.25	0.2	0.1	0.05
f	**Feature Detection** [% of Depth]	25	20	10	5	3	2	1	0.5	0.25					
g	**Feature Search** [%]	1	3	5	10	20	30	50	75	100	120	150	200	300	
h	**Bathymetric Coverage** [%]	1	3	5	10	20	30	50	75	100	120	150	200	300	

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14

P	OTHER POSITIONING ABOVE THE VERTICAL REFERENCE														
a	**Fixed Aids, Features Significant to Navigation** THU [m]	50	20	10	5	3	2	1	0.5	0.2	0.1	0.05	0.01		
b	**Fixed Aids, Features Significant to Navigation** TVU [m]	3	2	1	0.5	0.25	0.1	0.05	0.01						
c	**Floating Aids and Objects** THU [m]	50	20	10	5	2	1	0.5							
d	**Coastline** THU (high, low, MWL water lines, etc.) [m]	20	10	5	1	0.5	0.25	0.1							
e	**Features Less Significant to Navigation** THU [m]	50	20	10	5	3	2	1	0.5	0.2	0.1	0.05	0.01		
f	**Features Less Significant to Navigation** TVU [m]	3	2	1	0.5	0.3	0.25	0.1	0.05	0.01					
g	**Overhead Clearance and Range line, Sector Light Heights** THU [m]	10	5	2	1	0.5	0.2	0.1	0.05	0.01					
h	**Overhead Clearance and Range line, Sector Light Heights** TVU [m]	3	2	1	0.5	0.3	0.1	0.05	0.01						
i	**Angular Measurements** [degrees]	5	2.5	1	0.5	0.2	0.1	0.05							

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
W	**WATER FLOW**														
a	**Flow Direction** [degrees]	10	7.5	5.0	2.5	1.0	0.5	0.25	0.10						
b	**Flow Speed** [knots]	2	1	0.5	0.25	0.10									

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
N	**NATURE OF THE BOTTOM**														
a	**Bottom Characterisation Method** Note 2	PHY - VIS	PHY - LAB	PHY - VIS & LAB	INF	INF w/ GT (VIS)	INF w/ GT (LAB)	INF w/ GT (VIS & LAB)							
b	**Bottom Sampling Frequency** approximate [m] Note 2	As Req to GT	10,000	5,000	2,500	1,852	1,000	500	250	100	75	50	25	10	5

Note 1: To use the parameter "*b*", as a percentage of depth, multiply it by 100.

Note 2: PHY = Physical Sampling. VIS = Visual Analysis. LAB = Laboratory Analysis. INF = Inference Technique. w/ = With. GT = Ground Truth. As Req to GT = As Required to Ground Truth any Inference Technique (see section 3.8).

ANNEX A MATRIX GUIDANCE

A.1 Introduction

The Matrix, as presented in section 7.6, includes a range of selectable criteria for hydrographic survey parameters / data types. It is organised by the following data classes: Bathymetry, Other Positioning, Water Flow, and Nature of the Bottom.

The criteria are derived through a series of alphanumeric codes which reference the cells in the Matrix. A criterion requires three characters to reference a cell address:

1. The first character is a capital letter denoting the class of data.
2. The second character is a lower-case letter referencing the intended criteria by row.
3. The third character is a number referencing the intended criteria value by column.

The string should include only those parameters and data types required for both specification and classification of surveys. Omission of a cell reference indicates that there is no requirement for the associated criteria and that "0" should be used in required formulas.

Table A1 - Matrix Classes and Description

	Class	Description
B	Bathymetry	Depth and features
P	Other Positioning	Location of features above the vertical reference
W	Water Flow	Direction and speed of currents
N	Nature of the Bottom	Bottom characterisation

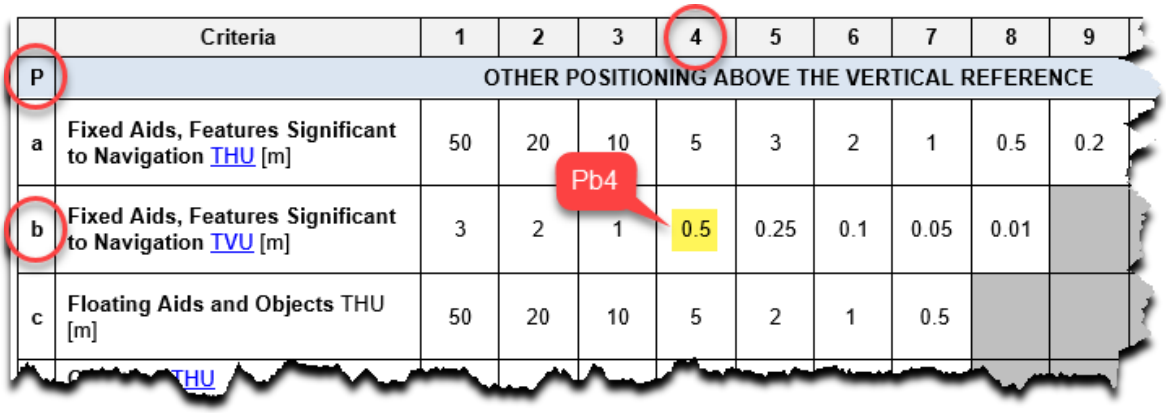


Figure A1 - Example: (Pb4) derivation of Fixed Aids, Features Significant to Navigation TVU = 0.5 m

A.2 Examples of Matrix Realisations:

A.2.1 Matrix Representations

Matrix realisations may be communicated in a variety of representations including: diagrams, tables, text strings, and shaded matrices.

A.2.2 Table Examples

The following table presents two examples of "Matrix Realisations": Order 1a Surveys, and a Customised Specification. This table includes the values associated with a Matrix cell. Although it may be helpful to provide those values in a technical specification for a survey, it is not explicitly necessary in order to communicate the requirement. Cells in colour highlight the differences between Order 1a and the customised specification, which is more demanding.

B	BATHYMETRY	Order 1a Value	Matrix Cell Ref.	Custom	Matrix Cell Ref.
a	**Depth** THU [m]	5	Ba8	5	Ba8
b	**Depth** THU [% of depth]	5	Bb3	5	Bb3
c	**Depth** TVU "a" [m]	0.5	Bc8	---	---
d	**Depth** TVU "b"	0.013	Bd6	0.010	Bd7
e	**Feature Detection** [m]	2 (≤40 m)	Be5 (≤40 m)	1 (≤40 m)	Be6
f	**Feature Detection** [% of Depth]	10 (>40 m)	Bf3 (>40 m)	10	Bf3
g	**Feature Search** [%]	100	Bg9	100	Bg9
h	**Bathymetric Coverage** [%]	≤ 100	≤ Bh9	100	Bh9
P	OTHER POSITIONING				
a	**Fixed Aids, Features Significant to Navigation** THU [m]	2	Pa6	2	Pa6
b	**Fixed Aids, Features Significant to Navigation** TVU [m]	1	Pb3	1	Pb3
c	**Floating Aids and Objects** THU [m]	10	Pc3	10	Pc3
d	**Coastline** THU (high, low, MWL water lines, etc.) [m]	10	Pd2	10	Pd2
e	**Topographic Features Less Significant to Navigation** THU [m]	20	Pe2	5	Pe4
f	**Topographic Features Less Significant to Navigation** TVU [m]	1	Pf3	1	Pf3
g	**Overhead Clearance and Range line, Sector Light Heights** THU [m]	5	Pg2	5	Pg2

h	**Overhead Clearance and Range line, Sector Light Heights** TVU [m]	1	Ph3	1	Ph3
i	**Angular Measurements** [degrees]	0.5	Pi4	0.5	Pi4
T	**WATER FLOW**				
a	**Flow Direction** [degrees]	10	Ta1	5	Ta3
b	**Flow Speed** Uncertainty [knots]	0.1	Tb5	0.1	Tb5
N	**NATURE OF THE BOTTOM**				
a	**Bottom Characterisation Method**	---	---	INF w/ GT (VIS & LAB)	Na7
b	**Bottom Sampling Frequency**	---	---	As Req to GT	Nb1

A.2.3 Text String Examples

The following text strings present examples of "Matrix Realisations": Order 1a Surveys, and a Crowd Sourced dataset example.

Order 1a Matrix text string example:

Classified according to the S-44 Matrix as:

Ba8, Bb3, Bc8, Bd6, Be5 (≤40m), Bf3 (>40m), Bg9, ≤Bh9, Pa6, Pb3, Pc3, Pd2, Pe1, Pf3, Pg2, Ph3, Pi4, Wa1, Wb5.

Can be divided into the separate parts as not all parameters need to be surveyed at all times depending on area and survey specification requirements. Classified according to the S-44 Matrix as:

- Bathymetry: *Ba8, Bb3, Bc8, Bd6, Be5 (≤40m), Bf3 (>40m), Bg9, ≤Bh9*
- Fixed Objects, Aids, Features Above the Vertical Reference Significant to Navigation: *Pa6, Pb3*
- Floating Aids and Objects: *Pc3*
- Coastline: *Pd2*
- Features Above the Vertical Reference Less Significant to Navigation: *Pe2, Pf3*
- Overhead Clearances and Range Line, Sector Light Heights: *Pg2, Ph3*
- Angular Measurements: *Pi4*
- Water Flow: *Wa1, Wb5*

Crowd Sourced Dataset Example:

A "Crowd Sourced" bathymetric dataset acquired in deep water, with a single beam echosounder and no sound velocity correction, could be classified by the use of TVU and THU (the coverage is of no use as it is not a systematic survey):

Classified according to the S-44 Matrix as: *Ba3, Bc5, Bd3*

Referencing:

The use of text strings for classification of datasets should be articulated with a clear reference to the S-44 Survey Order and / or Matrix, highlighting any variance from the Survey Order.

Examples could be: "C*lassified according to the S-44 Matrix as: (Ba8, Bb3...)"* or *"Classified according to the S-44 Survey Order and Matrix as: Special Order, **Ba12**"* (where Ba12 shows a further augmentation of Special Order in this case).

Note: the use of text strings alone has a higher probability of translation error.

A.2.4 Matrix Example

Example: Order 1b using the SPECIFICATION MATRIX

m = metres, all uncertainties at 95% confidence level, Order 1b cells

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
B	**BATHYMETRY**														
a	**Depth** THU [m]	500	200	100	50	20	15	10	5	2	1	0.5	0.35	0.1	0.05
b	**Depth** THU [% of depth]	20	10	5	2	1	0.5	0.25	0.1						
c	**Depth** TVU "a" [m]	100	50	25	10	5	2	1	0.5	0.3	0.25	0.2	0.15	0.1	0.05
d	**Depth** TVU "b" Note 1	0.20	0.10	0.05	0.023	0.02	0.013	0.01	0.0075	0.004	0.002				
e	**Feature Detection** [m]	50	20	10	5	2	1	0.75	0.7	0.5	0.3	0.25	0.2	0.1	0.05
f	**Feature Detection** [% of Depth]	25	20	10	5	3	2	1	0.5	0.25					
g	**Feature Search** [%]	1	3	5	10	20	30	50	75	100	120	150	200	300	
h	**Bathymetric Coverage** [%]	1	3	5	10	20	30	50	75	100	120	150	200	300	

EXAMPLE

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
P	**OTHER POSITIONING ABOVE THE VERTICAL REFERENCE**														
a	**Fixed Aids, Features Significant to Navigation** THU [m]	50	20	10	5	3	2	1	0.5	0.2	0.1	0.05	0.01		
b	**Fixed Aids, Features Significant to Navigation** TVU [m]	3	2	1	0.5	0.25	0.1	0.05	0.01						
c	**Floating Aids and Objects** THU [m]	50	20	10	5	2	1	0.5							
d	**Coastline** THU (high, low, MWL water lines, etc.) [m]	20	10	5	1	0.5	0.25	0.1							
e	**Features Less Significant to Navigation** THU [m]	50	20	10	5	3	2	1	0.5	0.2	0.1	0.05	0.01		
f	**Features Less Significant to Navigation** TVU [m]	3	2	1	0.5	0.3	0.25	0.1	0.05	0.01					
g	**Overhead Clearance and Range line, Sector Light Heights** THU [m]	10	5	2	1	0.5	0.2	0.1	0.05	0.01					
h	**Overhead Clearance and Range line, Sector Light Heights** TVU [m]	3	2	1	0.5	0.3	0.1	0.05	0.01						
i	**Angular Measurements** [degrees]	5	2.5	1	0.5	0.2	0.1	0.05							

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
W	**WATER FLOW**														
a	**Flow Direction** [degrees] Section 4.4	10	7.5	5.0	2.5	1.0	0.5	0.25	0.10						
b	**Flow Speed** [knots] Section 4.4	2	1	0.5	0.25	0.10									

	Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14
N	**NATURE OF THE BOTTOM**														
a	**Bottom Characterisation Method** Section 3.8 Note 2	PHY - VIS	PHY - LAB	PHY - VIS & LAB	INF	INF w/ GT (VIS)	INF w/ GT (LAB)	INF w/ GT (VIS & LAB)							
b	**Bottom Sampling Frequency** approximate [m] Section 3.8 Note 2	As Req to GT	10,000	5,000	2,500	1,852	1,000	500	250	100	75	50	25	10	5

EXAMPLE

Note 1: To use the parameter as a percentage of depth multiply by 100.

Note 2: PHY = Physical Sampling. VIS = Visual Analysis. LAB = Laboratory Analysis. INF = Inference Technique. w/ = With. GT = Ground Truth. As Req to GT = As Required to Ground Truth any Inference Technique.

ANNEX B GUIDELINES FOR QUALITY MANAGEMENT

Note: This annex is **not** an integral part of the S-44 Standards and will be removed when the information therein is fully incorporated into IHO Publication C-13, *Manual on Hydrography*.

Quality control: Quality evaluation procedure for maintaining standards in products by testing the output against the specification.

B.1 Quality Control

Quality control requires more than proving that the end results of the survey are within the required limits stated in the S-44. To achieve the required quality there are three important fields affecting the quality: Material, Procedures, and Personnel. All fields are essential for the quality control of the hydrographic products. Quality control is not just about figures and computations; rather it is a complete overview of all factors affecting the survey.

B.2 Equipment

The equipment in use must be capable of producing data that meets the required standards. First, the total propagated uncertainties of all equipment and corrections used to derive the reported surveyed value must be included. The temporal and spatial influence of the medium, in which measurements take place, must be considered in this total propagated uncertainty calculation. By an *a priori* calculation of the total propagated uncertainty in a certain environment, it can be determined if the instrumental setup is sufficient for the required quality. If uncertainties cannot be calculated prior to the survey, an alternative methodology of describing the achieved uncertainties must be undertaken to verify that the required standards will be met.

Secondly, the equipment in use should be free of (systematic) errors which must be determined by calibration and qualification.

The use of calibrated equipment that can achieve the required data quality is the first step for the quality control process. It is preferred to check the entire system in real conditions (in situ) before surveying, and every time a doubt occurs during the survey.

B.3 Procedures

Using standardised procedures for hydrographic data collection and processing can reduce the risk of errors. By describing the total of procedures, it is possible to incorporate checks and tests on errors that occur in an early stage of the process. This is important for errors that cannot be detected afterwards.

Procedures may involve complete flow schedules that can be used for external auditing and standardised data products. In the procedures, the *a posteriori* quality checks must be admitted.

B.4 Personnel

All survey work must be performed by qualified personnel. The personnel must be trained and capable. Formal qualifications, such as from CAT A and B accredited courses are preferred, but proven working

experience may be sufficient. Personal professional accreditation schemes should also be considered.

ANNEX C GUIDANCE FOR *A PRIORI* AND *A POSTERIORI* QUALITY CONTROL

Note: This annex is **not** an integral part of the S-44 Standards and will be removed when the information therein is fully incorporated into IHO Publication C-13, *Manual on Hydrography*.

The S-44 standards refer to quality standards for both *a priori* and *a posteriori* results. In this guidance a brief view on how to determine the uncertainties for *a priori* and *a posteriori* is given. Determining uncertainties is necessary for any technique used in hydrographic surveys. Methods to establish the uncertainty may differ greatly for each survey technique used.

C.1 *A Priori* Uncertainty

The *a priori* uncertainty is a theoretical value based on best practise estimations of all factors affecting the measurements. Each instrument used in the measurement and the environmental influences will add uncertainties to the grand total. Calculating the total uncertainty horizontally and vertically prior to the survey will affirm to the hydrographer that the required survey standards will be feasible with the selected equipment in the environment of the survey area. If the survey standards are not achieved, other equipment or survey techniques may be necessary for that particular environment.

During the survey, estimations of the equipment and environment uncertainties should be adjusted or assessed. By this adjustment, the *a priori* uncertainty is improved.

C.2 *A Posteriori* Uncertainty

Fundamentally the hydrographer is most interested in the *a posteriori* uncertainty.

Outside of a reference area it is not possible to determine the *a posteriori* uncertainty from the data set. The data set is the end result and contains all errors involved in the total process but it is not possible to calculate the *a posteriori* uncertainty from the data set. There are many techniques and procedures to check the hydrographic data set and they can provide proof that the data set is to be trusted, however no tool will calculate the *a posteriori* uncertainty of an area that is not well-known.

A preliminary task is to check the capability of the total system, to ensure that it can meet the minimal horizontal and vertical specifications and feature detection requirement, according to the specified order. Well known reference areas should be used to prevent any vertical offset on measurements. Qualification on these reference areas should be carried out periodically.

During the survey, consideration should be given to confirm the validity of the vertical model by assessing the spatial and temporal repeatability of the survey system.

ANNEX D GRIDDED BATHYMETRY CONSIDERATIONS

Note: This annex is **not** an integral part of the S-44 Standards and will be removed when the information therein is fully incorporated into IHO Publication C-13, *Manual on Hydrography*.

REFERENCES: Content from the following references was used in the composition of this Annex.

IHO S-100, The Universal Hydrographic Data Model – Edition 3.0.0 IHO

S-102, Bathymetric Surface Product Specification – Edition 1.0.0 IHO B-

11, IHO-IOC GEBCO Cook Book – September 2018

ISO 19107:2003 Geographic Information - Spatial Schema ISO

19115:2003 Geographic Information - Metadata

ISO 19123:2005 Geographic Information - Schema for Coverage Geometry and Functions Open

Navigation Surface Working Group, Requirements Document – Version 1.0

Open Navigation Surface Working Group, Format Specification Document - Description of Bathymetric Attributed Grid Object (BAG) - Version 1.6.3

Open Navigation Surface Working Group, A Variable Resolution Grid Extension for BAG Files – Version 1.2

Digital Elevation Model Technologies and Applications: The DEM User's Manual – 3rd Edition

GEBCO – Frequently Asked Questions: https://www.gebco.net/about_us/faq/#creating_a_bathy_grid

D.1 Introduction

As data sample densities from hydrographic sensors have increased, methods of sea floor representation have shifted from vector-based products such as selected soundings and contours, to gridded bathymetric models. The result of an individual hydrographic survey is now commonly stored as a digital grid or series of grids of differing resolutions. These grids often include node values for both depth and uncertainty and may also include accompanying information regarding contributing sample standard deviation, sample density, shoal sample values within the vicinity of the grid node, and even information to allow conversion between tidal datum and reference ellipsoid. For many hydrographic offices, production workflows now focus on these gridded bathymetric models as the data source instead of the full resolution sounding files. Exploitation of the gridded bathymetric data can reduce production timelines as they provide an appropriate level of information in a lighter-weight, digital package.

Gridded bathymetric models are also used for small-scale applications such as regional bottom characterisation. In many instances these grids are a combination of observed sample

data, survey gridded data, estimated data and interpolated data. This Annex will not address considerations for these types of grids compilations, as substantial information on this topic is maintained by the Joint IHO-IOC Committee for the General Bathymetric Chart of the Oceans (GEBCO).

D.2 Definitions

Area Representation: Representation of gridded data where the entire cell is assumed to be the same value, and changes only occur at the borders of cells. (The DEM User's Manual)

Bathymetric model: Digital representation of the topography of the bottom by coordinates and depths.

Grid: A network composed of two or more sets of curves in which the members of each set intersect the members of the other sets in a systematic way. (ISO 19123)

Grid Cell: An area defined within the interstices between the grid lines. (ISO 19123)

Grid Line Registration: Registration method where grid nodes are centred on the intersection of the grid lines. (GEBCO)

Grid Node: A data point, with an exact geographic location referenced by grid definition and registration. The value contained within the grid describes selected information at this location. (ONSWG)

Holiday: An unintentional unsurveyed area within a given hydrographic survey where the spacing between sounding lines or surveys exceeds the maximum allowable limits (IHO Dictionary S-32).

Pixel Centred Registration: Registration method where grid nodes are centred in the grid cells. (GEBCO)

Surface Representation: Representation of gridded data where the grid node represents the surface value at the centroid of each cell. The area between cell centres is assumed to be a value between that of adjacent cells (The DEM User's Manual).

D.3 Grid Considerations

D.3.1 Grid Resolution

Gridded bathymetric models are commonly generated using a fixed resolution per a pre- defined depth range. A compromise is often made when selecting a fixed resolution over a given depth range, where ultimately the grid resolution cannot be chosen at the same time for the shallowest and the deepest depths.

In addition to the fixed resolutions per depth range, recent efforts in hydrographic data processing have allowed for the generation of variable resolution gridded bathymetric models. These models can be generated using fixed resolution per a pre-defined depth range (as with individual grids) or automated methods based on depth and achieved data density.

When the survey requirement calls for detection of features of set dimensions and the resultant gridded bathymetric model is to represent the results of the survey, accurate feature representation within the grid will require a grid cell size no greater than the size of the feature the gridded bathymetric model is

required to depict, although it is recommended that a cell size of half the feature is used.

The grid resolution should also be chosen to consider the achieved horizontal uncertainty of the input samples and the method for which this uncertainty is used in the chosen gridding method or algorithm.

Grid resolution should ultimately be determined based on the intended use of the grid and therefore a survey may require grids of different resolutions to satisfy multiple purposes.

D.3.2 Sample Density

It is the responsibility of the hydrographic office or authority, to determine an acceptable data density requirement which allows for an accurate depiction of significant bottom features and reliable estimate of depth within the local vicinity of the grid nodes without allowing opportunity for data *holidays* to be masked by grid resolution. This determination requires surveyors to verify sensor feature detection performance prior to its use, including selection and employment of appropriate collection parameters.

If statistical gridding methods are to be employed, acceptable data densities should be specified with a minimum threshold of accepted samples per area (e.g. greater than or equal to five (5) samples per node). Data density requirements should also describe the percentage of nodes within the grid that are required to achieve this density, e.g. at least 95% of all nodes within the grid shall be populated with the minimum required density.

D.3.3 Grid Coverage

It is the responsibility of the hydrographic office or authority, to define a data gap or data holiday. The definition should describe the area on the bottom, by number of continuous nodes with no depth present.

When gridded bathymetric models are generated using a fixed resolution per a pre-defined depth range, overlap between adjacent grids should exist in order to ensure that no gaps in coverage between neighbouring grids are generated.

D.3.4 Hydrographer Overrides to Grid Nodes

When statistical gridding methods are employed, it is possible for the gridding algorithm to omit a significant shoal depth on a feature of interest. Tools exist inside many hydrographic data processing packages to override node values and manually force the model to honour a shoal depth. It is the responsibility of the hydrographic office or authority, to define the thresholds for when overrides are appropriate. Some thresholds will be uncertainty-based,
e.g. only override the statistically significant nodal depth value when the difference between the node value and nearest shoal sample exceeds the allowable total vertical uncertainty (TVU) at the nodal depth. Other thresholds may be defined by scale of the product that the data set was collected to support. Comments on feature selection and nodal override methods

should accompany the gridded bathymetric model to allow the end users to determine if it is appropriate for the intended use.

D.4 Gridding Methods

Several possible gridding methods for both dense and sparse data sets exist. The hydrographic office or authority is responsible for determining the appropriate method for the intended purpose of the resultant gridded data set. This determination should consider the implementation of the gridding method or algorithm in the selected software package. This determination should also consider the method of grid node representation and portrayal within the selected software.

The following list provides some of the methods commonly used when gridding bathymetric data sets:

- The **Shoalest Depth** method examines depth estimates within a specific area of influence and assigns the shoalest value to the nodal position. The resulting surface represents the shallowest depths across a given area. The use of shoalest depth values is often used for safety of navigation purposes.

- The **Deepest Depth** method examines depth estimates within a specific area of influence and assigns the deepest value to the nodal position. The resulting surface represents the deepest depths across a given area. The use of a deep depth surface is often used during post processing to identify outliers in the data set.

- The **Basic Mean** method computes a mean depth for each grid node where all soundings within the cell have the same weight.

- The **Statistical Median** method computes a depth for the node by ordering contributing samples sequentially and selecting the median value.

- The **Basic Weighted Mean** method computes an average depth for each grid node (whereby the inverse to the distance from the sounding location to the nodal position is used as weighting schema). Contributing depth estimates within a given area of influence are weighted and averaged to compute the final nodal value.

- The **Total Propagated Uncertainty (TPU) Weighted Mean** method makes use of the elevation and associated total propagated uncertainty for each contributing depth estimate to compute a weighted average depth for each nodal position.

- The **Combined Uncertainty and Bathymetric Estimator (CUBE)** algorithm makes use of the elevation and associated total propagated uncertainty for each contributing sounding to compute one or many hypotheses for an area of interest. The resulting hypotheses are used to estimate statistical representative depths at each nodal position.

- The **Nearest Neighbour** method identifies the depth value of the nearest sounding in distance from the nodal point within an area of interest. This method does not consider values from other neighbouring points.

- The **Natural Neighbour** interpolation method identifies and weights (as a function of the inverse of the surface of the smallest polygon – Voronoi tessellation – around the sounding value) a subset of input samples within the area of interest to interpolate the final nodal value.

- The **Polynomial Tendency** gridding method attempts to fit a polynomial trend, or best fit surface to a set of input data points. This method can project trends into areas with little to no data, but does not work well when there is no discernible trend within the data set.

- The **Spline** gridding method estimates nodal depths using a mathematical function to minimise overall surface curvature. The final "smoothed" surface passes exactly through the contributing input depth estimates. This Spline algorithm is considered a sparse data gridding method.

- The **Kriging** gridding method is a geostatistical interpolation method that generates an estimated surface from a scattered set of points with a known depth.

D.5 Grid Uncertainty

The uncertainty associated with the elevation value contained within gridded bathymetric models can be described using a variety of methods, which may include:

Raw Standard Deviation is the standard deviation of samples that contributed to the node.

Standard Deviation Estimator is the standard deviation of samples captured by a hypothesis algorithm (e.g. CUBE's standard output of uncertainty).

Product Uncertainty is a blend of Standard Deviation Estimator uncertainty and other measures which may include Raw Standard Deviation, and the average vertical uncertainty from the subset of samples used to generate the hypothesis that represents the node.

Historical Standard Deviation is an estimated standard deviation based on historical/archive data.

Other uncertainty types may be specified. Methods for uncertainty estimation should be documented within the accompanying grid metadata.

The uncertainty types listed above describe the vertical uncertainty of the node depth. The resultant grid may exhibit a higher than expected uncertainty value if the bathymetric profile is not represented at an appropriate grid resolution, e.g., a node uncertainty value may be higher than anticipated along sharp sloping bathymetry.

If required, obtaining a horizontal uncertainty for a grid node could be accomplished by calculating a basic or distance weighted mean of the horizontal uncertainty values from the samples that contributed to the grid node.

D.6 Applicability

Gridded bathymetric models are a common product of a hydrographic survey; however, the utility of the model representation begins well before a survey data set is finalised as this data can also be used to verify survey requirements during hydrographic collection and certify quality of a data set during data set validation efforts.

D.6.1 Survey Data Collection

Gridded bathymetric models can provide valuable information regarding underway bottom sample density and identification of significant bottom features. These models can be leveraged to assess where full feature search has been achieved and conversely where holidays exist. Monitoring of these items during survey operations is necessary for the qualification of field data completeness prior to departing the survey area.

D.6.2 Survey Data Validation

Gridded bathymetric models can serve as a comparison tool to examine depth data consistency within a survey and the presence of random and systematic data set errors. These models can also serve as a comparison tool between neighbouring surveys and between different collection sensors. Comparisons between high resolution gridded data and legacy point data can also be accomplished to provide statistics on differences and aid in the prioritisation scheme for future product updates. Comparison of gridded depth and associated nodal uncertainty is another common method used in determining whether a survey data set complies with required uncertainty thresholds as well.

D.6.3 Survey Data Deliverable

As mentioned throughout this annex, gridded bathymetric models in the presence of survey logs, reports and other metadata are sufficient to serve as the authoritative result and deliverable of the survey. Gridded models also serve as the direct input for the generation of products supporting safety of navigation and other protection of the marine environment objectives.

D.7 Metadata

To ensure gridded bathymetric models are fit for purposes that include and extend beyond safety of navigation, an appropriate level of metadata describing the data set is required. IHO S-102, the Bathymetric Surface Product Specification, provides Metadata elements derived from S-100 and from ISO 19115 and ISO 19115-2. Elements described within S-102 include mandatory, optional and conditional items. Following this specification, conclusive metadata for gridded bathymetric models will include information describing the data set, depth correction type, uncertainty type, grid reference and coordinate system information, as well as temporal descriptions, grid construction methods, and persons responsible for product generation.

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End of Thesis