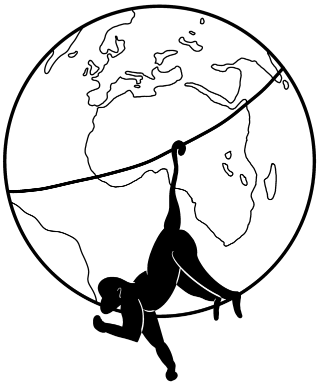
Snapshot GNSS for wildlife tracking



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Abstract

Location data is valuable for the study of wild animals. It is often collected using animal-borne tags that utilise global navigation satellite systems (GNSS), such as the Global Positioning System (GPS). Snapshot GNSS is a particular approach to positioning with GNSS that requires only a few milliseconds of the satellite signal for every location fix. The processing of these snapshot recordings can then be delayed, often until after the deployment, when the necessary satellite data is available in public databases, and power is no longer a concern. This is unlike the traditional GNSS approach, which requires multiple full seconds of signal to calculate a position on-device. Due to this reduction in radio on-time by several orders of magnitude, snapshot GNSS tags exhibit significantly lower energy consumption. Battery capacity is typically the largest contributor to the size and weight of a tag. This suggests that snapshot GNSS may be particularly well-suited for wildlife tracking, where tags need to be small and light to avoid affecting the animal.

However, some traditional GNSS tags now offer low-power modes that can reduce energy consumption per location fix when taking frequent fixes. Additionally, snapshot GNSS tags have higher storage needs than traditional ones, as they need to store raw signal snapshots. It is therefore not obvious how the two technologies compare for any particular application. There is currently no literature on this, making it difficult for users to make an informed decision when choosing between them.

Furthermore, only a small number of commercial products and research prototypes implement snapshot GNSS. Many of these systems rely on high-quality snapshots, requiring complex hardware, and none of them are open-source. This limits their suitability for transparent and reproducible science and inhibits further research into the technology.

This thesis presents four main contributions to address these issues:

1. **An evaluation of snapshot GNSS with low-quality snapshots:** I demonstrate that 12 ms 1 bit snapshots sampled at only 4.092 MHz can yield median accuracies better than 15 m, which is suitable for many wildlife tracking applications.

2. **An analysis of the energy advantage of snapshot GNSS:** I compare a model snapshot GNSS receiver with a traditional GNSS receiver that offers low-power modes. I show that while both systems can provide similar fix frequencies for short deployments, snapshot systems significantly outperform traditional ones for longer deployments.

3. **SnapperGPS:** I present SnapperGPS, a complete and open-source implementation of a snapshot GNSS system. The custom receiver has a component cost of under \$30 and has already been successfully used in multiple wild animal tracking studies. In a deployment on loggerhead sea turtles, SnapperGPS was able to match the spatial and temporal resolution of a high-end commercial marine tag in a side-by-side comparison.

4. **A SnapperGPS variant for tracking small seabirds:** I show how I adapted SnapperGPS for seabird tracking. This variant can provide significantly more frequent fixes than the popular i-gotU GT-120 tag, especially for long deployments. Additionally, it is smaller, lighter, and comparable in price.

SnapperGPS serves as an open-source foundation for further research into snapshot GNSS technology and provides ecologists with a field-tested snapshot GNSS system. This work also includes a comparative analysis to help users assess if a snapshot solution provides an advantage for their application.

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List of acronyms and initialisms

A-GNSS	Assisted global navigation satellite system
ATP	Adaptive Trickle Power
C/A	Coarse acquisition
CO-GPS	Cloud-Offloaded GPS
CTN	Coarse time navigation
ENIG	Electroless nickel immersion gold
FMB	Maio Biodiversity Foundation
OSH	Open-source hardware
GNSS	Global navigation satellite system
GPS	Global Positioning System (U.S. GNSS)
GLONASS	Global Navigation Satellite System (Russian GNSS)
GPIO	General Purpose Input/Output
GSM	Global System for Mobile Communications
IC	Integrated circuit
IF	Intermediate frequency
LiPo	Lithium polymer (battery)
PCB	Printed circuit board
PCM	Protection circuit module
PLA	Polylactide
POM	Polyoxymethylene
PRN	Pseudorandom noise
PTF	Push To Fix
RTC	Real-time clock
SNR	Signal-to-noise ratio
SWD	Serial Wire Debug
TPU	Thermoplastic polyurethane
TTFF	Time to first fix
UHF	Ultra high frequency
VHF	Very high frequency

Chapter 1

Introduction

1.1 Motivation

Accelerating climate change and other anthropogenic pressures are driving an ongoing global mass extinction event, indicating extreme ecosystem disruptions [2–6]. These changes have wide-ranging implications for many important issues, such as zoonotic threats, nature conservation efforts and wild animal welfare. Addressing these pressing problems requires increased research into wild animals and their interactions with the environment.

This field is known as animal ecology. It explores research questions such as how animals adapt to environmental changes, how they interact with members of their own and other species, and how they travel through landscapes. Modern ecology research increasingly relies on technology for data collection, significantly expanding the quality and quantity of their data sets compared to traditional methods such as direct observation.

Location data is one important kind of data used to study animals in the wild. It is most commonly collected by attaching devices to animals. There are many commercial suppliers of wildlife tracking technology [7–18]. However, researchers complain about high costs, large and heavy batteries, high failure rates, and low-quality data [19–23]. There appears to be a need for further research and development to create more efficient, reliable, and cost-effective wildlife tracking technologies.

1.2 Global navigation satellite systems (GNSS)

Most location tracking systems use global navigation satellite systems (GNSS), such as the Global Positioning System (GPS). GNSS satellites continuously transmit radio signals containing their precise orbit parameters. A receiver on Earth with a good view of the sky can infer its position by calculating its distance to multiple visible satellites using this information. Traditional GNSS location tracking devices implement all the signal processing on the tag to calculate a position estimate. Without additional information, this may require the radio receiver to be powered on for thirty seconds to obtain the required satellite data from a cold start. As a result, traditional GNSS devices typically have high energy demands to (i) power the radio receiver and (ii) perform the necessary processing.

To address this, many traditional GNSS systems now offer low-power modes that wake up regularly for a signal refresh to keep an up-to-date record of the satellite data. If this tracking data is available when attempting a position fix, the radio may only need to be powered on for a few hundred milliseconds instead of thirty seconds for a cold start[1,2]. However, when tracking wildlife, sky visibility is often not continuous because animals may hide under cover or dive underwater. Regular satellite data updates may therefore not always be possible. In those cases, traditional GNSS systems fall back on energy-intensive cold starts, limiting deployments.

1.3 Snapshot GNSS

Snapshot GNSS is an alternative approach that offers consistently low energy consumption for every location fix. A snapshot GNSS device records only a few mil-

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[1] Data sheet: Multi Micro Hornet (ORG1510-R01), `http://web.archive.org/web/20211123152616/https://origingps.com/wp-content/uploads/2021/01/Multi-Micro-Hornet-ORG1510-R01-Datasheet-Rev3.0.pdf` (archived 2021-11-23)

[2] Data sheet: MAX-8, u-blox GNSS modules, `https://web.archive.org/web/20201112042121/https://www.u-blox.com/sites/default/files/MAX-8_DataSheet_(UBX-16000093).pdf` (archived 2020-11-12)

liseconds (a so-called snapshot) of the raw satellite signal for each requested position fix. All signal processing is delayed until the device is recovered when power is no longer a concern. Any necessary historical satellite data can be looked up in public databases, so there is no need for a regular satellite data refresh on the device.

The snapshot GNSS approach has three notable advantages for wildlife tracking:

- **Low power consumption**

  Snapshot GNSS tags have very low power consumption because (i) their radio receiver is only powered on for a few milliseconds per position fix, and (ii) the signal processing can be delayed until the device is recovered and power is no longer a concern. Traditional GNSS receivers, on the other hand, have high power demands, limiting their deployment length. As explained above, they therefore often offer low-power modes to extend deployment times under certain circumstances. These low-power modes reduce average power consumption per fix, but only when taking frequent successful fixes over short deployments. A snapshot GNSS receiver has consistently low power consumption per fix, no matter how recent the previous fix was.

- **Short acquisition time**

  A snapshot is always only a few milliseconds long, regardless of the state of the receiver. Short acquisition times are crucial in settings where a tag may only get very short windows of clear view of the sky. A common wildlife tracking application with such a restriction is the tracking of marine animals with short surfacing times, as GNSS signals do not travel well underwater.

- **Instant position on trigger**

  A snapshot receiver can always be woken up to take an immediate snapshot in just a few milliseconds. A cold start on a traditional GNSS system, on the other hand, may require up to 30 s to provide a position estimate without any additional information. This can be avoided with a regular satellite data refresh, but even then, the receiver may need to be powered on for up to 10 s to provide a position estimate. A short reaction time can be a necessary feature in wildlife tracking scenarios where ecologists are interested in how an animal reacts to external stimuli, e.g. the call of a group member or predator sounds.

A small number of commercial systems and research prototypes for snapshot GNSS receivers already exist (see Section 2.5.4) [24–35]. However, current snapshot GNSS solutions exhibit two major disadvantages:

- **Complex hardware**

  Short snapshots are prone to interference. Current proprietary solutions and research prototypes address this by using higher sampling rates (e.g. 8 MHz [27,30] or 16 MHz [24,28]) or collecting long snapshots (e.g. 20 ms [25] or 30 ms [35]), often with multi-bit resolution (e.g. 8 bit [27] or 16 bit [29]), resulting in the need for specialised complex hardware.

- **Closed-source design**

  At the time of writing, none of the existing snapshot GNSS solutions are entirely open-source. This makes it impossible for the community to effectively make improvements or adapt the systems for applications with specialised requirements. It is also possible that these systems perform hidden data processing steps, such as smoothing or outlier removal. This limits the reproducibility and interpretability of any research results obtained with these systems.

Furthermore, there is no literature analysing how snapshot GNSS and traditional GNSS systems compare in scenarios where the latter might be able to rely on low-power modes. This makes it difficult for users to decide what type of tag is appropriate for their application.

1.4 Research objectives

Snapshot GNSS appears to have significant advantages for many wildlife tracking scenarios. However, the lack of open systems, the complexity of existing hardware and the absence of any literature comparing snapshot GNSS to traditional GNSS may have led to these being largely overlooked.

The goal of this thesis is to address these gaps by (i) investigating if snapshot GNSS systems with low complexity hardware are feasible, (ii) analysing how snapshot GNSS and traditional GNSS compare in practice, and (iii) developing a fully open-source snapshot GNSS system.

Through this research, I aim to improve the understanding of the potential of snapshot GNSS for wildlife tracking and facilitate its adoption where appropriate.

1.5 Contributions

This section contains an overview of the main contributions presented in this thesis.

Demonstration of the feasibility of a snapshot GNSS receiver with low-quality GNSS signal samples

Using a simple radio receiver built from off-the-shelf parts, I show that 12 ms 1 bit snapshots sampled at only 4.092 MHz can yield median accuracies better than 15 m with an antenna that measures 25 mm × 25 mm. Implementations of snapshot GNSS systems in the literature generally rely on higher-quality snapshots, either by using longer samples, higher sampling rates or higher bit resolution. This leads to higher power consumption, increased storage requirements and the need for more complex hardware. These results demonstrate that it is feasible to build a snapshot GNSS system that uses low-quality snapshots, which can be implemented with simple and low-cost hardware.

Analysis of the energy advantage of snapshot GNSS

By design, Snapshot GNSS receivers have lower energy use per location fix as they need much less radio on-time. However, as mentioned above, modern implementations of traditional GNSS devices often offer low-power modes that can lower the energy required per fix, provided successful fixes are frequent enough. Additionally, a snapshot GNSS receiver is usually constrained by storage, as a raw snapshot needs significantly more storage than a set of coordinates. It is therefore not immediately obvious whether snapshot GNSS receivers outperform traditional GNSS receivers for every deployment.

I investigate this question by comparing a particularly low-power traditional GNSS receiver with a model snapshot GNSS receiver. I demonstrate that a traditional GNSS receiver can provide fixes about as frequently as a snapshot GNSS receiver for short deployments by relying on low-power modes. However, as deployments get longer, the maximum possible fix frequency decreases. Eventually, a traditional receiver needs to perform a cold start for every fix, significantly increasing its energy use. As a result, a snapshot GNSS receiver offers a particularly large advantage over a traditional GNSS receiver for long deployments.

For applications that can use a 100 mA h battery, a snapshot GNSS receiver will significantly outperform a traditional GNSS receiver for deployments longer than about a week. The exact size of this difference depends on the implementation details of the receivers. In the case of the models used in this work, the snapshot GNSS receiver outperforms the traditional GNSS receiver by an order of magnitude once the traditional receiver needs to perform a cold start for every fix.

Co-development of SnapperGPS

Building on the results of the initial feasibility experiments, I co-developed SnapperGPS, an open-source, low-cost and low-power location tracking system, specifically designed for wildlife tracking applications. SnapperGPS has a component cost of under $ 30 and can record enough data for over ten thousand location fixes. SnapperGPS is the first fully open-source snapshot GNSS implementation. It provides a basis for further research and development on snapshot GNSS technology.

SnapperGPS has also since been used in the field by multiple research groups, demonstrating its suitability for wild animal tracking. This includes a set of deployments on nesting loggerhead sea turtles in Cape Verde in 2021, which I organised with the Maio Biodiversity Foundation and Arribada. Due to its ability to provide a location fix within only a few milliseconds, independent of how long ago the previous fix was, snapshot GNSS tags are well suited for tracking air-breathing animals that live in the ocean. This makes marine applications a particularly interesting use case for snapshot GNSS technology. The 2021 Cape Verde deployment resulted in the first set of location data on this particular nesting population, as previously available solutions had been too expensive.

In another set of deployments that I organised with researchers from the University of Pisa and the Sea Turtle Research, Rescue and Rehabilitation Centre DEKAMER in Turkey, SnapperGPS was used to track sea turtles in the Mediterranean Sea. The SnapperGPS tag was deployed alongside a SeaTrkr tag by Telonics, a commercial tag that costs over £2000 but offers some real-time tracking. SnapperGPS was able to provide a spatial and temporal resolution similar to the SeaTrkr tag. This demonstrates that SnapperGPS provides a viable low-cost alternative to high-end commercial solutions for marine tracking when real-time tracking is not necessary.

Development of a SnapperGPS variant for bird tracking

Another interesting use case for snapshot GNSS technology is tracking small birds, as they have particularly strict requirements regarding the weight and therefore power consumption of the tag.

I developed a variant of the SnapperGPS hardware specifically for tracking birds. In a collaboration with the OxNav research group from the University of Oxford, a set of these bird variant tags was successfully used to track the foraging trips of nesting Manx shearwaters on the island of Skomer in Wales. The SnapperGPS bird variant continues to be used by the OxNav group, and over one hundred tags have been deployed since 2022.

I show that the SnapperGPS bird variant can provide significantly higher fix frequency than the commonly used i-gotU GT-120 for the same deployment length while being smaller and lighter at a similar price.

1.6 Academic publications

Below is a list of academic publications that have resulted from the work presented in this thesis, in order of publication date.

A. Matthes, J. Beuchert, A. Davies, J. Patino-Martinez, and A. Rogers, **SnapperGPS: Deployment of a low-cost snapshot GNSS receiver to track loggerhead sea turtles**, in *Proceedings of the 40th International Sea Turtle Symposium (ISTS40).* International Sea Turtle Society, 2022. [36].

J. Beuchert, **A. Matthes**, and A. Rogers, **SnapperGPS: Open hardware for energy-efficient, low-cost wildlife location tracking with snapshot GNSS**, *Journal of Open Hardware*, vol.7, no. 1, 2023. [37].

P.-Y. Hsing, B. Johns, and **A. Matthes**, **Ecology and conservation researchers should adopt open source technologies**, *Frontiers in Conservation Science*, vol. 5, p. 1364181, 2024. [38].

Currently under review in *Methods in Ecology and Evolution*: **A. Matthes** and A. Rogers, **Comparing snapshot GNSS with traditional GNSS for wildlife tracking applications**, submitted in 2024.

1.7 Thesis outline

The rest of this thesis is structured as follows. First, Chapter 2 provides the relevant background. Chapter 3 presents the experiments that demonstrate the feasibility of a snapshot GNSS receiver with low-quality GNSS signal samples. Chapter 4 compares the potential deployment space for both a snapshot GNSS system and a traditional GNSS system with low-power modes. Chapter 5 then describes SnapperGPS, an open-source snapshot GNSS system, specifically designed for wildlife tracking applications. The chapter also outlines multiple real-world deployments of the system. Chapter 6 presents a SnapperGPS variant for tracking small seabirds and compares it with popular commercial options. Chapter 7 summarises the main contributions and provides an outlook on potential future research directions. Appendix A includes a paper discussing why ecology researchers should adopt open-source technologies.

Chapter 2

Background

2.1 Motivations for studying wild animals and ecosystems

This section describes four potential motivations for studying wild animals. They are (i) understanding and improving wild animal welfare, (ii) conserving and restoring natural ecosystems, (iii) securing ecosystem services for humans, and (iv) monitoring zoonotic threats to humans.

These issues have become increasingly urgent as we are currently living through an accelerating mass extinction event [2–5]. Even under conservative estimates for the background rate of species loss, the loss of vertebrates between 1900 and 2015 would have taken between 800 and $10,000$ years to occur naturally [3]. At the time of writing, the International Union for Conservation of Nature (IUCN) Red List of Threatened Species includes over 37400 species under extinction, which accounts for 28% of all assessed species [39].

This increasing loss of species can be explained by human activities that exert pressures on ecosystems [2, 3, 5, 6]. These include direct species exploitation, such as overfishing and overhunting, but also habitat degradation, for example through deforestation or pollution. Human-induced climate change has additionally sped up habitat destruction, most notably through more frequent occurrences of extreme weather conditions, such as droughts, fires, and floods. These changes prompt increased urgency to study ecosystems and the wild animals that inhabit them.

2.1.1 Understanding and improving wild animal welfare

Good estimates are difficult to obtain, but wild animals significantly outnumber humans and farmed animals, even if one only considers terrestrial vertebrates. In a 2021 study, researchers estimated the total number of wild birds alone to be around 50 billion [40]. By comparison, farmed chickens (which account for the large majority of livestock numbers, when excluding aquatic animals and insects) numbered around 25 billion at any given time in 2023 [41].

Some authors argue that many of these abundant wild animals are likely to experience significant suffering since starvation, dehydration, disease, parasitism, injury, predation and harsh weather are commonplace in nature [42–44]. However, there is still some disagreement about the scale of this suffering, with some researchers arguing that wild animals' lives are generally positive [45]. There is limited data to support either claim, and much of this discussion has so far been philosophical.

Independent of the debate over whether the lives of wild animals are generally good or bad, there is another divide among philosophers regarding any moral obligation and right to intervene. Some argue that humans only have duties to aid animals that they harmed [46,47]. However, others make the case that humans have a moral obligation to help wild animals, even if they did not cause their suffering [44,48,49].

Due to these fundamental philosophical disagreements, proposed actions are often controversial, especially if they are deemed "unnatural", such as intervening in predation [50, 51]. Less extreme interventions to help wild animals could include food provisions, shelter, or medical attention (e.g. vaccinations or disease treatments). However, any such action will have effects on the entire ecosystem, prompting the need for robust ecosystem models [43, 44, 51].

In conclusion, there is a need for significant further research, firstly to assess the welfare of wild animals, and secondly to develop potential interventions.

2.1.2 Conserving and restoring natural ecosystems

Another motivation for studying wild animals is the conservation and restoration of ecosystems. In this framework, ecosystems have a natural state that should be preserved or restored, although there is some diversity in philosophical views on this topic [52–55].

Conservation and restoration is achieved through multiple means, including field work, policy interventions, and outreach. Field work can include activities such as the removal of pollutants, the reintroduction of native species, and the elimination or control of invasive species [56]. Examples of policy interventions in this space would be the designation of protected areas, the creation of special legal protections for at-risk species, and the introduction of wildlife trade restrictions [57–59]. Outreach through effective messaging to the public can affect day-to-day behaviour (e.g. resource consumption, poaching, or littering) which can have a direct impact, but it can also lead to long-term changes in attitudes which in turn can lead to changes in policy [60].

Developing these interventions requires a robust understanding of the ecosystems in question, as well as continued monitoring during and after the interventions to assess their effectiveness and to modify them as needed. Effective conservation work clearly relies heavily on science outputs. However, turning research results into conservation action can be difficult, and conservation practitioners often rely on experience rather than evidence [61–66]. This gap between research and practice is a major problem with many causes [67]. One particularly commonly cited reason is that scientific literature is generally inaccessible to conservation practitioners. This can be caused by multiple factors, including paywalls, difficulty parsing technical language, and issues with discoverability of relevant research. In response to this problem, there has been a push to improve the accessibility of scientific research to conservation practitioners. Individual researchers can contribute to this by publishing short, audience-targeted summaries of their work, ideally in national languages [65]. There has also been a call for the introduction of intermediates between scientists and practitioners, who collect, curate, and summarise primary sources for practitioners, similar to how the healthcare field operates [61, 68].

Successful ecosystem conservation does not necessarily imply improved wild animal welfare. While these two goals can sometimes be aligned, they may also come into conflict. For example, an intentional reduction in the size of a stable and native population of some species would generally be considered a disruption of a natural ecosystem. A conservation programme may therefore try to reverse this change. However, such an intervention may be beneficial for the welfare of the individuals by reducing competition for resources or limiting the spread of disease [69].

2.1.3 Securing ecosystem services

Humans rely on stable ecosystems for so-called ecosystem services. These include breathable air, drinkable water, food (directly as in fish and game but also indirectly through fertile soil and pollination), climate regulation, flood protection, building materials and waste decomposition. Excessive species extinction can lead to destabilisation of ecosystems and loss of these services [70–72]. Some of these services can be replaced by technology, but it is unclear if this is possible at scale for all of them. This further emphasises the need for research into ecosystem functioning.

2.1.4 Monitoring zoonotic threats to humans

Zoonoses (infectious diseases that can be transmitted from animals to humans) are a significant and increasing concern for human health. A 2001 study found that 60% of infectious organisms known to infect humans can be transmitted between humans and animals [73]. Another study analysed infectious disease events between 1940 and 2004 and found that emerging infectious diseases are mostly zoonotic and the majority of them (72%) originate from wild animals, with a significant increase over time [74]. This trend appears to be driven by increased anthropogenic pressures, such as climate change and habitat destruction [75–77].

Understanding animal movements, interactions, and behaviour changes in response to environmental pressures can improve our understanding of the spread of zoonotic diseases. This can be used to predict and prevent future outbreaks, and to inform public health policy.

2.2 Wild animal research

The previous section explored several potential motivations for studying wild animals. However, like many scientific fields, wild animal research often just aims to advance knowledge, without any immediate application in mind. Most of the research on wild animals can be considered to fall under the umbrella of ecology, which is the study of how animals interact with their environment. This encompasses a range of sub-disciplines, although the boundaries between them and other branches of biology are not always clear-cut.

Behavioural ecology, or ethology, is the study of the behavioural patterns of animals, including both instinctual behaviours (e.g. hibernation, nest building, or some aspects of mating) and learned behaviours (e.g. tool use, certain hunting strategies, or avoidance of dangerous areas). It is a broad field and research often focuses on a specific type of behaviour.

Movement ecology is a sub-field of behavioural ecology that focuses on how and why animals move through landscapes. This includes movements for reasons such as foraging, hunting, mating, or migration. Research in this field might focus on understanding how an animal navigates during migration, or how they pick their routes to make the most efficient use of their energy.

The field of behavioural ecology also encompasses social interactions between animals, including both interactions within a species (e.g. for mating, parental care, or cooperation) and across species (e.g. predation, mutualism, or competition).

Evolutionary ecology studies how species have evolved to adapt to their environment. It considers both physiological adaptations (e.g. an ability to tolerate extreme temperatures, a particular beak shape, or exceptional hearing), as well as behavioural adaptations (e.g. migration patterns, mating calls, or nesting locations).

Ecology research also explores how environmental factors (e.g. climate, food availability, or noise pollution) affect individual animals. This sub-field is becoming increasingly relevant as ecosystems are increasingly disrupted by human activities.

2.3 Open-source hardware (OSH) for research

Recently, ecology, like many other branches of science, has been increasingly shifting towards employing open science principles [78, 79]. This includes practices such as publishing in open access journals, collaborating with the public in citizen science projects and making data open, but also covers the creation and usage of open-source hardware (OSH) [80–82].

Using OSH in research has multiple advantages. One of the most important ones is that it improves the transparency and reproducibility of scientific results. Closed-source tools can employ hidden data manipulation steps such as automatic outlier removal or smoothing. This creates the appearance of less noise, but reduces the scientific value of the data. Additionally, once a particular product is no longer available, any scientific results that rely on it may become impossible to reproduce. In contrast, OSH allows researchers to understand and control every step of the data collection process, making research results reliable and reproducible.

OSH is also often available at significantly reduced cost [82]. Manufacturers of closed-source hardware can charge high prices because they have a monopoly on the product. OSH, on the other hand, can be produced by anyone, so the price can be driven down by competition. Open design files also make it possible to maintain and repair equipment. This can otherwise be a source of further expenses and often waste, as users of closed-source hardware will typically have to rely on the original manufacturer for this.

Another major advantage of OSH is the option to modify it. This is particularly useful for ecology tools, which may have very unique requirements due to the wide variety of species and habitats that need to be studied. Any new modifications or improvements can be freely shared with the community, which can then build on them further.

Currently, barriers still hold back its wide adoption, but the OSH community is working on improving practices to facilitate the transition away from closed-source hardware [82–84].

2.4 Tools for wild animal research

Ecology research makes use of a range of technologies, in particular for wildlife monitoring [85]. The most commonly used ones are location trackers, cameras and accelerometers. Others include microphones, magnetometers, gyroscopes, and sensors for temperature, light, heart rate, or depth. Some types of animals have properties of particular interest, e.g. depth for marine animals or sound for birds, so different sensors are common for different species. Some of these technologies are general-purpose and can be bought off-the-shelf (such as cameras), but most are sold by suppliers specifically for the purpose of wildlife monitoring [7–18].

2.4.1 Accessing data on devices carried by animals

Some types of hardware used to collect ecology data are placed stationary in areas of interest (e.g. camera traps), other types need to be attached to animals (e.g.

accelerometers), and some even require an implant (e.g. rumen bolus implants). If they are affixed to an animal, the problem of data access arises. With some species, re-capture of animals is easy. In those cases, the data can be stored on the device and accessed once retrieved. However, the re-capture of a tagged animal is not always trivial. There are multiple technological solutions to this [86, 87].

The most convenient but also most expensive way to access data on a tag is remote data download. This is often achieved via satellite (e.g. Iridium [88], Argos [89], Globalstar [90] or general-use GSM, if available in the area). This works anywhere on Earth with sky visibility. However, sending data to a satellite requires a lot of power, which results in tags with large and heavy batteries. Satellite services also incur a recurring cost that will depend on the amount of information sent and the chosen constellation. Another option for remote data download is radio (usually UHF or VHF). This is a less power-intensive alternative to a satellite uplink but typically requires a person in the field with a receiver because its range is limited. Local wireless networks can also be used to remotely access data on moving tags. But this requires gateways to be placed in regions of interest, as range is again limited. If multiple animals are to be tagged, the tags can also be used as a peer-to-peer network to route data further [91].

In some applications, remote data download is useful (e.g. to monitor poaching in real-time), however, often the user can wait for the data until the study period is over. In those cases, support for remote data download just unnecessarily increases the cost and weight of the tag. To recover the data, the user needs to be able to find the tagged animal again. A commonly deployed technology to help with this is a simple radio beacon (typically VHF) that can be added to a tag for localisation via triangulation [92].

Such radio beacons are sometimes combined with a drop-off mechanism so the animal does not need to be caught and possibly tranquillised for tag recovery [87]. A drop-off mechanism also ensures that the animal is not burdened by the tag for longer than necessary and should therefore always be considered. A release could be triggered by a timer or an external signal, but simple passive mechanisms can be cheap alternatives. For example, a collar can be designed to have a weak point that weathers and eventually breaks. Adhesives used to attach a tag can be chosen to dissolve after an appropriate time. Such passive mechanisms can not guarantee a release at a specific time but they are a simple safeguard to ensure that the tag does not stay on the animal indefinitely.

However, in many cases, neither remote data download options nor recovery aids are necessary. Animals often predictably return to particular areas (e.g. nesting sites or water sources), making unaided recovery possible.

2.4.2 Wildlife location tracking technologies

There are multiple types of technology that can be used to track the location of wildlife, and there usually is a trade-off of cost and convenience when choosing between them [85, 86, 93]. The most commonly used technologies are radio tracking, direct satellite tracking and tracking via Global Navigation Satellite Systems (GNSS). They all require the user to first attach a tag to the animal they want to track. This section describes each option in more detail.

Direct triangulation via radio works by attaching a radio transmitter to the animal. Its signal can then be located by taking multiple bearings with a portable directional receiver [92]. Every location fix will then require some manual labour. However, it is possible to set up an array of radio stations to create an automated radio telemetry system (ARTS) [94, 95]. This may be worthwhile, especially for constrained study sites that are of long-term interest.

Another method for tracking an animal is to tag it with a transmitter that is powerful enough to send signals to a satellite constellation in Earth's orbit. The satellites can then receive that signal, determine the location of the transmitter, and relay that information back to the user. Currently, there is only one such active system that is used for wildlife tracking: the Argos system [89, 96]. An Argos tag sends a signal at a specific frequency. Argos then uses a set of satellites in polar orbit to pick up on that signal. Due to the relative motion of the satellite, the frequency of the signal will be Doppler shifted by some amount, which can be used to infer the location of the transmitter. The Argos system can also be used to send some amount of additional information, such as sensor data. The satellites re-transmit information they gather to a set of receiving stations back on Earth, which in turn forward the data to a processing service. Once the data is processed, the results are made available to the user. The accuracy of location fixes depends on the geometry of the satellite constellation relative to the tag at the time of communication [96]. In theory, locations can be accurate to 150 m, under ideal circumstances. In practice, however, errors are typically multiple hundred metres to multiple kilometres [97].

The most commonly used technology for tracking wild animals is GNSS. GNSS stands for global navigation satellite system, of which there are currently four with global coverage: GPS, Galileo, GLONASS and BeiDou [98–101]. The Global Positioning System (GPS) is the most well-known and most commonly used. As a result, GNSS tags are often just called GPS tags, even if they also use other systems.

Each global navigation satellite system is comprised of a set of satellites that are constantly transmitting navigation data to the Earth's surface. A GNSS tag includes a radio receiver that is tuned to GNSS frequencies. The collected satellite data can then be used to triangulate the position of the receiver. For more technical details on GNSS, see Section 2.5. GNSS can be combined with an upload functionality, typically radio or satellite, to allow for remote tracking, as explained previously in Section 2.4.1. This sometimes results in confusion around tracking technologies because satellites and radio can be used to both localise a tag *and* send location data that was acquired on the device using GNSS. This confusion is further fuelled by the fact that GNSS tracking also relies on satellites. However, GNSS constellations are distinct from constellations used just for communication and the Argos constellation. The term *satellite tracking* can therefore refer to multiple technologies.

2.5 Positioning with GNSS

Global navigation satellite systems (GNSS) work by ensuring that an observer on Earth always has line-of-sight with enough satellites to infer its position by measuring its distance to each satellite.

There are several such navigation satellite systems, including some smaller ones that have only limited coverage. The four systems with global coverage are the Global Positioning System (GPS, owned by the United States), Galileo (owned by the European Union), GLONASS (owned by Russia), and BeiDou (BDS, owned by China) [98–101]. GNSS satellites of these systems typically transmit multiple signals on multiple frequencies, some of which are exclusively intended for military use. Lower-cost civilian receivers often only receive a band around 1575.42 MHz, which covers the L1 and L1C GPS signals, the E1 Galileo signal and the B1C BeiDou signal.

The exact signal periods and modulation structures differ between the different systems, but the general principles are the same. The following is a brief overview of how GNSS satellite signals generally work, summarised from the interface control documents for GPS, Galileo, GLONASS, and Beidou [98–101]. I will provide more detailed information for the civilian GPS signal, which is also known as the coarse acquisition (C/A) signal. The C/A signal will be used as an example throughout this section.

Each GNSS satellite has its own unique public binary pseudorandom noise (PRN) code that is modulated into the carrier wave and repeats with a period of one or more milliseconds (depending on the GNSS) at the so-called chip frequency f_C.

For GPS, the C/A PRN codes are 1023 bit long and the chip frequency is $f_c = 1.023\,\text{MHz}$, which means that the code is repeated every millisecond. The PRN codes can be created with a simple shift register simulation [98]. They are Gold codes, which means that they have very small cross-correlations [102]. This makes it possible to isolate individual satellite signals even though multiple satellites in one constellations are using the same carrier frequency.

This signal with the PRN code modulation is then used to send navigation data bits that contain information needed for traditional satellite navigation, such as the precise on-board time and the orbit parameters of the satellite. This navigation data is modulated into the signal at a much lower frequency and takes multiple seconds to repeat, placing a limit on the time to first fix (TTFF).

For GPS, the navigation data bits are transmitted at 50 Hz. Those bits, in turn, make up words, subframes, pages, and finally, master frames. One master frame lasts 12.5 min and is considered one full navigational message. The subframes with the most crucial navigational information are repeated every 30 s.

This navigational signal is traditionally decoded in real-time and used to determine the position of a receiver. However, the data transmitted by GNSS satellites is also regularly collected and uploaded online by the U.S. Department of Homeland Security [103]. It therefore does not need to be decoded from the satellite signal if the position computation can be delayed. This is exploited with a snapshot GNSS approach, as discussed later in Section 2.5.4. In that case, only information at the PRN code level is necessary since the rest can be looked up elsewhere. For such an approach, recordings therefore only need to be a few milliseconds long.

2.5.1 GNSS radio receivers

A radio receiver is used to receive transmissions from GNSS satellites. In the commonly used superheterodyne design, the incoming signal from the antenna is mixed with a local oscillator. This creates a shifted version of the original signal at the difference between the original frequency and the local oscillator frequency, called the intermediate frequency (IF). The IF is fixed, and the receiver is tuned to a specific frequency by setting the local oscillator. The use of an IF allows for better selectivity because filters can achieve narrower bandwidths at lower frequencies.

The bandwidth needs to be broad enough to capture the sidebands around the carrier frequency, which contain the modulation information. For satellite signals, another effect needs to be taken into account. GNSS satellites travel at multiple kilometres per second, although different GNSS constellations have different orbit shapes and velocities. Most of this is tangential to the line-of-sight of an observer on Earth, but rising and setting satellites will have a non-negligible velocity along the line-of-sight, which results in a Doppler-shifted signal. For a stationary observer, this can cause frequency shifts of multiple thousand Hertz in either direction [104].

Another important property of the radio receiver is the sampling frequency. Generally, higher sampling frequencies yield better signal quality, but they also require more expensive hardware. For distortion-free signals, the sampling frequency should be at least twice the intermediate frequency (and a little more when accounting for the bandwidth and possible Doppler shift of the signal).

2.5.2 Signal acquisition

The first step in processing GNSS signals is the so-called acquisition [104]. During acquisition, the recording is searched for signals from any GNSS satellites. To do so, one needs to consider that (i) due to the relative velocity of the satellite and receiver along the line-of-sight, the signal will be Doppler-shifted by some amount, and (ii) recorded signals will usually not start at the first bit of the PRN code. A successful acquisition will for each satellite return:

- A measure of signal strength, such as a signal-to-noise ratio (SNR) that indicates how likely it is that this satellite's signal is actually in the recording.
- The Doppler shift (f_D) of the signal from that satellite. In the case of GPS signals, $f_D \in [-5\,\text{kHz}, 5\,\text{kHz}]$ for a stationary observer [104].
- A code phase (CP) that specifies where in the PRN code the recording starts. This is usually measured in chips, where one chip corresponds to one bit in the code. For GPS, the chipping frequency is $f_C = 1.023\,\text{MHz}$ and the code length is 1023 chips, so one chip is $T_C = 1/f_C \approx 978\,\text{ns}$ long and $CP \in [0, 1023)$ [98].

There are several acquisition algorithms that differ in performance and runtime [104]. Below is an outline of one possible implementation for acquiring GPS signals in a given recording.

At any one point in time, the GPS constellation has up to 32 operational satellites that can be checked for. Approximate knowledge about where and when the recording was taken can be used to infer which satellites could have been in the sky. The search can then be restricted to those. The discretised output from the radio receiver for one satellite signal (ignoring noise and other sources), sampled at sampling frequency f_S is given by:

$$s_{rec}(n) = C(n + N_{CP})D(n)\cos(2\pi(f_{IF} + f_D)T_S n + \phi) \tag{2.1}$$

where C and D are the PRN code and the navigation data for that satellite at the sampling frequency, f_{IF} is the intermediate frequency of the receiver, f_D is the Doppler shift, $T_S = 1/f_S$ is the sampling period, ϕ is the carrier signal phase and N_{CP} is the code phase of the signal, measured in samples. The code phase can also be expressed in units of time or, more commonly, in chips, here simply denoted as

CP. The relationship is given by:

$$\begin{aligned} N_{CP} &= \text{(code phase in samples)} \\ &= \text{(code phase in time)} \times f_S \end{aligned} \tag{2.2}$$

$$\begin{aligned} CP &= \text{(code phase in chips)} \\ &= \text{(code phase in time)} \times f_C \end{aligned} \tag{2.3}$$

Therefore:

$$CP = N_{CP}\frac{f_C}{f_S} \tag{2.4}$$

To detect the presence of a specific satellite signal in the recording, the acquisition algorithm correlates the received signal with what the signal is expected to look like. This locally created expected signal is given by:

$$s_{exp}(n) = C(n)\exp(2\pi i(f_{IF} + f_D)T_S n) \tag{2.5}$$

where f_D is looped over all possible values. Note the absence of any navigation data, as it is not known. Navigation data bits are transmitted at 50 Hz, so bit changes can occur every 20 ms. If the received sample contains such a bit change, the correlation between the expected and the received signal at the correct code phase and Doppler shift will be lower than without it. But for a strong signal the acquisition will usually still be successful.

The correlation between the expected and the received signal can be computed as:

$$corr(s_{exp}, s_{rec}) = IDFT(DFT(s_{exp})DFT^*(s_{rec})) \tag{2.6}$$

where DFT is the discrete Fourier transform, $IDFT$ is its inverse and DFT^* is its complex conjugate. The squared correlation at some sample $corr^2(n)$ is a measure of how likely it is that the received signal is described by the locally created signal, shifted by n samples. In the absence of noise and other signals, it will by highest when the local signal has the correct Doppler shift and at the sample $n = N_{CP}$. The signal-to-noise (SNR) ratio of that peak is given by:

$$SNR = \frac{\max(corr^2(s_{exp}, s_{rec}))}{\mathrm{mean}(corr^2(s_{exp}, s_{rec}))} \tag{2.7}$$

where the mean is taken over all possible f_D.

Figure 2.1 is an example of an acquisition result. It shows the Doppler shifts and code phases at which the correlation was highest, as well as the SNR of that peak. In this example, satellites 2, 5, 7, 9, 13 and 30 are clearly visible.

In the general case, the expected signal needs to be created and correlated with the received signal at all possible Doppler shifts $f_D \in [-5000\,\mathrm{Hz}, 5000\,\mathrm{Hz}]$. When the sampling frequency is lower than twice the intermediate frequency, aliasing effects occur so that a peak at any Doppler shift f will also have a mirror image at $-f$. In those cases, the search space can be halved to $[0\,\mathrm{Hz}, 5000\,\mathrm{Hz}]$. Furthermore, knowledge of the time and place of the recording can be cross-referenced with the GPS orbit data available online to not only check which satellites could have been visible in the sky but also to calculate at what Doppler shift their signal would have been measured.

Figure 2.2 shows the Doppler-shift-code-phase search space that the acquisition needs to cover, in the general case. It contains the squared correlation signal for satellite 30 from the example in Figure 2.1. In this case, the Doppler shift search space was searched in 100 Hz steps to make the signal visible. Smaller Doppler shift steps will generally improve acquisition results. Clearly, any reduction of the search space would be beneficial, both to reduce computation time and to avoid noisy peaks. How much the search space can be reduced depends on how good the time stamp and location estimate of the recording are.

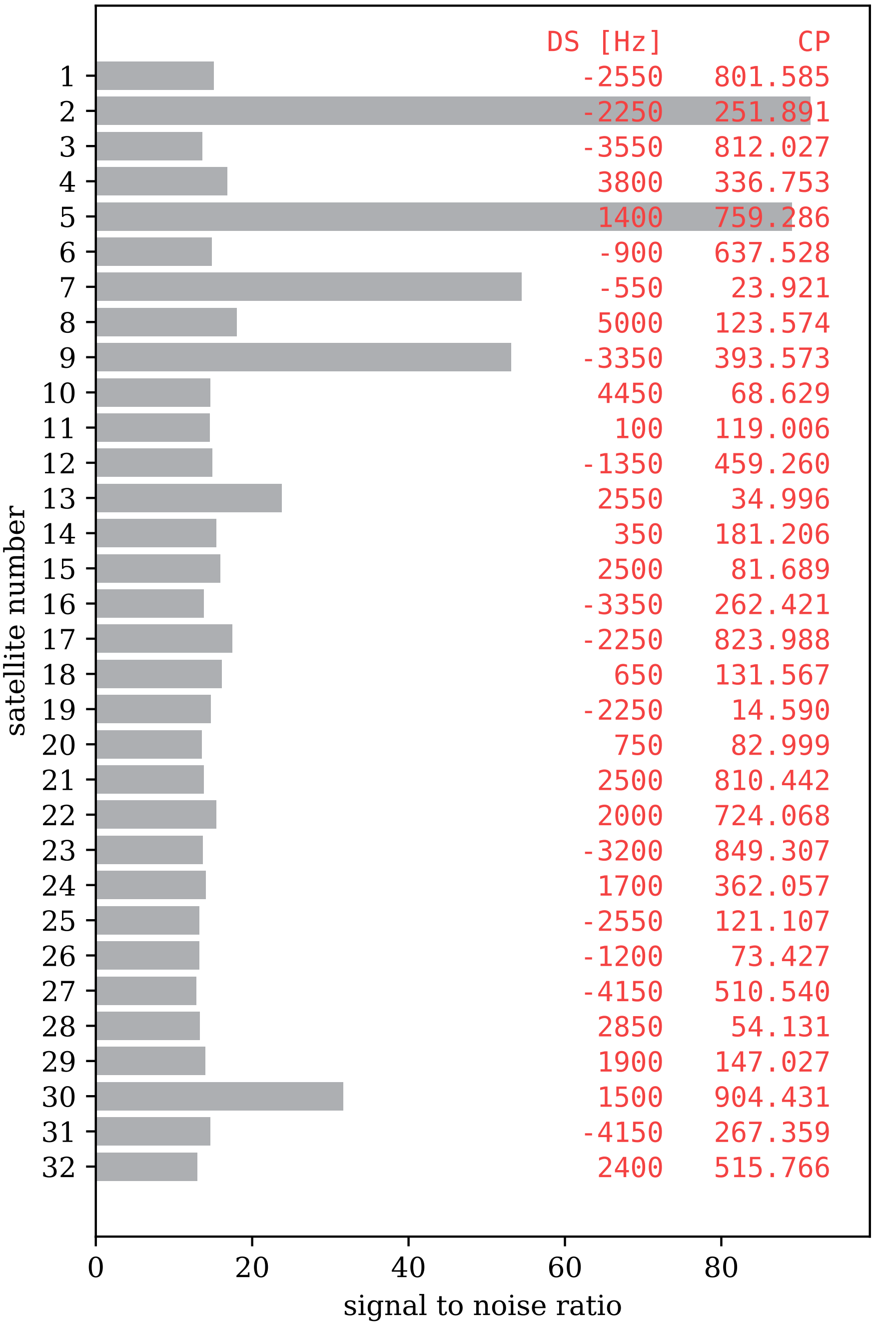

Figure 2.1: Example of a GPS acquisition output. Plotted are the signal strengths for each satellite. Also shown (in red) are the determined Doppler shift (DS) in Hertz, and the code phase (CS) in chips for each signal. This result was obtained from a 6 ms sample taken at 16.368 MHz. The Doppler shift space was searched in 50 Hz steps.

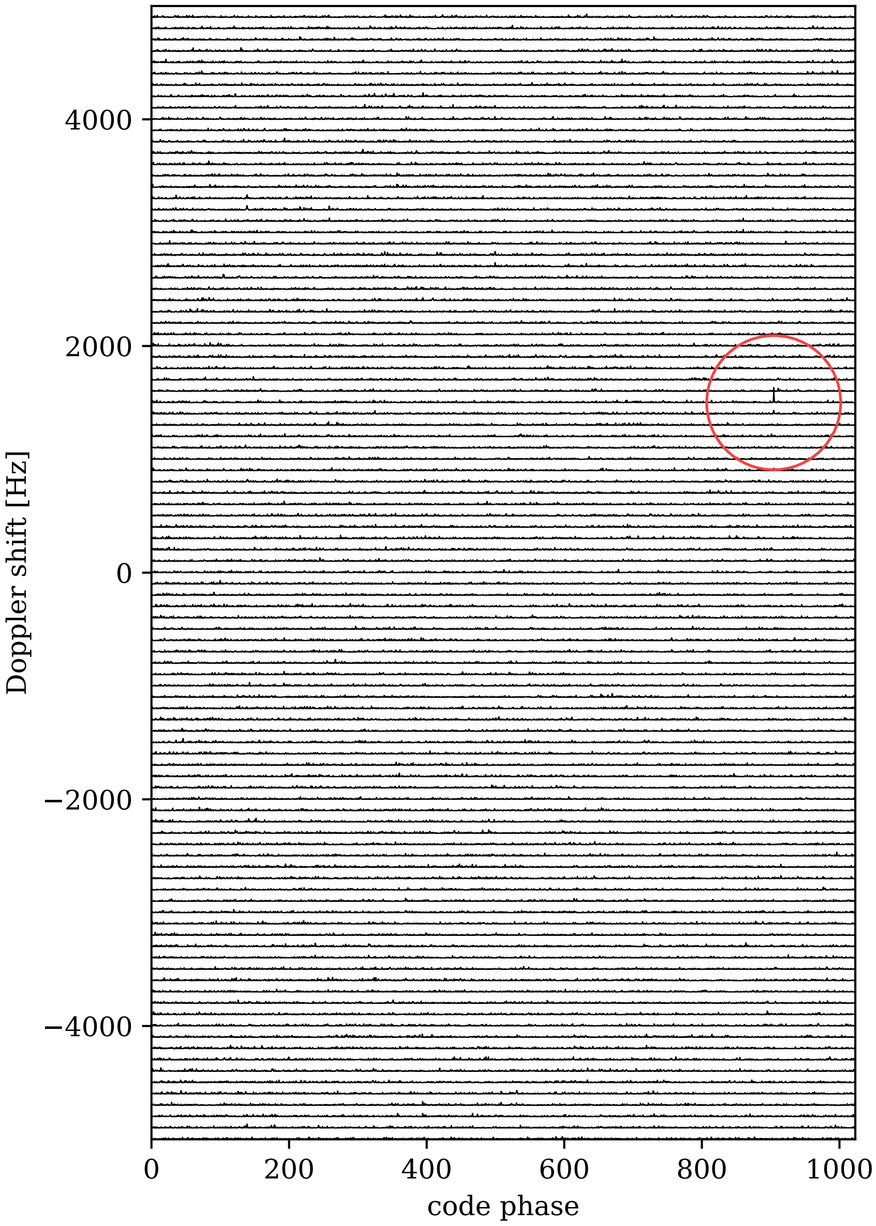

Figure 2.2: Example of a correlation signal showing the search space of Doppler shifts and code phases that the acquisition needs to cover in the case of GPS for a stationary observer. This is the correlation for satellite 30 from the same recording as in Figure 2.1. Note the peak at around $f_D = 1500\,\mathrm{Hz}$ and $CP = 900$. In this case, the Doppler shift space was searched in 100 Hz steps to make the individual correlation signals visible.

The precision of the code phase estimate determines the precision of the position fix, but it is limited by the sampling frequency. A difference in code phase of one chip corresponds to a position difference of $\Delta x = cT_C = c/f_C \approx 290\,\mathrm{m}$, where c is the speed of light. At a sampling frequency of $f_S = 4.092\,\mathrm{MHz}$, for example, the natural precision of the code phase estimate is about a quarter of a chip, which corresponds to a precision of only $\Delta x \approx 70\,\mathrm{m}$. Interpolation around the peak can increase precision [104].

2.5.3 Positioning

After the acquisition step identifies visible satellites as well as their code phases and Doppler shifts, this information can be used to continue with positioning. With a **traditional GNSS** approach, the acquired signals are tracked to read the navigation data. This data is then used to find the position of the visible satellites, the distance of the observer to the satellites, and finally, the position of the receiver [104]. With no additional information, this may require reading multiple minutes of the satellite signal.

Assisted GNSS (A-GNSS) is a method for reducing the time to first fix (TTFF) by providing some or all of that navigation data in another way, most commonly via cellular network [105]. If an estimate of the location and time is already known, this navigation data can additionally be used to reduce the Doppler shift search space during acquisition.

With so-called coarse time navigation (CTN), the location of a receiver can be inferred from the acquired code phases of visible satellites once the navigation data is available (either decoded from the satellite signal or obtained some other way) [105]. Starting from an initial guess of the receiver position and the time-stamp of the recording, CTN first calculates rough propagation times for all visible GPS satellite signals. For each possible precise receiver location, CTN can predict the expected code phase of the signal at that location, which can be compared to the measured value. CTN uses a non-linear least-squares method to find the position that minimises the difference between the expected and the measured code phases.

For CTN to be possible, the initial position guess needs to be good enough that the code phase can be used to distinguish between all possible receiver locations. In the case of GPS, a difference in code phase of one chip corresponds to a position difference of $\Delta x = c\,T_C = c/f_C \approx 290\,\mathrm{m}$, where c is the speed of light. So the 1023 chips in a GPS PRN code can differentiate positions across $1023 \times 290\,\mathrm{m} \approx 300\,\mathrm{km}$. To ensure that the code phase will be unambiguous, the accuracy of the initial position guess should therefore be better than 150 km.

2.5.4 Snapshot GNSS

Snapshot GNSS is an approach to positioning with GNSS, where the receiver records only milliseconds of the satellite signal. This is sufficient to find the code phase and Doppler shift of the signal but not enough to decode any further information it carries. The navigation data needs to be provided in a different way. As such, it can be understood as a type of A-GNSS. Typically, the processing is not carried out on the device. Instead, the raw snapshots are saved until the device is recovered.

There are three main snapshot parameters that affect the performance of the system: the snapshot length, the bit resolution and the sampling frequency.

Longer snapshots with higher bit resolution sampled at higher frequencies carry more information and have the potential to lead to better positioning performance. However, they also require more storage per snapshot. Additionally, multi-bit data streams require more complex hardware.

2.5.4.1 Commercial snapshot GNSS systems

It can sometimes be difficult to tell if a commercially available system is a snapshot system, as the term is not always used, and implementation details are typically not

Table 2.1: Commercial, proprietary snapshot GNSS systems

Company	**Technology**	**Products**	**Snapshot length**	
Lotek	FastGPS	F5G 234A, F5G 234B, F5G 334A	unkown	[31]
Advanced Telemetry Systems	-	G10	64 ms, 128 ms, 245 ms, 512 ms	[32]
Baseband Technologies	-	-	2 ms – 20 ms	[33]
Wildlife Computers	Fastloc ®	SPOT-F, SPLASH-F, SPLASH10-F...	10s of ms	[34]
NAVSYS Corporation	TIDGET	TrackTag ®	30 ms	[35]

shared. At the time of writing, there are at least five commercial snapshot GNSS systems. Table 2.1 lists them along with the advertised snapshot length, where available. With the exception of the one by Baseband Technologies, all of these systems are explicitly intended for wildlife tracking.

Lotek offers their FastGPS technology on multiple products, specifically designed for the tracking of marine animals, in particular penguins, pinnipeds and sea turtles [7]. Their tags weigh between 33 g and 46 g and they can be optionally equipped with a wet/dry sensor. Similarly, Wildlife Computers has a range of products using their Fastloc technology, also for marine animals [34]. Advanced Telemetry Systems offers their G10 Ultralite GPS logger as a small collar, a glue-on version and as a backpack [32]. It has been used on a variety of animals, including small mammals and turtles [106, 107]. The TrackTag by NAVSYS has been used to track wandering albatrosses in the Atlantic but the company mostly focuses on other commercial as well as military applications [35].

2.5.4.2 Research snapshot GNSS systems in the literature

A small number of research groups have published papers on snapshot GNSS innovations. They are listed in Table 2.2, alongside the snapshot parameters used. The table also indicates whether the publication included a dedicated hardware system, whether the system is open-source and how it has been tested. A few of these papers present dedicated complete snapshot receiver hardware to log data.

In 2012, researchers at Microsoft Research, the Federal University of Minas Gerais and the Harbin Institute of Technology published a snapshot approach called Cloud Offloaded GPS (CO-GPS). The system was implemented and tested on CLEO, a purpose-built device [29]. The system was tested in stationary scenarios in six locations and achieved a median accuracy of 27 m when using an approach that splits the snapshot into five parts.

In 2019, researchers at ETH Zurich published a paper on a particularly small and lightweight coin-cell-operated snapshot receiver [26]. This work expands on a previous paper from 2017 [27]. The researchers evaluated the system by placing it on top of a building. In this stationary test, all calculated positions were within 25 m of the ground truth position.

Most recently, a 2020 paper from the University of Otago described the FastFix algorithm, which was implemented on custom hardware. This FastFix tag uses a solar panel for power and has been successfully used to track albatross [24].

The code for the FastFix algorithm is open-source[1], although the hardware is not. None of the other snapshot systems presented in Table 2.2 have open-source hardware, firmware or software. This makes reproducing any results difficult and further research challenging.

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[1] Source code: `https://github.com/elec-otago/fastfix` (last updated 2023-08-02)

Table 2.2: Snapshot GNSS systems described in the scientific literature.

Year	Paper title	Snapshot parameters			Hardware	Open-source	Deployed	
2020	Estimating position from millisecond samples of GPS signals (the FastFix algorithm)	4 ms	1 bit	16.368 MHz	yes (FastFix tag)	software	yes, in the field on albatross	[24]
2019	Massive terminal positioning system with snapshot positioning technique	20 ms	1 bit	6.200 MHz	not a full system	no	stationary tests	[25]
2019	Multi-year GPS tracking using a coin cell	1 ms	2 bit	16.348 MHz	yes	no	stationary test	[26]
2017	Fast and robust GPS fix using one millisecond of data	1 ms	8 bit	8.000 MHz	not a full system	no	stationary tests	[27]
2016	Snapshot positioning without initial information	10 ms	?	16.368 MHz /38.192 MHz	not a full system	no	stationary test	[28]
2012	Energy efficient GPS sensing with cloud offloading	5 × 2 ms	16 bit	2.046 MHz	yes (CLEO)	no	stationary tests	[29]
2011	Collective detection and direct positioning using multiple GNSS satellites	1 ms – 10 ms	2 bit	8.184 MHz	not a full system	no	stationary tests	[30]

Chapter 3

Evaluation of positioning with low-quality signals

3.1 Introduction

As outlined in Chapter 1, the snapshot GNSS approach has multiple notable advantages, particularly for wildlife tracking applications. A small number of snapshot GNSS systems are already commercially available, and a few research prototypes exist, as listed in Section 2.5.4. However, none of the existing systems are completely open-source, preventing further research and development.

One of the goals of this thesis is to develop a new, fully open-source snapshot GNSS system to address this. The aim of this chapter is to evaluate the feasibility of developing such a system with low-cost, off-the-shelf components.

Existing snapshot GNSS systems in the literature use a variety of snapshot parameters, as can be seen in Table 2.2. These prototypes use snapshot lengths between 1 ms and 20 ms, bit resolutions between 1 bit and 16 bit and sampling frequencies between 2.046 MHz and 16.368 MHz.

Increasing any of these three parameters results in more signal information, which improves positioning. However, it also increases the complexity of the hardware required to handle the signal. Furthermore, higher-quality snapshots require more storage space, reducing the total number of snapshots that can be recorded per deployment. Longer snapshots also mean longer radio on-times, which leads to higher energy consumption.

Another major factor contributing to signal quality is the antenna used to collect the radio signal. Larger antennae tend to yield better signal quality but are typically more expensive and heavier. A light and low-cost solution therefore needs to be able to cope with signals from small antennae.

In this chapter, I evaluate the effect of different sample lengths and sampling frequencies on signal acquisition and CTN positioning performance. For simplicity, only GPS satellite signals are used for both acquisition and positioning. I consider sampling frequencies of 4.092 MHz, 8.184 MHz and 16.368 MHz, as well as sample lengths of 3 ms, 6 ms and 12 ms. I also compare three different active patch antennae between 10 mm × 10 mm and 25 mm × 25 mm in size.

Since single-bit data streams can be easily processed with low-cost hardware, this chapter only considers snapshots with 1 bit resolution.

I show that 12 ms snapshots with 1 bit resolution sampled at only 4.092 MHz are sufficient to achieve median localisation errors of less than 15 m with a 25 mm × 25 mm antenna. I also show that even smaller and cheaper antennae can still be used to generate practically useful position estimates, provided sampling frequencies and sample lengths are large enough.

3.2 Methods

This section describes the methods for the work presented in this chapter. It covers the hardware used to collect the raw data, the experimental conditions under which the data was collected, how it was prepared, and finally, how the results were obtained from the data.

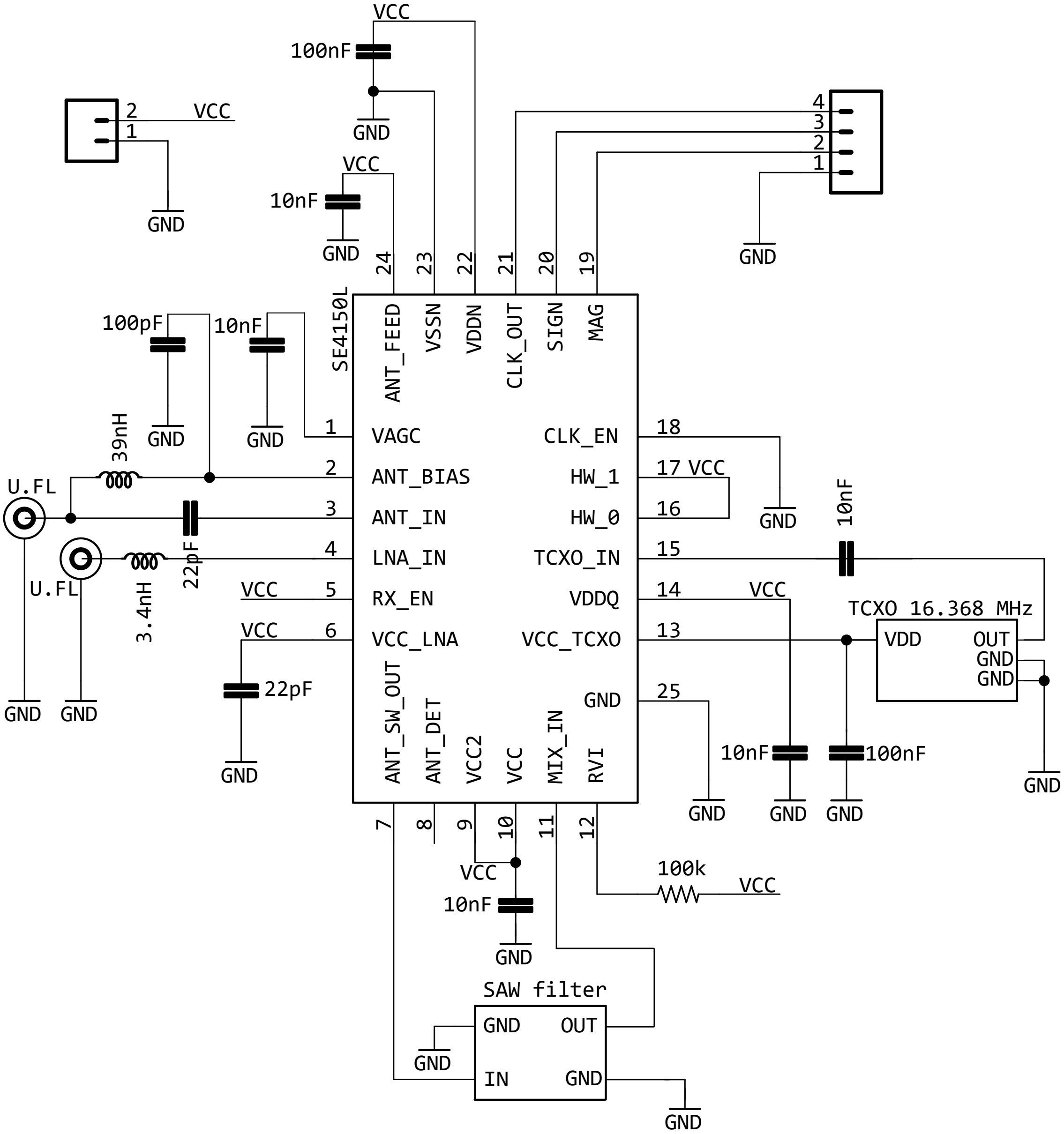

Figure 3.2: Schematic for the radio part depicted in Figure 3.1. See Table 3.1 for the full part numbers of the main components.

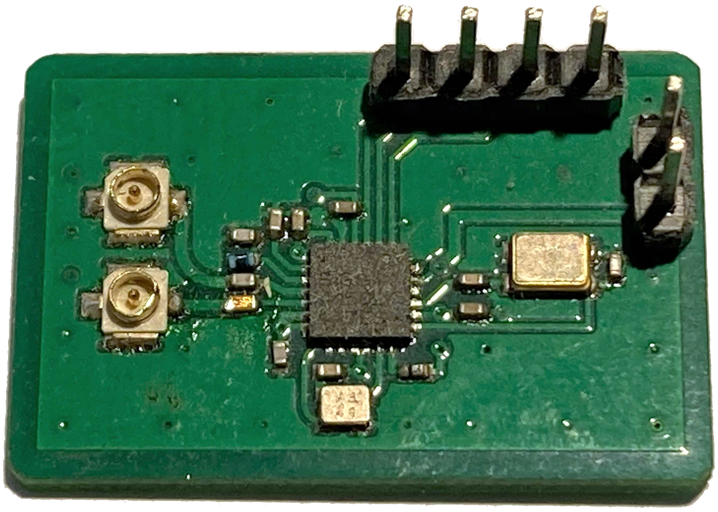

Figure 3.1: Photograph of the radio part. In the middle is the SE4150L GPS receiver chip (3 mm × 3 mm).

Table 3.1: The main components used for the radio part shown in Figure 3.1.

Component	Manufacturer	Part number
RF GPS receiver 1575.43 MHz	Skyworks Solutions	`SE4150L-R`
SAW filter 1575.43 MHz	Abracon	`AFS20A42-1575.42-T3`
Oscillator 16.368 MHz	TXC Corporation	`7Q-16.368MBG-T`

Table 3.2: Antenna models used for the results in this chapter.

Name	Manufacturer	Part number	Gain [dB]	Size [mm × mm]
ECHO19	Siretta	`ECHO19/0.1M/UFL/S/S/17`	16	10 × 10
ECHO27	Siretta	`ECHO27/0.1M/IPEX/S/S/26`	22	15 × 15
MAX	Maxtena	`MIA-GPS-25`	34	25 × 25

3.2.1 Hardware

The recordings used for this investigation were taken with an SE4150L GPS receiver IC by Skyworks[1]. This chip was chosen because it is particularly low-cost and low-power and requires less configuration than other options. The intermediate frequency of the radio receiver is 4.092 MHz. The radio receiver was operated with a

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[1] Data sheet: SE4150L GPS Receiver IC, `http://web.archive.org/web/20201207034114/https://www.skyworksinc.com/-/media/SkyWorks/Documents/Products/601-700/SE4150L_202445B_Discontinued.pdf` (archived 2020-12-07)

temperature-compensated oscillator and a surface acoustic wave (SAW) filter. This was set up on a custom PCB, as shown in Figure 3.1. Figure 3.2 includes the schematic for the PCB. The main components used are listed in Table 3.1.

Table 3.2 lists the three antenna models that were tested, sorted by size. They are all active patch antennae. Larger antennae tend to be heavier and more expensive but also typically offer a better signal-to-noise ratio. For each antenna model, two instances were tested, labelled A and B in the following. All models use U.FL (also known as I-PEX and other brand names), a miniature RF coaxial connector.

3.2.2 Recording parameters and data preparation

Recordings were taken on 1 September 2020 with good sky visibility. For each physical antenna, 100 ms of data were recorded with 2 bit resolution and with a sampling frequency of 16.092 MHz.

A 2 bit data stream introduces additional hardware complexity needs. Since this work focuses on potential low-cost implementations of a snapshot GNSS receiver, the recorded data was downsampled to 1 bit resolution.

Each full recording was then cut up into shorter samples, each offset by 1 ms from the previous one. This means that every sample will have the same code phase because the GPS coarse acquisition (C/A) code repeats every 1 ms. Samples with lengths of 3 ms, 6 ms and 12 ms were extracted.

Copies of these samples were then downsampled to create equivalent recordings with sampling frequencies of 8.046 MHz and 4.023 MHz. This resulted in 88 samples for each combination of antenna, sampling frequency and sample length.

3.2.3 Signal processing

An acquisition algorithm (as described in Section 2.5.2) was then run on these samples. For this chapter, only GPS satellites are considered. These can exhibit Doppler shifts of up to 5000 Hz. So acquisition needs to involve searching the entire possible Doppler shift range of $[-5000\,\mathrm{Hz}, 5000\,\mathrm{Hz}]$. However, for sampling frequencies of 8.046 MHz and less, a peak at any given Doppler shift f will also have a mirror image at $-f$, so that the search space can be reduced to $[0\,\mathrm{Hz}, 5000\,\mathrm{Hz}]$. For all the following results, the Doppler shift search was always done in 50 Hz steps. The acquisition step results in a code phase estimate, a Doppler shift estimate and a signal-to-noise ratio (SNR) for each GPS satellite.

After the acquisition step, a coarse-time navigation algorithm (CTN, as described in Section 2.5.3) was used to produce a position estimate for each sample. To run CTN, one needs to decide which code phase estimates from the acquisition step to use. Satellites with a clear line of sight to the receiver will typically have a very high signal-to-noise ratio (SNR). But other visible satellites may have SNR values similar to non-visible satellites, even if the code phase was correctly identified. If the signal quality is good, simply picking the satellites with the highest signal-to-noise ratio yields good results. With smaller antennae and lower sampling frequencies, this is no longer a reliable strategy. However, the 100 ms recordings are long enough to determine the true satellites and corresponding code phases. When running the acquisition on shorter samples, it is then possible to perfectly pick all the satellites for which the acquisition step found the correct code phase. The code phase was allowed to differ by up to one full chip. However, typically, the code phase was either consistent within 0.1 chips or completely off. In practice, good satellite-picking algorithms become important. But this method allows testing in the best-case scenario in which only correctly acquired signals are used.

CTN also requires an initial guess for the location and time of the recording. The initial guess for the time of the recordings is the timestamp rounded to the nearest minute. This is worse than what is typically possible in practice. The initial guess for the location was a randomly chosen point 7 km away from the true position.

The ground truth location was measured with a Reach RS+ module by Emlid[2] to an accuracy of 1 m.

3.3 Results

This section presents the results of the experiments, detailing the key findings. Section 3.3.1 first covers the findings related to acquisition results, and then Section 3.3.2 contains everything related to the position estimates obtained using CTN.

3.3.1 Acquisition results

Figure 3.3a shows the acquisition output (code phase and SNR) for the 88 consecutive 12 ms, 16.368 MHz samples taken with a Maxtena antenna. Depicted are the acquisition results for four of the satellites visible at the time. Some have higher SNR values than others, but all four satellite signals are correctly acquired in almost every sample.

Figure 3.3b shows the same acquisition results for the same signal samples, but this time downsampled to 4.092 MHz. Most satellite signals are still correctly acquired, although SNR values are generally lower. However, the downsampling made the already weak signal of Satellite 13 much harder to acquire. As a result, there are gaps in the code phase estimates for that satellite signal.

The navigation data in a GPS signal is transmitted at 50 Hz. This means that a bit change can occur every 20 s. Such a bit change will negatively affect the acquisition quality. This can be seen in Figure 3.3a, where it is particularly noticeable for Satellite 2 and Satellite 5. In those cases, it did not cause significant changes in the code phase estimate. However, in general, it is possible for bit changes to cause acquisition failures. This is more likely for lower-quality signals and may have been the cause for the code phase gaps in the case of Satellite 13 in Figure 3.3b.

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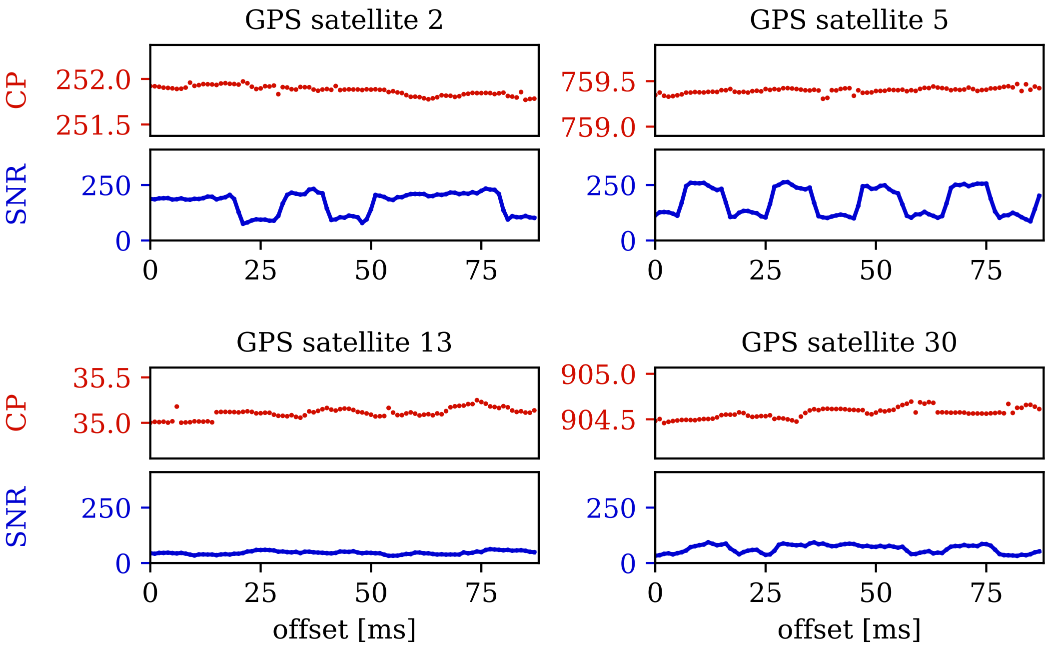
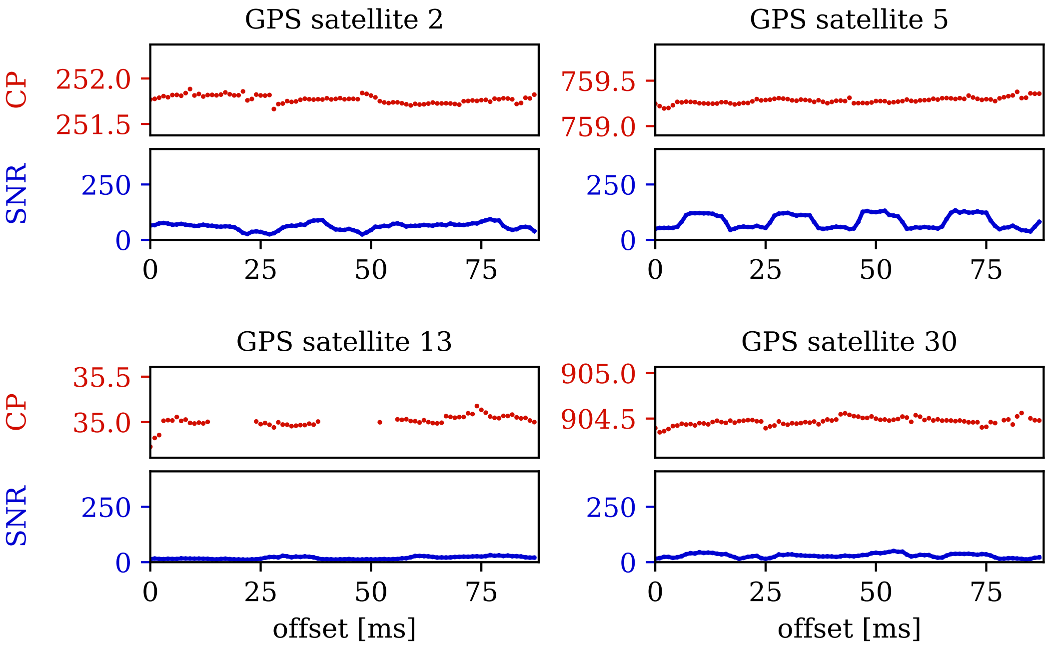
[2] Data sheet: Reach RS+, `http://web-old.archive.org/web/20201111151006/http://files.emlid.com/reachrs/Reach-RS-Plus-Datasheet.pdf` (archived 2020-11-11)



(a) Acquisition results for 16.368 MHz samples.



(b) Acquisition results for 4.092 MHz samples.

Figure 3.3: Acquired code phase (CP) and signal-to-noise ratio (SNR) for 88 consecutive 12 ms samples, sampled at (a) 16.368 MHz, and (b) 4.092 MHz with antenna MAX-A.

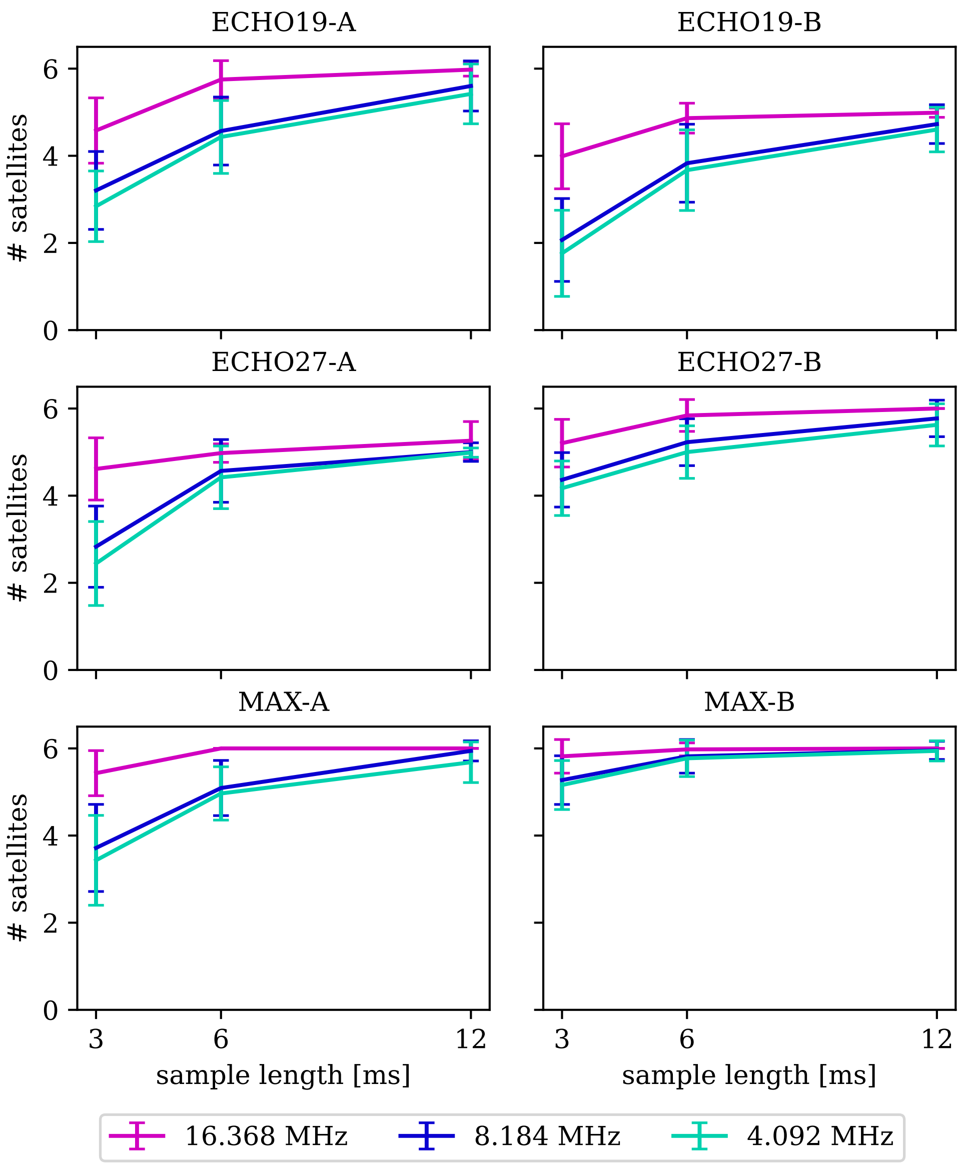


Figure 3.4: Average number of satellites with correctly acquired code phase as a function of sample length for all three considered sampling frequencies and all antennae. Error bars correspond to one standard deviation.

Figure 3.4 shows how the average number of correctly acquired satellite signals is affected by sample length and sampling frequency for each antenna. Here, only the six satellites with elevations above 20° at the time of the recording were checked. Depending on the environment, satellites below this threshold may still be visible.

As anticipated, higher sample lengths and higher sampling frequencies both generally improve acquisition results. Larger antennae also tend to improve results, although differences between two antennae of the same model are sometimes larger than differences across different models.

Successful positioning requires at least four correctly acquired satellite signals. This is because both the position and time of the receiver need to be estimated, resulting in a problem with four unknowns. Figure 3.4 shows that four satellites are, at least on average, not always available for all sampling parameters. Based on these acquisition results, it should be expected that positioning will sometimes not be possible, particularly with smaller antennae and at lower sampling frequencies as well as lower sample lengths. However, for all antennae, 12 ms samples, recorded at 16.368 MHz resulted in at least four correctly acquired satellite signals, on average. This suggests that all antenna models presented here could be used in practice with the considered radio setup, provided samples are sufficiently long and recorded with sufficiently high sampling frequency.

3.3.2 CTN positioning results

This section covers how different antennae, sample lengths and sampling frequencies affect the quality of CTN positioning using the acquisition results described in the previous section.

Figure 3.5 plots the median horizontal error for each combination of antenna, sampling frequency and sample length with a cut-off at 50 m. As a general trend, increasing sample length or sampling frequency decreases median error.

Larger antennae generally perform better, with the Maxtena performing the best. For 12 ms long recordings that were sampled at 16.368 MHz, the median horizontal error (taken over both antennae) is 10.5 m. But even the lowest tested sample length of 3 ms still results in median errors below 25 m, provided the sampling frequency is high enough. Similarly, even sampling frequencies of only 4.092 MHz can be compensated for by using 12 ms long samples.

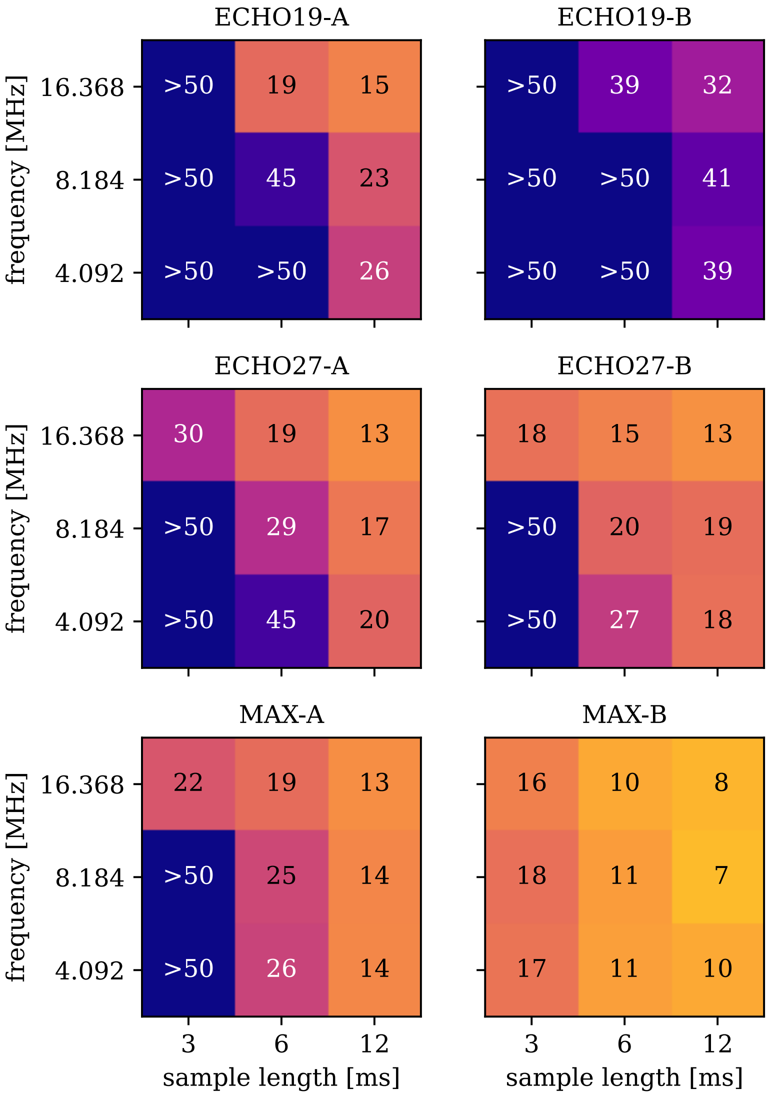


Figure 3.5: Median horizontal error in metres, as a function of sample length and sampling frequency for all antennae.

These results generally correspond well to the acquisition results from Figure 3.4, discussed above. Whenever fewer than four satellites are (on average) available for positioning, location estimates are generally very poor. Above that, more satellites tend to improve positioning.

A large median error does not necessarily imply that positioning is impossible. For this, other measures of performance need to be evaluated beyond just median error.

For a more complete picture, Figure 3.6 shows the cumulative horizontal error distribution for CTN results on 12 ms samples. The three different sampling frequencies

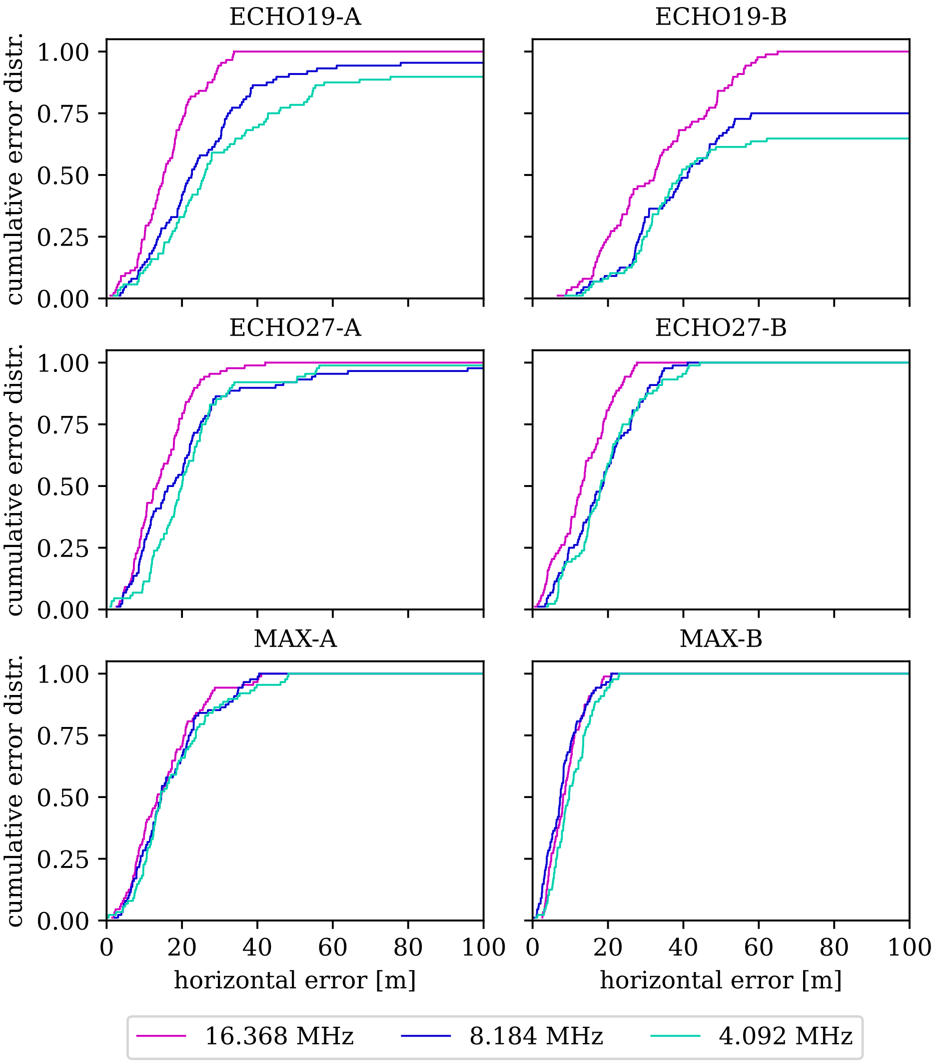


Figure 3.6: Cumulative horizontal error for 12 ms long snapshots.

are denoted as different colours. Figure 3.7 shows the same but for samples taken at 16.368 MHz. Here, the different colours correspond to different sample lengths.

For the parameters considered in Figure 3.6 and Figure 3.7, cumulative median errors generally plateau at less than 100 m. This means that a successful fix is typically at least that accurate. The height of the plateau indicates the fraction of successful positioning fixes. For the best antenna, the highest sampling frequencies, and the longest sample lengths, the plateau usually includes close to 100 % of the positioning estimates. This means that CTN typically always converges in those cases. However, there still can be significant differences in median error.

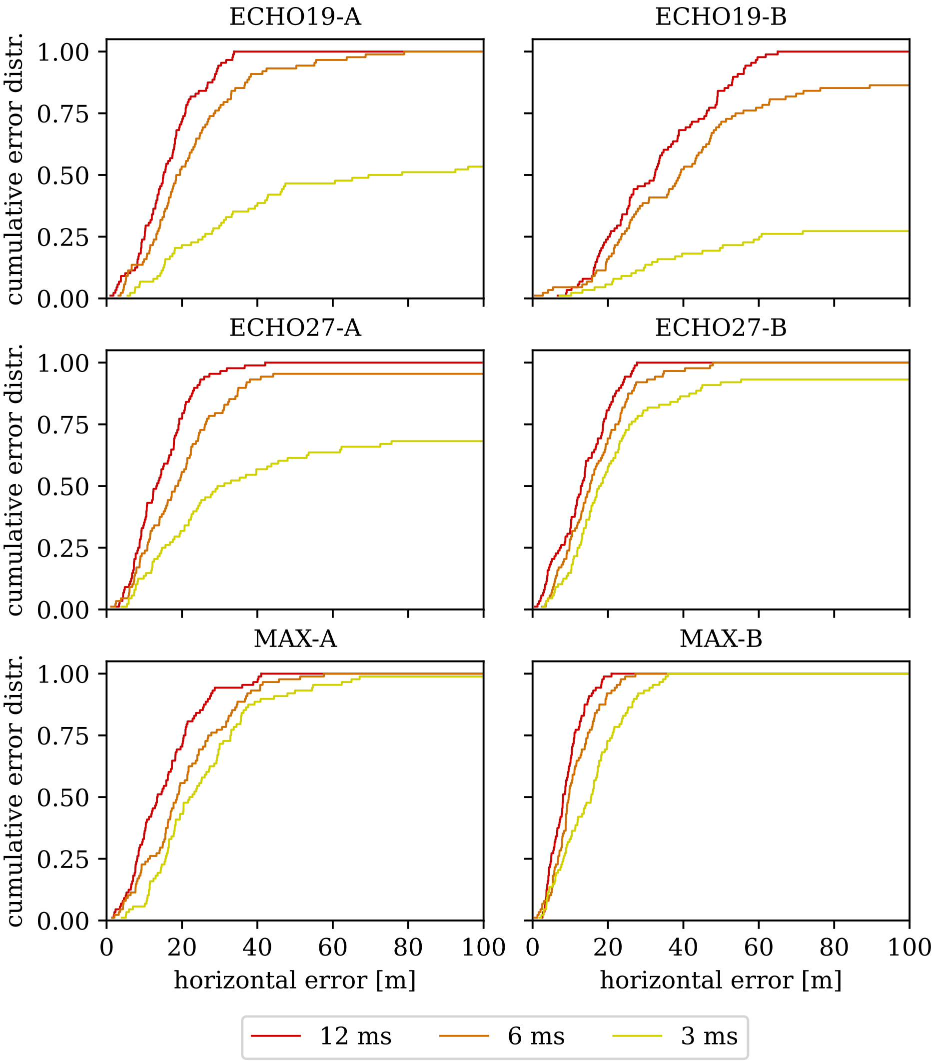


Figure 3.7: Cumulative horizontal error for snapshots sampled at 16.368 MHz.

In cases where the cumulative error plateaus with less than 100 % of the position estimates, the median error is less informative. This can be seen for antenna ECHO19-B in Figure 3.7. At a sampling frequency of 16.368 MHz, 3 ms samples perform poorly with a median error above 100 km. However, a quarter of position estimates still exhibit errors of less than 100 m. Completely unsuccessful estimates will be random and can therefore often be filtered out. In practice, this means that positioning is still possible. Successful position fixes are just less frequent. It is therefore important to consider the error distribution and not just the mean or median error.

3.4 Recommendations for developers

These results show that sampling frequency, sample length, and antenna size can be traded off against each other. For example, if high sampling frequencies are not supported by the chosen hardware, the snapshot length can be increased to compensate, and vice versa.

Both sampling frequency and sample length contribute linearly to the size of the snapshot. If storage is a limiting factor (whether in the form of working memory or main storage), a reduced sample length and/or sampling frequency may be acceptable, provided the antenna is sufficiently large. This means that applications that can tolerate bigger and heavier antennae may be able to increase their maximum deployment time (or increase their temporal resolution). Developers of snapshot GNSS tags should therefore consider making their snapshot parameters configurable, allowing users to adjust them to suit their application.

This chapter only considered a limited range of possible configurations. The conclusions can be extrapolated, but there are limits. Using the Nyquist-Shannon sampling theorem, the sampling frequency needs to be at least twice the chipping frequency. In the case of GPS, this is $f_{min} = 2 \times f_C = 2 \times 1.023\,\text{MHz} = 2.046\,\text{MHz}$. Additionally, the PRN codes in GPS signals repeat every millisecond. Samples much shorter than this will likely perform poorly, as excessively cropped PRN codes become difficult to distinguish.

3.5 Conclusion

This chapter presented experiments examining the effects of three different sampling frequencies and sample lengths on GPS signal acquisition and CTN positioning. The experiments also compared three different antennae of different sizes.

As anticipated, higher sampling frequencies and longer sample lengths generally improved both acquisition and positioning results. Larger antennae also generally performed better.

These results demonstrate that 12 ms snapshots, sampled at 4.092 MHz with 1 bit resolution already contain enough information to achieve median localisation errors under 15 m with a 25 mm × 25 mm antenna.

Chapter 4

Analysis of the energy advantage of snapshot GNSS

4.1 Introduction

Snapshot GNSS tags typically have much lower energy consumption than traditional GNSS tags. This is mainly due to their significantly shorter radio on-times per fix. A snapshot GNSS tag needs only a few milliseconds of radio signal to determine a location, while a traditional GNSS tag may need up to 30 s of continuous signal. Some traditional GNSS tags now offer low-power modes to address this. However, even then, a traditional tag is usually constrained by the available battery. Deployments eventually need to stop because the battery runs out. A snapshot tag, however, will typically be constrained by storage, not energy. This is because snapshots of raw radio signals take up significantly more storage than a set of location coordinates. It is therefore not obvious whether a snapshot GNSS tag will generally last longer than a traditional GNSS tag when making equally frequent location fix attempts. The goal of this chapter is to analyse how the two GNSS approaches compare for different deployment lengths.

Most wildlife tracking technology is proprietary, and detailed energy consumption profiles are usually not available. Here, I use the OriginGPS Multi Micro Hornet (ORG1510-R01) as an example of a traditional GNSS tag. I chose this model because it was designed specifically for low-power applications. Its data sheet also provides some detail on its implementation, unlike most other systems[1]. I compare this OriginGPS tag with a theoretical snapshot GNSS tag based on the feasibility results from Chapter 3. I consider both a version with simple flash storage and one using an SD card which provides much more storage but also requires more energy.

The following calculations neglect some details, including storage needed for firmware and file allocation tables, write speed changes when writing files close to the block size, leakage currents and voltage changes as the battery depletes. They are therefore likely to slightly overestimate the real-world performance of the systems.

I show that snapshot GNSS tags have a particularly large advantage for longer deployments where they can provide significantly more frequent location fixes.

4.2 Snapshot GNSS receiver

The three main contributors to the battery capacity needs of a snapshot receiver are (i) capturing snapshots, (ii) writing snapshots to storage, and (iii) keeping track of the on-board clock between snapshots.

For the latter, a typical low-power microcontroller consumes about 1 µA. This results in a battery charge consumption of $1\,\mu\mathrm{A} \times 365 \times 24\,\mathrm{h} \approx 8.8\,\mathrm{mA\,h}$ per year, or 43.8 mA h over five years.

The initial feasibility investigations presented in Chapter 3 show that 12 ms long signals sampled at 4.092 MHz with 1 bit resolution are already sufficient to achieve accuracies better than 15 m. One snapshot then requires

$$S^{snap} = 12\,\mathrm{ms} \times 4.092\,\mathrm{MHz} \times 1\,\mathrm{bit} = 49\,104\,\mathrm{bit} \approx 6\,\mathrm{kB} \tag{4.1}$$

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[1] Data sheet: Multi Micro Hornet (ORG1510-R01), `http://web.archive.org/web/20211123152616/https://origingps.com/wp-content/uploads/2021/01/Multi-Micro-Hornet-ORG1510-R01-Datasheet-Rev3.0.pdf` (archived 2021-11-23)

of storage. For a given battery size, there is a maximum useful storage S that can be embedded in the system. This constrains the maximum number of snapshots that can be captured to $N = S/S^{snap}$. The maximum possible deployment time at a given fix interval T can then be computed as $T \times N$, giving a linear relationship.

The results in Chapter 3 were obtained with an SE4150L GPS receiver[2]. The performance parameters quoted in its datasheet can be used to estimate the battery capacity needed to capture a snapshot. When active, the radio circuit consumes $I_{capture} = 15\,\mathrm{mA}$. The SE4150L includes an automatic gain control system which has a settling time of 10 ms. In total, the receiver will need to be powered on for $t^{snap}_{capture} = 12\,\mathrm{ms} + 10\,\mathrm{ms} = 22\,\mathrm{ms}$, resulting in a needed charge of

$$Q^{snap}_{capture} = I_{capture} \times t^{snap}_{capture} \approx 91.7\,\mathrm{nA\,h} \tag{4.2}$$

per snapshot.

For small batteries, serial flash is a commonly used storage solution. The supplier Winbond offers serial flash ICs in sizes 512 Mbit, 1 Gbit, 2 Gbit and 4 Gbit[3,4,5,6]. They exhibit a typical page program current draw of $I_{write} = 25\,\mathrm{mA\,h}$ and a typical page program time of $t^{snap}_{write} = 250\,\mu\mathrm{s}$. With a page size of 2 kB, one snapshot fills

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[2] Data sheet: SE4150L GPS Receiver IC, `http://web.archive.org/web/20201207034114/https://www.skyworksinc.com/-/media/SkyWorks/Documents/Products/601-700/SE4150L_202445B_Discontinued.pdf` (archived 2020-12-07)

[3] Data sheet: W25N512GVxxG/T/R, `http://web.archive.org/web/20211214110129/https://www.winbond.com/resource-files/W25N512GV%20Rev%20F%20042621.pdf` (archived 2021-12-14)

[4] Data sheet: W25N01GVxxxG/T/R, `https://web.archive.org/web/20211214131100/https://www.winbond.com/resource-files/W25N01GV%20Rev%20Q%20051721.pdf` (archived 2021-12-11)

[5] Data sheet: W25N02KVxxIR/U, `https://web.archive.org/web/20211214130810/https://www.winbond.com/resource-files/W25N02KVxxIRU_Datasheet_20210625_G.pdf` (archived 2021-12-14)

[6] Data sheet: W25N04KVxxIR/U, `http://web.archive.org/web/20211214111106/https://www.winbond.com/resource-files/W25N04KVxxIRU_Datasheet_20210903_B.pdf` (archived 2021-12-14)

Table 4.1: Table listing storage size (S) for four available serial flash ICs, the maximum number of snapshots (N) that could fit into S, the battery capacity needed to fill the entire storage (Q_{write}^{total}), the battery capacity needed to capture N snapshots with a SE4150L GPS receiver IC ($Q_{capture}^{total}$), and the total needed capacity to capture and store N snapshots ($Q^{total} = Q_{write}^{total} + Q_{capture}^{total}$).

S	N	Q_{write}^{total}	$Q_{capture}^{total}$	Q^{total}
512 Mbit	11k	60 µA h	1.0 mA h	1.1 mA h
1 Gbit	22k	110 µA h	2.0 mA h	2.1 mA h
2 Gbit	44k	230 µA h	4.0 mA h	4.2 mA h
4 Gbit	87k	460 µA h	8.0 mA h	8.5 mA h

three pages. This results in a charge consumption of

$$Q_{write}^{snap} = I_{write} \times t_{write}^{snap} \times 3 \approx 5.2\,\mathrm{nA\,h} \tag{4.3}$$

per snapshot. Table 4.1 summarises how many snapshots (N) can be stored by each storage size (S), the charge needed to fill the entire storage (Q_{write}^{total}), the charge needed to capture all of those snapshots ($Q_{capture}^{total}$), and finally the total needed charge ($Q^{total} = Q_{write}^{total} + Q_{capture}^{total}$). These results show that for serial flash, the energy needed for writing the snapshots to memory is almost negligible.

For larger batteries, SD cards become a feasible storage solution. SD cards have a minimum sequential write speed of 10 MB/s. Therefore the battery capacity needed to fill an entire SD card of size S can be estimated as

$$Q_{write}^{total} = \frac{S \times I_{write}}{10\,\mathrm{MB/s}} \tag{4.4}$$

where I_{write} is the maximum write current, which depends on the size of the SD card [1]. When using SD cards, it is important to ensure that the employed power source can handle this current draw. Table 4.2 gives an overview of available sizes of SD cards (S), the maximum number of snapshots they can store (N), their maximum write current (I_{write}), and resulting battery capacity requirements, as before.

Table 4.2: Table listing the storage size (S) and maximum write current (I_{max}) for four available SD card sizes, the maximum number of snapshots (N) that could fit into S, the battery capacity needed to fill the storage (Q_{write}), the battery capacity needed to capture N snapshots with a SE4150L GPS receiver IC ($Q_{capture}$), and the total needed capacity to capture and store N snapshots ($Q^{total} = Q^{total}_{write} + Q^{total}_{capture}$) [1].

S	N	I_{write}	Q^{total}_{write}	$Q^{total}_{capture}$	Q^{total}
16 GB	2.6M	10 mA	4 mA h	240 mA h	240 mA h
32 GB	5.2M	25 mA	22 mA h	480 mA h	500 mA h
64 GB	10.4M	35 mA	62 mA h	960 mA h	1020 mA h
128 GB	20.8M	45 mA	160 mA h	1910 mA h	2070 mA h

The results derived in this section show that even a snapshot receiver with a large 4 Gbit serial flash has very low power needs and can easily run on a small 100 mA h battery. 4 Gbit is enough for over 87,000 snapshots, which is sufficient to take a snapshot every ten minutes for a year. If larger batteries are an option, snapshot receivers with an SD card are an alternative, offering even more snapshot storage. With a 1000 mA h battery, a 32 GB SD card could be filled before power becomes a concern. This would be enough to store 5.2 million snapshots, or a snapshot every five seconds for a year.

4.3 Traditional GNSS receiver (OriginGPS example)

Unlike snapshot GNSS receivers, traditional GNSS receivers, like the OriginGPS Multi Micro Hornet, will be directly limited by the available battery capacity rather than indirectly through storage. This is because (i) the radio receiver needs to be turned on for seconds, not just milliseconds, to calculate positions, and (ii) only positioning results need to be stored, not raw radio signals.

To reduce energy use, many traditional GNSS modules now offer low-power modes that wake up regularly for a quick signal refresh to keep an up-to-date record of the satellite data[7,8]. If this satellite data is available when attempting a position fix,

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[7] See Footnote 1.

[8] Data sheet: MAX-8, u-blox GNSS modules, `https://web.archive.org/web/20201112042121/https://www.u-blox.com/sites/default/files/MAX-8_DataSheet_(UBX-16000093).pdf` (archived 2020-11-12)

the radio may only need to be powered on for a few hundred milliseconds instead of thirty seconds for a cold start because less additional information needs to be collected. This can reduce average power consumption per fix. However, it only provides an advantage when taking frequent fixes, because the satellite data is only valid for a limited amount of time, and each refresh also requires energy.

The Multi Micro Hornet offers two trade-marked low-power modes: Adaptive Trickle Power (ATP) mode can be used for fix intervals between one and ten seconds, and Push To Fix (PTF) mode can be used for fix intervals between ten seconds and two hours. ATP is optimised for use cases that require frequent fixes with low power consumption, whereas PTF is designed for scenarios that require the option to trigger unscheduled position fixes quickly. PTF mode is not meant for applications with regular fix intervals but still provides an improvement over simply performing a cold start for every fix. Both ATP and PTF rely on regular satellite tracking data updates to avoid slow and power-intensive cold starts.

For short deployments, ATP yields the highest possible fix frequency. ATP has a minimum fix interval of one second and a maximum fix interval of ten seconds. Higher fix intervals with ATP can be achieved by simply discarding fixes, however, at this point, deployment time no longer increases.

For longer deployments, PTF still provides an advantage over pure cold starts by performing a regular satellite data refresh. However, PTF is optimised for unscheduled triggered fixes, so it performs poorly compared to ATP in the context of regular fixes. PTF can be used for fix intervals between ten seconds and two hours.

For very long deployments, fixes have to occur sparsely. Eventually, fixes will always require a cold start.

The following shows how the power consumption for ATP, PTF and cold starts can be calculated from electrical characteristics provided by the Multi Micro Hornet data sheet, as listed in Table 4.3.

Table 4.3: Power-related electrical characteristics of the OriginGPS Multi Micro Hornet.

	Parameter	**Symbol**	**Value**
General	Power supply voltage	V_{CC}	1.8 V
Power	Full Power Tracking (GPS only)	P_{FPT}	72 mW
	Full Power Acquisition (GPS only)	P_{FPA}	82 mW
Current	CPU Only	I_{CPU}	15 mA
	Standby	I_{SBY}	100 µA
	Hibernate	I_{HIB}	50 µA
TTFF	Hot Start	Δt_{HS}	< 1 s
	Cold Start (GPS only)	Δt_{CS}	< 35 s

After a negligible start-up, ATP mode cycles through Full Power Tracking (P_{FPT} for $\Delta t_{FPT}^{ATP} = 100\,\mathrm{ms}$[9]), CPU Only ($I_{CPU}$ for $\Delta t_{CPU}^{ATP} = 100\,\mathrm{ms}$) and Standby ($I_{SBY}$ for $\Delta t_{SBY}^{ATP} = T - \Delta t_{CPU}^{ATP} - \Delta t_{FPT}^{ATP}$) with a period of $T^{ATP} \in [1\,\mathrm{s}, 10\,\mathrm{s}]$. Therefore, one ATP cycle with period T requires

$$Q^{ATP}(T) = \Delta t_{FPT}^{ATP} \times \frac{P_{FPT}}{V_{CC}} + \Delta t_{CPU}^{ATP} \times I_{CPU} + (T - \Delta t_{FPT}^{ATP} - \Delta t_{CPU}^{ATP}) \times I_{SBY} \quad (4.5)$$

PTF is a mode intended for scenarios where the user wants to trigger unscheduled fixes quickly. To avoid slow cold starts for such user requests, PTF performs a regular satellite data refresh. Similarly to ATP, PTF alternates between high-power tracking and low-power sleeping but at a slower frequency and using a different low-power mode. PTF cycles through Full Power Tracking (P_{FPT} for $\Delta t_{FPT}^{PTF} = 18\,\mathrm{s}$[10]), CPU Only ($I_{CPU}$ for $\Delta t_{CPU}^{PTF} = 100\,\mathrm{ms}$) and Hibernate ($I_{HIB}$ for $\Delta t_{HIB}^{PTF} = T - \Delta t_{CPU}^{PTF} - \Delta t_{FPT}^{PTF}$) with a period of $T^{PTF} \in [10\,\mathrm{s}, 2\,\mathrm{h}]$. Assuming that user requests are rare and typically require much shorter Full Power Tracking, one PTF cycle (and thereby one fix) requires

$$Q^{PTF}(T) = \Delta t_{FPT}^{PTF} \times \frac{P_{FPT}}{V_{CC}} + \Delta t_{CPU}^{PTF} \times I_{CPU} + (T - \Delta t_{FPT}^{PTF} - \Delta t_{CPU}^{PTF}) \times I_{HIB} \quad (4.6)$$

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[9] Δt_{FPT}^{ATP} can be between 100 ms and 800 ms, but $\Delta t_{FPT}^{ATP} = 100\,\mathrm{ms}$ is quoted as a typical value.

[10] Δt_{FPT}^{PTF} can be up to 30 s, but $\Delta t_{FPT}^{PTF} = 18\,\mathrm{s}$ is quoted as a typical value.

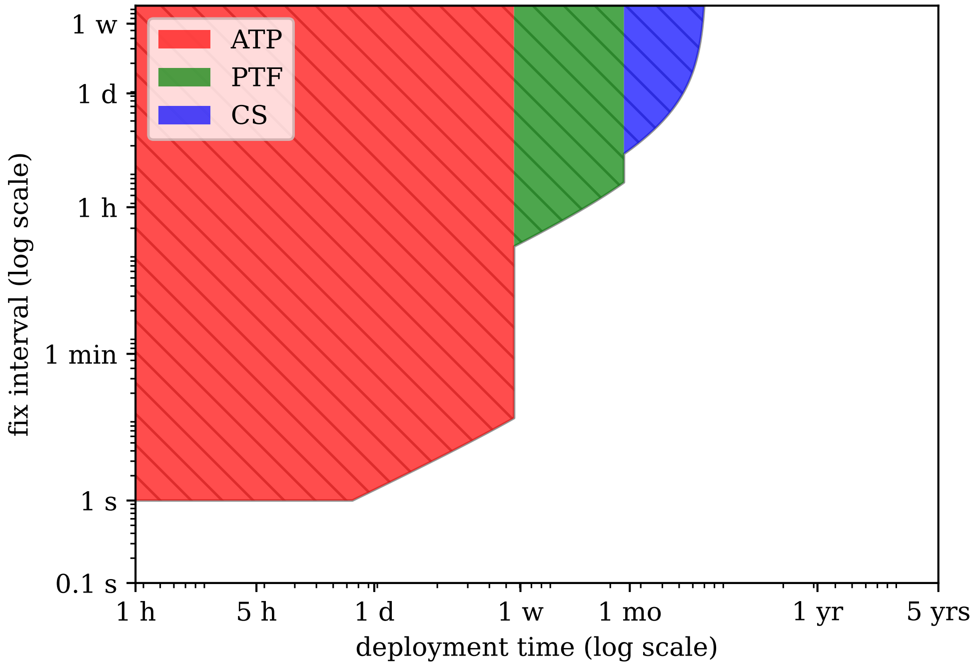


Figure 4.1: Space of possible deployment time and fix interval combinations for an OriginGPS Multi Micro Hornet with a 100 mA h battery.

In the worst case, the module needs to perform a cold start for each fix, which can take up to $\Delta t_{FPA}^{CS} = 35\,\mathrm{s}$ of Full Power Acquisition. Between fixes, the module can hibernate. One cold start fix cycle therefore requires

$$Q^{CS}(T) = \Delta t_{FPA}^{CS} \times \frac{P_{FPA}}{V_{CC}} + (T - \Delta t_{FPA}^{CS}) \times I_{HIB} \tag{4.7}$$

For each scenario (ATP, PTF and CS), the maximum deployment time on some battery with capacity Q^{total} can then be estimated by calculating the maximum number of fixes as $N = Q^{total}/Q$, where Q is Q^{ATP}, Q^{PTF} and Q^{CS}, respectively. The total maximum deployment time is then given by $T \times N$.

Figure 4.1 shows what these calculations mean in practice for the space of possible deployments with regular location fixes for the OriginGPS Multi Micro Hornet module running on a 100 mA h battery. The three regimes where ATP, PTF or CS are optimal are highlighted in different colours.

4.4 Advantage regimes

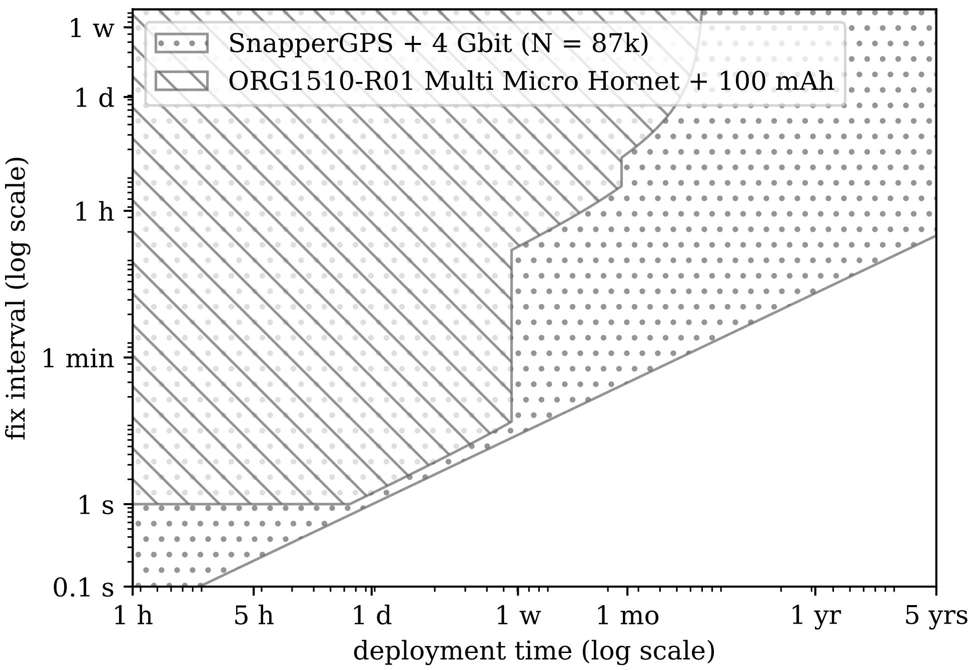
Figure 4.2 plots the space of possible deployments with constant fix intervals for both the snapshot GNSS receiver model considered in Section 4.2 and the traditional OriginGPS Multi Micro Hornet considered in Section 4.3. Figure 4.2a shows the deployment landscape for 100 mA h and Figure 4.2b the one for 1000 mA h.

In the case of extremely short deployments, a snapshot GNSS system can provide fixes multiple times per second, whereas most traditional GNSS systems typically have a cut-off above that. In ATP mode, the OriginGPS tag can provide fixes every second, for example. Taking very frequent fixes is rarely necessary but can be used to improve the precision of the location estimate by averaging.

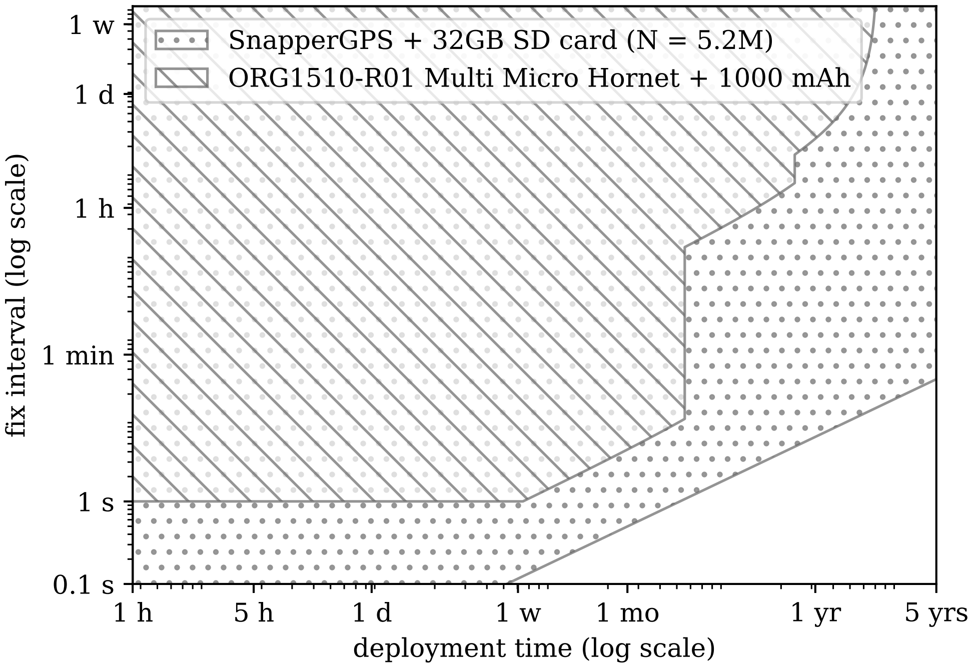
In the 100 mA h case, the OriginGPS module performs about as well as the theoretical snapshot GNSS receiver for short deployments of just a few days. This is due to the substantial energy savings made possible by the ATP power-saving mode.

However, for long deployments, the snapshot receiver exhibits a substantial advantage over the OriginGPS module. For a one-year deployment, for example, the snapshot receiver can take a snapshot every ten minutes rather than just once a day, like the traditional OriginGPS module. This large difference stems from the fact that low-power modes on traditional receivers require frequent fixes in order to maintain an up-to-date record of the satellite data, which becomes unfeasible for long deployments. Eventually, the traditional receiver will fall back to having to do a cold start for every fix, increasing its energy use per fix and limiting its maximum deployment time.

When larger batteries are an option, and SD cards become feasible, the snapshot receiver has an even larger advantage, even though it allows the traditional receiver to use its low-power mode for longer. For a 1000 mA h battery, the low-power modes of the OriginGPS module stop providing an advantage after a few months.



(a) Deployment landscape comparison for a snapshot GNSS tag with 4 Gbit of storage and an OriginGPS Multi Micro Hornet module running on a 100 mA h battery.



(b) Deployment landscape comparison for a snapshot GNSS tag with 32 GB of storage and an OriginGPS Multi Micro Hornet module running on a 1000 mA h battery.

Figure 4.2: Fix interval vs deployment time for a snapshot GNSS tag and an OriginGPS Multi Micro Hornet module running on (a) 100 mA h and (b) 1000 mA h. Note the logarithmic axes.

4.5 Recommendations for users

The results of the previous section demonstrate that snapshot GNSS tags can match and even surpass the performance of high-end traditional GNSS tags for applications with regular fixes. However, traditional GNSS tags are currently much more available and many researchers already have a supply of them. The deployment landscapes in Figure 4.2 can be used as a guide to decide whether a snapshot GNSS tag would provide a significant enough advantage for a particular application to justify the cost of finding and purchasing new hardware.

As a general rule, snapshot GNSS tags will be able to collect significantly more data for long deployments, when traditional GNSS tags can no longer maintain their low-power modes. The Multi Micro Hornet module is unusual, as its data sheet provides detailed information about its performance, making it possible to calculate that cut-off point. For most traditional GNSS tags, this information is not available. However, manufacturers sometimes provide a set of “typical” deployment parameters that can be used to roughly sketch out a deployment landscape[11]. Often, this is enough to identify the approximate location of the cut-off point and decide whether a snapshot GNSS tag would be beneficial. To draw the deployment landscape for a specific snapshot GNSS tag, the only important parameter is the number of snapshots the tag can store, which is usually provided in the data sheet.

Older models of traditional GNSS tags may not have any low-power modes. In this case, a snapshot GNSS tag will always provide a significant advantage.

4.6 Conclusion

In this chapter, I analysed how a modern implementation of a traditional GNSS receiver with low-power modes compares to a snapshot GNSS receiver for applications

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[11] See Section 6.7.3 for an example.

with regular location fix attempts.

For this comparison, I used a theoretical model of a snapshot GNSS receiver based on the feasibility results from Chapter 3. I compared that with the OriginGPS Multi Micro Hornet as an example of a traditional GNSS receiver.

The precise energy consumption of any particular receiver will depend on its hardware and software implementation details. However, the general shape of the landscape of fix frequency and deployment time combinations will be similar for other devices of the same technology.

I showed that snapshot GNSS receivers compare favourably to traditional GNSS receivers. Their advantage is particularly large for long deployments because the low-power modes employed by traditional GNSS receivers rely on frequent satellite data updates which become unfeasible for long deployments.

Chapter 5

SnapperGPS: An open-source snapshot GNSS system

5.1 Introduction

In Chapter 3, I demonstrated the feasibility of a low-cost snapshot GNSS receiver. In particular, I showed that 12 ms long snapshots, sampled at 4.092 MHz with 1 bit resolution, suffice to achieve median positioning errors of less than 15 m.

Then, in Chapter 4, I demonstrated that a system with these parameters can outperform a modern implementation of a traditional GNSS receiver with low-power modes, especially for long deployments.

In this chapter, I present SnapperGPS, a complete open-source implementation of a snapshot GNSS system built on the custom radio setup used in Chapter 3. SnapperGPS has already been successfully used in multiple wild animal tracking studies, some of which I describe in this chapter. I also compare SnapperGPS to a high-end commercial GNSS tag in a side-by-side comparison on sea turtles.

First, in Section 5.2, I present the design of SnapperGPS. Following the technical implementation details, Section 5.3 then focuses on the real-world impact of SnapperGPS. I outline several notable deployments of the system, including failed and ongoing experiments.

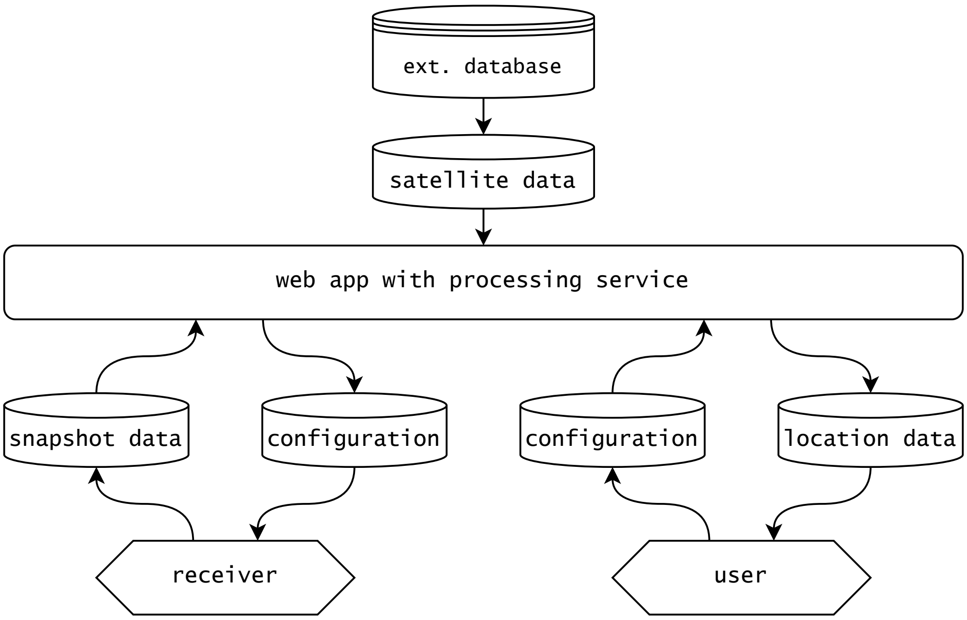

Figure 5.1: High-level system overview of SnapperGPS.

5.2 SnapperGPS

SnapperGPS is the first fully open-source implementation of a complete snapshot GNSS solution. The system relies on short, low-quality snapshots, allowing for the use of low-cost, simple, off-the-shelf components.

This section presents the SnapperGPS design. It covers the high-level system architecture, the technical implementation details and some application notes.

5.2.1 System design and user journey

SnapperGPS comprises three parts: (i) a small, low-power and low-cost radio receiver and data logger tag, (ii) a web application to configure the tag and read the collected data, and (iii) a signal processing chain to turn the recorded snapshots into location estimates.

The web application can also be used as a frontend for a signal processing service. This means that a user can use the web app for configuration, snapshot data upload and location data download without needing any programming knowledge.

Figure 5.1 shows the high-level system overview of SnapperGPS for this use case. There are then four main steps when deploying SnapperGPS:

1. Configuring the receiver with a recording schedule.
2. Deploying the receiver and recovering it at the end of the deployment.
3. Uploading the recorded snapshots for processing.
4. Downloading the computed track.

5.2.2 Receiver hardware

The main components of the SnapperGPS receiver are the radio, the microcontroller unit (MCU), and the flash memory. The MCU triggers the radio to turn on to record snapshots, which the MCU then stores in memory. This section describes each of these components in more detail.

SnapperGPS uses the SE4150L-R radio receiver IC by Skyworks Solutions[1]. It was selected for its high sensitivity, low power consumption, and low price. The radio IC is set up with a temperature-compensated oscillator and a SAW filter, as described in Chapter 3. With this setup, SnapperGPS can receive frequencies around 1575.42 MHz. This covers the L1 and L1C GPS signals, the E1 Galileo signal, and the B1C BeiDou signal.

The radio signal is sampled with an EFM32HG310F64 microcontroller unit (MCU) by Silicon Labs which uses a 32-bit ARM Cortex-M0+ core[2]. It was chosen for its low power consumption, both when active and when sleeping. The module offers five different energy modes (EM0-EM4), allowing for precise energy management.

Signals are captured with 1 bit amplitude resolution, as tested in Chapter 3. This

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[1] Data sheet: SE4150L `http://web.archive.org/web/20201207034114/https://www.skyworksinc.com/-/media/SkyWorks/Documents/Products/601-700/SE4150L_202445B_Discontinued.pdf` (archived 2020-12-07)

[2] Data sheet: EFM32HG `http://web.archive.org/web/20210306110941/https://www.silabs.com/documents/public/data-sheets/efm32hg-datasheet.pdf` (archived 2021-03-06)

means that the signal can be captured using the in-built USART. Using 1 bit resolution therefore avoids the need for any further complex hardware.

The chosen MCU also offers 8 kB of RAM which is enough to capture 4.092 MHz samples that are 12 ms long, since

$$4.092\,\mathrm{MHz} \times 12\,\mathrm{ms} \times 1\,\mathrm{bit} \approx 6\,\mathrm{kB} \leq 8\,\mathrm{kB} \tag{5.1}$$

During snapshot capture, the MCU uses the same clock frequency as the radio but otherwise falls back on its internal 14 MHz oscillator.

The captured snapshots are stored using a 512 Mbit flash by Winbond[3]. Each snapshot requires 6 kB, which means that the flash can store almost 11,000 snapshots.

All components are placed on one side of a two-layer printed circuit board (PCB) to keep manufacturing and assembly costs low. The SnapperGPS board uses a USB-C connector for configuration and data download. Additionally, the ground, the primary voltage (VDD), as well as three general purpose input/output (GPIO) pins of the MCU are exposed on the front via pads in the corner of the board. These can be used to add functionality, such as the option to externally trigger snapshots. The back of the board also exposes the Serial Wire Debug (SWD) pins (SWCLK, SWDIO) and the reset pin of the MCU. These can be used for debugging and flashing firmware. The SnapperGPS board additionally features two status LEDs that can also be useful for debugging.

The PCB can be powered via USB. When not connected, the board switches to battery power. It is set up to work with a lithium-ion polymer (LiPo) battery, which can be attached with a JST PH 2.0 connector. LiPo batteries have particularly high energy density, making them ideal for mobile applications. The PCB includes a

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[3] Data sheet: W25N512GVxxG/T/R, `http://web.archive.org/web/20211214110129/https://www.winbond.com/resource-files/W25N512GV%20Rev%20F%20042621.pdf` (archived 2021-12-14)

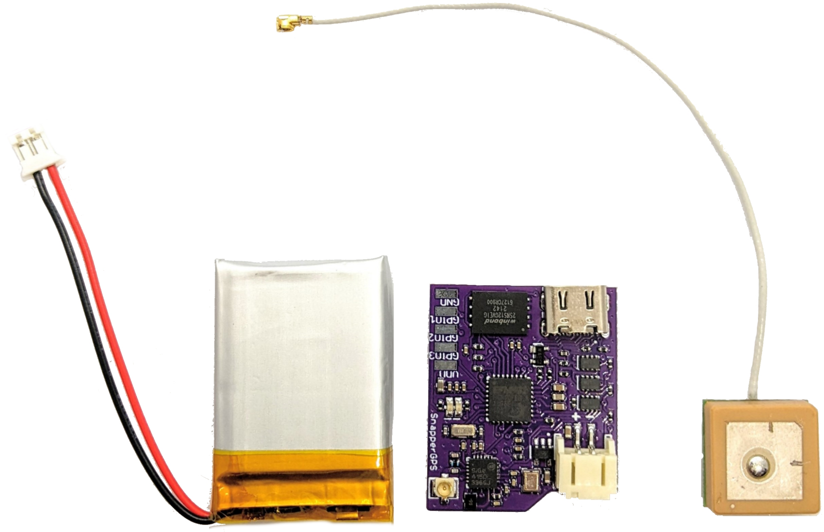

Figure 5.2: SnapperGPS PCB (middle), next to a 400 mA h LiPo battery (left) and an ECHO27 antenna by Siretta (right).

power regulator circuit to provide a consistent 3.3 V supply voltage, independent of whether power is provided via USB (5 V) or via battery (4.2 V at full charge). When not in use, the radio and the flash storage are cut off from power using MOSFETs to minimise energy loss.

The physical SnapperGPS PCB is 32.0 mm long and 27.3 mm wide. The weight depends on the thickness of the PCB, but for a standard 1.6 mm thick board with a typical copper thickness of $1\,\mathrm{oz/ft^2}$, the PCB weighs 4.3 g. Figure 5.2 shows the SnapperGPS PCB next to a 400 mA h LiPo battery and an antenna.

The component prices for the SnapperGPS PCB frequently changed over the course of development due to the 2020-2023 global chip shortage. For a batch of 100 boards, the unit price was typically under $50 in those years, including PCB manufacturing and assembly.

5.2.3 Receiver firmware

The SnapperGPS firmware is written in C. A SnapperGPS board that is not configured or has finished collecting snapshots, will enter shutdown mode (EM4). It can be woken up by connecting it via USB for configuration. If the board is configured to take snapshots, it will then alternate between sleeping (EM3) and capturing snapshots (EM0) once the USB cable is removed. Otherwise, it will enter shutdown mode again. The board will also enter shutdown mode once it has finished collecting snapshots. This can happen either because it has been scheduled to stop at a certain time or because storage has run out.

Every time a snapshot is collected, it is written to storage together with a timestamp, as well as a measurement of the battery voltage and the onboard temperature.

When the MCU is sleeping between snapshots, it keeps track of a real-time clock (RTC), which is used to trigger snapshots based on the configuration schedule. The RTC is not needed once all snapshots have been collected, so it is turned off in shutdown mode to save energy.

5.2.4 Signal processing

There is a public web application that can be used for configuring the device, uploading raw data and finally for downloading the computed location track[4]. The web application communicates with the SnapperGPS hardware via WebUSB, which is currently supported by Google Chrome and Microsoft Edge. This allows for configuration in the browser without the need to install additional software.

To configure a device, the user connects it to a computer via USB and opens the web app in their browser. There, the user can check the device status and set a start and end time for data capture, as well as a time interval between snapshots. At the end of a deployment, the user reconnects the device and uses the upload page to upload the recorded snapshots to the processing server. The service requires a rough estimate of the starting position (±10 km).

To process uploaded data, the processing service first pulls satellite navigation information from a public database [103]. Despite its name, SnapperGPS actually

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[4] SnapperGPS web app, `http://web.archive.org/web/20230224224236/https://snappergps.info/` (archived 2023-02-24)

uses multiple GNSS, not just GPS, but also Galileo and BeiDou, making use of over ninety satellites in total. However, it is still common to use the term GPS to refer to any satellite navigation system, whereas GNSS is a relatively unknown term outside of technical discussions.

Once the navigation data is available, the backend then calculates a position, an uncertainty estimate and a corrected timestamp for each snapshot. The employed algorithms are open-source and published [108]. See Section 2.5 for more details on GNSS positioning.

5.2.5 Application notes

This section covers important application details to be aware of when deploying SnapperGPS, including deployment limits, performance, antenna choice and what to consider when enclosing and attaching a SnapperGPS receiver.

5.2.5.1 Deployment limits and performance

When sleeping between snapshots, the SnapperGPS board current draw is less than 2 µA. Capturing and storing a single snapshot uses less than 0.3 µA h. This means that the board consumes less than 1.8 mA h/yr. Filling the entire storage with snapshots takes another 3.3 mA h. Therefore, even a small 40 mA h battery can power a tag for multiple years.

The limiting factor for a deployment will typically be storage. The SnapperGPS board described previously can store just under 11,000 snapshots. This is enough for a snapshot every minute for one week or every hour for one year.

In a stationary test on a rooftop with an unobstructed view of the sky, the SnapperGPS system achieved a median error of 10 m. The test included 8,000 snapshots collected over several months. Note that the performance will heavily depend on the environment, as buildings, trees and people can all block satellite signals.

5.2.5.2 Antenna choice

Another important factor that greatly affects positioning quality is antenna choice. Any passive antenna with a U.FL connector can be connected to the SnapperGPS PCB. An antenna as small as 10 mm × 10 mm can be large enough if the view of the sky is good, such as in an open field or at sea. However, larger antennae may be needed for obstructed environments, such as forests, urban areas or near mountains.

Chapter 3 contains comparisons for four different antenna models with example data taken in an open field. Those results were obtained with the same radio setup but using a simpler positioning algorithm and relying only on GPS. The data can still be used to compare one antenna to another, however, SnapperGPS can be expected to generally perform better.

5.2.5.3 Enclosure and attachment orientation

In most real-world deployment settings, the SnapperGPS PCB needs an enclosure to protect it from damage, especially through water, which can cause unwanted electrical shorts.

It is important to ensure that the enclosure does not obscure the view of the antenna. A small amount of plastic is unlikely to have a noticeable effect on the signal quality, but metal reflects radio waves and can therefore not be used to cover the antenna. Metal also has the disadvantage that it can short out components on the PCB if not insulated well.

When attaching the enclosure to the object or animal of interest, it is crucial to ensure that the antenna is oriented to point up at the sky. In cases with exceptionally good sky visibility (e.g. on a bird flying over an empty landscape, such as the open ocean) it may also be possible to get good results with an antenna pointed sideways, but this is generally not the case.

5.3 Deployments of SnapperGPS

This section presents a small number of notable deployments of SnapperGPS on wild animals. It includes details on the methods of enclosure and attachment used, as well as results, where available.

For this thesis, deployments on marine animals were prioritised. One of the main advantages of the snapshot GNSS approach is a consistently short acquisition time. This is particularly useful for applications with brief windows of opportunity for signal capture, such as the tracking of marine animals with short surfacing times, like sharks and dolphins. Since GNSS signals do not travel underwater, signals can only be acquired when the animal breaks the surface. A traditional GNSS tag will often fail to resolve a position fix, as it may require many seconds to do so. When sky visibility is not an issue, traditional GNSS tags can cache satellite tracking data to reduce this acquisition time, but this is often not feasible when tracking an animal that only surfaces rarely. For this reason, snapshot GNSS tags have a particularly large advantage over traditional GNSS tags when tracking marine animals, making this an interesting type of application to study.

There are many marine species that surface frequently enough to be tracked with GNSS tags. However, nesting sea turtles present an especially interesting case for multiple reasons. Every species of marine turtle exhibits different nesting behaviour, but for the ones considered here, mature females come ashore every few years to lay their eggs on the beach. Instead of laying all their eggs at once, they lay several clutches of eggs. Between clutches, the turtles return to the ocean for about two weeks. This so-called internesting interval is interesting to study as it is particularly important for species survival. It also presents a unique opportunity to study how turtles navigate, as individuals will typically return to the same beach. This also means that recovery of any deployed technology is possible without the need for a boat or any remote tracking capabilities. Additionally, most sea turtles have a hard carapace that tags can be glued onto, as opposed to, for example, a shark that would require a more invasive dorsal fin mount with stricter form factor requirements. All of these factors make nesting sea turtles particularly interesting deployment candidates for testing SnapperGPS.

5.3.1 Sea turtles in Cape Verde

In 2021, I organised a set of deployments on nesting loggerhead sea turtles (Caretta caretta) on the island of Maio, Cape Verde. This work was done in collaboration with the Maio Biodiversity Foundation (FMB) and the Arribada Initiative.

For this, a set of SnapperGPS tags was equipped with a simple surfacing sensor. It works by measuring the time needed to charge a 100 pF capacitor through two contacts on the enclosure. This can be used to estimate the resistance of the surrounding medium. If the tag is submerged, the capacitor charges quickly through the conducting sea water. But at the surface, this connection is broken, which should create a strong signal change. The saltwater switch is implemented using a small PCB that connects to two screws in the enclosure and then back to three of the GPIO pins on the SnapperGPS board, as can be seen in Figure 5.4.

The SnapperGPS enclosure for this deployment is modelled after an existing turtle tag enclosure by Arribada [109]. The final version can be seen in Figure 5.3. The top is milled from polyoxymethylene (POM), a type of thermoplastic, and the bottom is milled from a 5 mm sheet of aluminium. The enclosure is 8.8 cm long, 5.6 cm wide and 2.4 cm high. It is tested to be waterproof at 10 bar using a standard 2.5 mm thick nitrile o-ring with 70 ShA hardness. 3D-printed inserts hold the components in place to prevent movement and possible short-circuiting. Most of these inserts were printed in hard polylactide (polylactic acid, PLA), as seen in Figure 5.4, except for the shield that insulates the electronics against the aluminium base. This shield was printed in flexible thermoplastic polyurethane (TPU) to prevent damage to the component side of the PCB and to ensure a tight fit against the base.

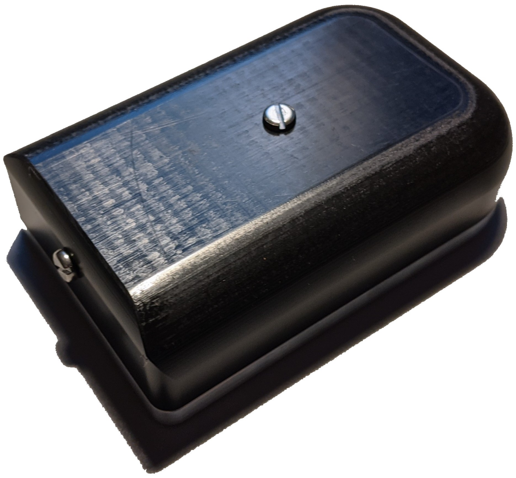

Figure 5.3: The enclosure used to deploy SnapperGPS on loggerhead sea turtles.

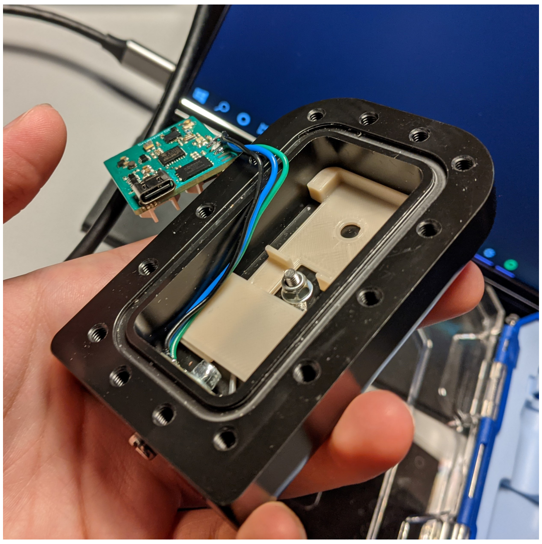

Figure 5.4: The inside of the SnapperGPS turtle tag enclosure.

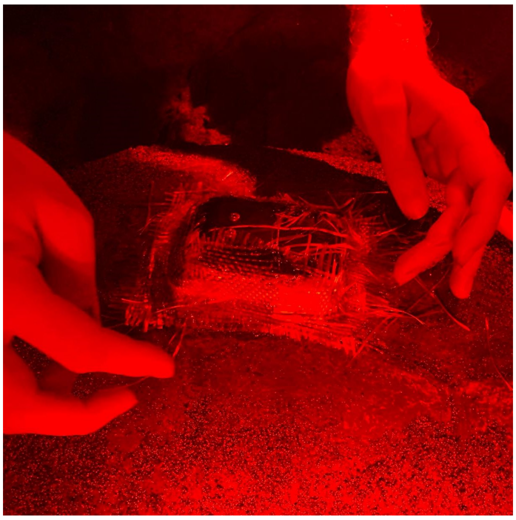

Figure 5.5: SnapperGPS tag attached to the turtle's carapace using fibre glass matting and two-part epoxy.

Figure 5.6: A SnapperGPS enclosure after being deployed on a loggerhead sea turtle for two weeks.

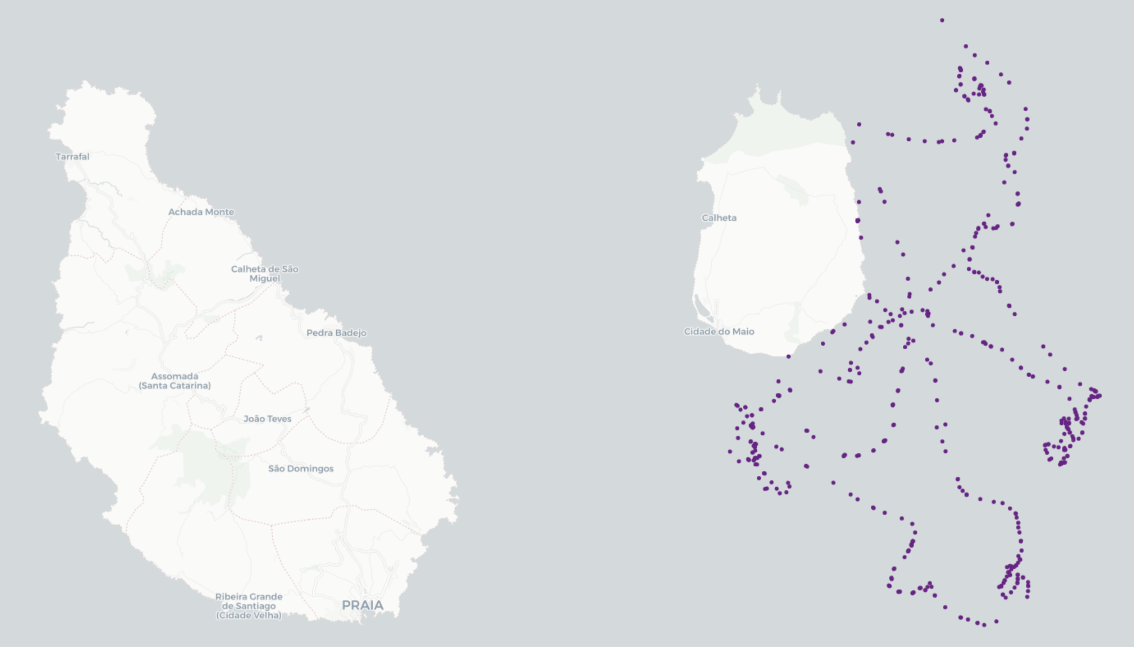

Figure 5.7: Track of a nesting loggerhead sea turtle recorded with a SnapperGPS tag. A location fix was attempted every two minutes. This tag failed a few days before the turtle returned to the beach.

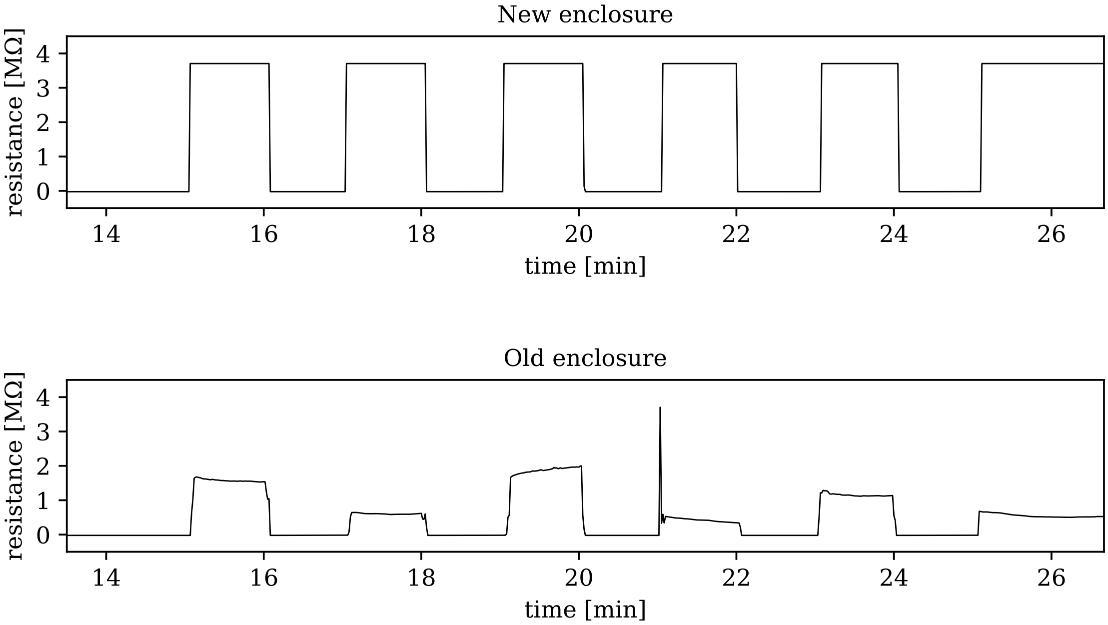

Figure 5.8: Comparison of resistance measurements. The upper plot shows data taken with a newly manufactured enclosure. The data in the lower plot was taken with an enclosure after it spent two weeks on a turtle in the ocean.

The COVID-19 pandemic delayed this fieldwork. Most tags were deployed several weeks into the nesting season. This meant that tagged turtles were more likely to be on their last clutch and therefore less likely to return. Out of twenty deployed tags, nine were recovered. The tags had mixed success. Snapshots taken on the open sea had a full view of the sky with many visible satellites, which resulted in high-quality positioning. However, the saltwater switch was a lot less robust than submersion tests on land had suggested. Many tags only triggered at the beach of origin and the beach of return but rarely on the water. But some tags did record partial tracks. One particular device had a malfunctioning saltwater switch that was almost continuously reporting a surfacing event. This meant that the device took a snapshot every two minutes. Most snapshots were taken underwater and therefore contain no satellite signals. However, some coincided with actual surfacing events. The resulting track is shown in Figure 5.7.

Without a second saltwater switch on the tag to compare against, it is difficult to be sure what caused the switch to fail in the ocean, despite being reliable in saltwater tests on land. Firstly, it is possible that loggerhead sea turtles do not always lift their carapace out of the water when coming to the surface. However, the fact that the malfunctioning tag did record a full track suggests that this is not the case because GNSS signals can be blocked by just millimetres of water. Nevertheless, some limited water pooling or a very thin water film on the enclosure could still let some GNSS signals through, while already being enough to connect the contacts of the saltwater switch, resulting in undetected surfacing events. This effect was not observed in tests on land, but these did not account for the epoxy and fibreglass matting used to attach the tag to the turtle. As can be seen in Figure 5.5, this attachment method results in some glue and glass fibres on the enclosure. These can create water pooling that connects the switch contacts without blocking GNSS signals. Additionally, tags can experience damage over the course of the deployment, as shown in Figure 5.6. Such scratches make it easier for water to pool on the enclosure. They also affect the electrical properties of the exposed screws used as contacts for the saltwater switch.

Figure 5.8 compares resistance measurements of a newly machined enclosure and an enclosure that had been on a turtle for two weeks but had since been cleaned. For this experiment, the tags were left in sea water for 15 min before being removed and re-submerged five times for 5 min at a time, respectively. Finally, the tags were removed from the water again. These results show that damage to the enclosure alone is already enough to affect the effectiveness of a resistance measurement to detect surfacing events. This difference is not large enough to explain the complete failure of the saltwater switch in the ocean, though.

The goal of this deployment was to demonstrate that a snapshot receiver can provide position fixes even with very short windows of opportunity because of its short acquisition times. However, without a functioning saltwater switch, these results do not give enough information on surfacing behaviour to clearly show this advantage. Nevertheless, this deployment provided novel insights into the internesting behaviour of loggerhead sea turtles. Biologists had never been able to track sea turtles around the island before, as existing solutions had always been prohibitively expensive. Furthermore, even though results show that the employed surfacing detection method is not reliable, they also show that simply attempting fixes at regular intervals and then filtering in post-processing is a valid strategy, albeit wasteful.

5.3.2 Sea turtles in Turkey

In May 2023, two SnapperGPS tags were deployed on nesting loggerhead sea turtles at Dalyan beach in Turkey. This work was a collaboration with researchers from the University of Pisa in Italy and the Sea Turtle Research, Rescue and Rehabilitation Centre DEKAMER in Turkey.

For this experiment, the turtles were captured at their nesting beach, relocated via boat and then released in the ocean. The goal of this was to observe how the turtles would navigate back to the beach. The deployed tags were recovered once the turtles returned to the nesting beach.

The SnapperGPS tags were co-deployed with SeaTrkr tags by Telonics[5]. These are proprietary GNSS tags that support data upload to the Iridium satellite system for remote tracking. They are equipped with a surfacing sensor that triggers GNSS data collection and Iridium transmissions. The SeaTrkr is not a snapshot GNSS receiver, but it offers a proprietary quick fix positioning (QFP) mode, which can provide a position fix in as little as 3 seconds. However, as explained in Chapter 4, this best-case scenario is only possible if there was a recent successful fix. One SeaTrkr tag costs about €2,500, making it a relatively high-end tracking solution.

Figure 5.9 shows the two sets of tracks that were recorded. The tracks recorded by SnapperGPS tags are shown in purple and the ones recorded by SeaTrkr tags are shown in green. The SeaTrkr track in this figure is the logged GNSS location data, as opposed to the real-time location data available during the deployment via satellite uplink. Remote tracking information typically has much lower temporal resolution because satellite uploads are energy-intensive and rare.

Almost every GNSS recording taken at the surface will have perfect sky visibility, so it is expected that both the SnapperGPS tag and the SeaTrkr tag will have very good spatial resolution. As a result, both sets of tracks are very close to each other whenever both devices were able to resolve a position fix.

In this case, the temporal resolution is also very similar, however, this is largely a coincidence due to the configurations chosen for both tags.

With a snapshot GNSS receiver, such as SnapperGPS, doubling the snapshot frequency leads to double the number of successful location fixes (assuming the fix interval is much smaller than the average dive interval). SnapperGPS only needs

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[5] Data sheet: SeaTrkr GPS/Iridium Marine Systems, `https://web.archive.org/web/20231221174320/https://www.telonics.com/products/gps4Marine/seatrkr.php` (archived 2023-12-23)

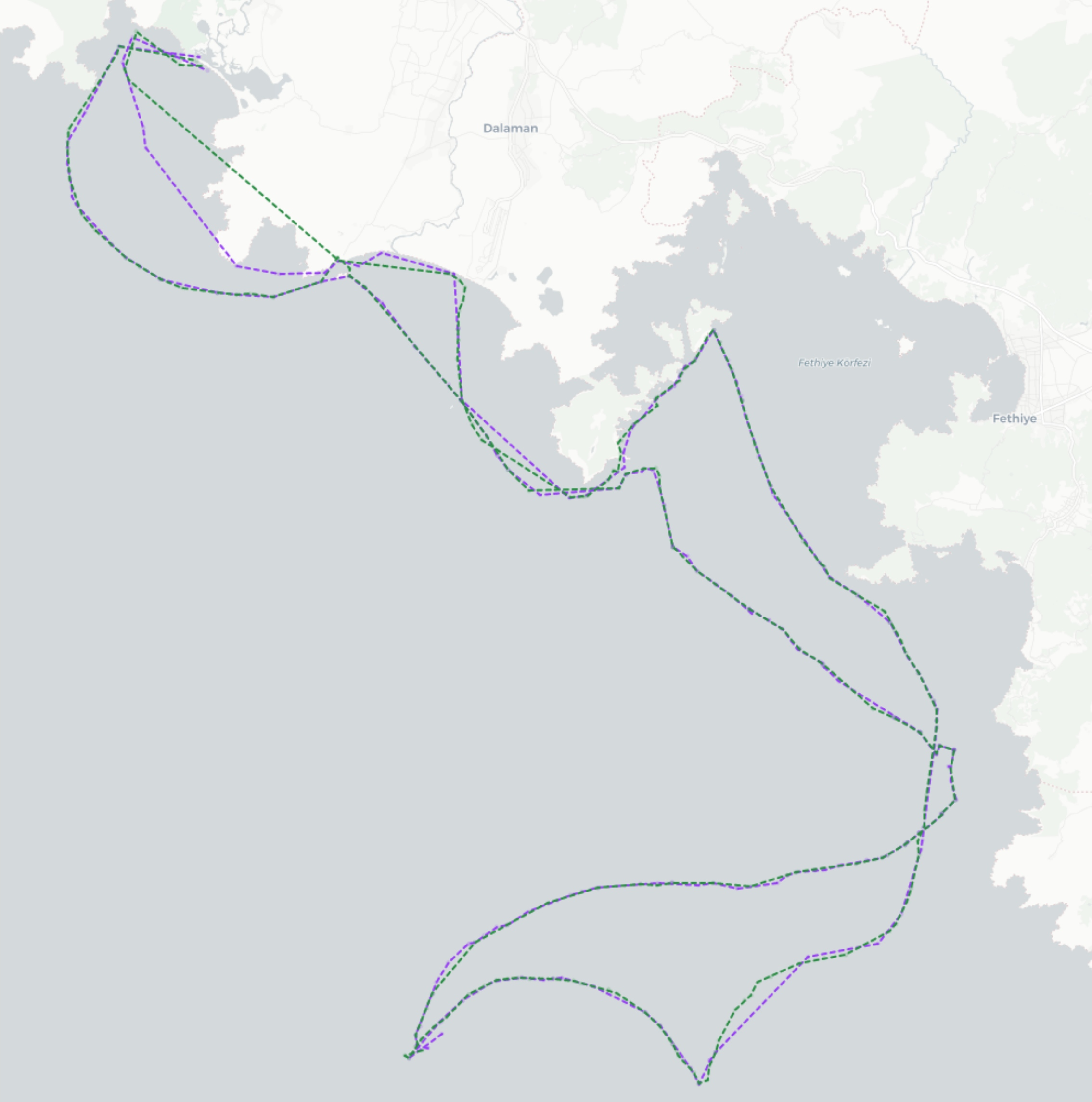

Figure 5.9: Two sets of turtle tracks. Both individuals were released in the ocean at the same location and returned to the same beach. The purple tracks were recorded with SnapperGPS tags and the green tracks were recorded with a SeaTrkr tag by Telonics. For this visualisation, the location fixes were connected with straight lines. Map by Leaflet, OpenStreetMap and CartoDB positron.

a few milliseconds to get a position, which is much faster than the turtle's diving behaviour. This means that SnapperGPS almost always achieves a location fix if the turtle is above the surface when a snapshot is taken. So if the turtle spends 10% of its time above the surface, then 10% of the snapshots will yield a position fix. Increasing the snapshot frequency will therefore always improve temporal resolution.

The Telonics software or hardware is not open-source, so the exact behaviour of the SeaTrkr tag is not known. However, there are technical limitations to a traditional GNSS approach. If the SeaTrkr tag has satellite data available from a recent fix, it can get a fix after only 3 s of good sky visibility. But recent satellite data may not be available if the turtle spends much time underwater. In the worst case, a traditional GNSS tag needs 30 s of uninterrupted sky visibility for a location fix. This means that, even with perfect surfacing detection, not every surfacing event will lead to a position estimate. Some surfacing events will be too short, or there might be too much water splashing on the tag. As a result, the temporal resolution of the SeaTrkr tag is limited by the length of surfacing events and would not necessarily increase with more frequent fix attempts.

If, at any point, the SnapperGPS tag is able to get a position estimate and the SeaTrkr tag is not, then that probably means that the surfacing event was too short for a traditional GNSS fix. There is no way to change the configuration of the SeaTrkr tag to get a fix in that case. On the other hand, if the SeaTrkr tag gets a fix and the SnapperGPS tag does not, then that just means that the snapshot frequency was not high enough. If the snapshot frequency had been higher, the SnapperGPS tag would have definitely gotten a fix. This is because if the SeaTrkr tag gets a fix, there are definitely multiple consecutive seconds of sky visibility and SnapperGPS only needs milliseconds. It is therefore surprising that the temporal resolution of both tracks is so similar.

There are a few instances where one tag was temporarily able to achieve more frequent fixes than the other. In Figure 5.9 this is most noticeable in the top left corner. In the case of one of the turtles, the SnapperGPS tag was able to provide more fixes than the SeaTrkr tag for a significant portion of the track just before the turtle returned to the beach. This indicates that the turtle had very brief surfacing events during that segment.

These results demonstrate that a SnapperGPS tag can provide similar spatial and temporal resolution as a high-end commercial GNSS tracking device that uses a surfacing sensor to time positioning attempts.

For a more informative comparison, the tags would need to both be equipped with a surfacing sensor. By timing the positioning attempts to coincide with surfacing events, the SeaTrkr tags were able to significantly reduce wasted positioning attempts. The SnapperGPS tags, on the other hand, took most snapshots underwater, wasting storage. Furthermore, battery capacity should be kept the same. Ideally, both tags would also be equipped with the same antenna. In this example, the Telonics tag provided real-time tracking information, which significantly increased its energy consumption. For a fair comparison, this should be disabled.

5.3.3 Other notable deployments and causes for failures

This section presents a selection of other small deployment collaborations, including ongoing and failed experiments. These deployments demonstrate the versatility of a general purpose solution but also the challenges that come with it.

In 2023, Travis Thomas at the University of Florida conducted deployments of multiple SnapperGPS tags on local turtles. Five tags were deployed on river cooters (Pseudemys concinna) and three further tags were deployed on gopher tortoises (Gopherus polyfemus).

The river cooter tags were potted in resin, leaving only the connectors exposed for access. For deployments, these can then be sealed with rubber plugs and some glue.

Figure 5.10: A SnapperGPS tag on a river cooter. Credit: Travis Thomas

Figure 5.11: A SnapperGPS tag on a gopher tortoise. Credit: Travis Thomas

A resin enclosure can be very durable without adding as much bulk as the milled enclosures used in the sea turtle applications discussed previously in this chapter. However, potting anything in hard resin is generally irreversible, making repairs or modifications of the electronics impossible. Figure 5.10 shows this resin tag on a river cooter.

Gopher tortoises dig burrows, so it is particularly important to avoid any unnecessary bulk. To achieve a slim profile, these tags were sealed with a strip of heat shrink tubing. Heat shrink tubing is cheap and adds minimal size and weight, making it a popular choice for wildlife tracking. However, it provides little protection and should only be used in applications where damage is unlikely. Figure 5.11 shows a heat-shrink protected tag on a Gopher tortoise. The SnapperGPS tags were deployed alongside VHF radio tags to make recovery easier. At the time of writing, both studies in Florida are still ongoing.

In the winter of 2022/2023, a SnapperGPS tag was deployed on a sea turtle near the coast of Kenya by researchers with the Olive Ridley Project. The tag was deployed

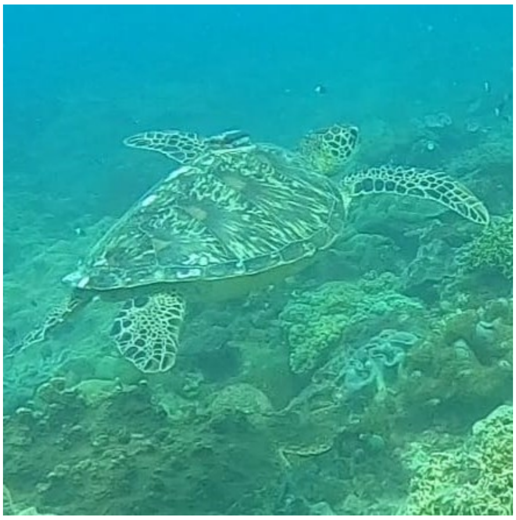

Figure 5.12: A SnapperGPS tag on a sea turtle in a coral reef near Kenya. Credit: Joana Hancock, Denis Moser

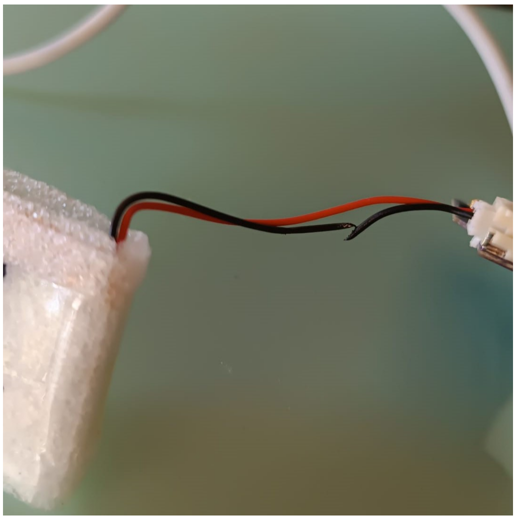

Figure 5.13: A broken LiPo battery cable. Credit: Joana Hancock

in a custom enclosure based on the design used for the deployments on loggerhead sea turtles in Cape Verde. It was also glued to the carapace, as can be seen in Figure 5.12. Unfortunately, this tag did not yield any data because the battery cable was damaged when the tag was assembled after configuration, as can be seen in Figure 5.13.

Physical damage is a common cause of failures when deploying any electronics on animals. It is therefore important to test any new enclosure methods in the intended setting. Special care should be taken if any loose cables are involved.

In the summer of 2022, Kim Lewandowski and Tim Doherty at the University of Sydney deployed SnapperGPS tags on woylies (Bettongia penicillata) in Australia. Woylies are small marsupials that are critically endangered. The goal of this research was to monitor local and translocated animals in a protected environment without predators. The SnapperGPS tags were set up on custom collars alongside VHF radio tags. The VHF transmitters allow for easy relocation of the animal and doubled as a counterweight on the collar to ensure that the SnapperGPS antenna would always point to the sky. Figure 5.14 shows the collar and Figure 5.15 shows a woylie

Figure 5.14: A custom collar with a SnapperGPS tag and a VHF transmitter. Credit: Kim Lewandowski

Figure 5.15: A woylie carrying the collar. Credit: Kim Lewandowski

carrying the collar. In the end, these collars could not be used as they prevented the woylies from moving freely. This demonstrates one of the main difficulties of developing technologies that interact with animals. Every species and individual has different form factor requirements and a general-purpose solution will typically require modification for any particular application.

Finally, another common cause for poor results is a lack of high-quality data at the start of a deployment. This is required for successful processing, as the first few snapshots are used to estimate the frequency offset of the radio setup. To make sure that this is possible, it is recommended to leave the tag at a known location with good sky visibility for at least 50 snapshots at the start of every deployment to ensure good results.

5.4 Conclusion

This chapter presented SnapperGPS, a complete snapshot GNSS solution comprising all the required software and hardware. The custom receiver is small, light and low-cost. This is the first fully open-source snapshot GNSS system and, as such, can be used as a basis for further research and development.

SnapperGPS has already been deployed on multiple species of wild animals, including sea turtles, freshwater turtles, and tortoises. In a co-deployment with a high-end commercial marine GNSS tag, it was able to provide similar spatial and temporal resolution. This demonstrates that SnapperGPS is not just a research prototype but a practical tool for wildlife tracking.

Chapter 6

A SnapperGPS variant for birds

6.1 Introduction

In Chapter 5, I described SnapperGPS, a snapshot GNSS location tracking system that has already been successfully deployed on multiple larger species. However, a low-power snapshot GNSS tag is particularly useful for tracking small animals.

In this chapter, I show how I modified the SnapperGPS design to track small seabirds. I present the first set of field deployments of this novel SnapperGPS bird variant on nesting Manx shearwaters (Puffinus puffinus) in Wales. In a comparison with the popular i-gotU GT-120 tag, I show that the SnapperGPS bird variant can provide higher fix frequencies while being smaller, lighter and comparable in price.

The chapter is structured as follows. First, Section 6.2 gives an overview of existing GNSS tags for this application and motivates the need for a new solution. Section 6.3 details the target species and deployment conditions. Section 6.4 explains how these factors affect the design requirements for a new tag. Then, Section 6.5 presents the changes made to SnapperGPS to address these needs and create the bird variant. Section 6.6 describes the first field deployment of the new tag on Manx shearwaters in 2022. Section 6.7 compares the SnapperGPS bird variant against the specifications of two existing GNSS bird tracking tags in terms of cost, size, weight and fix frequency. Then, Section 6.8 compares the SnapperGPS bird variant and the i-gotU GT-120 tag under field conditions. Finally, Section 6.9 concludes the chapter.

6.2 Existing GNSS-based bird tags and common problems

The first use of GNSS location data logging tags on Manx shearwaters was reported in 2008 [110]. This was achieved with a custom tag, adapted from previously published tag designs, which were originally developed for homing pigeons [111, 112]. The modified tags are 30 mm × 60 mm × 8 mm large and weigh 17 g, including waterproofing and attachment. Failure rates were high. Tags often failed to acquire positions or ran out of battery, sometimes before the birds even left the island. Fewer than half of all trips were recorded fully.

Since this first deployment on Manx shearwaters, technology has improved. However, many of the same issues have remained. This section discusses these problems in more detail and motivates the need for a new solution.

6.2.1 The landscape of existing solutions

Custom tags, like the one used in the original Manx shearwater tracking study are occasionally used in wildlife tracking research [113–118]. They allow researchers to tailor the tag to the specific requirements of the study. However, such development can be time-consuming, expensive and requires expert knowledge.

Off-the-shelf solutions are generally much more practical for most researchers. However, products marketed for wildlife tracking are often expensive. Because of this, some of the most commonly used tools used in wildlife research are commercially available pet and personal GNSS loggers, particularly i-gotU tags by Mobile Action Technology [119–129].

The intended application for i-gotU loggers is to geotag photos while travelling and tracking sports routes[1]. However, they remain popular for wildlife tracking, as they

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[1] Reseller page: i-gotU GT-120, `https://web.archive.org/web/20240806123833/https://gpswebshop.com/products/i-gotu-gt-120-usb-gps-travel-sports-logger-water-resistant-usb-gps-65-nm-sirf-iii-gps-chipset?_pos=4&_sid=e3fc306cb&_ss=r&variant=44533948870` (archived 2024-08-06)

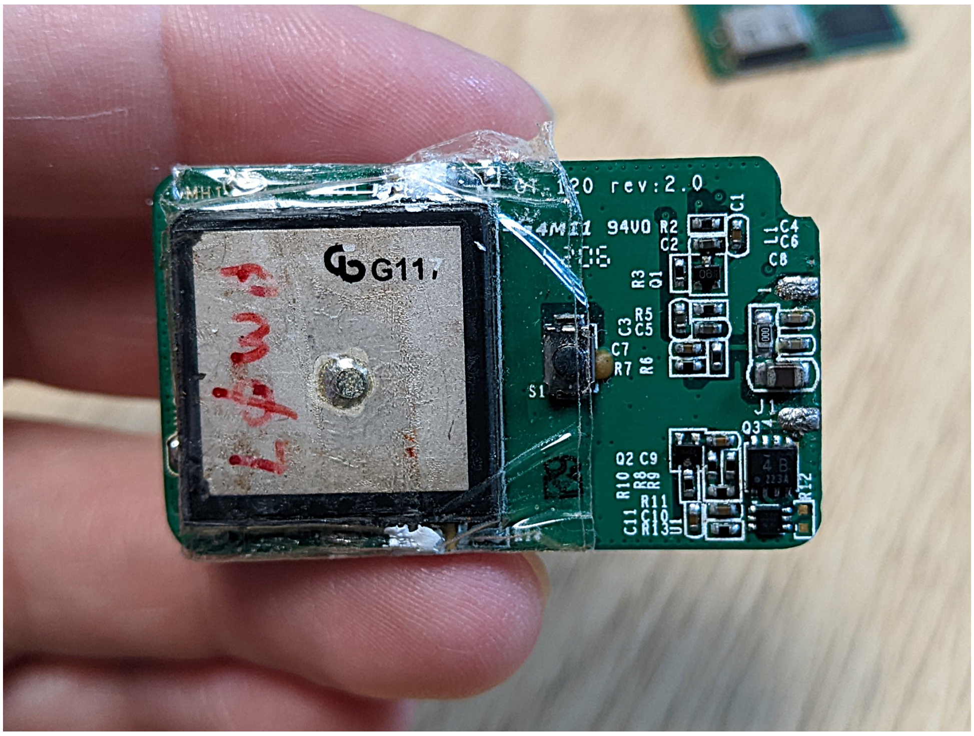

Figure 6.1: A modified GT-120 i-gotU tag, commonly used to track birds. This tag has a 250 mA h battery (not visible).

tend to be cheaper than application-specific tags. Researchers typically remove the plastic case and trim down the PCB to reduce size and weight [120, 130]. It is also common to replace the battery with a smaller or larger one to trade off deployment time and weight [119,120]. Figure 6.1 shows a photo of such a modified GT-120 tag.

6.2.2 Cost

Cost is generally a common concern for researchers in any field, but it is a particular limitation for wildlife research, where budgets are often small while needing to cover many other fieldwork expenses. In a 2022 survey, wildlife conservation practitioners most commonly cited cost as the key constraint for the use of technology [19].

The cost of tags carried by animals is particularly important, as tags are often lost, either because they fall off or because the animal is never resighted. A 2023 review examined primary research papers from 2006 to 2021 that reported tracking small migratory birds ($< 500\,\mathrm{g}$) with GNSS tags [131]. The review found that out of 908 birds tracked with archival GNSS tags across the considered studies, only 26% were sighted again at the end of the study and 22% of the deployed tags were retrieved. This review focused on migration studies, and shorter studies (such as the target deployment in this chapter) will typically have higher recovery rates. However, the risk of losing tags is generally a significant concern and further motivates the need for a low-cost tag to ensure a sufficient sample size.

Most commercially available wildlife tracking technology suppliers do not list their prices publicly, and researchers rarely publish the cost of their tools. In personal communication, researchers have shared costs of multiple hundred and occasionally over a thousand US dollars per tag for a location data logger without any uplink capabilities for remote tracking. I have received similarly high quotes from suppliers. Authors typically cite cost as the reason for choosing non-application-specific tags, such as i-gotU tags.

6.2.3 Failure rates

Wildlife tracking technology also often exhibits high failure rates. Tracking studies usually do not report these, but instead just state the size of the final dataset used for the analysis. However, some studies do include enough information to infer failure rates or report them directly. Out of the retrieved archival GNSS tags deployed on small birds in the review mentioned above, 20% had no data on them and more did not cover the full deployment [131]. Partial or complete failures of 10% or more appear to be common in wildlife tracking studies across species and technologies, although some of these reports may be outdated [21, 23, 106, 132, 133].

6.2.4 Weight restrictions

Any biologging tag should be as small and light as possible to avoid affecting the animal's behaviour or welfare [134]. A common target limit is 5% of the animal's body weight. More recently, this has often been reduced to 3%, especially for birds

[135]. For an adult Manx shearwater, this is 12 g - 13.5 g, depending on its size.

The modified GT-120 i-gotU tag shown in Figure 6.1 uses a 250 mA h battery and weighs 12.8 g. The material used for waterproofing and attachment to the bird adds another 3.0 g. This makes for a total weight of 15.8 g which is above the commonly used 3% weight limit for a Manx shearwater.

Exceeding the 3% limit is common when tracking small birds. The 2023 review study previously mentioned found that out of the studies that reported tag load, 71% used tag loads $\geq$ 3% of the bird's body mass and 16% used tag loads $\geq$ 5% [131].

Given the state of existing tags, the 3% threshold is a good target weight at the moment. However, it is worth noting that tags as light as 1.4% have still been shown to affect offspring size and mass in a related species, the sooty shearwater (Puffinus griseus) [136]. In Manx shearwaters, in particular, GPS tags weighing 4.2% of body weight have been shown to affect foraging behaviour, despite normal breeding success [123]. Tagged birds spent twice as much time away from the nest, and spent less time flying than untagged birds. Clearly, reducing weight as much as possible is desirable.

Researchers will typically set a limit for the relative load ahead of time and then only tag birds that are large enough to carry the tag. This means that it is possible that researchers will avoid tagging smaller individuals in the field. This biases the sample and can affect the results of the study. To avoid this, the target weight should be calculated for a small individual of the target species. For a Manx shearwater, this would be a bird weighing 400 g. A 3% limit leads to a 12 g target weight.

6.2.5 Fix frequency and deployment length

Another concern is the frequency of location fixes. With a traditional GNSS receiver, this is limited by the size of the employed battery. Researchers therefore typically need to trade off tag weight and temporal resolution of their data. Most datasets considered in the 2023 review study did not report enough information to determine the frequency of fixes [131]. Out of the three datasets that reported both a total number of fixes and deployment time for archival GNSS tags, the average fix frequency was only 0.97 location fixes per day. It is important to note that these were migration studies, and shorter studies are likely to have higher fix rates because the employed battery does not have to last as long. Furthermore, as explained in Chapter 4, traditional GNSS tags also generally perform better for shorter deployments.

The popular GT-120 i-gotU tag with a 230 mA h battery can last for up to five days if configured to take a snapshot every two minutes[2].

6.2.6 Closed-source hardware and software

Lastly, most wildlife tracking products, including i-gotU tags, are closed-source. They also typically require closed-source software to configure the hardware and to access any recorded data.

Closed-source hardware is a concern for multiple reasons. Firstly, it will eventually become obsolete when the manufacturer stops producing it. This means that studies will eventually no longer be replicable. Closed-source hardware is also more difficult to repair, which causes unnecessary waste or additional costs and delays when sending products back to the manufacturer for repair.

The closed-source nature of any associated software is also a concern. It is unknown if there is any hidden data manipulation, such as smoothing or track interpolation. This type of black box behaviour makes these products a poor fit for scientific research, as it limits the interpretability and reproducibility of any results. Furthermore, just like hardware, software will eventually become obsolete, making any

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[2] Data sheet: i-gotU GT-120, `https://web.archive.org/web/20240130121145/https%3A%2F%2Fcdn.shopify.com%2Fs%2Ffiles%2F1%2F2104%2F5147%2Ffiles%2FGT-120BvsGT-600B.pdf%3Fv%3D1658604661` (archived 2024-01-30)

hardware that depends on it unusable before it reaches the end of its life. Not only is this wasteful, but it is also a significant concern for long-term studies.

6.2.7 Conclusion

In conclusion, common issues with current tags for tracking small birds include cost, availability, weight, fix frequency and black box behaviour of closed-source products, demonstrating the need for a new solution. This chapter describes how SnapperGPS was modified to fill this gap.

6.3 Target deployment

To evaluate the performance of a new system in a real-world scenario, a target deployment is required. For this, I collaborated with the OxNav research group at the University of Oxford, which has been studying seabirds for many years. The group has experience with using i-gotU GT-120 tags as well as some application-specific tags, and requires a new tag to use in their research to address the issues outlined in Section 6.2.

The chosen deployment focuses on Manx shearwaters on Skomer in Wales. Manx shearwaters are seabirds that weigh 400 g - 450 g and measure 35 cm with a wingspan of 80 cm [137]. Figure 6.2 shows a photo of an adult bird. Manx shearwaters breed in large colonies around the British Isles where they nest in burrows [138].

In one breeding season, a couple produces a single egg in late April or May, which is incubated for around 51 days [137]. During this incubation period, the parents take turns staying with the egg and foraging for fish. An average foraging trip takes about six days, but birds carrying tags tend to have longer foraging trips. In a 2020 study, incubating Manx shearwaters on Skomer carrying 4.2% of their body weight spent an average of 10 days at sea [123]. After the chick hatches, the parents continue to take turns staying with the chick and foraging. At this point, foraging

Figure 6.2: An adult Manx shearwater.

trips become shorter and more frequent so that the parents can feed the chick until it is ready to fledge. This is known as the chick-rearing period.

Incubation and chick-rearing are critical times for the birds as they need to feed themselves and their chicks before migrating to South America for the winter. This makes this period interesting to study and a common target for tracking studies. It also presents a good opportunity to test a new system and see how it compares with existing solutions. The birds are just small enough to be at the size and weight limit supported by the popular i-gotU GT-120 tags. This particular population has also been tagged before, so the group has experience with the deployment process. The season lasts multiple months, allowing for multiple short deployments to be done in a single season. This offers some flexibility in case of any unexpected issues. Finally, the deployment is in the UK, limiting the travel required. This is especially important during the ongoing COVID-19 pandemic which has caused much field work to be postponed or cancelled. The fieldwork was organised to occur between May and July 2022.

6.4 Design requirements

Section 6.2 covered the general concerns around tracking tags for small birds. This section summarises the design requirements that are specific to the target deployment introduced in Section 6.3.

As explained previously, weight is a major concern for bird tags. A small adult Manx shearwater weighs 400 g. The target weight for the tag is therefore 12 g for a 3% limit. The waterproofing and attachment method used by the OxNav group adds 3 g, leaving 9 g for the electronics.

Weight is not the only factor to consider, though. Shape also plays an important role. Generally, long and flat designs are preferred to minimise drag while the bird is flying. This also makes it possible to attach the tag to the bird's back between the wings, which should minimise discomfort and interference with the bird's movements. It also makes it difficult for the bird to peck at the tag and potentially damage or remove it.

The employed tag needs to be able to log location data for at least two weeks to cover a complete feeding trip during incubation and leave extra capacity to account for time spent at the colony before the trip.

Finally, the tag needs to be waterproof. A Manx shearwater can reach prey from the surface but can also dive to a depth of 50 m to pursue fish [139]. These dives further increase the need for a small and flat design.

6.5 SnapperGPS hardware modifications

Due to its very low power consumption, a snapshot GNSS tag is well suited for tracking birds like the Manx shearwater, as it allows for the use of very small and light batteries. However, the original SnapperGPS design does not fulfil the design requirements for this application.

This project was started in December 2021. The SnapperGPS PCB that had been developed at this point measures 27 mm × 32 mm and weighs 4.3 g. For the previous deployments on sea turtles in Cape Verde, described in Chapter 5, the SnapperGPS PCB was equipped with a MIA-GPS-25 antenna by Maxtena which weighs 13.6 g, and a 400 mA h LiPo battery which weighs 8.7 g. This brings the total weight for the SnapperGPS tag, including the antenna and battery to 26.6 g. This is almost three times the target weight of 9.0 g.

This section outlines the changes made to the SnapperGPS design to create a new tag that is suitable for tracking small birds.

6.5.1 PCB layout changes

To reduce the size of the board, the GPIO pads were removed as there were no plans for any additional sensors to be added to the tag. Additionally, components were moved around to further reduce the width of the board. Overall, the PCB became 15% narrower and 9% longer. The new size is 23 mm × 35 mm. The antenna is meant to be fixed to the back of the board. To accommodate the cable connecting the antenna to the front of the board, two cut-outs were made on the sides of the PCB. This makes it possible to wrap the cable of the patch antenna, if necessary.

6.5.2 Component changes

The original SnapperGPS design uses the W25N512GVEIG by Winbond for storage, which has a capacity of 512 Mbit. This was replaced with the W25N01GVZEIG of the same line with a capacity of 1 Gbit. This change means that this SnapperGPS variant can store 21,800 snapshots, which is enough to take a snapshot every minute for 14 days.

To make the tag as flat as possible, the JST connector was removed. Instead, the battery is soldered directly to the board. To make it possible to charge the battery, a LiPo charging IC was added, which makes it possible to charge the battery directly via the USB port. The charging IC used is the MCP73832T-2ACI/OT by Microchip Technology. The board also includes a red LED that indicates the charging status of the battery.

Beyond these functional component changes, the design also had to be updated to accommodate the global chip shortage. This meant that some components had to be replaced with alternatives that were available at the time. This included the temperature-compensated crystal oscillator, the voltage regulator and multiple MOSFETs. The replacements were chosen based on their availability and compatibility with the existing design.

6.5.3 Manufacturing and assembly

To reduce the weight of the tag, the PCB was manufactured with a thickness of 0.8 mm, instead of the typical 1.6 mm. At the time, this was the smallest PCB thickness available from the manufacturer. The PCB alone weighs 2.6 g.

The PCBs were manufactured with an electroless nickel immersion gold (ENIG) finish to avoid oxidation, which is a particular concern for this application. The tags will be exposed to large temperature fluctuations, making condensation of any residual moisture in the sealed enclosure likely.

6.5.4 Battery and antenna choice

The battery used is a 40 mA h LiPo battery. This battery was chosen because it was the smallest battery that was available. The battery has a nominal voltage of 3.7 V and a maximum charge voltage of 4.2 V. It weighs 1.2 g.

The battery has a protection circuit module (PCM) that monitors the voltage of the cell as well as the current flowing in and out of the cell. The PCM will automatically disconnect the battery if any monitored parameters exceed safe limits. This is important as it prevents the battery from being overcharged or overdischarged, which

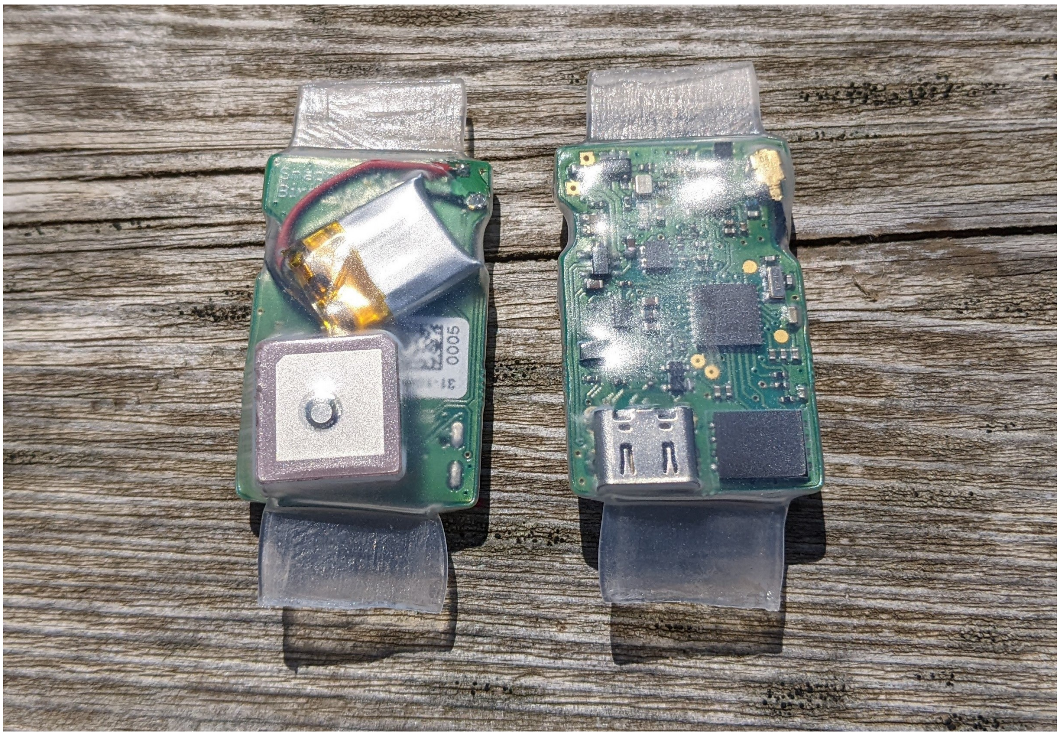


Figure 6.3: Two SnapperGPS bird variant tags, equipped with a 40 mA h battery and a APAM1368YB13V3.0 antenna. The tags have been sealed using heat shrink tubing.

could cause damage to both the battery and the connected electronics. It could also lead to overheating, making it a serious animal welfare concern. However, the total energy carried by the battery is small, limiting the potential for harm in the unlikely case of a PCM failure.

Manx shearwaters spend most of their time in sustained flight or sitting on open water. This means that the tag will usually have a clear line of sight to the sky, making the use of smaller antennae feasible. Unfortunately, antenna options were limited due to the global chip shortage at the time. The antenna used is the APAM1368YB13V3.0 by Abracon LLC. It is a ceramic patch antenna that measures 13 mm × 13 mm × 6 mm and weighs 4.6 g.

After being connected to the PCB, the antenna and battery are glued to the back of the board with double-sided tape to create one solid stack without any loose components. The total weight of the tag is 8.4 g.

Figure 6.4: SnapperGPS bird variant on a Manx shearwater.

6.5.5 Waterproofing

For the SnapperGPS deployments on sea turtles in 2021, custom-milled cases were used to protect the electronics. They were made out of aluminium and POM, making them sturdy and waterproof to large depths. The Manx shearwater can dive to a maximum depth of 50 m so waterproofing is again a major concern. However, custom-milled cases would be too heavy. Instead, the stack of electronics is enclosed using plastic heat shrink tubing, which is cheap, lightweight and flexible. A piece of tubing a little longer than the length of the PCB is cut and shrunk around the components with a heat gun. The ends of the tubing are sealed with a pair of needle-nose pliers or a hair iron while the plastic is still hot and soft. The final enclosed tag is shown in Figure 6.3. The tag is sealed after configuration, just before being deployed on a bird. After the deployment, the heat shrink can be carefully cut off to recover the data. Figure 6.4 shows the SnapperGPS bird variant tag on a Manx shearwater during the process of attachment.

6.6 Deployment results

The first field deployments of the SnapperGPS bird variant occurred between May and July 2022 and covered both incubation and chick rearing on Skomer. This work was carried out by researchers from the OxNav group.

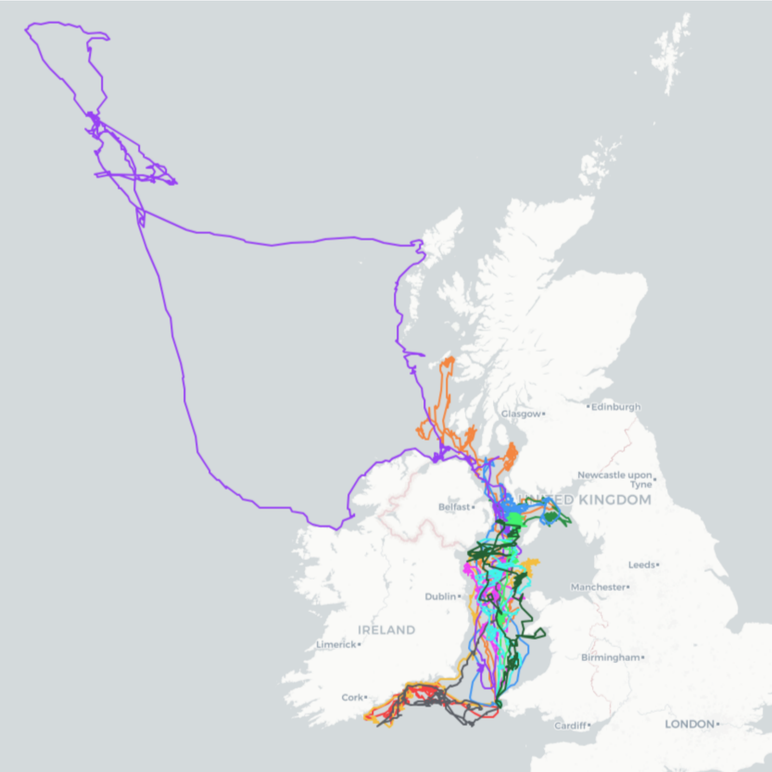
To achieve a deployment time of 14 days, the tags were programmed to take a snapshot once every minute. After configuration, the tags were sealed and then attached to the bird later on the same day.

The birds were tagged while they were in the burrow, before the anticipated return of their partner. This means there is always some time at the start of every recording without any location data because the bird is still underground. The burrows were checked regularly to keep track of which parent is in the burrow and to anticipate when the birds will leave and return. Once a bird returned, its tag was removed, and the logged data was downloaded.

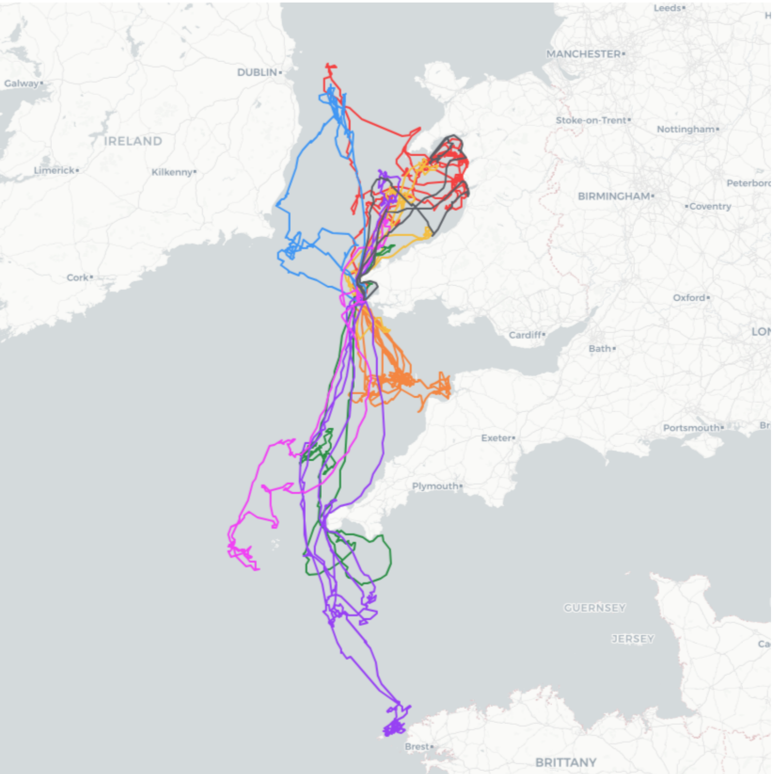
In total, 21 birds were tagged. Two lost their tag at sea, and one bird did not leave its burrow, leaving 18 actual deployments. All recovered tags recorded data, but in some cases, the storage ran out before the trip was completed. This happened when birds were tagged too early, which caused some storage to be used up before the bird actually left the burrow.

Figure 6.5 depicts the recorded tracks of the birds during incubation and chick rearing, respectively. Each colour represents one deployment on one bird. During incubation, birds make larger trips to feed themselves as much as possible. During chick rearing, the trips are shorter and more frequent, as the birds need to regularly return and feed their chick.

Data like this can be used to study the foraging behaviour of the birds. This can be useful to understand how changes in environmental variables (such as ship traffic, fishing activity, climate change or light pollution) affect the birds.



(a) Tracks recorded during the incubation period.



(b) Tracks recorded during the chick rearing period.

Figure 6.5: Manx shearwater tracks recorded by SnapperGPS bird variant tags in 2022. Every colour represents one deployment on one bird. Map by Leaflet, OpenStreetMap and CartoDB positron.

6.7 Comparison with i-gotU GT-120 and Technosmart Axy-Trek Marine

In this section, I compare the SnapperGPS bird variant with two other existing GNSS tags that are commonly used to study birds. One is the general-purpose GT-120 by i-gotU, a popular choice for birds due to its low cost. The other is the Axy-Trek Marine tag by Technosmart, a relatively expensive tag that is specifically designed for tracking small marine animals. Technosmart offers the option to customise this product when ordering. As a result, every tag is different and the specifications are not publicly available. For this comparison, I rely on two particular Axy-Trek Marine tags that have been used by the OxNav research group to track Manx shearwaters in the past.

This section compares these tags in terms of cost, size and weight. The data sheet of the GT-120 also lists its maximum deployment time for some fix frequencies, making it possible to additionally compare this performance metric.

6.7.1 Cost

Due to the global COVID-19 pandemic, the SnapperGPS bird variant PCBs were manufactured locally instead of overseas, where they would typically be produced at a much lower cost. This was done to reduce the risk of delays due to the pandemic, as well as general customs holdups. The PCBs were manufactured by Newbury Electronics in the UK. The cost of the manufacturing and assembly of the boards was £57 per board for a batch of 30. This also includes some capacitors and resistors which were provided by the manufacturer. However, most components had to be supplied from private stock. The global chip shortage makes it difficult to estimate the cost of these components, as they were bought individually whenever they came in stock, and prices varied greatly. In total, the cost of each SnapperGPS bird variant tag from the original batch was around £90, including the antenna and

Table 6.1: A comparison of the physical characteristics of the SnapperGPS bird variant, the i-gotU GT-120 (equipped with either a 250 mA h or a 320 mA h battery) and two custom Technosmart Axy-Trek Marine tags as can be seen in Figure 6.6. Shown are size (width x length x height), battery capacity, weight (including battery and antenna) and estimated cost.

Name	Size [mm^3]	Battery [mAh]	Weight [g]	Cost [£]
SnapperGPS				
bird variant	23 x 35 x 9	40	8.4	$\approx$ 30
i-gotU				
GT-120 + 250 mA h	23 x 39 x 10	250	12.8	$\approx$ 40
GT-120 + 320 mA h	23 x 39 x 10	320	13.7	$\approx$ 40
Technosmart				
Axy-Trek (small)	17 x 34 x 12	unknown	7.0	> 500
Axy-Trek (big)	22 x 45 x 10	unknown	13.8	> 500

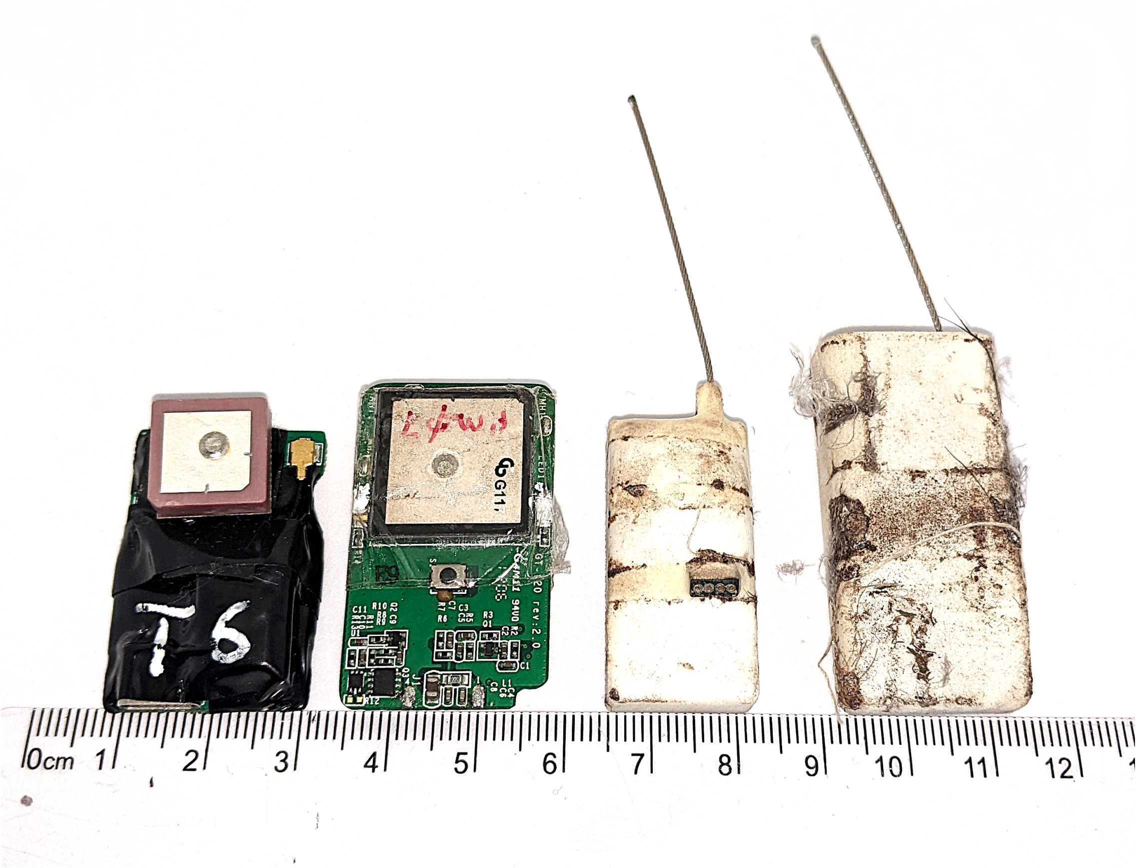


Figure 6.6: A SnapperGPS tag next to other commonly used tags for tracking birds. From left to right: SnapperGPS bird variant, GT-120 i-gotU tag and two custom Axy-Trek Marine tags by Technosmart. For size and weight, see Table 6.1

battery. In 2023, SnapperGPS bird variant tags were manufactured at £30 for a batch of 100. This is likely still somewhat unusually high as the global chip shortage was still affecting prices at this point. Note that the price will generally be higher if manufactured in smaller batches. Conversely, a larger batch will result in a lower cost per tag.

The i-gotU GT-120 costs between \$50-\$60 [120, 125]. This is roughly £40.

Application-specific tags are typically much more expensive, although most suppliers, including Technosmart, do not list their prices publicly. In personal communication, researchers have shared that they paid over £500 for a custom Axy-Trek Marine tag. It is important to note that these tags are customisable, and often include additional sensors. The cost of the tags can therefore vary depending on the customisation options chosen.

In conclusion, the SnapperGPS bird variant is much cheaper than tags marketed for wildlife tracking applications and comparable in price to the popular i-gotU GT-120, although the exact price will depend on the manufacturing batch size.

6.7.2 Size and weight

Figure 6.6 shows a SnapperGPS bird variant next to a GT-120 i-gotU tag and two bespoke Axy-Trek Marine tags by Technosmart. These have all been used by the OxNav research group to track Manx shearwaters during the incubation period. Table 6.1 compares the physical characteristics of these tags. It also includes the cost of each tag, as discussed above.

At 23 mm, the SnapperGPS bird variant is as wide as the GT-120 i-gotU tag, while being 10% shorter. The Axy-Trek tags by Technosmart are a little narrower, but generally, the SnapperGPS bird variant tag has similar dimensions as existing state-of-the-art bird tags.

A SnapperGPS bird variant tag with a 40 mA h battery weighs 8.4 g. This is a 34%

reduction in weight compared to a GT-120 i-gotU tag with a 250 mA h battery. Together with the waterproofing and attachment material, a SnapperGPS bird variant weighs 11.4 g. At this weight, it can even be used on small Manx Shearwaters that only weigh 400 g without exceeding the commonly used 3% weight limit, unlike the GT-120 and the larger Axy-Trek Marine tag. However, smaller tags are available, such as the smaller Axy-Trek Marine tag considered here, which weighs only 7.0 g.

Overall, the SnapperGPS board is smaller and lighter than the GT-120 tag and comparable in size and weight to Axy-Trek Marine tags.

6.7.3 Temporal resolution and maximum recording time

Most commercially available wildlife tracking tags do not have publicly available data sheets that detail their maximum recording time for a given fix interval. This makes performance comparisons difficult. However, the i-gotU GT-120 data sheet does include a small number of example configurations for a tag with a standard 230 mA h battery. This information can be used to sketch out the landscape of possible deployments, as shown in Figure 6.7. It plots the minimum fix interval for a given deployment time for both the GT-120 with stock battery and the SnapperGPS bird variant. Note that both axes use logarithmic scaling.

The SnapperGPS bird variant generally outperforms the GT-120. It provides a particularly large advantage after a few days. For deployments longer than one week, the SnapperGPS bird variant outperforms the GT-120 by multiple orders of magnitude. The shape of the curve for the GT-120 is similar to the one calculated for the OriginGPS Multi Micro Hornet considered in Chapter 4. This suggests that the GT-120 employs similar low-power modes as the Multi Micro Hornet.

For a two-week deployment, the SnapperGPS bird variant achieves a temporal resolution of one location fix every minute. At the same resolution, the GT-120 i-gotU tag can only last up to 80 h $\approx$ 3.3 d using the stock battery.

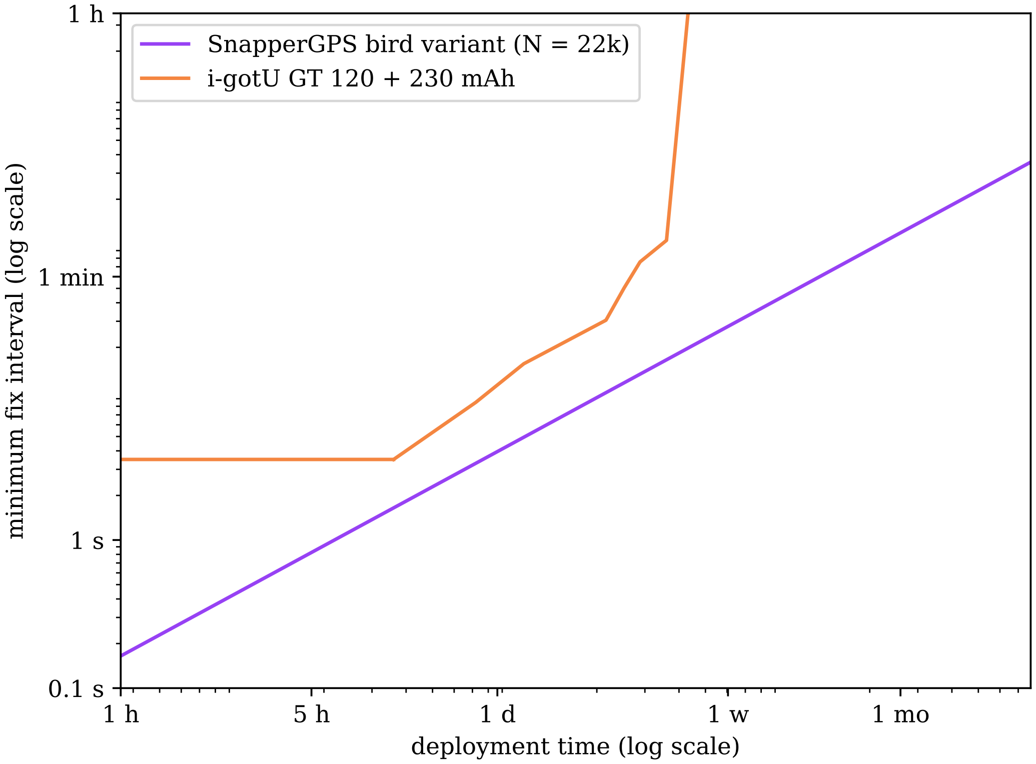


Figure 6.7: Minimum fix interval vs deployment time for a SnapperGPS bird variant (with 1 Gbit storage ≈ 22k snapshots) and an i-gotU GT-120 with stock battery.

6.8 Field performance comparison with GT-120

After the initial success of the SnapperGPS bird variant in 2022, the OxNav research group continued to use the tag in subsequent years. In the incubation period of 2024, they deployed a set of 36 SnapperGPS bird variant tags on a Manx shearwater population on the island of Copeland. In the same season, they also deployed 36 i-gotU GT-120 tags with 320 mA h batteries on the same population. This presents an opportunity to compare both tags under field conditions.

To achieve coverage of at least one incubation feeding trip, the GT-120 tags were configured to attempt a location fix every 5 minutes. As discussed in Section 6.7.3, the SnapperGPS bird variant can provide a higher temporal resolution than the GT-120. Because of that, the SnapperGPS bird variant tags were configured to take a snapshot every 2 minutes.

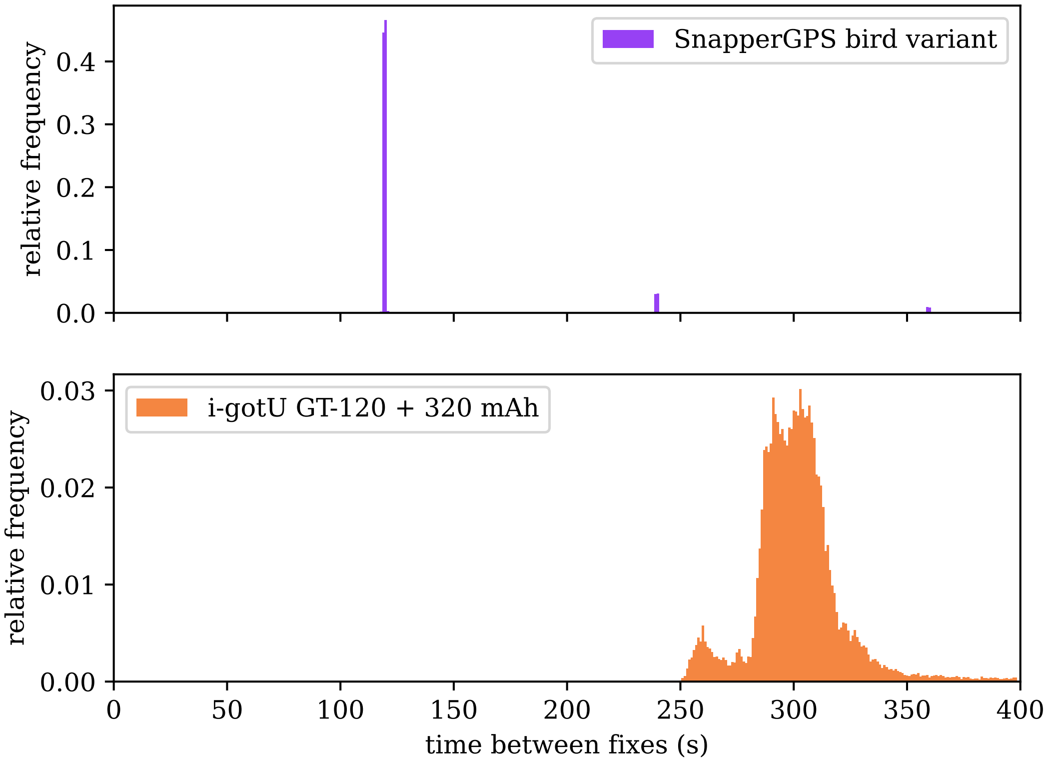


Figure 6.8: Distribution of fix intervals across all recordings from the 2024 Manx shearwater incubation season for the SnapperGPS bird variant and the i-gotU GT-120.

Figure 6.8 shows the distribution of successful location fix intervals across all recordings for each type of tag, respectively. A tag on a seabird generally has ideal sky visibility, interrupted only rarely by short dives. This means that location fix attempts are almost always successful. A traditional GNSS approach may sometimes be a bit faster or slower, depending on how the recording time lines up with the satellite data currently being transmitted by the visible GNSS satellites. A snapshot GNSS tag, on the other hand, will always take a snapshot at the configured interval. This is why the fix interval distribution of the SnapperGPS tag has almost no spread, compared to the GT-120 tag.

If a fix is attempted underwater with a SnapperGPS tag, the snapshot will simply not include any satellite data, and the position estimate will fail. The next snapshot will be taken at the next configured interval. This is why the main peak at 120 s is followed by smaller peaks at 240 s and 360 s. A traditional GNSS receiver like

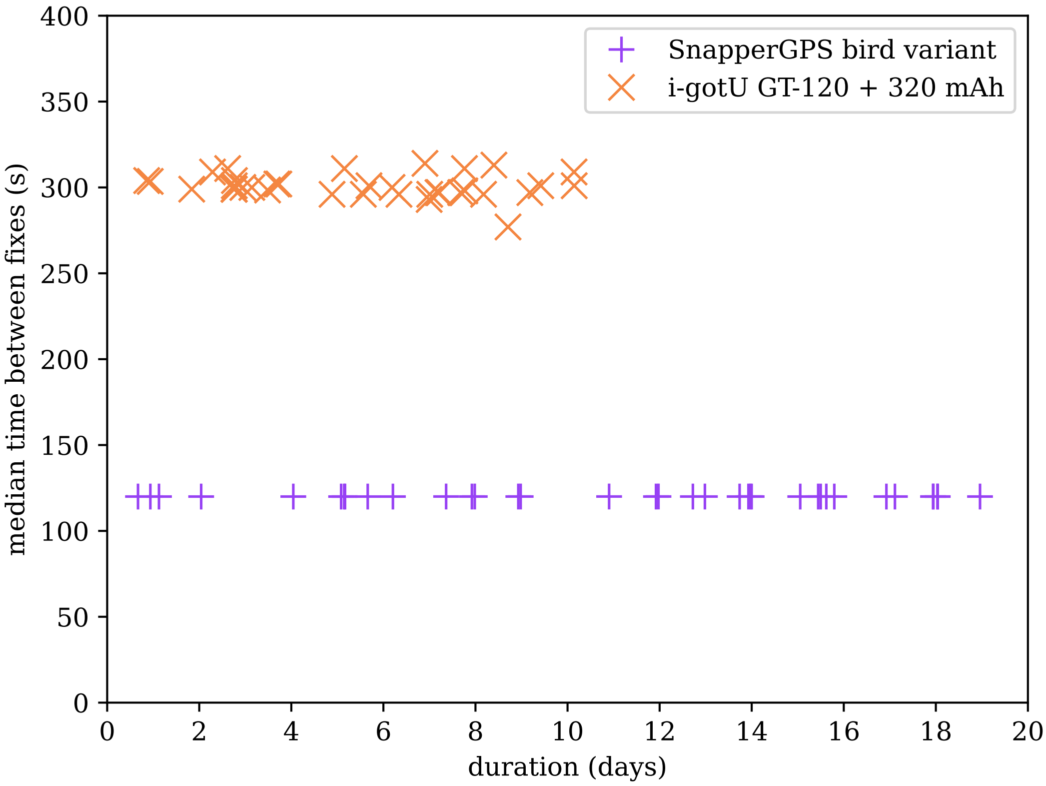


Figure 6.9: Median fix interval and total deployment duration for all recordings from the 2024 Manx shearwater incubation season for the SnapperGPS bird variant and the i-gotU GT-120.

the GT-120, on the other hand, will usually continue to attempt to read incoming satellite data until a fix is achieved, causing a tail in the fix interval distribution.

Figure 6.9 shows the median fix interval and the duration of each deployment from the 2024 Manx shearwater incubation period. The SnapperGPS bird variant tags lasted for deployments of up to 19 days, whereas the GT-120 tag lasted for up to 11 days while taking fixes 2.5 times less frequently. Note that in this season, tags were recovered when the bird was resighted. In the case of SnapperGPS tags, this was always before they stopped recording, so the deployment time is not the maximum possible deployment time. A SnapperGPS tag is limited by storage and will always be able to record the same number of snapshots. In the case of this bird variant, this maximum number is around 21,800 snapshots. At a snapshot interval of 2 minutes, this corresponds to a maximum deployment time of 30 days.

Overall, the SnapperGPS bird variant provides a higher temporal resolution than the GT-120 while also lasting longer. This difference becomes particularly significant for deployments longer than about a week, depending on the battery used.

6.9 Conclusion

This chapter described how SnapperGPS was modified to create a specialised variant for tracking birds, specifically Manx shearwaters during the breeding season.

Existing solutions for tracking birds are often too heavy or too expensive and always closed-source. The novel SnapperGPS bird variant was developed to address these issues. It outperforms commercially available tags in terms of temporal resolution while at least matching them in cost, weight and size. The design and manufacturing files are open-source, allowing for transparent and reproducible research[3].

The SnapperGPS bird variant was first deployed in 2022 and continues to be used by the OxNav research group. Since its development, over 100 SnapperGPS bird variant tags have been successfully deployed.

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[3] SnapperGPS bird variant design and manufacturing files, `https://github.com/amanda-matthes/snappergps_bird_variant`

Chapter 7

Conclusion

7.1 Summary of contributions

Snapshot GNSS systems have multiple advantages over traditional GNSS counterparts, especially for wildlife tracking. However, there is little literature comparing the two technologies. This makes it difficult for users to know which option is appropriate for their application. Furthermore, only a small number of research prototypes and commercial products implement the snapshot GNSS approach, and none of them are completely open-source. This makes further research difficult. It also limits the interpretability and reproducibility of any research data generated with these systems.

One goal of this thesis was to address this by developing a fully open-source snapshot GNSS solution. The first step towards this was a feasibility study to determine if snapshot GNSS could be implemented with low-cost, off-the-shelf hardware. This is only possible with relatively low-quality snapshots, making positioning challenging. Chapter 3, demonstrated that 12 ms 1 bit snapshots sampled at only 4.092 MHz can yield median accuracies better than 15 m.

Chapter 4 then analysed how a snapshot GNSS receiver compares to a modern implementation of a traditional GNSS receiver with low-power modes. It showed that snapshot GNSS receivers tend to outperform traditional GNSS receivers, especially for longer deployments. For applications that can use a 100 mA h battery, snapshot

GNSS receivers will significantly outperform traditional GNSS receivers for deployments longer than about one week. This novel analysis can help researchers decide which technology to use for their specific application.

Then, Chapter 5 presented SnapperGPS, an open-source, low-cost and low-power location tracking system specifically designed for wildlife tracking applications. The chapter also described multiple SnapperGPS deployments on wild animals, which were carried out in collaboration with wild animal researchers.

Seabirds present an especially challenging wildlife tracking application, as they require particularly small and lightweight tags. Chapter 6 described how SnapperGPS was adapted for the application of tracking the feeding trips of Manx shearwaters during egg incubation and chick rearing. The chapter showed that this SnapperGPS bird variant can provide significantly more frequent fixes than the commonly used i-gotU GT-120 while being smaller and lighter at a similar price. In 2022, the SnapperGPS bird variant had its first successful deployment on Manx shearwaters on the island of Skomer in Wales and it continues to be used in ongoing research.

7.2 Future directions

This section provides a list of potential future research and engineering directions that could be pursued based on the work presented in this thesis.

7.2.1 Researching snapshot GNSS technology

SnapperGPS can be used as a fully open-source foundation for further research and development of snapshot GNSS technology. Researchers can use the project as a starting point to develop and test new snapshot GNSS algorithms to improve performance. Potentially useful goals include reducing acquisition and location estimation times, improving accuracy, and increasing robustness in challenging environments.

7.2.2 Improving the SnapperGPS hardware

There are also a number of potential improvements that could be made to the SnapperGPS hardware. Firstly, any size and weight reduction would extend the range of animals that the device could be used for. This could be achieved by investigating other antenna options. The SnapperGPS versions presented here all use external active ceramic patch antennae. Integrated antennae could be used to reduce the size and weight of the device. However, they are likely to produce lower-quality signals. It is therefore possible that other changes would be necessary, such as an increase in snapshot length. This would lead to increased energy consumption of the device and reduce the number of snapshots that could be stored.

Since storage is the limiting factor for a snapshot GNSS tag, increasing the storage capacity of SnapperGPS could be very beneficial. Chapter 4 includes estimates of how adding an SD card would extend deployment times. This is only feasible for applications that can tolerate somewhat higher tag size and weight, as the SD card would require additional battery capacity. However, for some applications, the increased deployment time would be worth the trade-off.

The SnapperGPS hardware can be fragile, especially under field conditions. Battery cables and antenna connectors are particularly common points of failure. Robust housing solutions are one potential way to address damage during deployments. However, with the current design, housings still need to be opened to configure the device and download any data via the USB connector. A more robust, fully sealed housing design that allows for data download and battery charging would be a significant improvement.

7.2.3 Developing more application-specific SnapperGPS variants

The SnapperGPS hardware is designed to be a general-purpose GNSS data logger. However, there are some common applications that could benefit from a more specialised design. Chapter 6 described how SnapperGPS was adapted for the application of tracking small seabirds. Other potentially useful specialised SnapperGPS variants could include a collar for terrestrial mammals or an ear tag for very large animals where a collar would be impractical.

7.2.4 Extending the SnapperGPS hardware with other sensors

Another useful improvement to the SnapperGPS hardware would be the addition of other sensors. Potentially useful types of data to sense include acceleration, humidity, pressure, light level, and sound. These sensors could be used to infer animal behaviour and environmental conditions.

A large advantage of logging sensor readings alongside GNSS data is that recordings can be accurately timestamped. Onboard clocks on sensor loggers suffer from time drift, which accumulates over long deployments. Every GNSS-based location estimate includes a precise timestamp, which can be used to correct the time drift in the sensor data. This is particularly useful for applications that require high temporal resolution, such as fine-scale animal behaviour studies.

7.2.5 Improving accessibility of the SnapperGPS hardware

Even though SnapperGPS is completely open-source, manufacturing a SnapperGPS receiver involves the printing and assembly of a custom PCB. This presents a barrier to entry for many potential users.

Group purchasing campaigns are one potential way to make SnapperGPS more accessible. They work by collecting orders for a product before it is produced. This allows for bulk orders to be placed, reducing the cost per unit. A potential user would only need to place an order and wait for enough orders to be collected before the product is manufactured. This does cause some delay in receiving the product, but it can significantly reduce the cost of the hardware and make it more accessible to a wider range of users.

Group purchasing campaigns have previously been shown to be successful for a similar project, the AudioMoth by Open Acoustic Devices, an open-source acoustic logger for environmental monitoring [140].

Once a product has had multiple successful group purchasing campaigns on some platform, indicating enough demand, the product can sometimes be manufactured ahead of time and stocked by a distributor. This allows users to purchase the product immediately, without having to wait for a group purchasing campaign to be completed. This has happened in the case of the AudioMoth, which is now stocked by both GroupGets and LabMaker. GroupGets still offers group purchasing campaigns for users who want a lower price and are willing to wait for enough orders to accumulate.

7.3 Conclusion

In conclusion, this thesis has advanced the field of wildlife tracking by (i) demonstrating that snapshot GNSS systems with simple hardware are possible, (ii) analysing how snapshot GNSS systems compare against new implementations of traditional GNSS systems with low-power modes, and (iii) presenting SnapperGPS, a fully open-source snapshot GNSS system that has already been successfully used in multiple wild animal tracking studies.

The comparative analysis can help users make an informed decision when choosing between snapshot and traditional GNSS for their application. For cases where a snapshot solution is advantageous, SnapperGPS offers a field-tested implementation. Additionally, SnapperGPS serves as a foundation for further research and development of snapshot GNSS technology.

Appendix A

Ecology and conservation researchers should adopt open-source technologies

A.0 About

This appendix chapter includes the contents of the paper "Ecology and conservation researchers should adopt open source technologies" which I co-authored with Pen-Yuan Hsing and Brianna Johns. The paper was published in the journal *Frontiers in Conservation Science* in May 2024. My contributions to the paper include co-writing the original draft as well as editing the paper in response to reviewer comments. The appendix includes the paper text as it was submitted to the journal for publication, with minor edits to fit the thesis style.

A.1 Introduction

In light of globally declining biodiversity [2, 141] and threats to both rare and common species [142, 143], there are calls to utilize modern technologies for monitoring and conservation [144–147]. Technologies are deployed to improve data collection and analysis in both terrestrial and aquatic environments [148]. These advancements can enable more efficient data collection compared to traditional survey methods [149] and aid crowdsourced data collection and processing [150, 151]. There are emerging communities of practice, such as Conservation X Labs[1] or WILDLABS[2] which report on the state of conservation technology [152] and provide guidelines on socially responsible use [153].

The advancement of conservation technologies coincides with the increased adoption of open science practices. As defined in the Recommendation on Open Science ratified by the United Nations Educational, Scientific and Cultural Organization [154], open science entails inclusive, equitable, and sustainable approaches to scientific practices and outputs. Ecological research has increasingly adopted these practices [83], notably through more open and FAIR data [79, 155]. There also exists open-source software used in biodiversity research, such as the R programming language [156] and analytical packages built on it.

However, unlike software and data, the hardware used for ecological research is still typically closed-source (i.e. proprietary), and its designs (and accompanying software source code) are legally restricted, preventing others from studying, reproducing, or modifying them.

Apart from just increasing effort and cost when adapting existing equipment to new contexts, closed-source hardware also reinforces global inequalities. As reviewed by Arancio, the manufacturing and dissemination of scientific equipment is often monopolized by entities in the Global North. This creates barriers for researchers in the Global South including, but are not limited to, prohibitive costs, lack of availability, and technical support. They lead to epistemic injustice, where research questions are constrained by the physical tools researchers are allowed to access or modify. Additionally, the vendor lock-in and forced obsolescence of closed-source hardware mean that users are legally barred from maintaining them. This creates e-waste, which has been described as a form of environmental crime [157].

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[1] `https://conservationx.com/`

[2] `https://wildlabs.net/`

One solution to these problems is open-source hardware. It is defined as hardware whose design is "made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design"[3]. In our view, while open-source hardware is beginning to be adopted for ecology research [83,148], its potential is still largely untapped.

We are researchers with experience in both ecology and open-source hardware communities. In this opinion article, we argue for wider recognition and adoption of open-source hardware in biodiversity research. Among other benefits, we provide examples demonstrating how open-source hardware can: reduce upfront and maintenance costs; enable adapting to novel contexts; and improve research quality and transparency. We end with suggestions for individuals and institutions on adopting open-source hardware in research.

A.2 Reducing upfront and maintenance costs

By its nature, closed-source hardware allow their manufacturers to command a high price through monopolies. In contrast, anyone can manufacture and sell hardware based on an open-source design, so the cost of purchase can be close to the actual manufacturing cost. One study suggests that open-source hardware can create cost savings of up to 87% compared to closed-source functional equivalents [158].

SnapperGPS[4] is one example of such low-cost open-source hardware for ecology research. It is a location data logger specifically designed for wildlife tracking [37]. In contrast with proprietary equivalents costing thousands of USD, the component cost of a SnapperGPS receiver is under $ 30, making it accessible to research groups with lower budgets. The project also has a discussion forum[5] where the community can ask questions, discuss issues, provide technical support, and share experiences.

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[3] Open Source Hardware Definition: `https://www.oshwa.org/definition/`

[4] `https://snappergps.info`

[5] `https://github.com/orgs/SnapperGPS/discussions`

Because users have complete access to the hardware design files, they can also maintain and repair their equipment independently, rather than having to rely on the original manufacturer who has an incentive to sell new units instead of repairing existing ones. Any knowledge about repair and maintenance can also be freely shared with the community further helping other users, without expensive support contracts or infringing on intellectual property restrictions. This is exemplified by the Appropedia Foundation[6], an online community where sustainability researchers share designs and provide mutual help on the repair and maintenance of open-source hardware [159].

A.3 Adapting to novel contexts

Off-the-shelf proprietary technology is unlikely to fit every application well. Ecologists, in particular, may need specific hardware properties to accommodate unique environments or species. However, modifying devices to meet research needs is difficult with closed-source hardware, because its designs are not shared and modifications are not permitted. In the case of open-source hardware, however, modifications can be added to an existing design and even be published as a new version that can then be freely manufactured and used by future researchers.

OpenFlexure[7] exemplifies this advantage. It is an open-source, low-cost, lab-grade microscope, originally developed for microscopy in biomedical research [160]. Its design has since been adapted to many other contexts. For example, researchers trialling OpenFlexure for orchid bee identification in Panamanian rainforests found the device was not suited for their use case, which does not require high magnification but does need robustness under field conditions. In response, the researchers adapted OpenFlexure into a dissection microscope that is easy to use and repair in the field. At the time of writing, the first version of this design has been completed, and

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[6] `https://www.appropedia.org`

[7] `https://openflexure.org/`

feedback from field trials is being incorporated into the next version [161].

A.4 Improving the quality and transparency of research

Closed-source hardware is opaque, preventing researchers from fully understanding how the equipment operates. This makes identifying systematic errors difficult, especially if the manufacturer has a monopoly on the technology so that users have no alternatives for comparison.

This problematic “black box” effect of closed-source devices is exemplified by CTDs, an oceanographic instrument that measures salinity, temperature, and depth. These three variables are essential for almost all marine scientific studies. Commonly-used closed-source CTDs are not only expensive (at least several thousand USD), but also require costly maintenance services. In recent years, the OpenCTD was developed as an open-source CTD for coastal oceanographic research [162], along with openly published calibration procedures[8]. Notably, in addition to making this technology more accessible, the OpenCTD team identified a systemic problem of handheld proprietary CTDs being out of calibration but remaining in field use (Thaler, pers comms). This error remained undetected for years until a comparison could be made with OpenCTD devices, and underscores the crucial role for open-source hardware to improve research quality and transparency.

A.5 Discussion

Open-source hardware and software enshrine the freedoms to study, reproduce, modify, and distribute them without restrictions. They enable equitable access to technology, allowing context-relevant and cost-effective adaptations with the potential to improve research quality and transparency. The examples we used to illustrate these benefits are part of a growing movement, which seeks to adopt open-source

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[8] `https://github.com/OceanographyforEveryone/OpenCTD/blob/main/Documentation/Manual/OpenCTD_CalibrationDataManagement.pdf`

hardware in ecology and conservation research [83, 148, 163, 164]. We end this opinion article with suggestions for publishing open-source hardware in a reproducible way and reforming institutional policies to encourage its development.

A.5.1 Publishing open-source hardware

In recent years, best practices have emerged to ease the publication and reproducibility of open-source hardware in scientific research. For example, the Open Know-How specification [165] defines structured metadata to accompany hardware designs, such as requiring a bill of materials (BOM) or listing key contact persons. This metadata is stored in a YAML-formatted file, and is published with design files in a public repository (e.g. platforms such as GitLab or GitHub) similar to current best practice for software. Crucially, Open Know-How specifies that hardware designs should be published with open-source licenses, the most popular of which are the three CERN Open Hardware licenses[9].

Once hardware designs are published, detailed information about their fabrication and use can be published in peer-reviewed journals such as the Journal of Open Hardware[10] or HardwareX[11]. A variety of hardware with biodiversity applications has been published this way, from a camera trap for benthic marine organisms [166] to a strain gauge for measuring wind damage to trees [167]. In support of these academic journals is the DIN SPEC 3105 standard [168], which defines guidelines for effective peer review of hardware documentation and reproducibility.

A.5.2 Reforming institutional policy to encourage open-source hardware

Research institutions and funding bodies should support open-source hardware as a key pillar of open science, as recognized in the UNESCO Recommendation on

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[9] `https://cern-ohl.web.cern.ch/`

[10] `https://openhardware.metajnl.com/`

[11] `https://www.hardware-x.com/`

Open Science [154]. Actionable policy guidance has been developed for universities [169], including embedding open-source hardware in open science training; creating career pathways for developing open-source hardware; and developing mechanisms to monitor adoption.

A common misconception is that open-source hardware cannot be commercially viable. But in actuality, open-source hardware allows commercialization and multiple profitable open hardware business models have already been demonstrated [170]. Successful examples from biology research include IORodeo[12] (a producer of laboratory analytical equipment), NinjaPCR[13] (a seller of digital real-time polymerase chain reaction (PCR) machines), or the Arribada initiative[14] (a consultancy for biodiversity research and developer of hardware kits for biologging and satellite tracking). In light of these successes, university technology transfer offices (TTOs) should update their policies to support open-source hardware [169], including using its development as a way to achieve sustainable development goals [171].

A.6 Conclusion

The urgency of the biodiversity crisis is connected to technological waste and global inequalities [157,172,173]. As biodiversity researchers, we have an ethical imperative to adopt open-source hardware as part of the solution. In addition, with growing popular interest in biodiversity conservation [174], the use of open-source hardware (and software) would signal transparency and accountability that strengthens public trust in science. In this opinion piece, we highlighted the progress that open-source hardware can enable for ecology research.

Lastly, we note that biodiversity researchers are not the only ones who would benefit from open-source hardware. Anyone considering open-source hardware for their re-

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[12] `https://iorodeo.com/`

[13] `https://qninja.hisa.dev/`

[14] `https://arribada.org/`

search could engage with global practitioner communities, including the Gathering for Open Science Hardware[15], Open Science Hardware Foundation[16], Internet of Production Alliance[17], or the Open Source Hardware Association[18]. They collectively sustain ongoing discourse on the development and use of open-source hardware, and reflect a growing recognition for its role in scientific research.

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[15] https://openhardware.science/

[16] https://opensciencehardware.org/

[17] https://www.internetofproduction.org/

[18] `https://www.oshwa.org/`

Bibliography

[1] Technical Committee, SD Card Association, "SD Specifications Part 1, Physical Layer Simplified Specification, Version 8.00, September 23, 2020," 2020. [Online]. Available: https://www.sdcard.org/downloads/pls/pdf/?p=Part1_Physical_Layer_Simplified_Specification_Ver8.00.jpg&f=Part1_Physical_Layer_Simplified_Specification_Ver8.00.pdf&e=EN_SS1_8

[2] S. H. Butchart, M. Walpole, B. Collen, A. Van Strien, J. P. Scharlemann, R. E. Almond, J. E. Baillie, B. Bomhard, C. Brown, J. Bruno *et al.*, "Global biodiversity: Indicators of recent declines," *Science*, vol. 328, no. 5982, 2010. [Online]. Available: https://doi.org/10.1126/science.1187512

[3] G. Ceballos, P. R. Ehrlich, A. D. Barnosky, A. García, R. M. Pringle, and T. M. Palmer, "Accelerated modern human–induced species losses: Entering the sixth mass extinction," *Science Advances*, vol. 1, no. 5, 2015. [Online]. Available: https://doi.org/10.1126/sciadv.1400253

[4] S. L. Pimm, C. N. Jenkins, R. Abell, T. M. Brooks, J. L. Gittleman, L. N. Joppa, P. H. Raven, C. M. Roberts, and J. O. Sexton, "The biodiversity of species and their rates of extinction, distribution, and protection," *Science*, vol. 344, no. 6187, 2014. [Online]. Available: https://doi.org/10.1126/science.1246752

[5] G. M. Almond, R.E.A., T. Petersen *et al.*, *Living Planet Report 2020 - Bending the curve of biodiversity loss.* World Wildlife Fund, 2020. [Online]. Available: http://pure.iiasa.ac.at/id/eprint/16870/1/ENGLISH-FULL.pdf

[6] E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo, *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.* Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019. [Online]. Available: https://doi.org/10.5281/zenodo.3831673

[7] Lotek, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823164930/https://www.lotek.com

[8] Wildlife Computers, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823164658/https://wildlifecomputers.com

[9] VECTRONIC Aerospace, archived on 2021-08-23. [Online]. Available: http://web.archive.org/web/20210823164117/https://www.vectronic-aerospace.com/view-all

[10] Telenax, archived on 2021-08-23. [Online]. Available: http://web.archive.org/web/20210824221319/https://telenax.com

[11] GPS Collars, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823163718/https://www.gps-collars.com/Wildlife-Research

[12] Telemetry Solutions, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823163527/https://www.telemetrysolutions.com/wildlife-tracking-devices

[13] TechnoSmArt, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823163147/https://www.technosmart.eu

[14] Cellular Tracking Technologies, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823162231/https://celltracktech.com

[15] e-obs, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823165453/https://e-obs.de/products.html

[16] Arribada, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823161930/https://arribada.org/horizon

[17] Wildlife ACT Innovations, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823165453/https://wildlifeactinnovations.com/products

[18] NFC Group, archived on 2021-08-23. [Online]. Available: https://web.archive.org/web/20210823152755/https://www.tracks360.com/asset-tracking-solutions/gps-rfid-tracking-industries/wildlife-conservation

[19] T. Speaker, S. O'Donnell, G. Wittemyer, B. Bruyere, C. Loucks, A. Dancer, M. Carter, E. Fegraus, J. Palmer, E. Warren *et al.*, "A global community-sourced assessment of the state of conservation technology," *Conservation Biology*, vol. 36, no. 3, 2022. [Online]. Available: https://doi.org/10.1111/cobi.13871

[20] N. R. Hahn, S. P. Bombaci, and G. Wittemyer, "Identifying conservation technology needs, barriers, and opportunities," *Scientific Reports*, vol. 12, no. 1, 2022. [Online]. Available: https://doi.org/10.1038/s41598-022-08330-w

[21] S. Renshaw, N. Hammerschlag, A. J. Gallagher, N. Lubitz, and D. W. Sims, "Global tracking of shark movements, behaviour and ecology: A review of the renaissance years of satellite tagging studies, 2010–2020," *Journal of Experimental Marine Biology and Ecology*, vol. 560, 2023. [Online]. Available: https://doi.org/10.1016/j.jembe.2022.151841

[22] K. M. Dore, M. F. Hansen, A. R. Klegarth, C. Fichtel, F. Koch, A. Springer, P. Kappeler, J. A. Parga, T. Humle, C. Colin *et al.*, "Review of GPS collar deployments and performance on nonhuman primates," *Primates*, vol. 61, 2020. [Online]. Available: https://doi.org/10.1007/s10329-020-00793-7

[23] A. Matthews, L. Ruykys, B. Ellis, S. FitzGibbon, D. Lunney, M. S. Crowther, A. S. Glen, B. Purcell, K. Moseby, J. Stott *et al.*, "The success of GPS collar deployments on mammals in Australia," *Australian Mammalogy*, vol. 35, no. 1, 2013. [Online]. Available: https://doi.org/10.1071/AM12021

[24] T. C. Molteno, "Estimating position from millisecond samples of GPS signals (the "FastFix" algorithm)," *Sensors*, vol. 20, no. 22, 2020. [Online]. Available: https://doi.org/10.3390/s20226480

[25] M. Wang, H. Qin, and T. Jin, "Massive terminal positioning system with snapshot positioning technique," *GPS Solutions*, vol. 23, no. 2, 2019. [Online]. Available: http://doi.org/10.1007/s10291-018-0821-z

[26] M. Eichelberger, F. von Hagen, and R. Wattenhofer, "Multi-year GPS tracking using a coin cell," in *Proceedings of the 20th International Workshop on Mobile Computing Systems and Applications.* Santa Cruz CA USA: ACM, 2019. [Online]. Available: https://doi.org/10.1145/3301293.3302367

[27] P. Bissig, M. Eichelberger, and R. Wattenhofer, "Fast and robust GPS fix using one millisecond of data," in *Proceedings of the 16th ACM/IEEE International Conference on Information Processing in Sensor Networks - IPSN '17.* ACM Press, 2016. [Online]. Available: https://doi.org/10.1145/3055031.3055083

[28] I. Fernández-Hernández and K. Borre, "Snapshot positioning without initial information," *GPS solutions*, vol. 20, no. 4, 2016. [Online]. Available: https://doi.org/10.1007/s10291-016-0530-4

[29] J. Liu, B. Priyantha, T. Hart, H. S. Ramos, A. A. F. Loureiro, and Q. Wang, "Energy efficient GPS sensing with cloud offloading," in *Proceedings of the 10th ACM Conference on Embedded Network Sensor Systems - SenSys '12.* ACM Press, 2012. [Online]. Available: https://doi.org/10.1145/2426656.2426666

[30] P. Axelrad, B. K. Bradley, J. Donna, M. Mitchell, and S. Mohiuddin, "Collective detection and direct positioning using multiple GNSS satellites," *Navigation: Journal of The Institute of Navigation*, vol. 58, no. 4, 2011. [Online]. Available: https://doi.org/10.1002/j.2161-4296.2011.tb02588.x

[31] "Lotek FastGPS Series," archived on 2024-06-26. [Online]. Available: web.archive.org/web/20240626131954/https://www.lotek.com/wp-content/uploads/2017/10/FastGPS-Series-Spec-Sheet.pdf

[32] Advanced Telemetry Systems Australia, "ATS G10 Ultralite GPS," archived on 2021-12-29. [Online]. Available: http://web.archive.org/web/20211229114608/https://nebula.wsimg.com/2c21477b3a3e90c8279c4b5979312195?AccessKeyId=CEA7BFCD16F82D670903&disposition=0

[33] Baseband Technologies, "Snapshot positioning - next generation GNSS receiver for low power applications," archived on 2019-11-26. [Online]. Available: http://web.archive.org/web/20191126120757/http://www.basebandtech.com/wp-content/uploads/Snapshot-Receiver.pdf

[34] "Fastloc® GPS: The most reliable and efficient way to acquire location," archived on 2024-07-01. [Online]. Available: http://web.archive.org/web/20240701003713/https://wildlifecomputers.com/data/technologies/fastloc/

[35] A. K. Brown, P. Brown, and N. Corporation, "Ultra low-power GPS recorder (TrackTag®)," in *Proceedings of ION 61st Annual Meeting*, vol. 6. Citeseer, 2005.

[36] A. Matthes, J. Beuchert, A. Davies, J. Patino-Martinez, and A. Rogers, "SnapperGPS: Deployment of a low-cost snapshot GNSS receiver to track loggerhead sea turtles," in *Proceedings of the 40th International Sea Turtle Symposium (ISTS40).* International Sea Turtle Society, 2022.

[37] J. Beuchert, A. Matthes, and A. Rogers, "SnapperGPS: Open hardware for energy-efficient, low-cost wildlife location tracking with snapshot GNSS," *Journal of Open Hardware*, vol. 7, no. 1, 2023. [Online]. Available: https://doi.org/10.5334/joh.48

[38] P.-Y. Hsing, B. Johns, and A. Matthes, "Ecology and conservation researchers should adopt open source technologies," *Frontiers in Conservation Science*, vol. 5, 2024. [Online]. Available: https://doi.org/10.3389/fcosc.2024.1364181

[39] IUCN, "The IUCN Red List of Threatened Species. Version 2021-1," 2021. [Online]. Available: https://www.iucnredlist.org

[40] C. T. Callaghan, S. Nakagawa, and W. K. Cornwell, "Global abundance estimates for 9,700 bird species," *Proceedings of the National Academy of Sciences*, vol. 118, no. 21, 2021. [Online]. Available: https://doi.org/10.1073/pnas.2023170118

[41] Food and A. O. of the United Nations with major processing by Our World in Data, "Chicken - stocks (animals) - FAO," 2023, accessed on 2024-10-06. [Online]. Available: https://ourworldindata.org/explorers/animal-welfare?country=~OWID_WRL&Metric=Live+animals+%28stocks%29&Animal=Chickens&Per+person=false

[42] B. Tomasik, "The importance of wild-animal suffering," *Relations. Beyond Anthropocentrism*, vol. 3, no. 2, 2015. [Online]. Available: https://doi.org/10.7358/rela-2015-002-toma

[43] O. Horta, "Animal suffering in nature: The case for intervention," *Environmental Ethics*, vol. 39, no. 3, 2017. [Online]. Available: https://doi.org/10.5840/enviroethics201739320

[44] K. Johannsen, *Wild animal ethics: The moral and political problem of wild animal suffering.* Routledge, 2020. [Online]. Available: https://doi.org/10.4324/9780429296673

[45] H. Browning and W. Veit, "Positive wild animal welfare," *Biology & Philosophy*, vol. 38, no. 2, 2023. [Online]. Available: https://doi.org/10.1007/s10539-023-09901-5

[46] C. Palmer, *Animal ethics in context.* Columbia University Press, 2010.

[47] S. Donaldson and W. Kymlicka, *Zoopolis: A political theory of animal rights.* Oxford University Press, USA, 2011.

[48] C. Faria, *Animal ethics in the wild: Wild animal suffering and intervention in nature.* Cambridge University Press, 2022.

[49] O. Horta, *Making a stand for animals.* Routledge, 2022.

[50] J. Everett, "Environmental ethics, animal welfarism, and the problem of predation: A Bambi lover's respect for nature," *Ethics and the Environment*, 2001.

[51] N. Delon and D. Purves, "Wild animal suffering is intractable," *Journal of Agricultural and Environmental Ethics*, vol. 31, 2018. [Online]. Available: https://doi.org/10.1007/s10806-018-9722-y

[52] I. M. Hertog and E. Turnhout, "Ideals and pragmatism in the justification of ecological restoration," *Restoration ecology*, vol. 26, no. 6, 2018.

[53] G. M. Mace, "Whose conservation?" *Science*, vol. 345, no. 6204, 2014.

[54] D. F. Doak, V. J. Bakker, B. E. Goldstein, and B. Hale, "What is the future of conservation?" *Trends in Ecology & Evolution*, vol. 29, no. 2, 2014.

[55] C. Sandbrook, "What is conservation?" *Oryx*, vol. 49, no. 4, 2015.

[56] W. J. Sutherland, L. V. Dicks, S. O. Petrovan, and R. K. Smith, *What works in conservation.* Open book publishers, 2021.

[57] N. E. Heller and E. S. Zavaleta, "Biodiversity management in the face of climate change: a review of 22 years of recommendations," *Biological conservation*, vol. 142, no. 1, 2009.

[58] R. T. Kingsford, J. E. Watson, C. J. Lundquist, O. Venter, L. Hughes, E. Johnston, J. Atherton, M. Gawel, D. A. Keith, B. G. Mackey *et al.*, "Major conservation policy issues for biodiversity in oceania," *Conservation Biology*, vol. 23, no. 4, 2009.

[59] N. E. Duffus, A. Echeverri, L. Dempewolf, J. A. Noriega, P. R. Furumo, and J. Morimoto, "The present and future of insect biodiversity conservation in the neotropics: policy gaps and recommendations," *Neotropical Entomology*, vol. 52, no. 3, 2023.

[60] L. Thomas-Walters, J. McCallum, R. Montgomery, C. Petros, A. K. Wan, and D. Veríssimo, "Systematic review of conservation interventions to promote voluntary behavior change," *Conservation Biology*, vol. 37, no. 1, 2023.

[61] A. N. Kadykalo, R. T. Buxton, P. Morrison, C. M. Anderson, H. Bickerton, C. M. Francis, A. C. Smith, and L. Fahrig, "Bridging research and practice in conservation," *Conservation Biology*, vol. 35, no. 6, 2021.

[62] W. F. Laurance, H. Koster, M. Grooten, A. B. Anderson, P. A. Zuidema, S. Zwick, R. J. Zagt, A. J. Lynam, M. Linkie, and N. P. Anten, "Making conservation research more relevant for conservation practitioners," *Biological Conservation*, vol. 153, 2012.

[63] A. T. Knight, R. M. Cowling, M. Rouget, A. Balmford, A. T. Lombard, and B. M. Campbell, "Knowing but not doing: selecting priority conservation areas and the research–implementation gap," *Conservation biology*, vol. 22, no. 3, 2008.

[64] W. J. Sutherland, A. S. Pullin, P. M. Dolman, and T. M. Knight, "The need for evidence-based conservation," *Trends in ecology & evolution*, vol. 19, no. 6, 2004.

[65] Y. Fabian, K. Bollmann, P. Brang, C. Heiri, R. Olschewski, A. Rigling, S. Stofer, and R. Holderegger, "How to close the science-practice gap in nature conservation? information sources used by practitioners," *Biological Conservation*, vol. 235, 2019.

[66] C. N. Cook, M. Hockings, and R. Carter, "Conservation in the dark? the information used to support management decisions," *Frontiers in Ecology and the Environment*, vol. 8, no. 4, 2010.

[67] J. C. Walsh, L. V. Dicks, C. M. Raymond, and W. J. Sutherland, "A typology of barriers and enablers of scientific evidence use in conservation practice," *Journal of Environmental Management*, vol. 250, 2019.

[68] W. J. Sutherland, N. G. Taylor, D. MacFarlane, T. Amano, A. P. Christie, L. V. Dicks, A. J. Lemasson, N. A. Littlewood, P. A. Martin, N. Ockendon *et al.*, "Building a tool to overcome barriers in research-implementation spaces: The conservation evidence database," *Biological Conservation*, vol. 238, 2019.

[69] S. Eckerström Liedholm, L. Hecht, and V. Elliott, “Improving wild animal welfare through contraception,” *BioScience*, 2024. [Online]. Available: https://doi.org/10.1093/biosci/biae071

[70] W. V. Reid, H. A. Mooney, A. Cropper, D. Capistrano, S. R. Carpenter, K. Chopra, P. Dasgupta, T. Dietz, A. K. Duraiappah, R. Hassan *et al.*, *Ecosystems and human well-being, Synthesis: A report of the Millennium Ecosystem Assessment.* Island Press, 2005. [Online]. Available: https://www.millenniumassessment.org/documents/document.356.aspx.pdf

[71] D. U. Hooper, E. C. Adair, B. J. Cardinale, J. E. Byrnes, B. A. Hungate, K. L. Matulich, A. Gonzalez, J. E. Duffy, L. Gamfeldt, and M. I. O’Connor, “A global synthesis reveals biodiversity loss as a major driver of ecosystem change,” *Nature*, vol. 486, no. 7401, 2012. [Online]. Available: https://doi.org/10.1038/nature11118

[72] J. Bélanger and D. Pilling, *The state of the world’s biodiversity for food and agriculture.* Rome: Food and Agriculture Organization of the United Nations (FAO) Commission on Genetic Resources for Food and Agriculture, 2019. [Online]. Available: http://www.fao.org/3/CA3129EN/CA3129EN.pdf

[73] L. H. Taylor, S. M. Latham, and M. E. Woolhouse, “Risk factors for human disease emergence,” *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, vol. 356, 2001.

[74] K. E. Jones, N. G. Patel, M. A. Levy, A. Storeygard, D. Balk, J. L. Gittleman, and P. Daszak, “Global trends in emerging infectious diseases,” *Nature*, vol. 451, 2008.

[75] T. Allen, K. A. Murray, C. Zambrana-Torrelio, S. S. Morse, C. Rondinini, M. Di Marco, N. Breit, K. J. Olival, and P. Daszak, “Global hotspots and correlates of emerging zoonotic diseases,” *Nature communications*, vol. 8, no. 1, 2017.

[76] R. Rupasinghe, B. B. Chomel, and B. Martínez-López, “Climate change and zoonoses: A review of the current status, knowledge gaps, and future trends,” *Acta Tropica*, vol. 226, 2022.

[77] S. Morand and C. Lajaunie, “Outbreaks of vector-borne and zoonotic diseases are associated with changes in forest cover and oil palm expansion at global scale,” *Frontiers in veterinary science*, vol. 8, 2021.

[78] J. S. S. Lowndes, B. D. Best, C. Scarborough, J. C. Afflerbach, M. R. Frazier, C. C. O’Hara, N. Jiang, and B. S. Halpern, “Our path to better science in less time using open data science tools,” *Nature Ecology & Evolution*, vol. 1, no. 6, 2017. [Online]. Available: https://doi.org/10.1038/s41559-017-0160

[79] S. E. Hampton, S. S. Anderson, S. C. Bagby, C. Gries, X. Han, E. M. Hart, M. B. Jones, W. C. Lenhardt, A. MacDonald, W. K. Michener *et al.*, “The Tao of open science for ecology,” *Ecosphere*, vol. 6, no. 7, 2015. [Online]. Available: https://doi.org/10.1890/ES14-00402.1

[80] G. Newman, A. Wiggins, A. Crall, E. Graham, S. Newman, and K. Crowston, “The future of citizen science: emerging technologies and shifting paradigms,” *Frontiers in Ecology and the Environment*, vol. 10, no. 6, 2012. [Online]. Available: http://doi.wiley.com/10.1890/110294

[81] O. J. Reichman, M. B. Jones, and M. P. Schildhauer, "Challenges and opportunities of open data in ecology," *Science*, vol. 331, no. 6018, 2011. [Online]. Available: https://doi.org/10.1126/science.1197962

[82] J. M. Pearce, *Open-source lab: How to build your own hardware and reduce research costs.* Newnes, 2013.

[83] A. P. Hill, A. Davies, P. Prince, J. L. Snaddon, C. P. Doncaster, and A. Rogers, "Leveraging conservation action with open-source hardware," *Conservation Letters*, vol. 12, no. 5, 2019. [Online]. Available: https://doi.org/10.1111/conl.12661

[84] S. Oberloier and J. M. Pearce, "General design procedure for free and open-source hardware for scientific equipment," *Designs*, vol. 2, no. 1, 2018. [Online]. Available: https://doi.org/10.3390/designs2010002

[85] J. J. Lahoz-Monfort and M. J. Magrath, "A comprehensive overview of technologies for species and habitat monitoring and conservation," *BioScience*, 2021. [Online]. Available: https://doi.org/10.1093/biosci/biab073

[86] S. M. Tomkiewicz, M. R. Fuller, J. G. Kie, and K. K. Bates, "Global Positioning System and associated technologies in animal behaviour and ecological research," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 365, no. 1550, 2010. [Online]. Available: https://doi.org/10.1098/rstb.2010.0090

[87] B. Thomas, J. D. Holland, and E. O. Minot, "Wildlife tracking technology options and cost considerations," *Wildlife Research*, vol. 38, no. 8, 2011. [Online]. Available: https://doi.org/10.1071/WR10211

[88] "Iridium developer resources," archived on 2021-08-30. [Online]. Available: http://web.archive.org/web/20210830140009/https://www.iridium.com/developer-resources/

[89] "How Argos system works?" archived on 2021-08-30. [Online]. Available: http://web.archive.org/web/20210830134052/https://www.argos-system.org/using-argos/how-argos-works/

[90] "Globalstar service plans," archived on 2021-08-16. [Online]. Available: http://web.archive.org/web/20210816152127/https://www.globalstar.com/en-us/service-plans

[91] P. Juang, H. Oki, Y. Wang, M. Martonosi, L. S. Peh, and D. Rubenstein, "Energy-efficient computing for wildlife tracking: Design tradeoffs and early experiences with ZebraNet," in *Proceedings of the 10th international conference on Architectural support for programming languages and operating systems*, 2002. [Online]. Available: https://doi.org/10.1145/605397.605408

[92] W. W. Cochran and R. D. Lord Jr, "A radio-tracking system for wild animals," *The Journal of Wildlife Management*, 1963. [Online]. Available: https://www.jstor.org/stable/3797775

[93] R. B. Harris, *Tracking wildlife by satellite: Current systems and performance.* US Department of the Interior, Fish and Wildlife Service, 1990, no. 30.

[94] R. Kays, S. Tilak, M. Crofoot, T. Fountain, D. Obando, A. Ortega, F. Kuemmeth, J. Mandel, G. Swenson, and T. Lambert, “Tracking animal location and activity with an automated radio telemetry system in a tropical rainforest,” *The Computer Journal*, vol. 54, no. 12, 2011. [Online]. Available: https://doi.org/10.1093/comjnl/bxr072

[95] Š. Řeřucha, T. Bartonička, P. Jedlička, M. Čížek, O. Hlouša, R. Lučan, and I. Horáček, “The BAARA (Biological AutomAted RAdiotracking) system: A new approach in ecological field studies,” *PloS one*, vol. 10, no. 2, 2015. [Online]. Available: https://doi.org/10.1371/journal.pone.0116785

[96] Argos user’s manual - Worldwide tracking and environmental monitoring by satellite. Accessed on 2021-08-23. [Online]. Available: https://www.argos-system.org/manual

[97] D. P. Costa, P. W. Robinson, J. P. Arnould, A.-L. Harrison, S. E. Simmons, J. L. Hassrick, A. J. Hoskins, S. P. Kirkman, H. Oosthuizen, S. Villegas-Amtmann *et al.*, “Accuracy of ARGOS locations of pinnipeds at-sea estimated using Fastloc GPS,” *PLOS ONE*, vol. 5, no. 1, 2010. [Online]. Available: https://doi.org/10.1371/journal.pone.0008677

[98] A. Flores, “NAVSTAR GPS Space Segment/Navigation User Segment interfaces - Incorporation of IRN-IS-200J-001,” *U.S. Space Force*, 2020. [Online]. Available: https://www.gps.gov/technical/icwg/

[99] European GNSS (GALILEO) Open Service, “Signal-in-space interface control document, Issue 2.0, January 2021,” accessed on 2021-08-23. [Online]. Available: https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_OS_SIS_ICD_v2.0.pdf

[100] Russian Institute of Space Device Engineering, “Global Navigation Satellite System, GLONASS - Interface control document, Navigational radiosignal in bands L1, L2 (Edition 5.1),” accessed on 2021-08-23. [Online]. Available: http://russianspacesystems.ru/wp-content/uploads/2016/08/ICD_GLONASS_eng_v5.1.pdf

[101] “BeiDou Navigation Satellite System, Signal in space interface control document, Open service signal B1I (Version 3.0),” archived on 2021-08-03. [Online]. Available: https://web.archive.org/web/20210803090519/http://m.beidou.gov.cn/xt/gfxz/201902/P020190227593621142475.pdf

[102] R. Gold, “Optimal binary sequences for spread spectrum multiplexing (corresp.),” *IEEE Transactions on Information Theory*, vol. 13, no. 4, 1967. [Online]. Available: https://doi.org/10.1109/TIT.1967.1054048

[103] The U.S. Department of Homeland Security, “GPS NANUs, almanacs, OPS Advisories, & SOF,” accessed on 2021-08-23. [Online]. Available: https://www.navcen.uscg.gov/?pageName=gpsAlmanacs

[104] J. B.-Y. Tsui, *Fundamentals of Global Positioning System receivers: A software approach.* John Wiley & Sons, 2005. [Online]. Available: https://doi.org/10.1002/0471712582

[105] F. van Diggelen, *A-GPS: Assisted GPS, GNSS, and SBAS.* Artech House, 2009.

[106] L. A. McMahon, J. L. Rachlow, L. A. Shipley, J. S. Forbey, T. R. Johnson, and P. J. Olsoy, "Evaluation of micro-GPS receivers for tracking small-bodied mammals," *PloS one*, vol. 12, no. 3, 2017. [Online]. Available: https://doi.org/10.1371/journal.pone.0173185

[107] M. M. Cochrane, D. J. Brown, and R. A. Moen, "GPS technology for semi-aquatic turtle research," *Diversity*, vol. 11, no. 3, 2019. [Online]. Available: https://doi.org/10.3390/d11030034

[108] J. Beuchert and A. Rogers, "SnapperGPS: Algorithms for energy-efficient low-cost location estimation using GNSS signal snapshots," in *Proceedings of the 19th ACM Conference on Embedded Networked Sensor Systems*, 2021. [Online]. Available: https://doi.org/10.1145/3485730.3485931

[109] "Arribada green sea turtle tag enclosure," archived on 2021-08-29. [Online]. Available: http://web.archive.org/web/20210829120122/https://www.irnas.eu/arribada-pitstop-turtle-tag/

[110] T. Guilford, J. Meade, R. Freeman, D. Biro, T. Evans, F. Bonadonna, D. Boyle, S. Roberts, and C. Perrins, "GPS tracking of the foraging movements of Manx Shearwaters Puffinus puffinus breeding on Skomer Island, Wales," *Ibis*, vol. 150, no. 3, 2008. [Online]. Available: https://doi.org/10.1111/j.1474-919X.2008.00805.x

[111] K. Von Hünerbein, H.-J. Hamann, E. Rüter, and W. Wiltschko, "A GPS-based system for recording the flight paths of birds," *Naturwissenschaften*, vol. 87, 2000. [Online]. Available: https://doi.org/10.1007/s001140050721

[112] I. Steiner, C. Bürgi, S. Werffeli, G. Dell'Omo, P. Valenti, G. Tröster, D. P. Wolfer, and H.-P. Lipp, "A GPS logger and software for analysis of homing in pigeons and small mammals," *Physiology & behavior*, vol. 71, no. 5, 2000. [Online]. Available: https://doi.org/10.1016/S0031-9384(00)00409-1

[113] H. R. Kauth, R. C. Lonsinger, A. J. Kauth, and A. J. Gregory, "Low-cost DIY GPS trackers improve upland game bird monitoring," *Wildlife Biology*, vol. 2020, no. 2, 2020. [Online]. Available: https://doi.org/10.2981/wlb.00653

[114] C. J. Foley and C. Sillero-Zubiri, "Open-source, low-cost modular gps collars for monitoring and tracking wildlife," *Methods in Ecology and Evolution*, vol. 11, no. 4, 2020. [Online]. Available: https://doi.org/10.1111/2041-210X.13369

[115] J. A. Fahlbusch and K. J. Harrington, "A low-cost, open-source inertial movement GPS logger for eco-physiology applications," *Journal of Experimental Biology*, vol. 222, no. 23, 2019. [Online]. Available: https://doi.org/10.1242/jeb.211136

[116] J. W. Karl and J. E. Sprinkle, "Low-cost livestock global positioning system collar from commercial off-the-shelf parts," *Rangeland Ecology & Management*, vol. 72, no. 6, 2019. [Online]. Available: https://doi.org/10.1016/j.rama.2019.08.003

[117] D. A. McGranahan, B. Geaumont, and J. W. Spiess, "Assessment of a livestock GPS collar based on an open-source datalogger informs best practices for logging intensity," *Ecology and evolution*, vol. 8, no. 11, 2018. [Online]. Available: https://doi.org/10.1002/ece3.4094

[118] L. Quaglietta, B. H. Martins, A. de Jongh, A. Mira, and L. Boitani, “A low-cost GPS GSM/GPRS telemetry system: performance in stationary field tests and preliminary data on wild otters (Lutra lutra),” *PloS one*, vol. 7, no. 1, 2012. [Online]. Available: https://doi.org/10.1371/journal.pone.0029235

[119] E. M. Baum, “Monitoring domestic sheep energy requirements and habitat selection on summer mountain range using low-cost GPS collar technology,” *Brigham Young University*, 2021. [Online]. Available: https://scholarsarchive.byu.edu/etd/9177

[120] L. M. Paden and K. M. Andrews, “Modification and validation of low-cost recreational GPS loggers for tortoises,” *Wildlife Society Bulletin*, vol. 44, no. 4, 2020. [Online]. Available: https://doi.org/10.1002/wsb.1126

[121] A. Kane, E. Pirotta, S. Wischnewski, E. J. Critchley, A. Bennison, M. Jessopp, and J. L. Quinn, “Spatio-temporal patterns of foraging behaviour in a wide-ranging seabird reveal the role of primary productivity in locating prey,” *Marine Ecology Progress Series*, vol. 646, 2020. [Online]. Available: https://doi.org/10.3354/meps13386

[122] E. J. Critchley, W. Grecian, A. Bennison, A. Kane, S. Wischnewski, A. Cañadas, D. Tierney, J. L. Quinn, and M. J. Jessopp, “Assessing the effectiveness of foraging radius models for seabird distributions using biotelemetry and survey data,” *Ecography*, vol. 43, no. 2, 2020. [Online]. Available: https://doi.org/10.1111/ecog.04653

[123] N. Gillies, A. L. Fayet, O. Padget, M. Syposz, J. Wynn, S. Bond, J. Evry, H. Kirk, A. Shoji, B. Dean *et al.*, “Short-term behavioural impact contrasts with long-term fitness consequences of biologging in a long-lived seabird,” *Scientific Reports*, vol. 10, no. 1, 2020. [Online]. Available: https://doi.org/10.1038/s41598-020-72199-w

[124] C. Richards, O. Padget, T. Guilford, and A. E. Bates, “Manx shearwater (Puffinus puffinus) rafting behaviour revealed by GPS tracking and behavioural observations,” *PeerJ*, vol. 7, 2019. [Online]. Available: https://doi.org/10.7717/peerj.7863

[125] C. A. de la Rosa, “An inexpensive and open-source method to study large terrestrial animal diet and behaviour using time-lapse video and GPS,” *Methods in Ecology and Evolution*, vol. 10, no. 5, 2019. [Online]. Available: https://doi.org/10.1111/2041-210X.13146

[126] C. Knight, D. Bailey, and D. Faulkner, “Low-cost global positioning system tracking collars for use on cattle,” *Rangeland ecology & management*, vol. 71, no. 4, 2018. [Online]. Available: https://doi.org/10.1016/j.rama.2018.04.003

[127] B. M. Allan, J. P. Arnould, J. K. Martin, and E. G. Ritchie, “A cost-effective and informative method of GPS tracking wildlife,” *Wildlife Research*, vol. 40, no. 5, 2013. [Online]. Available: https://doi.org/10.1071/WR13069

[128] B. Dean, R. Freeman, H. Kirk, K. Leonard, R. A. Phillips, C. M. Perrins, and T. Guilford, “Behavioural mapping of a pelagic seabird: combining multiple sensors and a hidden Markov model reveals the distribution of at-sea behaviour,” *Journal of the Royal Society Interface*, vol. 10, no. 78, 2013. [Online]. Available: https://doi.org/10.1098/rsif.2012.0570

[129] M. P. Harris, M. I. Bogdanova, F. Daunt, and S. Wanless, “Using GPS technology to assess feeding areas of Atlantic Puffins Fratercula arctica,” *Ringing & Migration*, vol. 27, no. 1, 2012. [Online]. Available: https://doi.org/10.1080/03078698.2012.691247

[130] B. Porter, “A summer studying shearwaters,” *InsideEcology*, 2017. [Online]. Available: https://web.archive.org/web/20240416164542/https://insideecology.com/2017/10/16/a-summer-studying-shearwaters/

[131] A. R. Iverson, J. L. Schaefer, S. M. Skalos, and C. E. Hawkins, “Global positioning system (GPS) and platform transmitter terminal (PTT) tags reveal fine-scale migratory movements of small birds: A review highlights further opportunities for hypothesis-driven research,” *Ornithological Applications*, vol. 125, no. 3, 2023. [Online]. Available: https://doi.org/10.1093/ornithapp/duad014

[132] T. S. Jung and K. Kuba, “Performance of GPS collars on free-ranging bison (Bison bison) in north-western Canada,” *Wildlife Research*, vol. 42, no. 4, 2015. [Online]. Available: https://doi.org/10.1071/WR15038

[133] N. Hammerschlag, A. J. Gallagher, and D. Lazarre, “A review of shark satellite tagging studies,” *Journal of Experimental Marine Biology and Ecology*, vol. 398, no. 1-2, 2011. [Online]. Available: https://doi.org/10.1016/j.jembe.2010.12.012

[134] C. R. McMahon, N. Collier, J. Northfield, F. Glen *et al.*, “Taking the time to assess the effects of remote sensing and tracking devices on animals,” *Animal Welfare-The UFAW Journal*, vol. 20, no. 4, 2011. [Online]. Available: https://doi.org/10.1017/S0962728600003158

[135] D. G. Barron, J. D. Brawn, and P. J. Weatherhead, “Meta-analysis of transmitter effects on avian behaviour and ecology,” *Methods in Ecology and Evolution*, vol. 1, no. 2, 2010. [Online]. Available: https://doi.org/10.1111/j.2041-210X.2010.00013.x

[136] J. Adams, D. Scott, S. McKechnie, G. Blackwell, S. A. Shaffer, and H. Moller, “Effects of geolocation archival tags on reproduction and adult body mass of sooty shearwaters (Puffinus griseus),” *New Zealand Journal of Zoology*, vol. 36, no. 3, 2009. [Online]. Available: https://doi.org/10.1080/03014220909510160

[137] M. Brooke, *The Manx shearwater.* T&A D POYSER, 1990.

[138] C. Stone, A. Webb, and M. Tasker, “The distribution of Manx shearwaters Puffinus puffinus in north-west European waters,” *Bird Study*, vol. 41, no. 3, 1994. [Online]. Available: https://doi.org/10.1080/00063659409477217

[139] A. Shoji, B. Dean, H. Kirk, R. Freeman, C. M. Perrins, and T. Guilford, “The diving behaviour of the Manx shearwater Puffinus puffinus,” *Ibis*, vol. 158, no. 3, 2016. [Online]. Available: https://doi.org/10.1111/ibi.12381

[140] “AudioMoth,” archived on 2021-01-23. [Online]. Available: http://web.archive.org/web/20210123081814/https://www.openacousticdevices.info/audiomoth

[141] IPBES, “Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services,” IPBES, Bonn, Germany, Tech. Rep., 2019. [Online]. Available: https://doi.org/10.5281/zenodo.3831673

[142] R. Dirzo, H. S. Young, M. Galetti, G. Ceballos, N. J. B. Isaac, and B. Collen, "Defaunation in the Anthropocene," *Science*, vol. 345, no. 6195, 2014. [Online]. Available: https://doi.org/10.1126/science.1251817

[143] K. J. Gaston and R. A. Fuller, "Commonness, population depletion and conservation biology," *Trends in Ecology & Evolution*, vol. 23, 2008. [Online]. Available: https://doi.org/10.1016/j.tree.2007.11.001

[144] S. L. Pimm, S. Alibhai, R. Bergl, A. Dehgan, C. Giri, Z. Jewell, L. Joppa, R. Kays, and S. Loarie, "Emerging technologies to conserve biodiversity," *Trends in Ecology & Evolution*, vol. 30, no. 11, 2015. [Online]. Available: https://doi.org/10.1016/j.tree.2015.08.008

[145] J. J. Lahoz-Monfort, I. Chadès, A. Davies, E. Fegraus, E. Game, G. Guillera-Arroita, R. Harcourt, K. Indraswari, J. McGowan, J. L. Oliver, J. Refisch, J. Rhodes, P. Roe, A. Rogers, A. Ward, D. M. Watson, J. E. M. Watson, B. A. Wintle, and L. Joppa, "A call for international leadership and coordination to realize the potential of conservation technology," *BioScience*, vol. 69, no. 10, 2019. [Online]. Available: https://doi.org/10.1093/biosci/biz090

[146] S. A. Wich and A. K. Piel, *Conservation Technology*, 1st ed. Oxford, United Kingdom: Oxford University Press, 2021. [Online]. Available: https://doi.org/10.1093/oso/9780198850243.001.0001

[147] A. K. Schulz, C. Shriver, S. Stathatos, B. Seleb, E. G. Weigel, Y.-H. Chang, M. Saad Bhamla, D. L. Hu, and J. R. Mendelson, "Conservation tools: the next generation of engineering–biology collaborations," *Journal of The Royal Society Interface*, vol. 20, no. 205, 2023. [Online]. Available: https://doi.org/10.1098/rsif.2023.0232

[148] J. J. Lahoz-Monfort and M. J. L. Magrath, "A comprehensive overview of technologies for species and habitat monitoring and conservation," *BioScience*, no. biab073, 2021. [Online]. Available: https://doi.org/10.1093/biosci/biab073

[149] R. R. Witt, C. T. Beranek, L. G. Howell, S. A. Ryan, J. Clulow, N. R. Jordan, B. Denholm, and A. Roff, "Real-time drone derived thermal imagery outperforms traditional survey methods for an arboreal forest mammal," *PLOS ONE*, vol. 15, no. 11, 2020. [Online]. Available: https://doi.org/10.1371/journal.pone.0242204

[150] L. J. Dorward, J. C. Mittermeier, C. Sandbrook, and F. Spooner, "Pokémon Go: Benefits, costs, and lessons for the conservation movement," *Conservation Letters*, vol. 10, 2017. [Online]. Available: https://doi.org/10.1111/conl.12326

[151] D. Fraisl, G. Hager, B. Bedessemp, M. Gold, P.-Y. Hsing, F. Danielsen, C. Hitchcock, J. M. Hulbert, J. Piera, H. Spiers, M. Thiel, and M. Haklay, "Citizen science in environmental and ecological sciences," *Nature Reviews Methods Primers*, vol. 2, no. 64, 2022. [Online]. Available: https://doi.org/10.1038/s43586-022-00144-4

[152] T. Speaker, S. O'Donnell, G. Wittemyer, B. Bruyere, C. Loucks, A. Dancer, M. Carter, E. Fegraus, J. Palmer, E. Warren, and J. Solomon, "A global community-sourced assessment of the state of conservation technology," *Conservation Biology*, vol. 36, no. 3, 2022. [Online]. Available: https://doi.org/10.1111/cobi.13871

[153] C. Sandbrook, D. Clark, T. Toivonen, T. Simlai, S. O'Donnell, J. Cobbe, and W. Adams, "Principles for the socially responsible use of conservation monitoring technology and data," *Conservation Science and Practice*, 2021. [Online]. Available: https://doi.org/10.1111/csp2.374

[154] UNESCO, "UNESCO Recommendation on Open Science," United Nations Educational, Scientific and Cultural Organization, Tech. Rep. CL/4363, 2021. [Online]. Available: https://unesdoc.unesco.org/ark:/48223/pf0000379949.locale=en

[155] M. D. Wilkinson, M. Dumontier, I. J. Aalbersberg, G. Appleton, M. Axton, A. Baak, N. Blomberg, J.-W. Boiten, L. B. da Silva Santos, P. E. Bourne, J. Bouwman, A. J. Brookes, T. Clark, M. Crosas, I. Dillo, O. Dumon, S. Edmunds, C. T. Evelo, R. Finkers, A. Gonzalez-Beltran, A. J. G. Gray, P. Groth, C. Goble, J. S. Grethe, J. Heringa, P. A. C. 't Hoen, R. Hooft, T. Kuhn, R. Kok, J. Kok, S. J. Lusher, M. E. Martone, A. Mons, A. L. Packer, B. Persson, P. Rocca-Serra, M. Roos, R. van Schaik, S.-A. Sansone, E. Schultes, T. Sengstag, T. Slater, G. Strawn, M. A. Swertz, M. Thompson, J. van der Lei, E. van Mulligen, J. Velterop, A. Waagmeester, P. Wittenburg, K. Wolstencroft, J. Zhao, and B. Mons, "The FAIR guiding principles for scientific data management and stewardship," *Scientific Data*, vol. 3, 2016. [Online]. Available: https://doi.org/10.1038/sdata.2016.18

[156] R Core Team, "R: A language and environment for statistical computing," Vienna, Austria, 2023. [Online]. Available: https://www.R-project.org/

[157] L. Bisschop, Y. Hendlin, and J. Jaspers, "Designed to break: planned obsolescence as corporate environmental crime," *Crime, Law and Social Change*, vol. 78, no. 3, 2022. [Online]. Available: https://doi.org/10.1007/s10611-022-10023-4

[158] J. M. Pearce, "Economic savings for scientific free and open source technology: A review," *HardwareX*, vol. 8, 2020. [Online]. Available: https://doi.org/10.1016/j.ohx.2020.e00139

[159] ——, "The case for open source appropriate technology," *Environment, Development and Sustainability*, vol. 14, no. 3, 2012. [Online]. Available: https://doi.org/10.1007/s10668-012-9337-9

[160] J. T. Collins, J. Knapper, J. Stirling, J. Mduda, C. Mkindi, V. Mayagaya, G. A. Mwakajinga, P. T. Nyakyi, V. L. Sanga, D. Carbery, L. White, S. Dale, Z. J. Lim, J. J. Baumberg, P. Cicuta, S. McDermott, B. Vodenicharski, and R. Bowman, "Robotic microscopy for everyone: The OpenFlexure microscope," *Biomedical Optics Express*, vol. 11, no. 5, 2020. [Online]. Available: https://doi.org/10.1364/BOE.385729

[161] J. Stirling and A. Quitmeyer, "Creating a field dissection microscope that can be built in the field," Digital Naturalism Laboratories, Gamboa, Panama, Tech. Rep., 2023. [Online]. Available: https://doi.org/10.18258/50700

[162] A. Thaler, K. Sturdivant, R. Neches, and J. Levenson, "The OpenCTD: a low-cost, open-source CTD for collecting baseline oceanographic data in coastal waters," *Oceanography*, 2024. [Online]. Available: https://doi.org/10.5670/oceanog.2024.602

[163] O. Berger-Tal and J. J. Lahoz-Monfort, “Conservation technology: The next generation,” *Conservation Letters*, vol. 11, no. 6, 2018. [Online]. Available: https://doi.org/10.1111/conl.12458

[164] D. Zeuss, L. Bald, J. Gottwald, M. Becker, H. Bellafkir, J. Bendix, P. Bengel, L. T. Beumer, R. Brandl, M. Brändle, S. Dahlke, N. Farwig, B. Freisleben, N. Friess, L. Heidrich, S. Heuer, J. Höchst, H. Holzmann, P. Lampe, M. Leberecht, K. Lindner, J. F. Masello, J. Mielke Möglich, M. Mühling, T. Müller, A. Noskov, L. Opgenoorth, C. Peter, P. Quillfeldt, S. Rösner, R. Royauté, C. Mestre-Runge, D. Schabo, D. Schneider, B. Seeger, E. Shayle, R. Steinmetz, P. Tafo, M. Vogelbacher, S. Wöllauer, S. Younis, J. Zobel, and T. Nauss, “Nature 4.0: A networked sensor system for integrated biodiversity monitoring,” *Global Change Biology*, vol. 30, 2024. [Online]. Available: https://doi.org/10.1111/gcb.17056

[165] M. of the Open Know-How Working Group, “Open know-how specification,” Internet of Production Alliance, Tech. Rep., 2022. [Online]. Available: https://standards.internetofproduction.org/pub/okh/release/1

[166] J. W. Humbert, K. L. Onthank, and K. Williams, “The open-source camera trap for organism presence and underwater surveillance (OCTOPUS),” *HardwareX*, vol. 13, 2023. [Online]. Available: https://doi.org/10.1016/j.ohx.2023.e00394

[167] J. Nickl, S. Kolbe, and D. Schindler, “Enhancing TreeMMoSys with a high-precision strain gauge to measure the wind-induced response of trees down to the ground,” *HardwareX*, vol. 12, 2022. [Online]. Available: https://doi.org/10.1016/j.ohx.2022.e00379

[168] DIN e.v., “DIN SPEC 3105-1:2020-07 Open Source Hardware,” Beuth Verlag GmbH, Tech. Rep., 2020. [Online]. Available: https://doi.org/10.31030/3173063

[169] J. Arancio, “Supporting open science hardware in academia: Policy recommendations for science funders and university managers,” Center for Science, Technology & Society, Drexel University, Tech. Rep., 2023. [Online]. Available: https://doi.org/10.5281/zenodo.8030029

[170] J. M. Pearce, “Emerging business models for open source hardware,” *Journal of Open Hardware*, vol. 1, no. 1, 2017. [Online]. Available: https://doi.org/10.5334/joh.4

[171] S. Faez, J. Urra, V. Saggiomo, J. de Vos, and S. Illamparuthi, “Creating an open-source hardware ecosystem for research and sustainable development,” Zenodo, Tech. Rep., 2023. [Online]. Available: https://doi.org/10.5281/zenodo.8301858

[172] J. Arancio, “From inequalities to epistemic innovation: Insights from open science hardware projects in Latin America,” *Environmental Science & Policy*, vol. 150, 2023. [Online]. Available: https://doi.org/10.1016/j.envsci.2023.103576

[173] I. Kubiszewski, C. Ward, K. E. Pickett, and R. Costanza, “The complex relationships between economic inequality and biodiversity: A scoping review,” *The Anthropocene Review*, 2023. [Online]. Available: https://doi.org/10.1177/20530196231158080

[174] G. H. de Oliveira Caetano, R. Vardi, I. Jarić, R. A. Correia, U. Roll, and D. Veríssimo, “Evaluating global interest in biodiversity and conservation,” *Conservation Biology*, vol. 37, no. 5, 2023. [Online]. Available: https://doi.org/10.1111/cobi.14100