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Friars, physicists, and natural philosophers in medieval Oxford

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Abstract. This paper examines how medieval Europe became the birthplace of many technical devices, including the mechanical clock, the geared windmill, and other automatic and labour-saving inventions. It also examines how the mathematical sciences were cultivated in 14th-century Oxford with studies of the mathematics of accelerating bodies, number theory and related problems.

Medieval Europe was a place of extraordinary technological innovation since in addition to mathematical and philosophical developments, post-1000 AD Europe was rapidly developing into a dynamic commercial culture which prized ingenuity and self-acting mechanisms. The shaped iron Coulter Board Plough, for instance, enabled a man to plough a field faster and ensured deeper drainage than could be done with the traditional 'scratch' plough.

Then a powerful wooden gear train, the work of the 'millwright', not only enabled the grinding of more cereal crops, but also the sawing of timber beams and the operation of large 'trip' forge hammers for engineering work that minimised the need for animal and human muscle power, whilst in wet and windy northern Europe ingenious minds saw ways in which nature might be harvested other than by traditional 'blood, sweat and toil'. Instead, trained minds were increasingly being required to keep complex accounts for traders operating between London, Antwerp and Venice, for schools for the rising generations and for a coordinated timekeeping system. Thus the mechanical clock, powered either by weights or springs, would become the archetype of the new self-acting, self-controlling machine, especially when it played tunes and mechanised knights engaged in mock-battles, as with the clock in Wells Cathedral and other great churches. Then as rich merchants wanted their own 'self-ringing bells', the clock was rapidly miniaturised to become the watch, as production costs were driven down so that by 1660 every prosperous master artisan owned or else aspired to possess his own watch. Just as three centuries later Henry Ford and William Morris would show the world how the assembly line transformed the manufacture of motor vehicles, so did the specialist manufacture of individual watch parts, designed to be assembled by London craftsmen, who would finally place their own names on the completed timepieces. Several places in Lancashire, such as Prescot, near Liverpool, developed this horological components trade and the young Transit of Venus astronomer, Jeremiah Horrocks had relatives working in this trade.

Yet perhaps the most influential discoveries of medieval science-based technology were those concerning optics. For while Alhazen (Ibn al-Haytham) had discovered the 19-degree refractive angle between the Sun and the horizon to be the cause of the morning and evening twilight, and Friar Roger Bacon explored the internal refractive angle within a globe of water around 1260, it was perhaps Alessandro della Spina's and Salvino degli Armati's invention of spectacles that first made the polished glass lens a defining instrument of western civilisation [1]. Music with its intimate relationship with

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arithmetic and mathematics was similarly mechanised as keys controlling pipes and strings produced the virginal, harpsichord and most complex of all, the organ to create increasingly elaborate harmonic devices. Even warfare and violence were caught up in the passion for efficient mechanisation, as firstly the simple gunpowder cannon became the clumsy hand-held ‘arquebus’, followed by the wheel lock musket and then the pistol.

1. The astrolabe

Yet perhaps the most characteristic and widespread precision device of the medieval world, both Arabic and European, was the astrolabe (figure 1). Its front plate was engraved with a stereographic projection of the sky with its radiating lines converging to a point indicating a specific terrestrial location (figure 1 (c)) . Indeed it is from this point that it is often possible for a modern scholar to date or at least establish an era for the instrument, using the precession of the equinoxes. Then on top of this fixed projection plate was the ‘rete’ or net (so called from its resemblance to a net) which could be rotated around the appropriate constellation plate. In some ways the device is still with us in the amateur astronomer’s ‘planisphere’ or constellation-finder. A rotating transparent plastic disc now forms an alternative to the metal rete [2].

All astrolabes shared the same basic design, whether they were Arabic or European. Arabic astrolabes sometimes carried the name and location of the maker or commissioner in flowing, decorative Arabic script. For some European instruments it is relatively easy to work out a region or even a point of origin, such as the 9.75-inch-diameter astrolabe of c. 1390 in the collection at Merton College, University of Oxford. Its latitude range extends from the Cape Verde Islands in the south to 52 degrees, the latitude of London in the north. Another Merton astrolabe of c. 1350 of 14.25 inch-diameter with its latitude of 52 degrees north might well have been of local Oxford or London manufacture. Those north European lands referred to as Holland and the Low Countries, separately renowned for their fine paintings, maps and decorative metalwork, also became a centre for astrolabe and mathematical instrument-making. Arsenius of Louvain’s 13.25-inch-diameter instrument is an exquisitely engraved astrolabe, the scale divisions being very exact geometrically, as will be shown below.

The first scientific text in the English language was Geoffrey Chaucer’s *Treatise on the Astrolabe* of c. 1390 [3], written for ten-year-old ‘Lyte Lowys my sone’ and showing a rete, or star plate, after the latitude of Oxford. Indeed Lowys, or Lewis, must have been a precocious young teenager if he could understand the complexities that underpinned his father’s *Treatise*. Tragically the lad must have died young, for no more of him was heard of him.

Chaucer’s *Treatise* was written in clear 14th-century English and its very existence suggests a considerable familiarity with technical subjects at the time, for even some of the *Canterbury Tales* contain references to astronomy and astronomical instruments as part of the rationale of the tale. In *The Miller’s Tale,* which tells of an Oxford student’s, Master Nicholas’s, subterfuges to gain access to his elderly landlord’s beautiful young wife, Master Nicholas mentions the writings of Ptolemy and the use of an astrolabe to predict an impending second Deluge as a way of ensuring time and space for access to the fair Alisoun. So, one wonders, did the Oxford undergraduates of 1390 generally have a familiarity with astrolabes and digests of Ptolemy? There are certainly references to cheap, basic devices in parchment and wood, considering the practical need to find the time or fix the Feasts and Festivals of the Church and civil years. After all professional gentlemen would have been of necessity literate in English and Latin, even if it were of the ‘dog’ variety, and fixing dates and festivals was a necessity in an age before printed almanacs and diaries.

It is easy to feel amazement at the sophistication of the front plate of the astrolabe, but yet more applications became possible if the brass plates were turned over to provide solutions for calendrical work, while its 360-degree graduated border and ‘alidade’ arm and sights could be useful to the surveyor, architect and engineer, and for the teaching of practical geometry.

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(a) (b) (c)

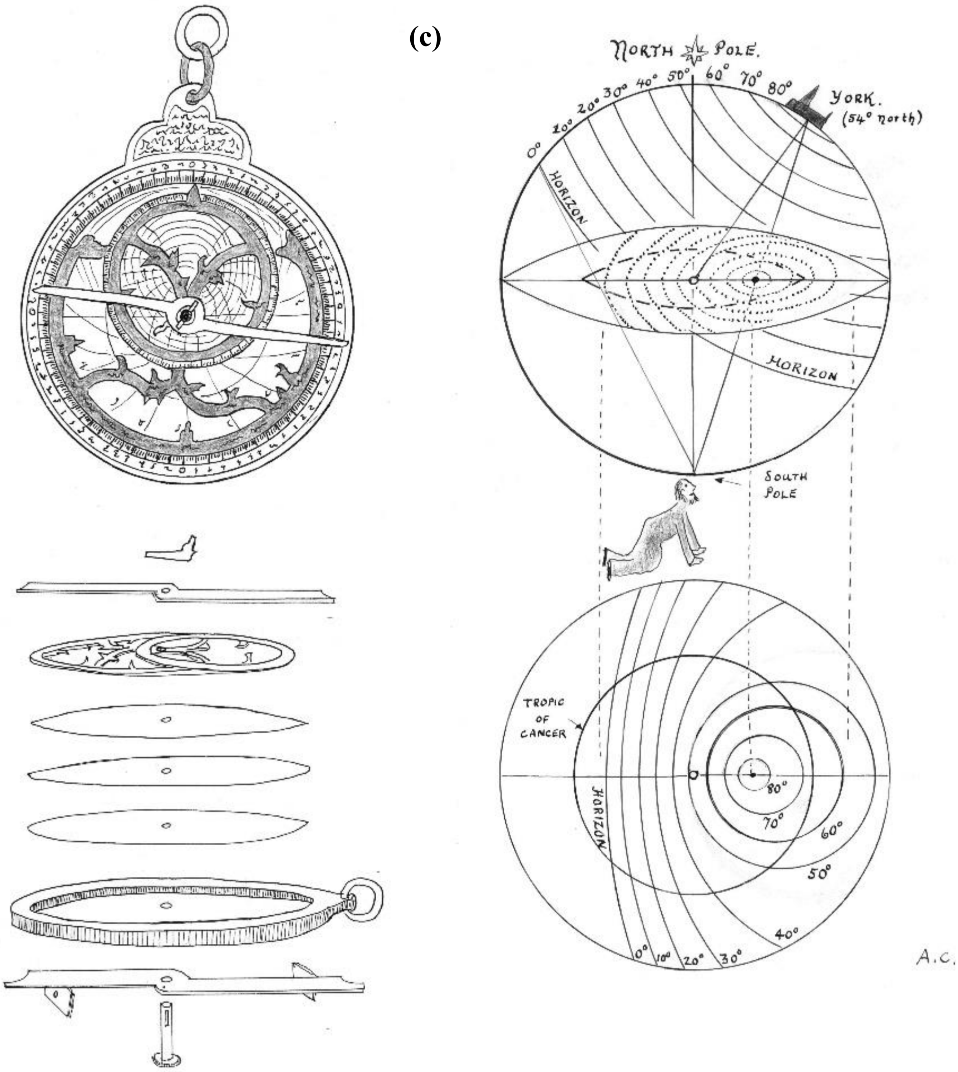

Figure 1. (a) An astrolabe of Arabic manufacture, as indicated by the elaborate ‘crown’ and suspension rings. **(b)** The ‘climate’ or latitude plates of the astrolabe are removable and the plate correct for the user’s location is placed uppermost. The rete is positioned above it and all are locked into place by the Dog or Horse pin placed through the central hole. **(c)** Stereographic projection. Imagine the Earth as a great transparent sphere rotating about Polaris or the Pole Star. To an imaginary observer outside the transparent sphere and looking directly upwards towards Polaris, the English city of York would stand at 54 degrees north from the equator as the Earth circuited Polaris once in 24 hours. If a line were to be dropped down, it would form an angle with the equator plate and as this plate rotated, scribe a circular line around the central hole. This exercise could be performed for all the five or so brass ‘climate ’ or latitude plates in the astrolabe from Alexandria to Spitzbergen. One had only to know the region of the world one was in, select the appropriate plates and re-assemble them with the local climate plate uppermost.

2. The Oxford Calculators

The astrolabe was used in a variety of ways by that group of priest–scientists generally referred to collectively as the ‘Oxford Calculators’ from their formal association with Merton, Balliol and other

Oxford colleges. In many respects, these men were concerned with motion, impetus, the nature of 'force' and what caused bodies to move, accelerate and stop. They included William of Heytesbury, Richard Swineshead, and John Dumbleton. One of the leading members of this group was Thomas Bradwardine, whose *Tractatus* of 1328 analysed the mathematical nature of infinity and infinitesimal numbers. If, for example, in Ptolemaic terms the Sun orbits the Earth an infinite number of times, could the Moon, travelling twelve times faster, orbit it twelve times faster? Thus this posed the problem of what exactly infinity is.

Another problem involved that of the 'mean speed theorem', or law of acceleration, and what exactly its nature was. When an object moved from stationary and picked up speed, such as might a waggon with perfectly smooth wheels when moving down a perfectly smooth slope, how did it accelerate? Was it occasioned by an infinite number of acceleration points, each building upon the other or did one best envisage it as analogous to a continuous smooth curve? This and related problems of mathematics, motion and velocity were dealt with in Oxford by Richard Dumbleton, the Franciscan Regent Simon Tunsted and John Killingworth. Galileo Galilei in the 16th century would return to the problem and the mathematical proportions of acceleration which it involved. Somewhat unfairly, one might say, nowadays the mean speed problem and its graphical expression are often generally associated with Galileo and not with the mathematical physicists of the medieval Merton School [1]. These men were not directly calculating with astrolabes or other instruments, but the proportionate mathematics involved in their often theoretical work would not have been possible without prior mathematical training involving the astrolabe.

3. Richard of Wallingford

Richard's career covered pretty well the whole gamut of mathematical and technological achievement possible at that time. He was the son of William, the Wallingford blacksmith and Isabella, and he died at the age of 44 in 1336 as Abbot of St Alban's Abbey, a royal advisor and an engineer of genius. Richard never lost those practical skills learned at his father's ironworking workshop in Wallingford, which was then in Berkshire and he was not ashamed in later years to display them on a later picture of himself, albeit now with abbot's mitre and abbotal (similar to a bishop's) staff in the act of making a mathematical instrument.

The Wallingford family, however, were clearly not poor, being members of the comfortably off urban artisan and business community, for William and Isabella could afford to send young Richard to be educated at a small monastic school run by the monks of the local Benedictine Priory. Here he would have had his first contact with mathematics, geometry and no doubt astrolabes, along with Latin, some sections of the Bible and theology. He then went on to leave Wallingford and travel the thirteen or so miles to Oxford to join the novitiate of the Benedictine Community at Gloucester Hall, which in more recent times was refounded as Worcester College, which it still remains today. Here William would no doubt have attended a variety of lectures at the early University of Oxford.

At Oxford, Richard came to display a true genius for things mathematical and was especially interested in calculation and computation, and how complex procedures could be sped up and simplified. These included the devising of his renowned 'Albion' or 'All–By–One' device, which was an early form of equatorium, designed to facilitate quick and accurate planetary calculations [4]. In some ways this would later influence the 15th-century torquetum of Petrus Apianus and Johannes Müller (alias Regiomontanus), a device for integrating equatorial and altazimuth celestial coordinates in a single observation (figure 2) [5]. The torquetum has been equated to a modern theodolite, fixed onto a plate in the equatorial plane and capable of rotating around the centre of the equatorial plane, while also being capable of measuring angles between the horizon and the zenith. Richard's mathematical work invariably involved physical devices, another of which was his rectangulus, whereby calculations could be performed using graduated straight rods. Indeed one might consider Richard as a pioneer of integrated observational calculating devices which would lead to the slide rule and other mathematical aids.

Richard's most famous device, however, was his great clock in St Alban's Abbey, of which foundation he had become Abbot around 1327 (figure 3 (a)). Involved as he was with improving the

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fabric of the Abbey, including the re-covering of the roof with lead sheets, perhaps his greatest project was the design, construction and inauguration of the great clock. Large astronomical clocks were already to be seen elsewhere by 1300, such as at Wells Cathedral and other places in Europe, but Richard's was the most sophisticated. For one thing, its escapement, which controlled the falling of the driving weights, was in advance of the less accurate 'verge and foliot' then in general use.

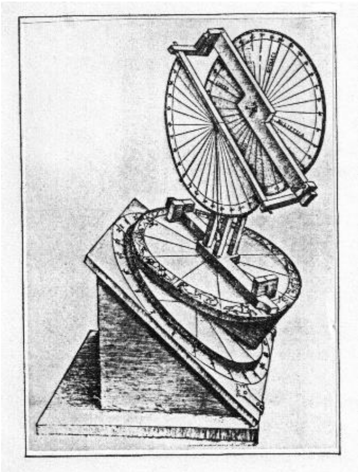

Figure 2. The torquetum of Regiomontanus, c. 1560, the design of which was probably influenced by the Albion, or 'All–by–One', invented around 150 years earlier by Richard of Wallingford.

Richard's St Albans's clock centred in many ways upon a 7-foot-diameter astrolabe plate, upon which could be traced the motions of the Sun, Moon and planets against the stars. He appears to have begun work on it soon after 1299 and it would become the wonder of St Alban's Abbey, remaining so until the Reformation over two centuries later when neglect and the actions of the Reformers led to its destruction. Yet fortunately the now recently deceased scholar John D. North and others succeeded in locating a large collection of descriptions and 'engineering drawings' in the Bodleian Library at Oxford from which working replicas of the clock could be built [5].

(a)

(b)

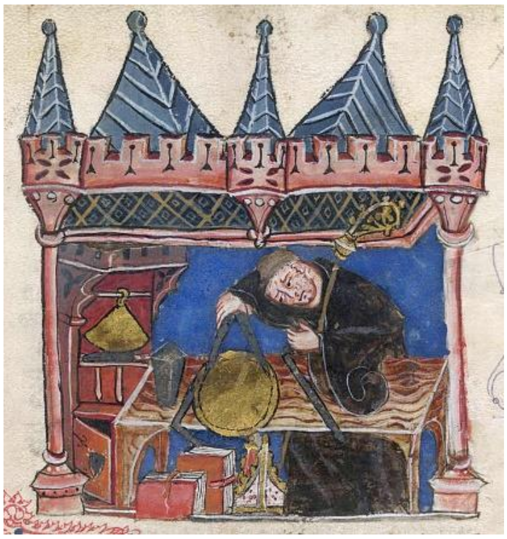

Figure 3. (a) Richard of Wallingford in his full vestments as Abbot of St Alban's Abbey, pointing to a clearly miniaturised picture of his great clock. **(b)** Richard of Wallingford at his workbench, scribing a brass disc with a large pair of dividers, while still wearing his abbot's habit and resting his abbotal staff on his arm. The newly-leaded Abbey roof, funded partly through Richard's activities, is also shown. Note the black blotches on his face, indicating the leprosy from which he died aged 44.

One replica was constructed at the Rockford Time Museum in Illinois, USA with an even more detailed one in Saint Alban's Cathedral, the former Abbey Church. Richard's depictions of himself in illustrated Abbey annals, complete with abbot's mitre and episcopal staff, working at a bench graduating an instrument with the beautifully leaded roof of the Abbey above, yet with the blotched face of a leper, say it all at a glance. For here, in this snapshot image, is Richard as Abbot, working bench craftsman, horologist, improver of the Cathedral fabric and leper with the disfiguring malady which killed him at the age of 44 (figure 3 (b)) [5].

4. Measuring early instrument scales

Yet how accurate, in angle-measuring terms, are other late medieval instruments, all of which were in use in one form or another well into the 17th century and beyond? It could be suggested that they might be tested in two ways: (1) by measuring early graduations with modern engineering devices and (2) by constructing modern replicas and checking them against the sky. And I have done both. Of course, the laying-out of a circular scale is based on Euclidean geometry, using a compass and carefully dividing it six times into the circle. This will give sections of 60 degrees and further bisection of each of these will give sections of 30 degrees. The 30 degrees are simply added to the 60 degrees to obtain the 'perfect' 90-degree right-angle result. Such scales can be laid out on a drawing board, a sheet of brass or a fine-grained piece of wood.

I began this approach in a systematic way in 1972, as part of the research for my Oxford doctoral thesis, *Dividing the Circle*. The History of Science Museum at Oxford has an almost unique collection of medieval and Renaissance European and Arabic astrolabes in the world, and of these I selected over a dozen European instruments from between 1450 and 1650 that seemed especially finely made. I confined this study to European astrolabes, for beautiful as the Arabic pieces were, they were the product of a specific cultural craft tradition, although they would no doubt have yielded similar results.

5. Measuring some early astrolabes in Oxford

Around 1973, the University of Oxford Department of Engineering Science very generously loaned me a fine modern dividing engine, which we set up in the basement workshop of the History of Science Museum. The rotation of the engine's 11.5-inch-diameter circular measuring plate was controlled by a precision micrometer screw and verniers reading to thousandths of an inch. A low-power microscope with crosswires was next adjusted to look down at the edge of the circular plate. For measurement purposes I chose twenty-two 360-degree scales from twelve individual instruments. Each astrolabe was first placed centrally on the circular plate of the dividing engine and the microscope adjusted so that its horizontal crosshair appeared to form a tangent to the degree scale about to be measured. Then by carefully turning the tangent screw that controlled the rotating plate, one could measure in thousandths of an inch the distance between each engraved degree division. Yet although the individual degree engravings were measured from a straight line, they could easily be converted to arc minutes by calculation. Consequently it became possible to work out the potential angle-measuring accuracy of an individual instrument, notwithstanding other factors, such as the accuracy or eccentricity of the central pivot hole or the user's skill when observing.

Some of the astrolabes in the Museum collection, however, did not warrant careful engine measurement, such as that fine-looking piece known as 'Chaucer's astrolabe' of c. 1350, as even a preliminary examination with a hand-held magnifying glass revealed significant discrepancies between degree divisions. When plotting the error distributions around the 360-degree scale on some instruments, one might sometimes detect a 'reflection' or 'two-fold rotational symmetry' with the error distribution of, let us say, the quadrant of the circle containing degree numbers 1 to 90 being mirrored in the section containing degree numbers 180 to 270. This suggested that one quadrant of the circle might have been laid out by precise original geometry, whereas the 'reflecting' quadrant was simply copied from it across the central hole or pin, using a ruler and scribe. Could this indicate a form of mass manufacture in a busy workshop where one scale was being used to help generate another? [4]

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6. Reconstructing some other early graduated instruments

Just like Richard of Wallingford, medieval and Renaissance astronomers, surveyors and craftsmen experimented with how straight rods in conjunction with the observer's eye could be used to delineate celestial and terrestrial angles. Perhaps the most widely used of these was what was generically referred to as the cross-staff, baculus or staves (figure 4 (a)). For if an observer had a straight rod of a given length, 36 inches for example, and attached to its end in an exact right angle another shorter rod equipped with moveable sights, the device could be used to measure exact angles without the need to divide a whole circle. The cross staves, in their various forms, were simple instruments, yet very versatile and capable of considerable accuracy. By the 16th century they had passed through a variety of design variations to suit the needs of the astronomer, surveyor and navigator. All of them could be laid out by simple, direct geometry. Indeed if a 'master drawing' of the rods and curves was laid out on a flat surface, they could be copied on to *any* pieces of wood that were laid alongside them, thus facilitating a form of mass-manufacture.

Using Renaissance texts such as Thomas Fale's instructions for sundial-making, *Horolographia* (1593) as my guide I have constructed, graduated and used all of these cross-staff variants and I can personally vouch both for their convenience of usage and by 16th-century standards, their accuracy.

Another widely-used Renaissance and post-Renaissance instrument was the quadrant, in its various sizes, from 6-inch-radius hand-held pieces to larger mural instruments such as those devised by Tycho Brahe and those in the early Greenwich Observatory (figure 4 (b)). The larger the radius of the quadrant, the bigger would be the degree spaces, which would hence be capable of smaller and more precise angular sub-divisions. Tycho's individual degrees were equipped with cross-lines which could read down to single arc minutes. To test their practicability, I incorporated them into my own reduced-size Tychonic quadrant and sextant, along with pairs of 'peg and slit' sights (figure 4 (c)), which permitted a parallax-free alignment of a star being measured, in a way that observing it through a pair of small holes did not [6].

But one instrument that carried no degree divisions, yet was divided in its own way, was the nocturnal or night dial (figure 4 (d)). These were regularly made between the 15th and late 17th centuries, and were used for telling the time of night by the Great Bear constellation. A hand-sized portable instrument, usually in wood, a nocturnal consisted of a months of the year circular dial, which formed part of the handle, on top of which rotated a smaller denticulated plate showing the hours before and after midnight with a large 'midnight' pointer. This 'hours of the night' plate was denticulated so that in the dark the user could read off the hours that had elapsed before or after midnight and hence obtain the time. They simply had to look through the small hole at the centre of the instrument at the Pole Star, Polaris and turn and align the alidade or central pointer with the Great Bear. Simple as the nocturnal was, it could be a surprisingly accurate means of measurement in experienced hands, and my replica with practice is reliable to under 10 minutes when compared with a clock. Indeed it was cheapness, accuracy and easy availability that kept the nocturnal in use until the 18th century, when it was overtaken by ever-cheapening clocks and watches.

In total I have reconstructed and replicated quite a variety of Renaissance graduated instruments, including armillary spheres, a working 15th-century mechanical clock and even some of the pieces constructed by the Jesuit missionaries for the Imperial Observatory in Beijing in the late 17th century. For the very mechanically-minded Emperor K'ang Hsi was fascinated by western technical devices, most especially the 'self-ringing bells' or mechanical clocks first introduced into China by the Jesuits as objects of wonder.

Far from languishing in a 'Dark Age', late-medieval Europe was a place abounding in mathematical and technological wonders. When we re-measure its astrolabes and other devices and then go on to replicate them in the workshop and contemplate their makers' theoretical contributions to physics in the mean speed theorem, our respect and admiration for the age's friars, physicists and natural philosophers can only be transformed into true admiration.

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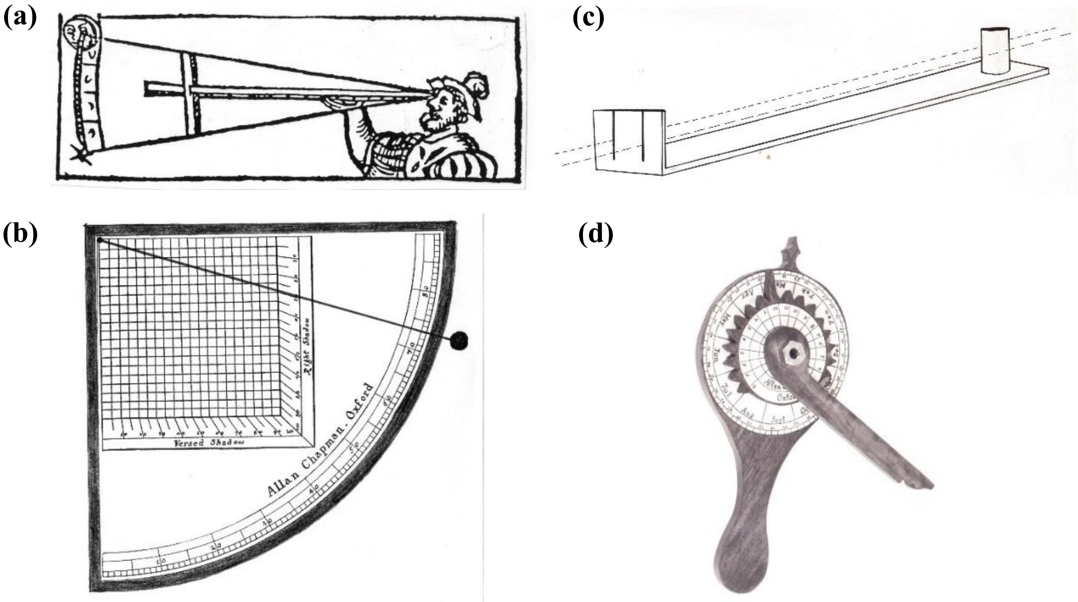

Figure 4. (a) Measuring an angle with a simple cross-staff. One simply slid the movable pointers so that when the instrument was lifted up to the eye the pointers appeared to enclose the pair of astronomical bodies to be measured, such as the Sun and Moon. They would form parts of a circle which could then be converted from angular sections to degrees and minutes. **(b)** A hand-held six-inch-radius quadrant. One could sight a star or the top of a tower by simply looking along upper edge, then trapping the string with one's finger on the 90-degree scale. **(c)** Tychonic diagonals fitted with 'peg and slit' sights that greatly reduced observational parallax error. **(d)** A nocturnal. The base showed the months of the year and was surmounted by a denticulated (and hence touch-sensitive) hours plate and the alidade or pointer, both of which rotated around a cylindrical central pivot through which, when placed up against the eye, the user could see Polaris.

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