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Observational Methods and Procedures for the Mariner's Astrolabe

Nicolàs de Hilster

The practical assessment of the accuracy of the mariner's astrolabe has been the subject of discussion in *The Mariner's Mirror*. This article gives further insight on this topic, based on period knowledge and statistical analysis of period and modern data. In addition, reference to more modern studies on this topic is given in an attempt to complete the list previously presented. It will not explore the influence of period tables for refraction and declination and the influence of longitude on the latter as these factors only affect the calculated latitudes, not the observations themselves.

Key words: mariner's astrolabe, accuracy assessment, period methods, procedures and data

The mariner's astrolabe, made of wood or cast in bronze,¹ has a (partially) graduated limb and a pivoting alidade with visors to measure the altitude of celestial bodies through sighting holes (pinnules, see figure 1). When reading contemporary sources it becomes clear that, together with the cross-staff, the mariner's astrolabe was the most widely discussed nautical instrument for celestial navigation in the early modern period. Of the 147 contemporary sources which discuss nautical instruments for celestial navigation in the two centuries prior to the invention of the octant in 1731, 117 (80 per cent) contain a description of the cross-staff, while 85 (58 per cent) discuss the mariner's astrolabe. Not surprisingly, the instrument still continues to inspire debate.

A recent note by Sir Robin Knox-Johnston on the assessment of the accuracy of the astrolabe led to a response by Wolfgang Köberer.² The latter showed that more tests had been done regarding its accuracy, both prior to and after the test mentioned by Knox-Johnston, and all well before Knox-Johnston wrote his note. Köberer also referred to my research on the astrolabe and other early navigational instruments and used one of my graphs with permission.

That graph was based on observations taken on land in 2010 with a replica of the Valentia astrolabe, the same type of instrument that Knox-Johnston used, but this time cast in bronze instead of the lighter electroform copy.³ Coincidentally

1 Wright, *Certain Errors*, 15. The Spanish teacher of cosmography and navigation, Martín Cortés, even mentions that they were made of 'a plate of copper or laton [brass] (whiche for this purpose is better then any other metall)', see Cortés, *The Arte of Navigation*, fo. 69v.

2 Knox-Johnston, 'Practical Assessment', W. Köberer, 'On the attempts'.

3 For more details see below. The National Maritime Museum in Greenwich owns three electroform copies of the Valentia astrolabe which vary in weight between 1 and 2 kilograms. The copy Knox-Johnston used weighs 2,023 grams, which is only 12 per cent less than the original (2,270 grams). The copy I used weighs 2,685 grams (18 per cent more than the original). With thanks to Knox-Johnston for putting his astrolabe on the scales for me.

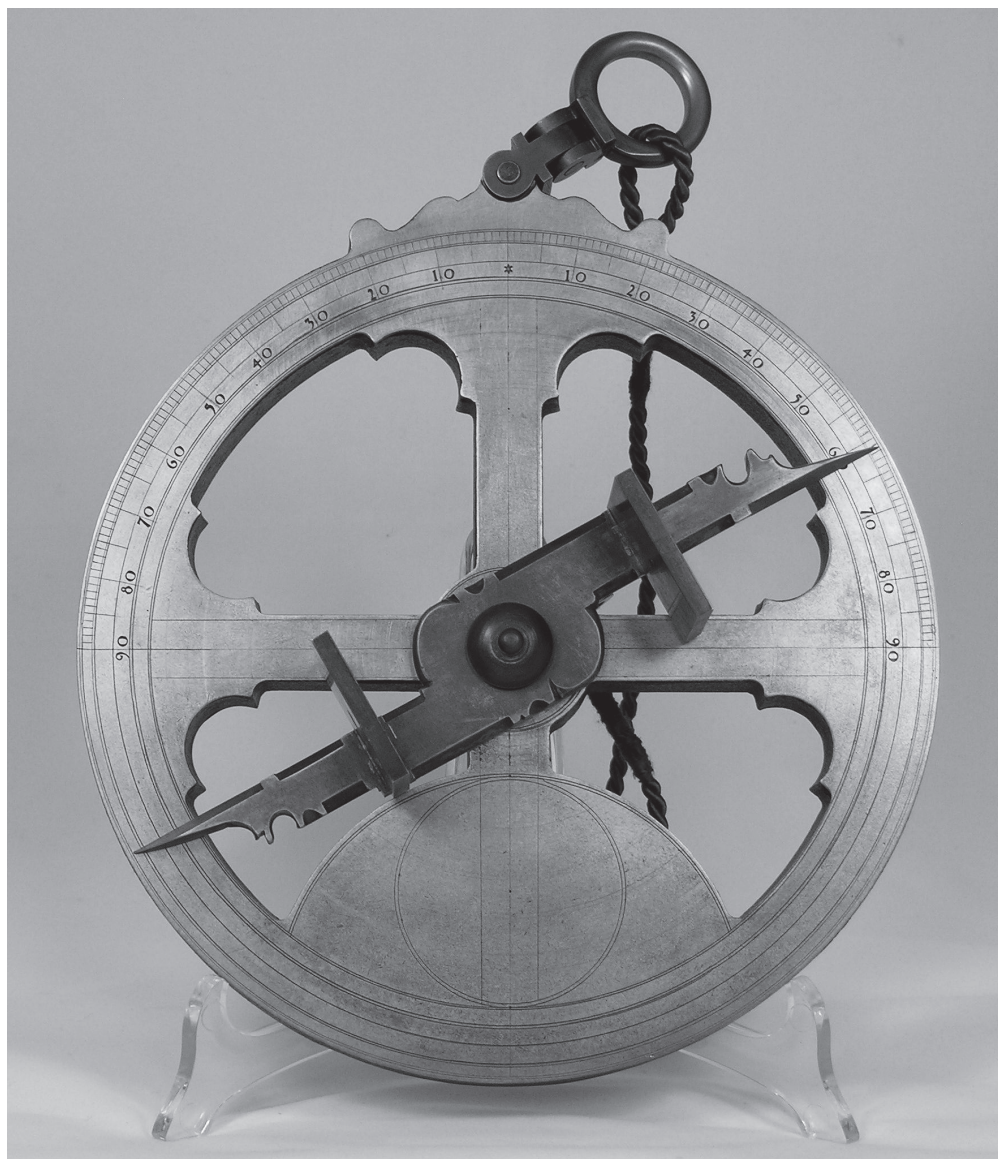


Figure 1 Replica of the Valentia astrolabe used by the author to collect data (author's photograph)

only a few weeks before Köberer wrote his note I had the opportunity to go out on the North Sea to collect data with a range of seventeenth-century navigational instrument replicas and reconstructions, including this replica.

Knox-Johnston did not explain in his note how the astrolabe was used by early modern users nor how the observations he reported were taken. In my opinion the accuracy of the mariner's astrolabe can only be properly assessed once we fully understand how they were made, tested and used by period users.

Sources of error

Before discussing the manufacture and use of the mariner's astrolabe it is useful to consider some of the common sources of error. In his note Köberer mentions the following sources of error:

- Faults of the instrument:
 - Faulty division of the arc – scale error;
 - Faulty alignment of the pinnules;
 - Eccentricity of the alidade;
 - Faulty suspension;
 - Observer error;
 - Influence of refraction

In addition to these I would add the following items to the sources of error associated with the instrument itself:

- Weight distribution within the main body of the instrument;
- Weight distribution within the alidade;
- Symmetry and straightness of the alidade;
- Quality of the pinnules.

Köberer mentions the research by Allan Chapman on the scales of scientific (astronomical) astrolabes and that he had not included any mariner's astrolabe in his work. No such research has ever been done regarding the mariner's astrolabes, while some research on the pinnules has been done by myself.

Construction, verification and use

Methods of constructing, verifying and using mariner's astrolabes are known from primary sources. The examiner of pilots of the Amsterdam chamber of the Vereenigde Oost-Indische Compagnie (VOC, the Dutch East India Company), Cornelis Jansz Lastman (fl. 1619–52), wrote that the divisions could be tested using a pair of compasses and partially by the eye.⁴ He does not inform us how exactly this had to be done, but others, like Edward Wright (1558–1615), fellow of Caius College, Cambridge, and lecturer of navigation for the East India Company, did explain how an astrolabe should be divided using a compass, thereby giving the reader a way to test the divisions.⁵

The alignment of the pinnules had to be tested in two planes; parallel to the alidade pointers to see if they show the correct altitude, and perpendicular to the body of the instrument to see if the observations are made in the same plane as the divided limb.⁶ Both could again be tested using a pair of compasses. To do the former the alidade had to be set at the 'top point'. Then the compass was set with one point in the pinnule and with the other at a degree-mark on the limb. The compass could be moved to the opposite side of the alidade while keeping one point in the pinnule and

4 Lastman, *Beschrijvinge*, 150.

5 Wright, *Certain Errors*, 15–17.

6 Lastman, *Beschrijvinge*, 150.

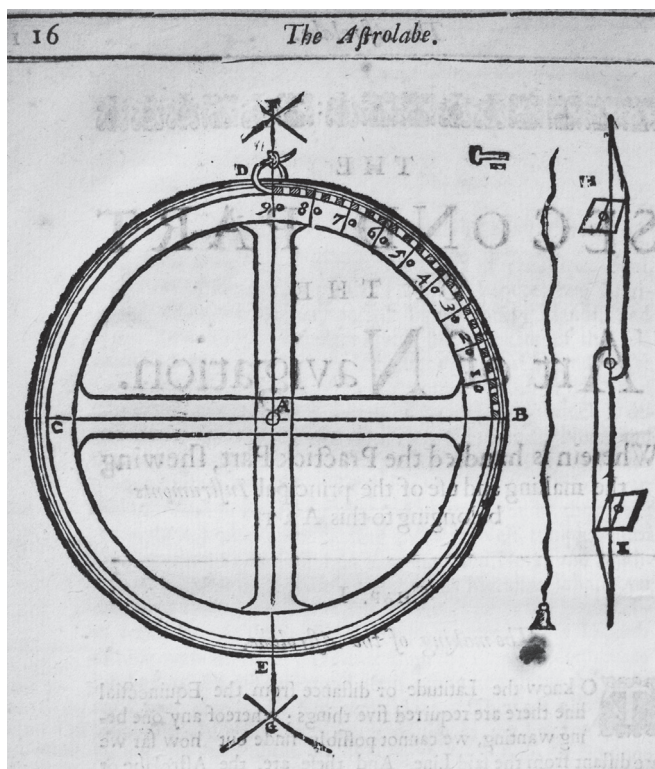


Figure 2 Wright's sketch of the astrolabe and plumb bob (courtesy of the Scheepvaartmuseum, Amsterdam)

the other point should then arrive at the same but opposite degree as it was before. The latter could be done by taking the height of the pinnule above the face of the body using a compass, and comparing it with the height of the other pinnule.

The eccentricity of the alidade could be tested by simply turning it around and see if the pointers remained at the same distance from the engraved circles on the limb.⁷

The weight distribution of the astrolabe had to be tested in two planes as well; perpendicular to the face of the instrument to see if the astrolabe measures in the vertical plane, and parallel to see if the instrument has an index error.⁸ Both could be done using a plumb bob on a thin thread. For the former, the astrolabe was suspended from 'a nail in a doorpost' while the plumb bob was suspended close to the surface of the instrument at the alidade side and a parallel gap should be visible between them.⁹ About the latter Wright wrote that the zenith line of the astrolabe was compared to a plumb line (see figure 2). If it did not hang parallel one had to 'continue cutting off

7 Lastman, *Beschrijvinge*, 150.

8 Ibid.; the index error is the difference between the true altitude or zenith angle of the alidade and the deviated average reading from the divided limb caused by the astrolabe not hanging vertically.

9 Cortés mentions that this was done before the alidade was added to the instrument, but that would cause the instrument to tilt again once the alidade was in place, see *The Arte of Navigation*, fo. 69v.

some thing, and lightning that side towards which the thred [*sic*] doth fall, until it hang even with the foresaid line'.¹⁰

The 'faulty suspension' mentioned by Köberer concerns hinge friction. Lastman wrote that due to this, astrolabes may be forced by about a quarter of a degree off the true vertical.¹¹ The solution to this problem is given as we will see below under instrumental procedures.

Captain Daniel New-House (fl. 1685) provided an even more simplified method of testing the astrolabe by the horizon. He wrote that one had to place the alidade:

exactly on the said Horizon Line [of the astrolabe], look through the two Vanes (or sights) on any sensible Point on the Horizon, then turning your Instrument so, that the sight that was next to your Eye be now farthest from you [. . . and] look again, and if you can see the same point [. . .] you may conclude that the Horizontal Line of your *Astrolabe* . . . is Parallel to the Horizon¹²

The weight distribution of the alidade is not mentioned. The alidade usually is point symmetrical around its axis (i.e. the two ends of the alidade are exact copies of each other as if they were rotated 180 degrees around the alidade's axis), but when not properly made it could affect the observations. In the case of the Valentia replica the weight of the alidade is about 7 per cent of the whole instrument and although any fault in the symmetry will only be a fraction of that (unless the fault is very obvious), it may add weight to one side of the instrument and cause it to deviate from the vertical. It should therefore be tested or dealt with by proper procedure. Instrumental evidence seems to indicate that this error was dealt with in practice.¹³

Little is written on the construction of the pinnules. Apart from the diameter, which had to be 'as bygge as may conteyne a great pynne [. . .] to take the altitude of the Starres [. . . or . . .] so subtile and small as a fyne sowing needle [. . .] to take the altitude of the Sunne',¹⁴ the quality of them (i.e. how they had to be pierced or drilled into the metal) is not described in the contemporary literature, only that 'the outwarde parte of them be bygger, and lesse within'.¹⁵ Although a seemingly irrelevant issue, the pinnules will affect the observations seriously when not properly made.¹⁶

Instrumental procedures

How meridian altitudes were taken by period navigators is perhaps the most important issue in understanding how the accuracy of the mariner's astrolabe should be assessed.

The period during which one had to take the observations has been described in contemporary literature. According to the writer of applied mathematics, William Bourne (fl. 1565–88), the moment one had to start was determined by a magnetic compass:

¹⁰ Wright, *Certaine Errors*, 17.

¹¹ Lastman, *Beschrijvinge*, 150.

¹² Newhouse, *The Whole Art*, 151.

¹³ See below.

¹⁴ Cortés, *The Arte of Nauigation*, fo. 70v, Stimson, *The Mariner's Astrolabe*, 23.

¹⁵ Cortés, *The Arte of Nauigation*, fo. 70v.

¹⁶ See below.

as soone as you see that the Sunne is come unto the South by East, then beginne to take the height of the Sunne [. . . while one had to continue to . . .] Still observe ye same, until you see the Sunne at the highest and beginning to descende, and then have you finished.¹⁷

Bourne also wrote that you may prove that the astrolabe 'dothe hang upright' during the observations by moving 'the Alhidada unto the same number of the degrees and minutes on the other side [. . .] and [. . .] taking the height of the Sunne againe'. If any difference was found one had to 'rebat from the greatest height halve the diversitie'.¹⁸ Two decades later Thomas Harriot (1560–1621), the mathematician, adviser to Sir Walter Raleigh and the 'most celebrated man . . . who cultivated all the sciences and excelled in all',¹⁹ repeated this in almost the same phrasing:

But if you doubt of the true hanging of the astrolabe, you may move your Index quickly to the same degree on the other side & hold it towarde the sonne. If you find the sunne shine thorough as before your astrolabe hangeth well. Otherwise you are also to move the Index till you have also the altitudo on that side. which had, compare with the other & note the difference. The half of that difference adde to the lesse altitude or substracte from the greater; And you have the altitude of the sonne as exacte as if your astrolabe had hang truly upright.²⁰

So the average of these two observations was taken, a procedure well known to land surveyors and still in use today to eliminate index errors in theodolites. Depending on the side the engraved vertical limb points to, they refer to observations made in face left or face right. The difference with the procedure used in land surveying is that, by pre-setting the alidade on the astrolabe in the other face, the second reading may be biased.

From above procedures it becomes clear that the meridian altitude was the result of two readings at the most; one in face left and one in face right taken just before the next observation(s) showed 'the sunne beginning to descende' again. As the observations are all affected by random error, this means that an observer may stop observing well before the moment of the meridian passage when, due to these random errors, a few observations were taken too high and followed by more correct but lower observed altitudes before noon.

Alternatively the correct moment of the meridian passage was determined by a pocket dial, which could also affect the moment the navigator stopped observing. In his journal of the journey from Lisbon to Goa in 1538 the fourth viceroy of Portuguese India and later 'Admiral of the Navy of the Coast',²¹ Dom João de Castro (1500–48), described that this actually happened.²² Each day meridian altitudes were taken by multiple persons, including himself, using astrolabes. On 2 June he noted:

17 Bourne, *A Regiment*, fo. 26r. Although this part deals with observing with the cross-staff Bourne refers to this method on the next page when dealing with the mariner's astrolabe.

18 *Ibid.*, fo. 27v.

19 Words from his former memorial plaque in the church of St Christopher's parish that was destroyed in the Great Fire of 1666, see: Shirley, *Thomas Harriot*, 474.

20 Harriot, BL Add MS6788, fo. 485r.

21 Freire de Andrade, J., *The Life*, item 16 of the preface, 10.

22 Teixeira da Moto 'L'Art de Naviguer'.

At noon we took the Sun, and each checked the height, the pilot said it was already descending, immediately, without further consideration [. . .] I myself waited and the doctor and the boatswain, as we knew the contrary, and while they checked the sun with their astrolabes, I found that the pilot had taken the Sun on the horizon [at] 43 degrees and the master a half [degree] more, one sailor [had] $42\frac{1}{2}$ [degrees], the other 43; I had at that time taken $43\frac{1}{2}$ [degrees], and the boatswain $42\frac{2}{3}$ [degrees]: but, while continuing so, I swear, for an hour, the Sun went as far up as to the height of 44 degrees, as found by the boatswain with his astrolabe, he began to say that the sun had set him over 44 degrees; which made the two sailors to take the Sun again, they found the height up to 44 degrees; the doctor at that time, went to the master and obliged him to take the sun again and found the same 44 degrees; having seen that, the pilot again took the Sun and found the same 44 [degrees] and more.²³

D. João de Castro, who had 'learnt Mathematicks of Peter Nonnius',²⁴ continues his logbook blaming the use of four different pocket dials which, being made at different geographical locations, had different corrections for magnetic variation by which they showed differences in time of up to 40 minutes. He also noted that this happened again on another six days during this five month journey. In all these cases he obliged them to re-take their observations.²⁵

From instrumental evidence it seems that there may have been another instrumental procedure. Several of the surviving astrolabe alidades show markings to distinguish the two pointers from each other.²⁶ This means that it was important to know which pointer of the alidade was used in the observation and implies that either only one or both pointers had to be used at all times. So far I have not found any primary source explaining this procedure and the reason(s) for it. From a theoretical point of view it would be necessary if the centre of the line through the two pointers of the alidade did not coincide with the centre of the instrument. In that case the pointer nearest to the line through the pinnules would give the best results. As a faulty weight distribution within the alidade could affect observations, this too could be a reason for marking the pointers.

In addition to these procedures the location aboard the vessel where the observations had to be taken was mentioned as well. Spain's royal cosmographer Pedro de Medina (1493–1567) wrote that one should take position near the mast at the middle of the ship.²⁷ The images in Medina's works show a navigator standing with the instrument held with a stretched arm (see figure 3, left).²⁸ Bourne added that this should be done as low as possible.²⁹ The Dutch translation of Bourne's work by navigator and cartographer Lucas Jansz Waghenaeer even mentions that the observer

23 Ibid., 146, translated by the author from Teixeira da Moto's Portuguese to French translation. Please note that all of these observations were made on one day during a single meridian passage.

24 Freire de Andrade, J., *The Life*, 1.

25 Teixeira da Moto 'L'Art de Naviguer', 146.

26 Stimson, *The Mariner's Astrolabe*, 60–1, 75, 83, 101, 119.

27 Medina, *Arte de Nauegar*, fo. LXXr.

28 Ibid., passim.

29 Bourne, *De Konst der Zeevaerd*, fo. 21r.

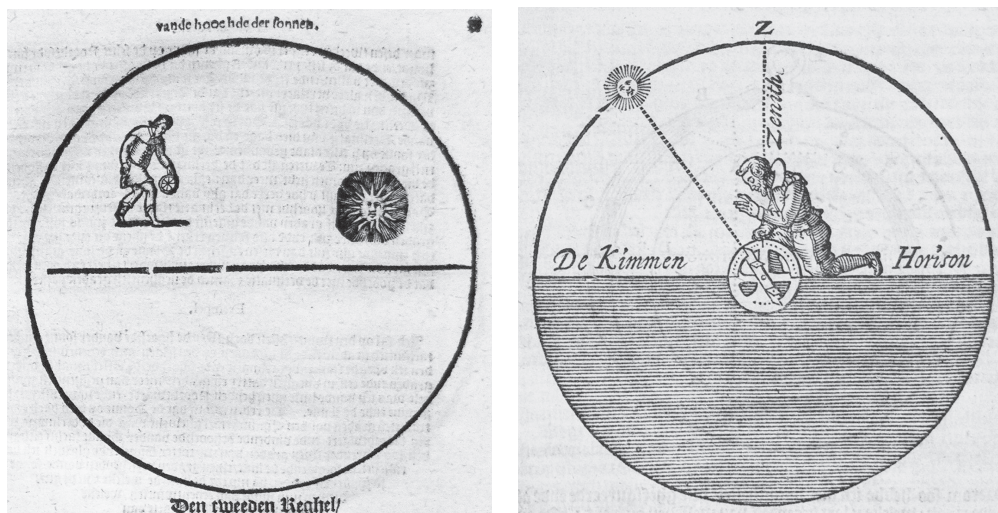


Figure 3 Left, holding the mariner's astrolabe according to Medina and right, holding the mariner's astrolabe according to Metius (courtesy of the Scheepvaartmuseum, Amsterdam)

had to sit down,³⁰ while Waghenauer added in his own work that it should be done with the astrolabe between the legs.³¹

Alternatively the instrument could be held while kneeling on one knee as shown in seventeenth-century Dutch literature (figure 3, right).³² The kneeling and seated methods have the advantage that the arm that holds the instrument can be supported by the knee, while the reduced distance between the eye and the instrument makes it easier to observe. In addition, the seated method allows the observer to concentrate only on the instrument, not on his own stability.

Britain's foremost marine cartographer Sir Robert Dudley (1574–1649) even went a step further. He wrote that it would be good to stay in the middle of 'two strong circles', as used with the magnetic compass (i.e. gimbals) in the lowest part of the vessel.³³ In that way one would feel the movement of the sea and the vessel much less.

As mentioned above, friction in the hinge could affect observations by about a quarter of a degree. According to Lastman the solution to this was to have the astrolabe hanging 'free floating' from the finger (i.e. that the suspension ring runs freely over the finger) or to use a piece of thin round wood through the suspension ring.³⁴ According to the Spanish teacher of cosmography and navigation, Martín Cortés (d. 1582), the instrument had 'a rynge or handle with a hole whereby you

30 Bourne, *De Konst der Zeevaert*, fo. 21r.

31 Waghenauer, *Thresorerie*, 17.

32 Metius, *Nieuwe Geographische Onderwysinge*, 21. Most seventeenth-century Dutch pilot books show a very similar image.

33 Dudley, *Dell'Arcano del mare*, vol. 5, 16. He wrote, 'che nell'osservare l'altitudine in Mare com uno solamente, sarrebe ben fatto, ch'egli stelle in mezzo di due cerchi forti, all'usanza di Bussola, e nella parte piu bassa del Vascello; e così sentirà assai meno il movimento del Mare, e del Vascello.'

34 Lastman, *Beschrijvinge*, 150.

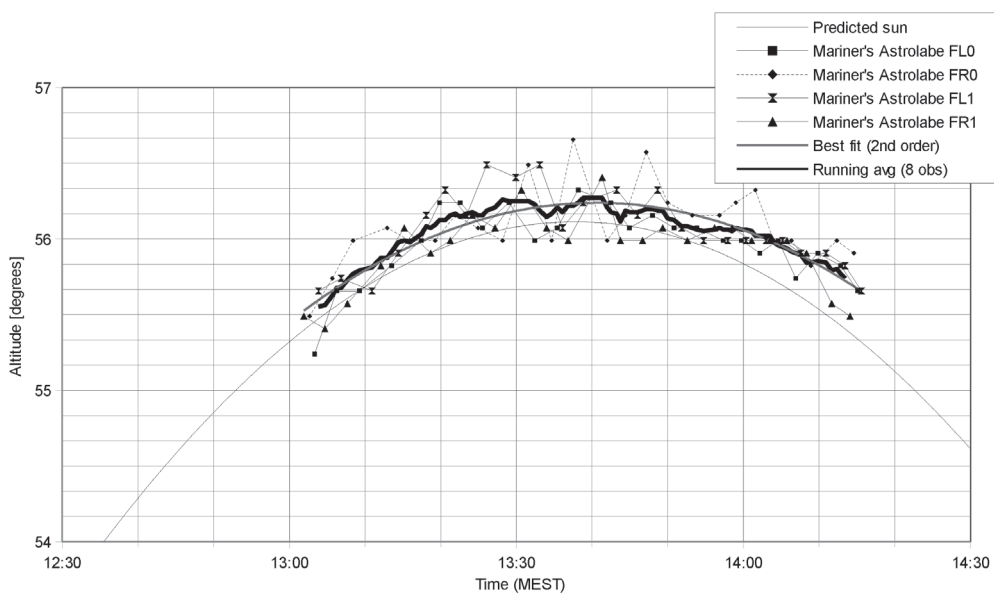


Figure 4 The first full series of observations with the *Valentia replica*. Measuring the sun's altitude, 14 May 2010 at Castricum, North Holland, in the Netherlands, $52^{\circ}33'13''\text{N}$, $4^{\circ}40'01''\text{E}$.

may hange the Astrolabe by a threede or lyne to take the altitude'.³⁵ This method would also overcome the friction induced errors.

The replica

In 2006 I decided it was time to get my own replica. As I did not have the tools and machines to create brass instruments I turned to German historian of science and clockmaker Günther Oestmann who had recently cast a copy of one of the Skokloster astrolabes. With kind cooperation of senior curator Richard Dunn of the National Maritime Museum in Greenwich I drew up the plans for the replica. Oestmann had the body and alidade cast at a foundry and constructed and divided the instrument, which was presented to me four years later.

The replica is cast from a modern bronze alloy,³⁶ 182 millimetres in diameter, 16.3 millimetres thick and weighs 2,685 grams (the *Valentia* astrolabe is 178 millimetres in diameter, 17 millimetres thick and weighs 2,270 grams). The procedures mentioned by Bourne and Harriot revealed an index error of 20 arc minutes, caused by the alidade being not completely straight. Due to this the pinnules were not in line with the ends of the pointers. Luckily my workshop and skills had grown over the years so correcting this error was now a minor issue.

Two new series of observations showed that on average the astrolabe gave altitudes some 11 arc minutes too high, regardless of being taken in face left or face right and with either pointer of the alidade (see figure 4). The reference data was checked rigorously and as the error could not be explained by an erroneous weight distribution, the quality of the scales or alidade, another error source had to be the reason for this.

³⁵ Cortés, *The Arte of Navigation*, fo. 69v., Barrera-Osorio, *Experiencing Nature*, 131.

³⁶ The alloy used is CuSn10-C.

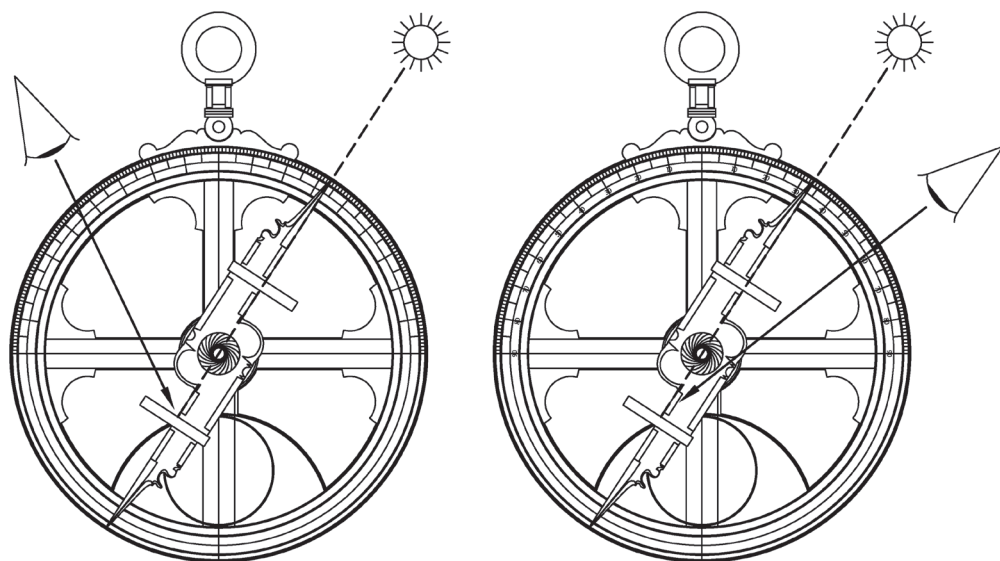


Figure 5 The forward (left) and backward (right) observation methods (author's drawing)

Subsequent tests showed that the error depended on the direction the lower vane was looked at (see figure 5). If used in the usual forward fashion, facing the sun and looking onto the alidade from above the upper vane, the altitudes were too high, but when observing in a backward fashion with the observer's back towards the sun and looking towards the alidade from below the upper vane the altitudes became too low.

A close-up of the vanes of the alidade revealed the cause; the pinnules were drilled and the resulting burr was taken off using a countersink (see figure 6, left), leaving an approximate 0.15 millimetres wide bevelled edge. Depending on the angle they were looked at, the edge would completely disappear on one side, therefore enlarging the pinnule in that direction.

The observer tries to position the spot of light from the upper pinnule as exactly as possible over the pinnule in the lower vane. Due to the bevelled edge the alidade is turned too far away from the eye to get an equally distributed light spot around the lower pinnule. Drilling a 1.3 millimetre diameter hole removed the bevel and the resulting burr was scraped off.

The question that arose from the bevelled pinnules was whether or not period astrolabe makers would also have used a drill and countersink to create their pinnules.

Bengt Kylsberg, curator at the Skokloster Castle, Sweden, kindly produced some close-up pictures of the vanes of two of their mariner's astrolabes. Both showed that the pinnules were not drilled, but pierced. On one of the instruments the piercing left a crater shaped pinnule in the vane (see figure 6, centre), while at the other it was more flat, but pear-shaped (see figure 6, right). The crater can be compared to the bevelled pinnule mentioned above and therefore it may be expected that similar observation errors will occur with this and other similarly pierced astrolabes.

Although the pear-shaped pinnule of the other astrolabe was flat, the non-round shape of it may also result in observation errors, but it is difficult to predict what exactly will happen.

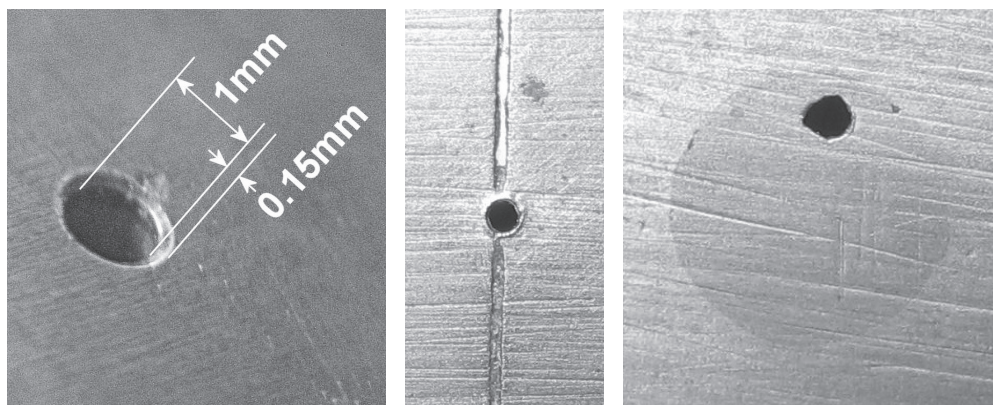


Figure 6 Left, the bevelled edge of one of the 1 millimetre diameter pinnules of the *Valentia* replica (author's photograph); centre, one of the pinnules of the *Skokloster II* astrolabe and right, one of the pinnules of the *Skokloster I* astrolabe (photographs courtesy of Bengt Kylsberg).

Additional modern studies

The bibliography of modern studies on the accuracy of the astrolabe in Köberer's note already mentions the works by Slafter (1882), Forty (1983), Michea (1987), Chapman (1990), Gilchrist (1990), Malhão Pereira (1994) and Van der Werf (1997).³⁷

The main problem with modern studies is that they often lack statistics and a description of the procedure used in the observations.³⁸ As has become clear from the above procedures and will be shown below, the average observed altitude is almost irrelevant. In that respect it does not even matter whether or not the procedure described by Bourne and Harriot was used. If that procedure was used the average error should be zero, any remaining error is due to the pinnules, observer or reference data. Without it the average error only tells us something about that individual instrument-observer combination, but nothing about the accuracy of the mariner's astrolabe in general. Furthermore it usually remains unclear what type of astrolabe was used in modern studies, whether it was tested for instrumental errors, and – if the construction is known – it seldom resembles the average period instrument.

In addition to Köberer's bibliography I would like to add 'Early Altitude Measuring Instruments: The mariner's astrolabe' by J. Luykx and *Experiências com Instrumentos e Métodos Antigos de Navegação* by J. M. Malhão Pereira.³⁹

Luykx wrote a number of articles on nautical instruments in the period 1984 to 1990, the third of which discussed the accuracy of the astrolabe. He wrote that 'Normal accuracy was only to one or two degrees' and showed the results of three land-based sessions all consisting of ten observations. The first two sessions used

³⁷ Slafter, 'History', Forty, 'Sources', Michea, 'L'Histoire', Chapman, *Dividing*, Gilchrist, 'Latitude Errors', Malhão Pereira, 'Experiências' and Van der Werf, 'Het Astrolabium'.

³⁸ Forty ('Sources'), Malhão Pereira ('Experiências' and *Experiências*) and Van der Werf ('Het Astrolabium') mention probable errors or standard deviations of the observations, none of the modern works describe the observation method, while only Malhão Pereira indicates that observations were taken while standing as in Medina.

³⁹ Luykx, 'Early Altitude Measuring Instruments', Malhão Pereira, *Experiências*.

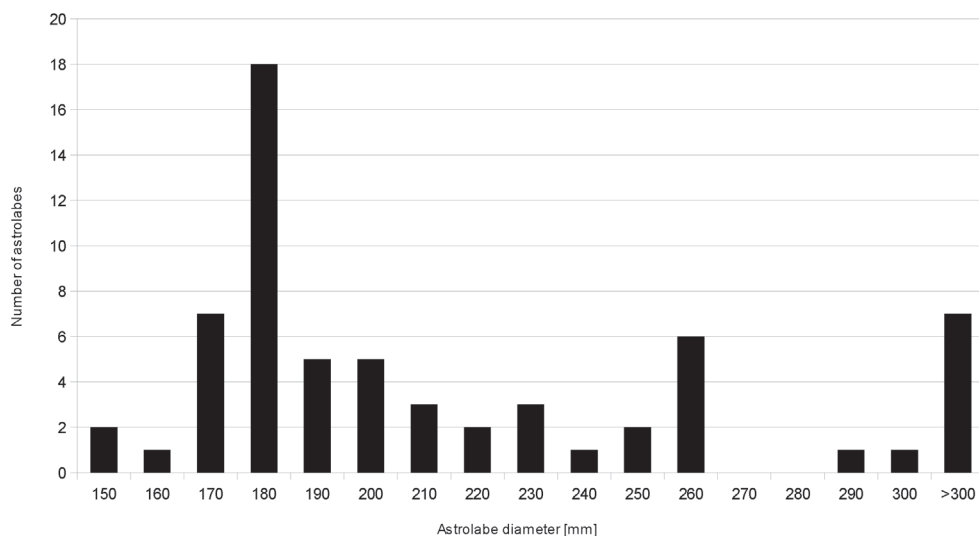


Figure 7 Mariner's astrolabe diameters based on Alan Stimson's work (1988)

the sun, the last Sirius. The average errors in latitude were given as -3.2 , -6.9 and -2.5 arc minutes. No standard deviations, data or graphs were given to indicate the accuracy of these results. The instrument he used was made of brass and 'based on a Portuguese instrument dated 1555'.⁴⁰ With 160 mm diameter and 1.5 lb it was however only 70 per cent of the size and half the weight of the original and smaller than the average mariner's astrolabe (see figure 7).⁴¹

Malhão Pereira's work is the continuation of his 1994 work mentioned by Köberer. Both works are based on data acquired during journeys with the Portuguese Naval Training Ship NRP *Sagres* (a 295-foot barque). Although the results of the mariner's astrolabe of the 2000 journey are not given, Malhão Pereira writes that the '*muitas observações efectuadas confirmámos as conclusões obtidas nas anteriores experiências*' (many observations confirmed the findings obtained in previous experiments [author's translation]).⁴²

Modern observations

With the last large error source removed from the Valentia replica it was finally fit for service. Observations were done while seated and usually within a window starting from half an hour before until half an hour after the meridian passage of the sun. Timing was done using a one second accurate radio controlled clock. Positioning was done using a hand-held GPS receiver with a horizontal accuracy of approximately 10 metres. All data was corrected for refraction and treated as intercepts, so compared to the calculated altitude of the sun using several algorithms to ensure proper calculation at a single arc minute level or better.⁴³

As indicated above the interesting part of modern observations is not the average

⁴⁰ This instrument can be found as NMM2 in Stimson, *The Mariner's Astrolabe*, 60.

⁴¹ Stimson, *The Mariner's Astrolabe*, 183–6.

⁴² Malhão Pereira, *Experiências*, 10–12.

⁴³ For one of these algorithms see NREL's MIDC SPA Calculator.

Table 1 Observations with the Valentia replica

Date	Observer	Location	Obs.	Results in arc minutes			
				I.E.	P.E.	Average	STDEV
14.5.2010	author	Land	100	0.0	3.6	10.1	10.1
16.5.2010	author	Land	24	-1.7	1.3	16.5	8.5
Overall	author	Land	124	-0.3	3.2	11.4	9.8
17.5.2010	author	Land	48	-0.3	3.4	3.7	13.3
24.5.2010	author	Land	64	0.4	3.3	-3.4	14.2
Overall	author	Land	112	0.1	3.3	-0.4	13.8
25.5.2010	author	Land	32	3.1	4.4	-5.5	10.1
4.6.2010	author	Land	40	2.6	2.6	3.3	8.3
4.7.2010	author	Land	56	2.1	3.9	-0.9	10.4
16.6.2012	author	Land	24	0.4	3.0	-0.2	6.4
29.9.2013	author	Land	76	0.6	1.7	-2.3	7.8
6.10.2013	author	Land	72	-0.7	3.2	-4.8	6.1
Overall	author	Land	300	1.1	3.0	-2.0	8.1
30.8.2013	APMP	Sea	60	-4.5	2.0	-5.2	29.0
1.10.2013	APMP	Land	64	3.3	3.2	5.6	17.6
Overall	APMP	n.a.	124	-0.5	2.6	0.4	n.a.

error, but the standard deviation that comes with it. Period observers only relied on one observation, which at best was checked in the other face with a biased second observation. Thus we will have to look at the chance that a single observation was correct instead of focusing on averages. The standard deviation tells us what the 68 per cent chance is to get an altitude within that value and thus how much we can rely on a single observation.

So far 660 observations have been taken with the Valentia replica during 12 sessions by two observers: 536 by the author and 124 by a friend and former colleague Ad Pieters (APMP). A total of 236 observations were made before the instrument was corrected, while one session of 60 observations was taken at sea. All observations were taken in a sequence Face Left Pointer A (FL₀), Face Left Pointer B (FL₁), Face Right Pointer A (FR₀) and Face Right Pointer B (FR₁),⁴⁴ while not setting the alidade to the expected altitude – as mentioned by Bourne and Harriot – reduced the chance of biased observations. From these sequences the remaining instrumental errors and standard deviations were calculated and given in table 1.

The index error (IE) was calculated from the average FL observations minus the average FR observations.⁴⁵ The pointer error (PE) was calculated by taking the difference between the average pointer A and average pointer B observations. The average position error (Average) was found by averaging all observations. Finally,

⁴⁴ The actual order of these four measurements varied per session, but all sessions have been observed using these four observation types.

⁴⁵ It is mathematically impossible to discriminate between the alignment errors of the pinnules with the alidade and the uneven hanging of the instrument.

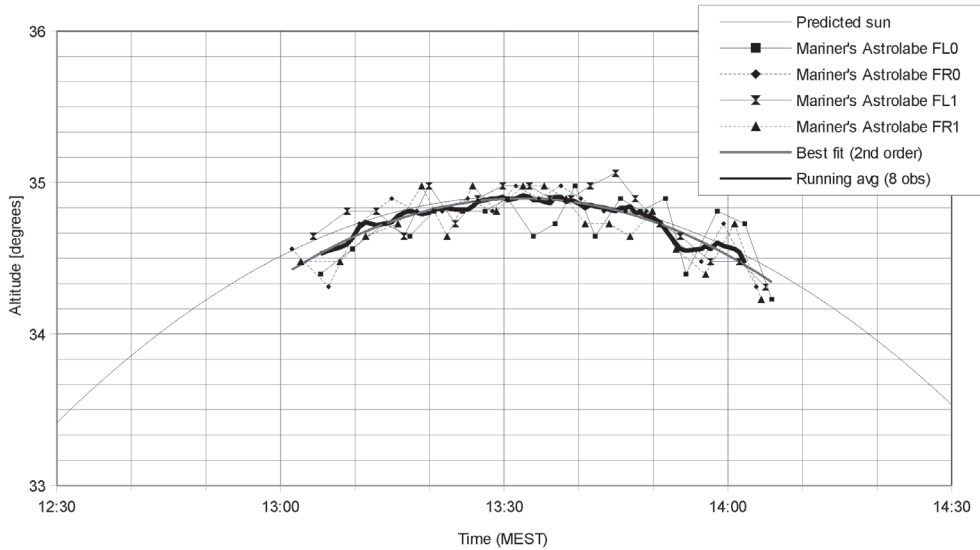


Figure 8 *Valentia replica* observations on land. Measuring the sun's altitude, 14 May 2010 at Castricum, North Holland, in the Netherlands, $52^{\circ}32'25''N$, $4^{\circ}39'01''E$.

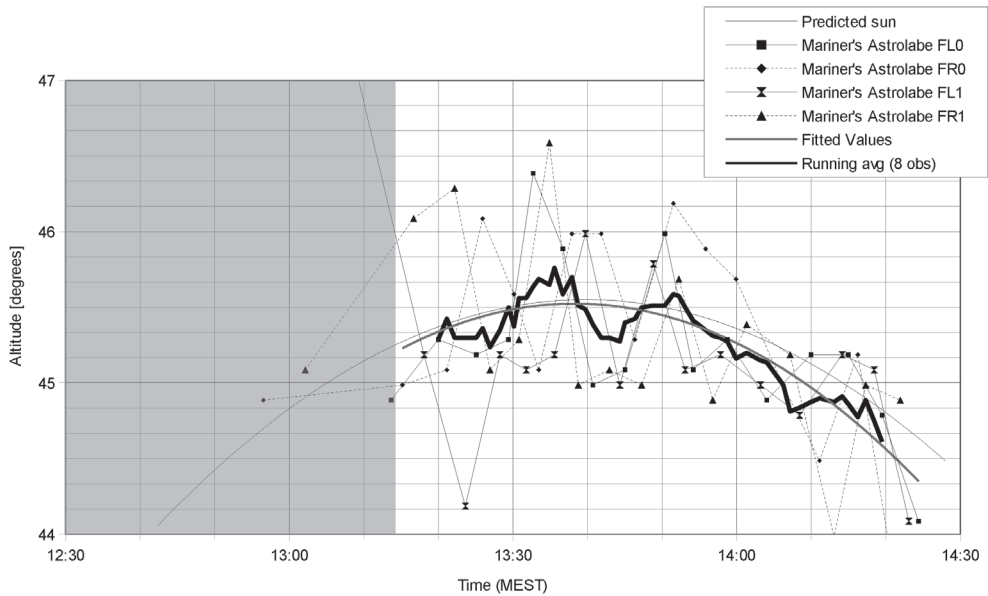


Figure 9 *Valentia replica* observations at sea. Measuring the sun's altitude, 30 August 2013 in the North Sea, north-west of Texel

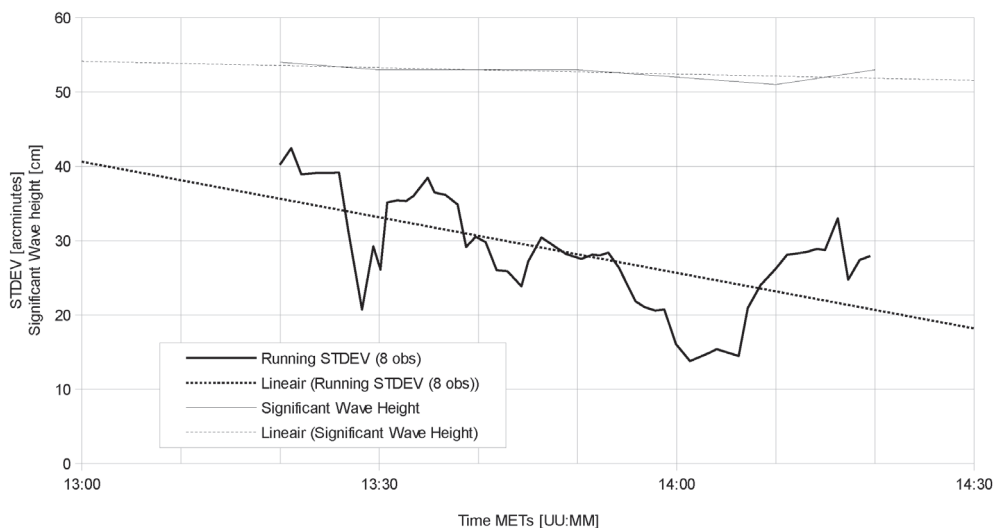


Figure 10 Temporal distribution of an inexperienced observer

and most importantly, the standard deviations (STDEV, (1σ , 68 per cent)) are given for all sessions.

The first four sessions were done with the uncorrected instrument with the bevelled pinnules still in place; they are the top four in the table. The first two of them (14 and 16 May 2010) consisted of forward observations only, the next two (17 and 25 May 2010) with alternating forward and backward groups of eight observations. Due to these two different methods the bevelled pinnules influence the averages of the first two sessions and the standard deviations of the second two.

As expected the land-based observations (see figure 8) are better than the ones taken at sea (see figure 9). The land based observations have a standard deviation of about 8 arc minutes, while at sea the standard deviation was approximately half a degree. The third observation of this sea session was written down incorrectly. Being part of a four observations sequence, this whole first sequence was ignored in the calculations (greyed out part of the graph).

As expected the averages in table 1 are all close to zero, apart from the first two series taken with the bevelled pinnules. The land based observations were better than those at sea, but it has to be noted that the former were taken by the author, while the latter were taken by Pieters. Although experienced with instrumental observations, this boat trip was the very first time he had used a mariner's astrolabe.

In his note Köberer wrote that it would 'have been interesting to see the temporal distribution of the observations'.⁴⁶ With the 60 observations Pieters took at sea a temporal distribution can easily be achieved (see figure 10). The graph shows a running standard deviation of eight readings, without the first four observations as explained above. The linear regression shows that over time the standard deviations become lower by as much as 50 per cent. The significant wave height over the same

46 Köberer, 'On the attempts'.

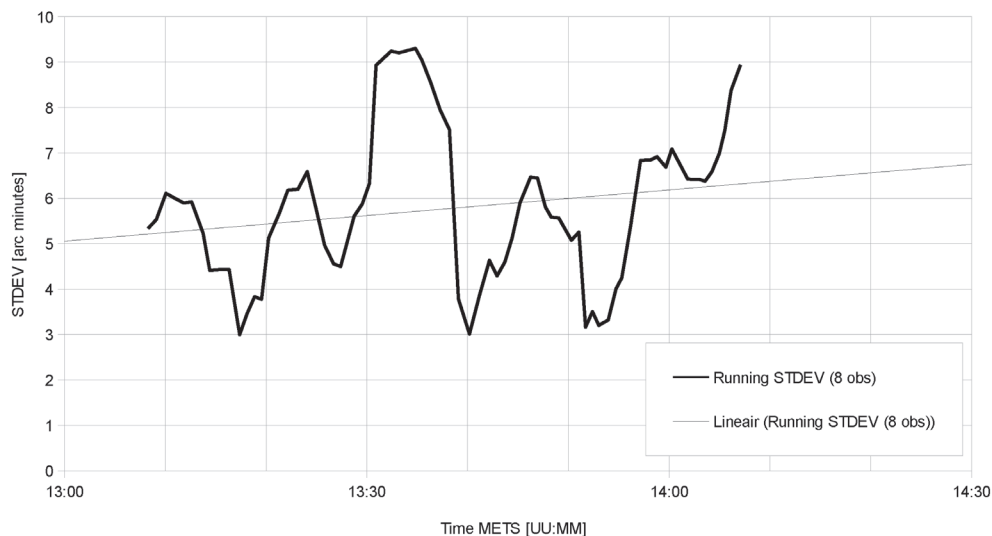


Figure 11 Temporal distribution of a reasonable experienced observer.

period as recorded at one of the nearby platforms in block Q1 of the North Sea shows a decreasing linear regression as well, albeit only 5 per cent.

We were sailing with a 46-foot sailing boat (a Beneteau 46) in 50 centimetres significant wave heights (90 centimetres maximum wave height) and the results found are therefore only valid for this combination, with this observer and this astrolabe. Since the boat was much smaller than typical ships of the period, its motions would have had a much greater effect on the accuracy of the observations. The main problem was the lateral movement of the observer, mainly caused by the yawing of the vessel. For practical reasons the observer was situated next to the companionway little under halfway between the stern and mast, instead of close to the mast as required.

To see if the regression line indeed showed the learning process of the observer and that it was not related to the minor change in sea state, a few weeks later Pieters took another series of 64 observations on land. Again the temporal distribution showed a negative trend, albeit now only 20 per cent improvement. Pieters' data also showed a standard deviation of 18 arc minutes, almost twice as good as at sea, but still more than twice the standard deviation of the author (8 arc minutes), confirming Köberer's suggestion that 'the observer error [of individual observers] may play a significant part in the accuracy of the angle measurements with an astrolabe'.⁴⁷

The temporal distribution of my own data shows that the standard deviations go up by 20 to 50 per cent over the whole session (as an example see figure 11). This seems to indicate that due to my experience the learning curve is very short and that with time my observations get worse probably due to fatigue and/or loss of concentration. Only the very first three sessions before the astrolabe was corrected showed similar regression lines to those of Pieters, indicating that I was reasonably experienced after that.

47 Ibid.

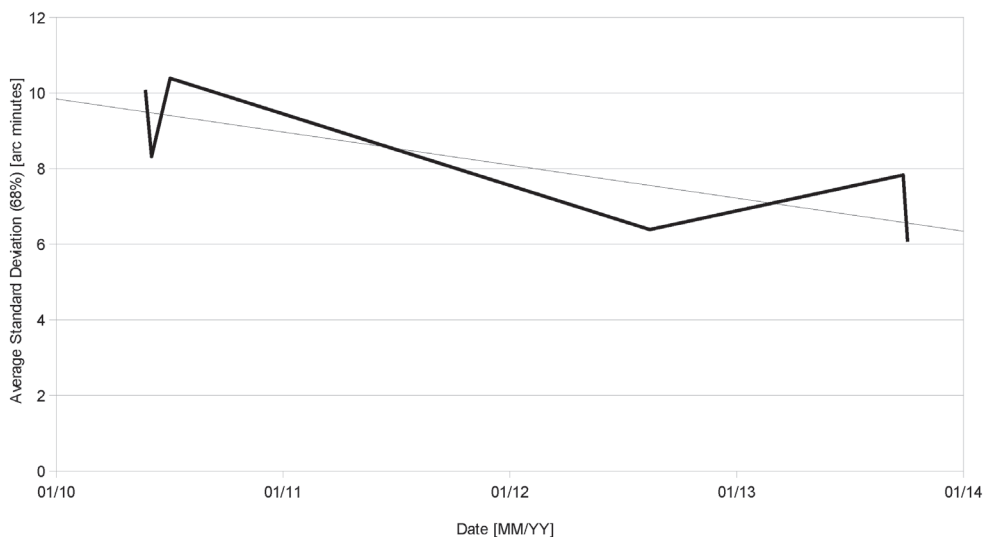


Figure 12 Temporal distribution of the author over all his sessions.

A temporal distribution over all sessions after the instrument was corrected using the average standard deviation per session as data shows an improvement of 30 per cent (see figure 12), indicating that I am still learning and that despite 536 observations I still have to classify myself as a not fully fledged observer.

Period observations

In 1958 an article on Mediterranean navigation and the start of oceanic astronomical navigation by A. Teixeira da Moto was published.⁴⁸ He referred to the 1538 journal of D. João de Castro which I already mentioned before.

Celestial observations were taken using mariner's astrolabes, the observations of which were given by Teixeira da Moto in a four-page table.⁴⁹ The observations are interesting for two reasons. First, some of the entries are not, as was common in period logbooks, in latitudes but in altitudes, so the raw measurements on the instrument. Second, on most days the observations were taken simultaneously by more than one person.

The altitude observations give us insight into the way period instruments were read. According to D. João de Castro these raw observations were noted to ensure that only individuals or the defects of astrolabes were judged, not the declination tables used in the calculations.⁵⁰ Due to their dimensions Iberian astrolabes were divided in whole degrees only. The logbook however shows entries in quarters, thirds and sixths of a degree, indicating that the fractions were derived by visual interpolation. When using the Valentia replica, which is divided in whole degrees as well, I find it no trouble to estimate to that same level.

From a frequency distribution (see figure 13) it becomes clear that the majority of the observations (70 per cent) were taken by two or more persons on board. Despite

⁴⁸ Teixeira da Moto, 'L'Art de Naviguer'.

⁴⁹ *Ibid.*, 142–5.

⁵⁰ *Ibid.*, 141.

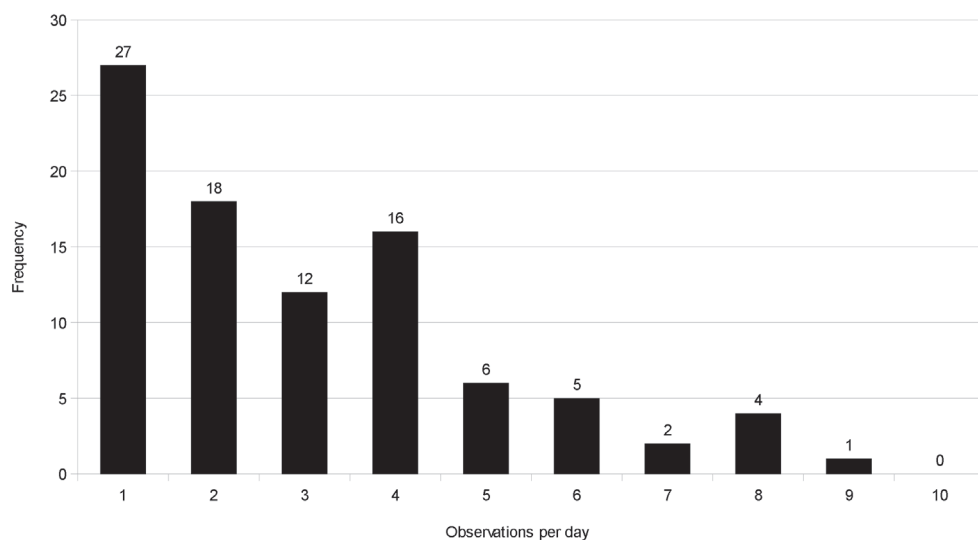


Figure 13 Observation frequency distribution based on D. João de Castro's journal of 1538

having only between two and nine observations per day I decided to calculate the standard deviations per day to analyse their frequency and temporal distributions.

The frequency distribution of the standard deviations (see figure 14) shows that the crew managed to fully agree for almost one third (31 per cent) of the days (i.e. zero arc minute standard deviation). This seems unlikely and with some speculation perhaps had more to do with desired social behaviour – like the moments the master and pilot were obliged to re-take their observations – than with independent thought. The next peak is of interest to us; it is well defined between 5 and 20 arc minutes (50 per cent of the observations), while a third peak can be found between 25 and 40 arc minutes (15 per cent of the observations). The rest of the data (5 per cent of the observations) falls between 50 and 70 arc minutes. So the navigators onboard João de Castro's vessel would have had agreement within 20 nautical miles for just over 80 per cent of the observed meridian passages.

Creating a temporal distribution of the data from D. João de Castro shows a 50 per cent improvement during that five month journey (see figure 15), indicating that the crew got better agreement in their readings over time down to about 10 arc minutes. Whether this was due to experience with the instruments or adapted social behaviour remains a question. The best observer in modern times, Ávila da Silva onboard of the NRP *Sagres*, managed to produce 61 observations with a standard deviation of just under 10 arc minutes, confirming above figure from D. João de Castro's crew.⁵¹

51 Malhão Pereira, 'Experiências', 176. It has to be noted that these observations were taken onboard of the 1755 tonnes *Sagres*, which is considerably larger than the period 100–600 tonnes vessels.

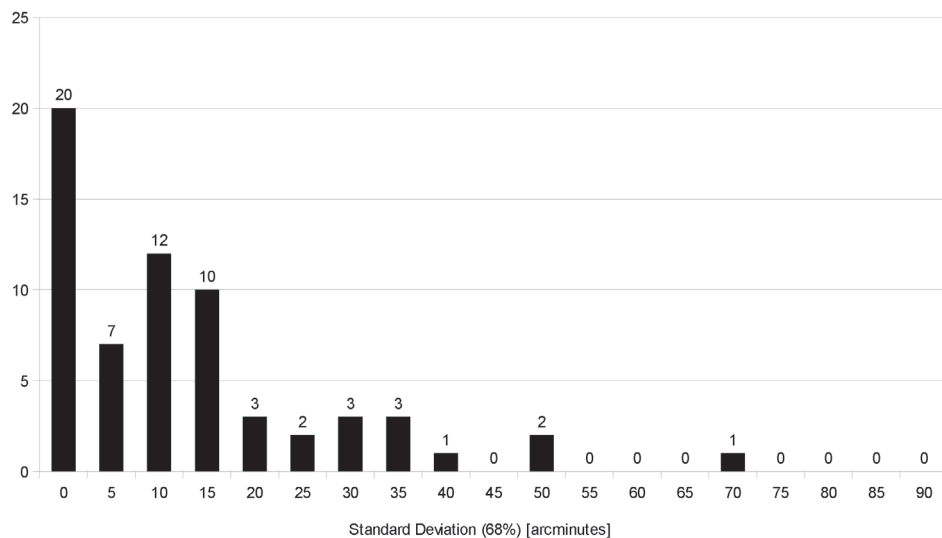


Figure 14 Standard deviation distribution based on D. João de Castro's journal of 1538

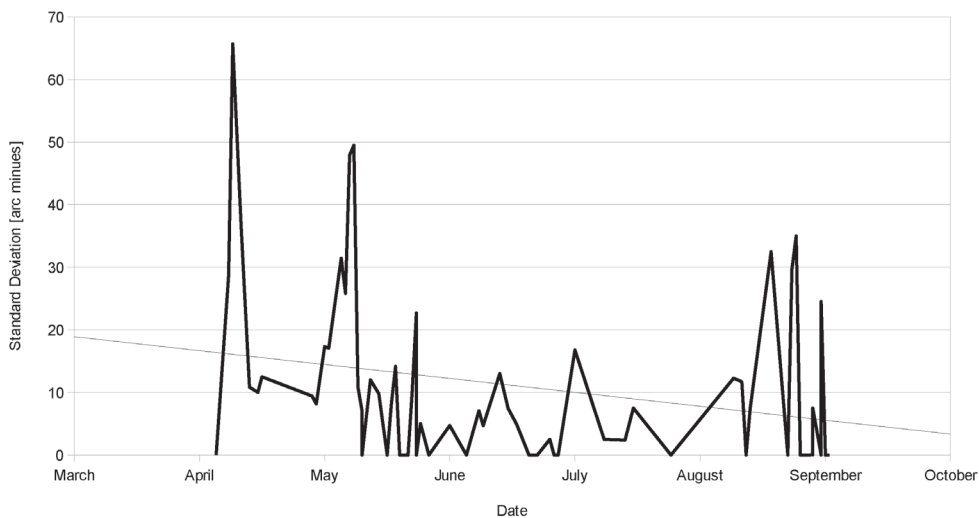


Figure 15 Temporal distribution based on D. João de Castro's journal of 1538

In his article on the history and causes of the incorrect latitudes in period journals Edmund Slafter wrote that what the observer

put down as the fraction of the degree, or minutes, was an absolute and sheer guess [and that the] minutes or fractions of degrees . . . are never to be relied upon, and are never correct except by accident.⁵²

These period and modern observations described above show that this may be true if

⁵² Slafter, *History and Causes*, 17–18.

attempting to judge down to individual minutes, but reliable observations to a sixth of a degree (10 arc minutes) were certainly feasible.

Conclusion

Assessing the accuracy of the mariner's astrolabe can only be done in a statistical manner using the same methods and instruments in use in early modern times. As the average is meaningless for the accuracy of the mariner's astrolabe in general, it is of no importance how close the average reading to the expected altitude is. Only how far the observations are scattered around it counts, as this tells us more about the chance that the true altitude is really found using the methods of period navigators. The current research indicates that assessing the accuracy of the mariner's astrolabe requires at least several hundred observations per observer over a prolonged period of time before we can say that the observer is fully fledged and even then another observer may achieve better results. When using an Iberian astrolabe on land an accuracy of 8 arc minutes is feasible for a reasonably experienced observer. Using the same astrolabe at sea depends on the observer, vessel and sea state, but 30 arc minutes can be achieved by an inexperienced observer. An analysis of period and modern data taken at sea shows that an 80 per cent agreement between observers within 20 arc minutes could be achieved and that an accuracy of 10 arc minutes is feasible. What has become clear above all is that in modern research more statistical data is needed, produced with more observers and properly made instruments of varying diameters to get a full picture of the accuracy of the mariner's astrolabe in general.

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