

During the global trade expansion of the Netherlands and England in the seventeenth century, instruments for celestial navigation underwent significant development in both countries. A relatively large number of instruments was developed in the seventeenth century. They were all based on ideas first formulated by Thomas Hood and Thomas Harriot.

Using period literature, simulations, experiments and field tests, most of the instruments have been thoroughly researched, providing a better understanding of their construction, use, diffusion, accuracy and limitations. We now have a better picture of the accuracies that could be achieved by an early modern observer and now know that this accuracy very much depended on whether Hood's or Harriot's concepts were used.

One of the worst disasters of early modern times, the loss of four of Sir Cloudesley Shovel's ships in 1707, was caused by a combination of inaccurate charts and biased instruments. The instruments were the ones mainly used by English mariners at the time, but were also the most inaccurate, as a result of their design.

In order to understand how this could happen, I posed the following research question:

*How did wooden navigational instruments evolve in the period 1590-1731, what was their common origin, how did they perform and why did the best not become the most widely used?*

For this the following additional questions are answered:

- Which instruments were created in the research period?
- Which instrument(s) became most widely used?
- Which factors dictate the accuracy of observations taken with them?
- Did their design features diffuse?
- How do replicas and reconstructions add to our understanding of the instruments?

By the end of the sixteenth century, the instruments commonly used for celestial navigation were the mariner's astrolabe, sea ring, and mariner's cross-staff. The last of those probably evolved from the Arab *kamal* in the early sixteenth century, rather than from the astronomical cross-staff as used by Levi ben Gerson in the fourteenth century. The mariner's cross-staff would result in a number of new staff-type instruments in the century after Hood introduced the shadow-casting method on a cross-staff in 1590. In order of appearance, the instruments introduced or significantly modified in the sixteenth, seventeenth and eighteenth centuries were Master Hood's cross-staff (f.l. 1590), Harriot's back-staffs (f.l. c.1595), John Davis' back-staffs (f.l. 1595), the mariner's cross-staff as a backstaff, the *knipboogh* and *cromme boogh* (f.l. 1600), the Davis quadrant (f.l. 1604), the removing quadrant (f.l. 1604), the cross-bow quadrant (f.l. 1604), the demi-cross (f.l. 1618), the *hoekboog* (f.l. 1623), the *spiegelboog* (f.l. 1660), the triangular quadrant (f.l. 1662), the plow (f.l. 1669), the almacanter's staff (f.l. 1672), the improved Davis quadrant (f.l. 1677), and the demi-quadrant (f.l. c.1750).

In 1731, John Hadley and Thomas Godfrey simultaneously invented the double reflecting octant, which was significantly more accurate than previous instruments. It was thanks to this instrument that it finally became clear that the most commonly used instrument to date was not as accurate as it seemed. Clearly in widespread use, the mariner's astrolabe, mariner's cross-staff, and Davis quadrant now stand out numerically when we look at text sources and surviving instruments. For comparison, the *hoekboog* was added to this list for two reasons. Firstly, the instrument was in basic shape, and thus in handling characteristics, similar to the Davis quadrant. Secondly, the *hoekboog* was based on a better underlying principle, making it a more accurate instrument, for which reason it was interesting to see whether this had an effect on its use. The *hoekboog* was, however, replaced in the Netherlands during the seventeenth century by the Davis quadrant. One of the reasons must have been the finer scales found on the latter, giving it a seemingly greater accuracy.

Two main features on instruments affect their accuracy. To understand them, the instruments have been characterised according to their design features introduced by Thomas Hood in 1590 and Thomas Harriot in 1594. The former used only one side of a cast shadow (Hood's single-sided shadow-casting method), while the latter used both sides (Harriot's double-sided shadow-casting method), believing this to be a better method. The observer no longer had to look into the sun while taking observations, while the size of graduations also grew significantly, making it easier to read the scales with greater precision. Hood's instrument was improved by Harriot, finally resulting in the first practicable backstaffs, so called as they were used while standing with one's back towards the sun, by captain John Davis around 1595. From experiments, it has been shown that Harriot was right and that Hood's shadow-casting method not only made observations less reliable, but also introduced a significant bias. The shape of the aperture of the horizon vane can be characterised in the same way as the shadow-casting method. Apertures either approached the

horizon from a single side, or allowed it to be centred around the horizon, thus a double-sided approach. I introduced the terms Hood's and Harriot's type aperture for these. Here too the single-sided method introduced a bias observation, which would add to that from the shadow-casting method. A wide variety of other error sources are discussed as well, including estimations of the biases resulting from them.

Ideas for backstaff-type instruments originated in England and diffused to the Netherlands and beyond in the last decade of the sixteenth century. Initial diffusion of the knowledge required to produce them took place through Davis, who joined a Dutch fleet to the East Indies in 1598. It was through his contact with Dutch commander Cornelis de Houtman that the knowledge came to the Netherlands, where new backstaff instruments soon appeared. Later in the seventeenth century, knowledge of the instruments that were designed on the continent diffused back to England, now through printed works.

Creating replicas and reconstructions of those instruments allowed me to take them into the field to put them to the test. From these tests, it became apparent that Harriot's shadow-casting method was indeed the better of the two. It also showed that differences between observers can be significant, in terms both of accuracy and precision. Even more important was the insight the building process gave into the production process and instrumental limitations. This in turn suggested how ideas might have diffused from England to the Netherlands.

Answering the additional questions resulted in other insights. From an inventory of surviving Davis quadrants, it became clear that their production shifted from England to America in the mid-eighteenth century. The accuracies of the scales of period instruments have been researched in theory and verified by analysing the scales of several surviving examples. The relationship between resolution and accuracy was also explored, showing that lower resolution does not necessarily result in a less accurate instrument. Likewise, the relationship between absolute and relative scale errors was explored, showing that it is better to judge an instrument on the relative errors than on absolute errors. Scale analysis showed that the instruments researched were divided with an accuracy better than 10 arc-minutes and that for most of them this was even well below 5 arc-minutes, sometimes even better than a single arc-minute. Finally, it was shown how difficult it is to properly assess the accuracy of period instruments using modern field tests, both due to the limitations of modern replicas and reconstructions and due to the observers themselves.

Answering the main research question, the evolution of instruments for celestial navigation in the research period was based on two basic ideas: the way the shadow is cast and how the instrument is aimed at the horizon. Each had two different solutions, introduced by Thomas Hood in 1590 and by Thomas Harriot around 1595.

No single instrument can be put forward as the common origin for the instruments that evolved in the research period. Master Hood's cross-staff was an important

common ancestor, as the first wooden staff-type instrument to use an attached vane to cast a shadow for the observation. Going further back in time, the instruments are related to the (mariner's) astrolabe and the *kamal*. The latter was ultimately based on measurements taken with the width of the human finger at a time when no instruments were used.

The shadow-casting instruments from the research period performed well. It has been shown that with most of the staff-type instruments, accuracies well under 5 arc-minutes could be achieved, but that when using instruments based on Hood's type of shadow-casting, considerable differences between observers may occur, to a greater degree than could be explained statistically. These differences are caused by human perception of the cast shadow, combined with Hood's single-sided shadow casting method. Once Harriot's double-sided shadow-casting method is used, observations become more consistent between observers. Using the best seventeenth-century instrument, the mariner's cross-staff with two apertures and a horizon vane, it is possible to obtain observations with an accuracy of just over 2 arc-minutes.

Which instrument became most commonly used varied regionally. In English-speaking parts of the world, the Davis quadrant was more commonly used, while in the Netherlands it was the mariner's cross-staff. It was the former instrument that was used among Shovel's fleet, of which several ships, in part because of the limitations of the instrument, tragically sank on the rocks of the Isles of Scilly.

