From Simple Quadrant to Space Sextant

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Fig. 1—The simple quadrant. Dating from antiquity it was an important navigation instrument through the 17th century.



Fig. 2—A Persian astrolabe (undated). This front view shows the pivoted index rule, the rete containing within its floral design pointed leaves representing the reference stars, and an underlying engraved plate of a projection of the celestial sphere. (From the author's collection.)

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Abstract

A STUDY OF THE HISTORY of the technology of navigation proves as rewarding and interesting to todays Navigator or Instrumentation Engineer as it does to the historian. This paper presents a pictorial survey and description of celestial data acquisition instrumentation from earliest times to the present. Principle features of each instrument and it's place in relation to the navigational concepts of it's day are discussed.

Introduction

The history of the technology of celestial navigation extends backward over many centuries of time, nations and peoples. The flow of progress, from antiquity through into the future, while, it seems, always positive, has certainly been uneven. Two periods of brilliant advance stand out, each associated with a major improvement in the technology of transportation; the first centered about the turn of the nineteenth century and the great age of the maritime

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No period has experienced such growth and development as has the present. The conventional marine sextant represents instrumentation of the distant past. It has taken only a few years for the once revolutionary bubble aircraft sextant to be surpassed by the automatic daylight star tracker. The next few years will show even greater change. Autonomous (self-contained) navigation for manned space flight must be dependent upon the prime use of celestial "observables". An ultra-precise space sextant already exists which will enable man to navigate in cis-lunar space. Lunar landing and surface exploration, both dependent on the navigational use of celestially derived data, are the next logical steps in the exploration of space. Within the lifetime of many of us man will land on Mars.

Yet the technology of this "new navigation", no matter how sophisticated it be, is still not closed upon itself; its roots lie in the past. Each step forward has been a step towards greater accuracy; towards a more complete determination of position and orientation. The development of an accurate knowledge of time has been integrally associated with the development of the techniques of celestial navigation. In this article we trace the technology of this sciencetransformed-art from its crude beginnings into our immediate future.

Navigation

Early instrumentation

The simple quadrant (Fig. 1) dates from antiquity, yet was still used by Magellan in 1519 for his circumnavigation of the globe. Originally an instrument of the astronomer and surveyor it was taken to sea where it was used to determine latitude by the altitude of either the pole star or the noonday sun. Increased accuracy was obtained by applying diurnal corrections for the rotation of Polaris about the true pole (based upon the orientation of the "Big Dipper") and for seasonal motion of the Sun along the ecliptic. This simple quadrant used a plumb-bob line as an artificial vertical and was graduated in degrees along the circumference of a vertically oriented quarter sector (hence quadrant) of a circle. Peep sights were along one radius, and the plumbbob line was suspended from the center of the circle. Size-limited for marine application and without optical magnification it was somewhat limited in accuracy.

The Astrolabe, the first sophisticated celestial

instrument combining sighting and computational functions, is most probably an Arab invention of the 7th century A.D. although there are some claims for its invention by Apollonius of Perga in the 3rd century B.C. and others for Hipparchus about 150 B.C. The earliest known example dates from the 10th century. Reduced to a simple sighting instrument it first appeared at sea just before 1500 A.D. However, it is the more complicated instrument as represented by the unit of Fig. 2, which deserves most of our attention.

This astrolabe is essentially a series of projections of the celestial sphere which enable the user to derive local time from a given star sighting. (The existence of an accurate value of reference time would have permitted the determination of longitude as well.) It consists of a sighting arm and scale (on the back) for measuring stellar altitudes and on the front, a metal plate (or plates, for various latitudes) engraved with an appropriate projection of the reference grid of the sphere, a scale for measuring



Fig. 3—The Davis Quadrant (or Back-Staff). It employs the visual horizon rather than a gravity determined vertical for solar altitude measurements.

the time, a second plate, called the rete, mounted above the main circular plate and cut away to form a map of the chosen reference stars, and an index rule pivoted to the center of the main plate. Although it too employed no optical magnification, its accuracy could be greater than that of a quadrant of comparible size, if careful and accurate techniques were employed in its fabrication. (Interestingly the illustrated instrument was used primarily for purposes of astrology rather than astronomy.)

In an attempt to achieve greater accuracy another Arab device called the Kamal, or crossstaff, first described to the western world by Levi ben Gerson in 1342, was introduced to marine navigation. Unlike the simple quadrant or astrolabe, it used the horizon rather than a gravity vertical for reference. While offering a significant increase in operational accuracy it still had several great disadvantages; the user had to spread his angle of vision in order to see two objects at once and had to look directly at the Sun. The invention by Captain John Davis. about 1595, of the backstaff (Davis quadrant) solved many of those problems. It consists basically of a large and a small arc with common centers of curvature (see Fig. 3). At this point is located the horizon vane while a shadow vane is placed on the small circle and a sighting vane on the large circle. The combined readings of both scales gives the Sun's altitude when alignment is achieved between the Sun produced shadow of the shadow vane on the horizon vane and the horizon as viewed through both the sighting vane and horizon vane. Although clumsy in use due to its size and shape it did yield reasonable accuracy for solar sightings. English instrument makers still produced Davis quadrants as late as the middle of the eighteenth century while American instruments dated as late as 1775 are known; this even after the invention of the Hadley quadrant, a more practical instrument.

Navigation comes of age

The prototype of the modern marine sextant was designed simultaneously in 1732 by John Hadley of England and Thomas Godfrey of Philadelphia. Known as the Hadley quadrant (Fig. 4) it is actually an octant, its scale ex-

tending over one eighth of a circle. Because of the use of mirrors for the superposition of the horizon and a celestial target, one arc degree of motion of its index arm results in two of motion of the celestial field. Thus a scale 45 degrees in physical length yields an altitude range of 90 degrees (hence its designation "quadrant"). For high altitude celestial targets, the use of the forward peep sight permits double horizon sightings for increased accuracy. Filters were introduced into the lines of sight for reducing the sun's intensity and vernier scales were developed which permitted readings to one arc minute (and in some instances, 30 arcseconds). Scale radii between 18 and 20 inches were first employed in order to achieve the desired accuracy although later instruments were reduced in size to almost half of these values. Telescopic



Fig. 4—A Hadley Quadrant made by the second Benjamin Cole of Fleet Street, London about 1750. The frame and index arm are of mahogany with a boxwood scale, ivory index edge, brass forward and rear peep sights and two colored filters which can be placed in either line of sight. (From the author's collection.)

sights were also eventually added to the basic instrument.

Techniques of navigation were developed almost hand-in-hand with the sighting instruments themselves. From antiquity navigators had limited themselves to parallel sailing due to their inability to determine longitude. Knowing the latitudes of their home port and destination they would sail north or south to the desired latitude and then east or west as the situation required. By the beginning of the 17th century the "method of lunar distances" had been established for the determination of longitude. However, neither sighting instruments nor methods of computation proved satisfactory to the task. Thus, the Board of Longitude was established in England in 1714 to find a better method for longitude determination. With the offer of a prize of 20,000 pounds for the invention of a high accuracy chronometer they set out to obtain this better solution. John Harrison invented such an instrument in 1735, finally producing a relatively small timepiece in 1761 which on one test lost only nine seconds in two months. Men being what they are, though, he did not receive the prize until 1773 at the age of 80 and then only because of the intervention of George III. During this same period of time, improvements were made in the "method of lunar distances"; the most significant by Nationiel Bowditch in 1802. Modern celestial navigation by the method of lines-of-position was first discovered in 1837 by 30-year-old Captain Thomas H. Sumner, a Harvard graduate and son of an United States Congressman from Massachusetts. (It should be noted that present aircraft celestial navigation is still based upon the use of precomputed sight reduction tables to generate appropriate lines-of-position.)

The length of scale of the Hadley quadrant proved inadequate in general for the observations required by the "method of lunar distances." The full circle of Tobias Mayer (1752) was the first answer to this problem. However, the sextant as devised by Captain John Campbell of the Royal Navy about 1757, proved to be a more satisfactory instrument. Basically a simple extension of the Hadley quadrant (See Fig. 5) it was easy to handle and read and offered sufficient accuracy for most navigational requirements. Not until Bowditch's method was developed though was there any real demand for such an instrument. Thus it was not until the early part of the nineteenth century that the sextant came into its own. Interestingly there is no basic difference between the marine sextant of today and that of 1830. Micrometer readout has replaced the tangent screw and its vernier and materials have changed, but very little else. A significant advance in the instrumentation for celestial navigation had to await the demands of the technology of aeronautics and astronautics.

The aerospace era

With the advent of long-range, night-flying aircraft celestial navigation received a new impetus. Now shortly after the marine sextant was invented, an attempt was made to extend its use to periods of darkness. This was done by providing a spirit level attachment. The observer brought the image of the celestial target being sighted into coincidence with the bubble of the spirit level. Such devices though never proved really effective. The needs of air navigation caused a redirection of effort to take place in the 1930's towards the realization of this early ob-



Fig. 5—An early sextant made by George Bradford of London about 1830. The frame is ebony, the index arm brass and the main and vernier scales are engraved on inlays of ivory. Three filters are provided in each line of sight. (From the author's collection).

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jective. The answer lay in the incorporation of an integrator with the sextant which would "average out" the deflections of the bubble from true vertical caused by the transverse accelerations experienced during flight. The Mark 5 sextant produced by the Eclipse-Pioneer Division of Bendix Aviation (Fig. 6) was an early example of such an instrument. Its basic shortcomings led to the development in the 1940's by the Kollsman Instrument Corporation of several improved instruments. Using either a pendulous mirror or bubble as the artificial horizon these instruments, in either the "stubby" form for use under astrodomes or the periscopic form, solved practically all of the then outstanding problems.

For use in high performance jet aircraft the periscopic sextant (Fig. 7) has proven most valuable. With only a small portion protruding above the skin of the aircraft, and only when in

Fig. 6—The Mark 5 bubble aircraft sextant manufactured by the Eclipse-Pioneer Division of Bendix Aviation and essentially designed in the 1930's. (From the author's collection.)

use, drag is greatly reduced. An air lock prevents loss of cabin pressure when the instrument is inserted into or removed from its azimuth mount. Although completely automatic celestial navigation systems now exist (whose discussion is unfortunately beyond the scope of this present article) the basic periscopic sextant is still in everyday use by the U. S. Air Force and the commercial airlines.

The advent of manned space flight has once



Fig. 7—A modern periscopic aircraft sextant shown in its azimuth mount which is normally mounted in the skin of the aircraft. It is still the operational mainstay of many present day aircraft. (Courtesy of the Kollsman Instrument Corp.)

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Fig. 8—The hand held space sextant developed in conjunction with the USAF Avionics Laboratory. It will enable the astronaut to effect navigation measurements from orbit. (Courtesy of the Kollsman Instrument Corp.)

again introduced an entirely new set of requirements and constraints for celestial navigation instrumentation. It is almost universally recognized that any autonomous (self-contained) scheme for space navigation must be based upon the "observables" of space flight. These include stadimetric ranging measurements to a given body based upon either total included angle or apparent curvature of the horizon, star-horizon angular measurements, star-landmark angular measurements, occultations, and star-planet angular measurements.

For the purpose of "back-up" to the prime spacecraft navigation system, the Kollsman Instrument Corporation has, in conjunction with the USAF Avionics Laboratory, developed a pair of hand held instruments. One is a space stadimeter while the other a space sextant (see Fig. 8). Both have been designed to work through the sight-angle-limited Gemini and Apollo windows. The former instrument derives range in terms of the measured curvature of a limited portion of the visible horizon. The later instrument provides a means for the measurement of star-horizon and star-landmark angles from the spacecraft. While schematically similar to the conventional marine sextant, its physical configuration differs drastically from the former. In addition to meeting the environmental requirements of space flight, the optical system has been designed to yield optimum performance with the various visual horizon signatures.

The most sophisticated sextant ever made is the one designed and developed by the Kollsman Instrument Corporation in conjunction with the MIT Instrumentation Laboratory for Project Apollo (see Fig. 9). It consists of two optical units, servoed one to the other, and aligned



Fig. 9—The Apollo Optical Navigation Unit consists of a scanning telescope (left) and high accuracy sextant (right). Developed in conjunction with the MIT Instrumentation Laboratory for NASA it will provide the basic input data for the Apollo autonomous navigation system. (Courtesy of the Kollsman Instrument Corp.)

within arcseconds to the Apollo Inertial Measurement Unit. The scanning telescope unit (a low power wide field acquisition instrument) provides initial alignment of the high power sextant unit. Sextant angle readout to a fraction of an arc-minute is provided by means of a trunnion axis resolver. Accuracy is maintained through the use of precision stainless steel worm and worm wheels (35 millionths of an inch) and beryllium structural elements. Manual over-rides are provided in the event of power failure. It is important to note that the instrument illustrated is of the Block I designation. The Block II Apollo Sextants contain an automatic horizon photometer and an automatic star tracker. Initial alignment is achieved under manual control and then the instrument is switched into the automatic tracking mode. At the present time it is certainly the most advanced navigation sextant ever to exist.

Epilogue

Clearly the distance between the simple quadrant of antiquity and the Apollo Space Sextant is more than just one of time. But if this distance is great, consider the next stage. Work is already underway on the problem of navigation on the lunar surface. Flight to and landing on Mars are no longer just the idle dreams of a decade ago. There are even advanced research teams concentrating on "transtellar navigation". If anything, we are only on the frontier of the great objectives of celestial navigation; certainly we are nowhere near the ultimate. Again, what has gone before will be but a prelude to the advances of the future.

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