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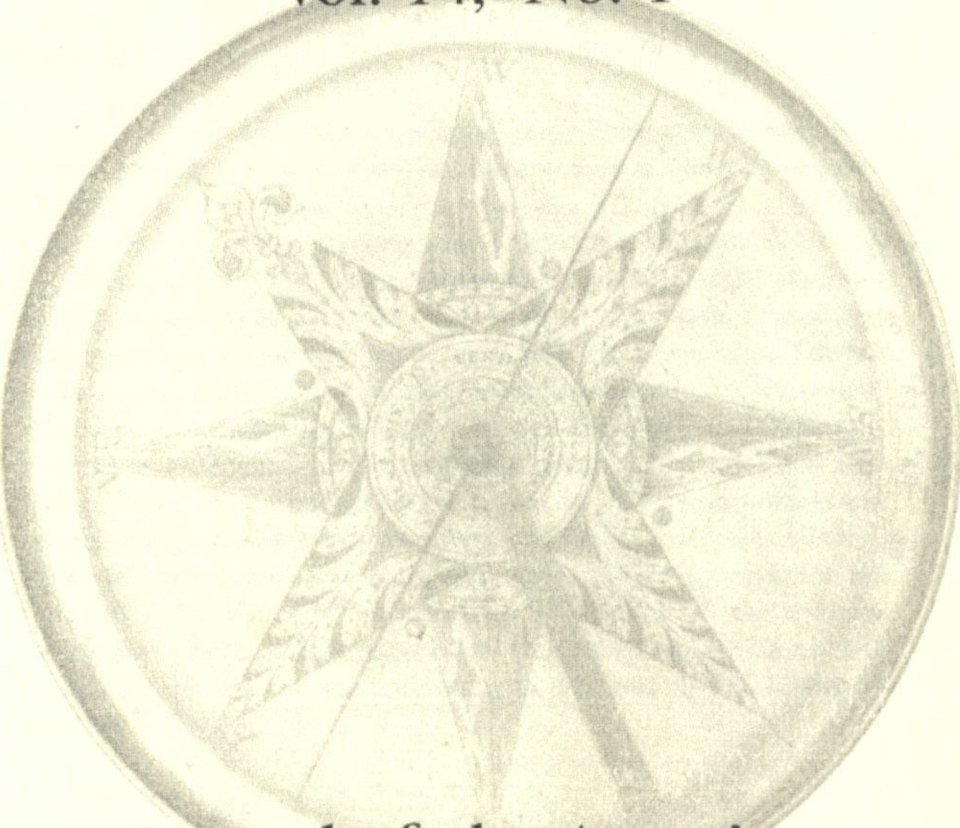

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THE WILLIS NAVIGATING MACHINE
A FORGOTTEN INVENTION

Willem F.J. Mörzer Bruyns

Abstract

To avoid the arithmetic for solving navigational calculations, early seamen preferred to use scientific instruments such as Gunter's quadrant and the plane scale. Even after the introduction of logarithms, in the first half of the 17th century, seamen, scholars and inventors kept on looking for mechanical ways to avoid arithmetic. This accelerated with the coming of aviation in the 1920s. The speed of aeroplanes necessitated finding one's position faster than on board ship. For this purpose, Edward Jones Willis, a consulting engineer, inventor and author in Richmond, VA, designed a Navigating Machine. Marine and aviation versions were patented in 1932 which performed the arithmetic to find a position line. The test report of Lt. Commander P.V.H. Weems USN, was favorable and several machines were manufactured by Heath & Co. in London. However, the machine was not widely used. Willis arranged for his machines to be placed in institutions in the US and UK but a recent survey shows that most appear to be lost. One, along with the US and UK patents and Willis' personal archives, was presented to The Mariners' Museum in Newport News, VA.

Introduction

The process to find a position line by means of celestial navigation - other than for finding latitude at meridian passage - consists of a number of phases. First an altitude observation of a celestial body must be taken with the simultaneous observation of Greenwich Mean Time. Secondly the Local Hour Angle for the observer's dead-reckoned (assumed) position must be found, followed by a calculation. Finally, the resulting position line has to be plotted in a chart. When more lines are obtained from several stars at the same time, their intersection will indicate the observer's position at the time of the observations. The first phase necessitates the use of a sextant and a marine chronometer; for the second, a Nautical Almanac, mathematical tables and arithmetic are required. Seamen have always tried to avoid the arithmetic part. In 1614 the Englishman John Napier invented logarithms which made complicated calculations easier. His countryman Henry Briggs adapted logarithms for navigational purposes, and in 1633 the Dutchman Adriaan Vlack published tables. This did not mean that navigators switched to logarithms directly. Scholars, seamen and scientific instrument makers went on looking for other ways to avoid or shorten arithmetic. One way was the computation of so-called 'short-method' tables containing trigonometric calculations, or certain elements of these, which had been done beforehand. The first short-method, by which the calculation for celestial navigation could be performed considerably quicker than with logarithms, was found by Sir William Thomson and E. Roberts in 1876. Other inventors, for the same purpose, designed diagrams or graphic methods. Finally there was the 'mechanical solution', with the use of scientific instruments. These included mathematical rulers with trigonometric and logarithmic scales, such as the Gunter's scale, designed by the Englishman Edmund Gunter in 1620, and the plane scale invented by his countryman John Aspley in 1627. They remained popular well into the nineteenth century. At the beginning of the twentieth century modern slide rules were invented, such as the *Nautisch-Astronomische und Universal Rechenstab* of c.1910 by R. Nelting, and produced by Dennert & Pape in Altona, Germany. In 1919 the American naval officer Armistead Rust patented a similar kind of slide rule for navigators, which too enjoyed some popularity.

The coming of aviation in the first decade of the twentieth century created a new challenge to navigation. At first pilots adopted traditional marine celestial navigation, but as flying distances and the speed of aeroplanes increased in the 1920s this took far too long to be worked out. By the time the position had been calculated it was of little or no use to the pilot, as since the observation the plane had covered a great distance. In order to keep pace with the demands of the increasing speed of aircraft, the first 'modern' navigating devices were soon designed. They can best be seen as a transitional phase between existing tools and electronic equipment. In other words: they formed the link between the Gunter's scale and the electronic pocket calculators which were designed in the 1970s especially to avoid arithmetic in celestial navigation. Among the first was the 'Baker Navigating Machine' of the early 1920s, by Commander T.Y. Baker RN, and popular with aviators. A successful navigational calculator, the 'Bygrave slide-rule', was designed by Captain L.G. Bygrave in 1922. It consisted of three concentric cylindrical tubes, and worked with the aforementioned Thomson short-method. It was used into the 1930s, the period when Edward Jones Willis, invented his arithmetic-avoiding navigating machine, which is the subject of this paper.[1]

Edward Jones Willis

Edward Jones was born in Savannah, Georgia, on April 1, 1866, but he grew up in Richmond, Virginia. His parents were John Pembroke Jones, a lieutenant in the old United States Navy and later captain in the Confederate States Navy, and Mary Willis Jones. As the Willis family name became extinct, Mary's father, Dr Francis T. Willis, had the Legislature change his only grandson's name to Edward Jones Willis.[2] He entered Stevens Institute of Technology in Hoboken, New Jersey, where he graduated as a mechanical engineer in 1885. Willis returned to Richmond were he fulfilled a number of commercial and civil appointments. During World War I, from 1916-1919, Willis was associated with the United States Fuel Administration and after that until 1921 he served as chairman of the Governor's Board of Mechanical Survey. It was probably after this that he established himself as an independent consulting engineer in Richmond, although he had already been active as an inventor for many years. In 1894 Willis obtained his first patent for a planimeter, an instrument that mechanically measures the area bounded by a closed curve.[3] This was one of the first planimeters designed specifically for measuring indicator diagrams of steam engines. Willis went on modifying his design and patenting the changes for the following thirty years.

It was probably shortly after World War I that Willis became interested in celestial navigation and wrote two books on the subject. In 1921 he published *The Mathematics of Navigation* (J.W. Fergusson & Sons, Richmond), followed in 1925 by *The Methods of Modern Navigation* (D. Van Nostrand Co, New York). The latter saw several editions and in 1935 a revised and enlarged edition was published in Glasgow by Brown, Son & Ferguson Ltd. which was well received by professionals on both sides of the Atlantic Ocean.[4] Willis appears to have been financially well off as, according to his letterhead stationary of 1940, he owned a number of farms in the vicinity of Richmond.[5] When his wife Bessie, née Fauntleroy, died in 1939 they were living at

Pembroke in Henrico County, West of Richmond. Willis died at Richmond, Virginia, on July 11, 1941. Before his death he had arranged for his intellectual inheritance to be taken care of. He left a Navigating Machine, its United States and United Kingdom patents, and the drawings, the jigs and patterns to The Mariners' Museum at Newport News, Virginia. He did so very modestly writing 'Please comprehend that I am not giving these things to the Museum to prolong my name or with any desire to have them kept in the Museum as a curiosity unless you so desire'.[6] The patents were assigned to the Museum, although the British patent had lapsed in 1936.

The Navigating Machine

The United States Patent for the Willis Navigating Machine was filed on June 24, 1930 (no. 1,845,860), and granted on February 16, 1932. The United Kingdom Patent was filed on July 1,1931 (no. 375084), and granted September 8 of the following year. In the patent the invention was named 'navigating instrument', but Willis explained that it should more properly be determined 'navigating machine', by which denomination it became generally known. The machine was designed to perform the calculations necessary to find a position line quickly, accurately and without arithmetic. All the navigator had to do was to

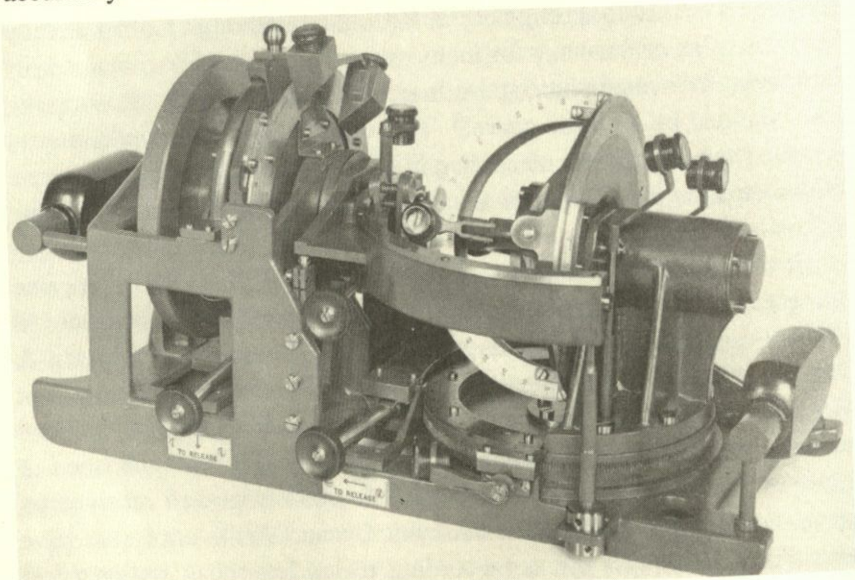

Fig. 1 The Willis Navigating Machine, ca. 1931.
Courtesy of The Mariners' Museum, Newport News, VA.

observe the altitude of the selected celestial body and the corresponding Greenwich time, and after using the machine construct the position line in the chart. When Willis patented his invention there were three traditional methods available to calculate a position line. They were the Sumner method by the American Captain Thomas H. Sumner, that of the French naval officer Marq de Blond de St. Hilaire, and the 'time-sight' method. The machine was designed to work for all three. These methods necessitated the calculation of the altitude, azimuth and hour-angle of the celestial body, for the observer's dead-reckoned position. The various data are elements of a spherical triangle, and the calculation involves spherical trigonometry. Depending on the experience of the observer the reducing of the observation of one celestial body, that is the calculation between the observation and the construction in the chart, takes about ten minutes. When a position from say four stars is required this adds up to about forty minutes. By setting the arcs of the machine, the spherical triangle was set mechanically and the required angles were read from the proper scales. Altitude and azimuth were read from the machine by setting it for the celestial body's declination (found in the *Nautical Almanac*), the observer's assumed latitude and the dead-reckoned hour-angle. In the case of the 'time-sight' method the required hour-angle and azimuth were found by setting the machine for declination, the assumed latitude and the observed altitude.[7] According to Willis the machine worked accurately and besides saving the drudgery of arithmetic and interpolations, also avoided possible mistakes. In the words of Willis, printed on the front page of his 1930 brochure, it "*Does for the Navigator what the adding machine does for the bookkeeper.*"

There were two versions of the machine, one for use at sea, the other for use in aircraft. The differences were in the weight and reading accuracy. The aviation type weighed 9 lbs. and had a maximum reading accuracy of up to five minutes of arc, the marine type weighed 27 lbs. and could be read up to one minute of arc. An aeroplane moves so rapidly that the speed in which its position is found is more important than knowing it within five minutes of accuracy. Heath & Co in London manufactured the machines at Willis's expense. The gift to The Mariners' Museum in Newport News includes a number of jigs that had been used to build the machine and for setting the axes at right angle. They had been made for Willis by the Zeiss Optical Head and according to him were besides very expensive, also highly accurate.

Obviously Willis tried to interest the United States Navy in his invention. If it were to be accepted and introduced he would be assured of success. Around the time he applied for the patent, Willis sent an aviation version of his machine to the Navy Department in Washington. This was subsequently tested at the Naval Observatory in Washington and the results reported to the Navy's Bureau of Aeronautics. The assistant chief of the Bureau, Captain J.H. Towers USN, sent the results to Willis in a letter dated October 17, 1930.[8] According to the Observatory the machine had twice as many disadvantages as advantages. The advantages were that it offered a slightly quicker [!] and less laborious method of reducing an observation and that its use eliminated mathematical errors. The disadvantages were that the machine would be unreliable or inoperative with the slightest blow, the adjustment of all parts should constantly be checked, the verniers were difficult to read even under the best circumstances, and finally the high cost of the machine, which was estimated at $500. The report concluded 'In view of the fact that the machine does not materially condense or simplify the processes of navigation, it is doubtful if it will be found to warrant the expense involved.' Willis probably did not accept these results, and asked for the machine to be tested by Lieutenant-Commander Philip Van Horn Weems USN (1889-1979), who was appointed as instructor of navigation at the Postgraduate School, Annapolis, Maryland in November 1930. He had published 'Star Altitude Curves' in 1928, which were named after him, and which were a major development in finding a ship's or aeroplane's position quickly, with a minimum of arithmetic. Weems was well known for his contributions to navigational science, both in the United States and abroad.[9] Because of their mutual interest and involvement in navigation there can be little doubt that Willis and Weems knew each other. In March 1931 Weems reported his findings on the aviation version of the machine to the Bureau of Navigation. He had tested it with about fifteen student-officers at the Postgraduate School. Among these were the Navy Lieutenants M.R. Derx, Miles Duval, F.W. Laurent, P.D. Lohman and S. Leith. The opinion expressed in the Weems-report differed from that of the Naval Observatory. Weems described the speed with which results could be obtained as 'impressive'. Average time for working a sight was about two and a quarter minutes, which was faster than for a 'short-method', and practice on the machine could improve on this time. The machine was sufficiently accurate, it was rugged and its construction the result of clever workmanship. The aviation version cost $250, the marine $500. Some favorable comments were made on additional use and the ease of operating the machine. In conclusion Weems called the invention 'a forward step in the solution of the navigation problem' and strongly recommended the Navy should acquire a few of both the marine and aviation version in order to do more tests and to encourage their final improvement. Individual reports of the naval lieutenants were included in Weems's report. Derx wrote that the machine was easy to operate and could be taught to someone without previous knowledge of navigation within a short period of time. Miles Duval gave some recommendations for improving the reading of the verniers, the adjustment screws, and the scales. He concluded that the machine would be especially useful on small ships such as submarines and destroyers. He advised the inventor to work with the Ford Instrument Corporation in order to adopt some of their ideas for precision instruments. Laurent's report was the least positive. He doubted if the advantages of the machine over computation and tabular methods were sufficient to warrant its purchase and use.

The machine was soon reviewed and commented on by professionals in the United Kingdom, where it was exhibited at the Olympia Shipping Exhibition, in London in 1931. Captain Alec Macdonald, a teacher at the Glasgow School of Navigation, Royal Technical College, published a praising comment in the *Nautical Magazine*.[10] He had examined an example of the aviation type and it was made available to several students at the School of Navigation, who quickly learned to handle it. They did a number of tests, probably however not at sea or in the air. The results were well within the limits of minimum accuracy. The author concluded that the machine would be of great value for air and marine navigators, especially for the former because of the speed with which a position line could be plotted. Macdonald wrote that Dr L.J. Comrie, head of H.M. *Nautical Almanac*, had examined the machine and had shown it to navigation instructors of the Royal Naval College in Greenwich. Comrie was positive, and also thought it especially useful for aerial navigation. According to Willis Comrie was not as much at home with the machine as J.P.M. Prentice, a British amateur astronomer, who apparently used it quite regularly.[11] In 1936 another British author, under the pseudonym 'Binnacle', paid tribute to Willis's contribution to navigation and his Navigating Machine (see note 4).

The Altitude-Azimuth Instrument

After the Navigating Machine Willis invented another, similar kind of navigational instrument. On May 21, 1935 the sixty-nine year old inventor filed a patent (no. 2,064,236, granted December 15, 1936), for the Willis Altitude-Azimuth Instrument, which was designed especially for aerial navigation. With his assumed latitude, the declination and hour angle, an experienced observer could obtain the azimuth and the altitude of a celestial body within two minutes. As far as known it was not offered to the Navy for examination, but was tried out at Maxwell Field, Alabama by Captain S.G. Pratt of the United States Army Air Corps, and reported on favorably by Weems.[12] It was easy to use and with a weight of less than 2 lbs. quite light and cost only about $150. It is clear that Willis had learnt from his previous machine as this one was lighter and cheaper, and was designed especially for aerial navigation. Unlike the Navigating Machine there is no indication as to the manufacturer of Altitude-Azimuth Instrument. There is a possibility that this machine was made

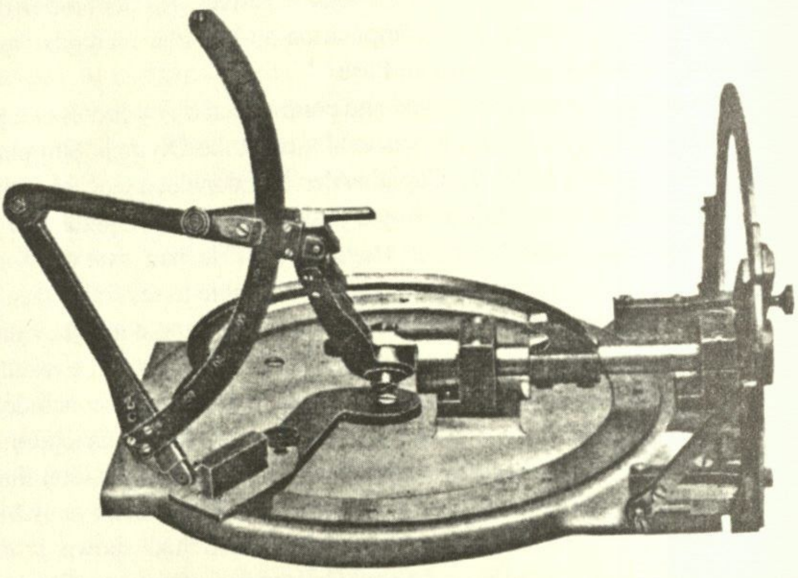

Fig. 2 The Willis Azimuth-Altitude Instrument, ca. 1936, as shown on a contemporary brochure produced by the inventor. Courtesy of The Mariners' Museum, Newport News, VA.

by Willis himself, as the gift to The Mariners' Museum includes a motor-driven graduating machine designed and constructed by him especially to graduate the arcs of the Altitude-Azimuth Instrument.

Final developments

All the compliments paid to Willis, especially on the Navigating Machine, were in vain, as it did not become the success for which he had hoped. The Navy had not ordered it and had not supported its further development. Perhaps this was due to the contradictory opinions of the Naval Observatory and Weems. Perhaps Willis's machine came too early and would have been successful at the beginning of World War II, when the war effort encouraged the development of navigational techniques. Wrong timing also seems to have been the fate of the 'Hagner Position Finder', a navigating machine designed by the former United States Navy Apprentice Fred H. Hagner in the 1930s. It was similar to the Willis machine, and also for sea and air navigation and for surveys on land. The Fairchild Aerial Camera Corporation of New York manufactured three versions.[13]

Some later machines were more successful. The originally French-designed 'Bastien position calculator' e.g. was taken up by Zeiss around 1940 and developed as the *Astronomisches Gerät*. It was successfully used by the German *Luftwaffe* and in U-boats. Another machine, the 'Astrograph', a device invented at Farnborough in 1940 and based on the use of the 'Weems Curves', was used by RAF pilots throughout World War II. Perhaps the Willis machine's weight was an objection after all. At least that was the reason that the German-designed *Sphero-trigonometer*, used on board the airship *Graf Zeppelin* in the late 1930s, and the *Spaero-triangulator*, based on the theodolite, did not become popular.[14]

Around 1936 Willis realized that his machine was not a success, and there is only a glimmer of hope in the letter of presentation of that and various parts to The Mariners' Museum, when he writes '…so that if there is a demand for the instrument the Museum could produce it, as I know I will never be able to make another.'[15] In the same letter Willis wrote that examples of the machine were also presented to the Science Museum[16] in London and to his alma mater, the Stephens Institute of Technology. The one in the Science Museum is still kept there (inv. no. 1936-318), the one at Stevens Institute could not be located.[17] In a note with the machine now in The Mariners' Museum, Willis wrote about the expensive jigs: 'They really have no value now for the purpose for which they were made, because none of these instruments have proven a financial success and no one would ever try to produce them again…'[15]

Before Willis's death the existing Navigating Machines were placed in various institutions. Besides those already mentioned in Newport News, London and Hoboken, the obituary in the *News Leader* (see note 2) lists their allocations, although it is not clear in all cases whether they were the marine or aviation-type. Two examples were at Wright Field, Dayton, Ohio, but in 1999 there was no trace of these in the collection of the Wright-Patterson Air Force Museum. Two went to the Unites States Bureau of Aeronautics, the historic collection of which apparently went to the National Air and Space Museum in Washington. That Museum now owns two aviation-type Navigating Machines, both were transferred there from the Naval Observatory prior to 1948, but possibly originating from the Bureau of Aeronautics (inv. nos. 1963-80 and 1963-81). Two machines were described as being 'on the Pacific Coast', a location difficult to define. In the United Kingdom the aviation type tested and described by Macdonald at the Royal Technical College (now University of Strathclyde), could not be located.[19] One was noted as being in 'Sunderland', by which possibly Sunderland Polytechnic in the United Kingdom was meant, now the University of Sunderland, which institution did not respond to my request for information. This was, unfortunately, also true for The British Astronomical Society (now British Astronomical Association) whereto one example supposedly went. Finally the obituary mentioned two machines in Rio de Janeiro. It has not been attempted to locate these. Although, according to Willis, there were quite a number of Altitude-Azimuth Instruments located all over the world, it has not been possible to locate any example.[20]

Conclusion

Willis was a successful engineer, inventor and author. His planimeter and navigational manuals were popular and widely used. He was less successful with his Navigating Machine. At first it was badly received by the Navy, although Willis's powerful ally Weems, and professionals in the United Kingdom reversed this opinion. Despite this, Willis started distributing the machines to museums within six years after being patented. He had arrived at the conclusion that there was insufficient professional interest for his invention. The later Altitude-Azimuth Instrument appears to have drawn even less interest. Navigators at sea obviously preferred (short-method) calculations above a mechanical solution. For use with air navigation the weight may have been the obstacle. An additional drawback may have been the price of the machines that, although not horrendous, was still far higher than that of mathematical tables. Whatever the reason for the lack of success, judging by the opinion of Weems the navigational inventions of Willis deserve to be remembered. The best way to do so is to preserve the few surviving examples, of which only four could be located. There are examples of the marine version in The Mariners' Museum and the Science Museum, and two of the aviation type, both in the National Air and Space Museum.

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Author's Address:

Kattenburgerplein 1
NL-1018 KK Amsterdam
Netherlands

Notes:

1. For the history of the various techniques, methods and machines see J.E.D. Williams, *From Sails to Satellites. The origin and development of navigational science* (Oxford, 1992), pp. 114-123; Charles H. Cotter, *A History of Nautical Astronomy* (London, 1968), pp. 309-342; and Ernst Crone, 'Middelen ter vereenvoudiging van de becijfering van het astronomisch bestek', *De Zee*, **54** (1942), pp. 265-275; **55** (1943), pp. 1-8, 23-31, 49-58, 79-87, 102-107 & 126-131. See also Peter Ifland, *Taking the Stars. Celestial Navigation from Argonauts to Astronauts* (Newport News & Malabar, 1998), pp. 187-188 and H.R. Bristow, 'Navigational Instruments on the 1927 Argos Flight', *Bulletin of the Scientific Instrument Society*, no. 62 (1999), pp. 17-18.

2. His obituary, 'E.J. Willis' Rites Sunday. Gifted Engineer Dies At 'Pembroke', Aged 75' appeared in *News Leader*, Saturday, July 12, 1941, and in the same issue John Stuart Bryan, 'Edward J. Willis'. About the Willis family, and especially Edward's grandfather, Dr Francis T. Willis, see Annie M. Lane, 'Reminiscences of Days That Have Passed' in The Washington, Georgia, *Weekly News-Reporter*, March 8, 1929.

3. Hyman A. Schwartz, 'The Willis Planimeter' in *Rittenhouse*, **7** (1993), pp.60-63. See also Peggy Aldrich Kidwell, 'Planimeter' in *Instruments of Science: An Historical Encyclopedia,* R. Bud and D.J. Warner, eds., (London & New York, 1998), pp. 467-469.

4. See for example the review by Lieutenant Delwyn Hyatt USN in *United States Naval Institute Proceedings*, **62** (July 1936), no. 401, and Binnacle, 'An Engineer Looks at Navigation' in *Nautical Magazine*, **135** (1936), pp. 219-223.

5. 'Pembroke' in Henrico County, 'Haymont', 'Gatewood' and 'Bullock' in Caroline County, 'Farmington' in Hanover County and 'Powhite' in Chesterfield County.

6. Letter from Edward J. Willis, Richmond, April 25, 1940 to J.T. Holzbach, Superintendent of The Mariners' Museum. In Collection File NQ 32.

7. For an extensive explanation see the brochure "The Willis Navigating Machine", published by Edward J. Willis, Richmond, VA, 1930. It is also described and illustrated in Willis's 1935 edition of *The Methods of Modern Navigation*, mentioned above.

8. This letter and the original Weems-report, mentioned hereafter, are kept in The Mariners' Museum. In Collection File NQ 32.

9. An official biography on Weems is held by the Operational Archives Branch of the Naval Historical Center, Navy Yard, Washington, DC. See also G.D. Dunlap, 'The Grand Old Man of Navigation', *The Navigator*, **25** (1978), pp. 5-8.

10. Alex. Macdonald, 'The Willis Navigating Machine', *Nautical Magazine*, **127** (1932), pp. 220-225.

11. Letter from Edward J. Willis, Richmond, August 17th, 1936 to H.R. Calvert, Assistant Keeper, The Science Museum, London (inv. no. 1936-318). Prentice was described by Willis as 'Director of the British Astronomical Society in London', and probably is same person who in 1934 discovered Nova Hercules.

12. P.V.H. Weems, 'The Willis Altitude-Azimuth Instrument', *Nautical Magazine*, **135** (1936), pp. 356- 358.

13. Fred H. Hagner, 'Hagner Position Finder', *United States Naval Institute Proceedings*, **63** (1937), pp. 1277-1282. According to Cotter (note 1) p. 342, Hagner's machine was based on the 'Solarometer', an invention of Lieutenant Beehler USN, in 1895.

14. For these devices see Williams (note 1), pp. 121-123.

15. Letter from Edward J. Willis, Richmond, May 16, 1936 to Homer Ferguson, The Mariners' Museum. In Collection File NQ 32.

16. Illustrated in Jean Randier, *l'Instruments de la marine* (Paris, 1977), p. 110, no. 128.

17. Information kindly supplied by Nydia Cruz, Assistant Curator S.C. Williams Library, Stevens Institute of Technology, Hoboken, NJ, March 16, 1999.

18. Now kept in Collection file NQ 32 at the Mariner's Museum.

19. Information kindly supplied by Lindsey Weir, Archival Assistant University of Strathclyde, February 4, 1999.

20. Letter from Edward J. Willis, Richmond, April 15, 1940 to W. Graham Scott, The Mariners' Museum. In Collection File, NQ 32.

Also Seen:

A SELECTION OF PAPERS ON SCIENTIFIC INSTRUMENTS IN OTHER PUBLICATIONS

A paper by Ronald K. Reed ("A Berthoud Chronometer Carriage Clock", *National Ass'n of Watch and Clock Collectors Bulletin*, **41** (1999), p.605-610) describes a beautifully made carriage clock signed Berthoud. Many of you will recognize this name from the French chronometer maker of the 18th century who competed with Harrison and Berthoud's countryman, LeRoy to build the first workable marine chronometer. Although Berthoud had some success, Harrison won the big prize but Berthoud managed to develop some important innovations that found their way into later examples. The chronometer from a hundred years later and described by Reed has some unique features as well and these are ably described by the author. Several photos and diagrams show the quality of the novel piece. Reed also builds his case for attributing it to Auguste-Louis Berthoud, (1828-1910) probably a grandson of the much better known chronometer maker who had died in 1807. Reed also concludes that the piece was made ca. 1870 being one of perhaps 150 made over his 27 year career. Carriage clocks have always held a place