Deborah Warner

Celestial navigation aloft: aeronautical sextants in the US

'Failure in navigation is often as serious as failure in the power plant or plane itself.' So wrote Philip Van Horn Weems, a 1912 graduate of the US Naval Academy who devoted his remarkable talents and energies to the promotion of celestial navigation aloft. This chapter focuses on American efforts to develop one of these instruments: the sextant that navigators used to determine their locations. It is based, in large part, on the Weems papers and the aeronautical instrument collections in the Smithsonian Institution.[1] Many of these instruments were technically octants rather than sextants, but since the two terms were often used interchangeably, I will refer to them all as sextants.[2]

Interest in aeronavigational instruments arose with the demonstration of the military potential of aviation during the First World War, and built slowly in the 1920s. The introduction of commercial transoceanic flights in the mid-1930s, together with growing international unrest, led to increased attention to this technology. The military services purchased large numbers of air sextants in the early years of the Second World War, and again during the Cold War, as did commercial airlines in the postwar period. Some air sextants were used aboard ships at sea.

With a standard sextant, the observer looked through the eyepiece and brought the image of a celestial body into coincidence with the actual horizon; with the air sextant, the observer brought the celestial image into coincidence with an artificial horizon. Early celestial navigation aloft took place in open cockpits. The pressurised aeroplanes of the early 1940s had observation domes for navigational use. To eliminate the problems caused by these domes, periscopic instruments were introduced.

Russell's experiments

American experiments with celestial navigation aloft began in 1918 when the Princeton astronomer Henry Norris Russell spent several months at Langley Field, Virginia, testing aeronavigational instruments under the auspices of the Army Bureau of Aircraft Production.[3] Russell's best results came with a marine sextant, equipped with a bubble level mounted above the telescope tube, that belonged to Robert W Willson, a professor of astronomy at Harvard University. Willson had designed a bubble sextant of this sort for nautical use in the 1890s, and an improved version for aeronautical use in

1910.[4] These instruments were probably made by Brandis & Sons of Brooklyn, New York. In 1925, three years after Willson's death, his estate applied for a patent on his bubble sextant design. The patent was issued in 1929 and assigned to Brandis & Sons Inc.[5]

Russell also used an air sextant with a pendulum-type artificial horizon, probably of the sort that Ernst G Fischer, the long-time chief of the instrument division of the US Coast & Geodetic Survey, would patent in the early 1920s. Russell reported good results with this instrument, but others found the form too large, heavy and complicated for actual use.[6] Fischer also designed a rapid-release lever for a sextant's micrometer that remained in use for many years.[7]

Richard Evelyn Byrd

A third American design, promoted by Richard Evelyn Byrd, has the bubble level mounted on the sextant frame near the filters for the horizon glass, on the opposite side from the telescope. Byrd was a 1912 graduate of the Naval Academy who commanded two naval air stations in Nova Scotia in 1918 and who supported the Navy's plan to fly large aircraft across the Atlantic. In 1919, when assigned the task of procuring navigational instruments for the Navy-Curtiss flying boats that would travel from Long Island to England, Byrd chose sextants made according to his design (Figure 1).[8] Since Weems was Byrd's colleague and classmate, it is not surprising that he had an instrument made for this historic occasion.[9] Later examples of the Byrd sextant were equipped with a Fischer rapid-release lever, a tangent screw with a micrometer drum reading to half minutes, and electric light bulbs to illuminate the level and the scale.[10]

Byrd filed a patent application in June 1919 and approached Brandis about producing his instrument for sale.[11] Negotiations broke

*Figure 1 Three Navy-Curtiss flying boats took off from Rockaway, Long Island, in early May 1919. Three weeks later, after stops in Nova Scotia, Newfoundland, the Azores and Lisbon, the NC-4 landed in Plymouth, England, thereby becoming the first plane to fly across the Atlantic. Richard Evelyn Byrd designed the sextants for this important adventure, and this is one of those instruments. It is marked 'BRANDIS & SONS, BROOKLYN, N.Y.'. PV H Weems, Byrd's colleague and classmate, donated this sextant to the Smithsonian in 1963. It is housed in the Armed Forces Collection of the National Museum of American History (AF*59054-N). (Smithsonian Institution)*

off when the courts decided that Byrd had been scooped by Luis de Florez, a mechanical engineer who had graduated from MIT in 1912 and had organised the Navy's Division of Aircraft Instruments and Accessories during the war.[12] Undeterred by this legal setback, Byrd continued to claim credit for the design. In an article describing the preparations for the flight that Byrd and Floyd Bennett made over the North Pole in the spring of 1926, the *New York Times* reported that Byrd had 'invented the so-called "bubble sextant," an air navigation instrument based on the principle of the carpenter's level'. This instrument, the piece continued, 'enables the flyer to obtain an artificial horizon and to calculate his position while in flight, even if the actual horizon is not visible', and it 'has added greatly to the safety and success of flights over long-distances without the aid of landmarks'.[13]

The Brandis Model 206

The Pioneer Instrument Company acquired control of Brandis in 1922 and hired Victor Carbonara, a clever engineer from Italy. Carbonara realised that air navigators never measured angles greater than 90°, and so could use an octant rather than a sextant. And if the octant had a micrometer rather than a vernier, it could be reduced in size. Brandis introduced their first air octant (the Model 206) in 1925. This had a radius of 5¼ inches, and was equipped with a Willson bubble telescope, a Fischer rapid-release lever, a drum micrometer and electrical illumination for the bubble and the divided arc. Carbonara was understandably proud of his achievement. But, aware that air instruments were 'far from being perfect', he asked navigators to 'relate their experiences and offer constructive criticism'.[14]

The Army tested a Model 206 at McCook Field in 1926 and designated it their Model A.[15] The Navy tested another at the Naval Observatory and designated it their Mark I, Model 2. The Navy Bureau of Supplies and Accounts then published specifications for this instrument that were based on the prototype and asked for bids to produce 15 examples. Brandis were the only bidders.[16]

Captain G H Wilkins, leader of the Detroit Arctic Expedition in 1926, had two examples of the Model 206.[17] Press reports noted that this 'Pioneer Octant' enabled the location of an aeroplane to be 'ascertained within ten miles under practically all conditions' and that Wilkins and his aviator, C B Eielson, set a new record by flying 140 miles north of Point Barrow, Alaska.[18] Piero Bonelli carried a Model 206 in his attempted flight from New York to Rome in 1928, as did the Byrd Antarctic expedition in September 1929.[19]

Brandis's slightly revised Model 206B was known to the Navy as the Mark I, Model 3. Charles Colvin, the founder of the Pioneer Instrument Co., opined: 'We do not think for a minute that our present sextant is the best that can be made, but we do think it is the best now being made and the Bureau of Navigation, Navy Department, evidently agrees with us as they have standardized on it.'[20] There were actually two versions of this instrument. One was designed to be held in the right hand; the other was to be held in the left hand 'so as to leave the right hand free to write down the time and the observed altitude'.[21] A 1930 advertisement noted that: 'It is indeed amazing that nobody ever thought before of making a sextant for the left hand so as to avoid the necessity of putting down the instrument or changing hands every time an observation had to be noted. The change of design from right to left was first proposed four years ago by the Bureau of Aeronautics of the United States Navy, and it has now met with general approval.'[22]

The Model 206C, introduced in 1930, had the legs on the front of the frame so that the instrument could be set down with the handle uppermost, two coloured objective caps to reduce glare in daylight observations, and a radium illuminator for star observations. The Navy designated this the Mark I, Model 4 and arranged to purchase 100 examples.[23]

The DARAD sextant

Another bubble sextant – this one designed by Noel Davis and Lawrence Radford, and developed by Keuffel & Esser – had enclosed optics and an external divided scale, and was so constructed that the observer looked down into the eyepiece at an angle of about 45°. Noel Davis was a graduate of the Naval Academy who, after having received further degrees from the Navy's aeronautical school at Pensacola and from Harvard Law School, was put in charge of all naval reserve flying in 1922. He and Radford filed a patent application for their sextant in February 1927. Davis died two months later, having crashed the plane in which he hoped to make the first non-stop flight across the Atlantic, from New York to Paris, and which he hoped to navigate 'using a new sextant of his own invention'.[24] Keuffel & Esser received a Navy contract to produce a number of these instruments but asked for 'flight tests and service comments' before producing them all. By the end of 1927 Keuffel & Esser were advertising the 'DARAD SEXTANT for use with or without natural horizon, Patents Pending' that they made 'for the U.S. Army and Navy, for use in Aerial and Marine Navigation'. This instrument had a retail price of $550. The Navy Bureau of Aeronautics published a technical note on the DARAD (which it knew as the Mark II, Mod 1) in early 1928.[25]

Keuffel & Esser introduced a new version of the DARAD (Navy designation Mark II, Mod 2, and Army designation A-3) in 1929.[26] This was lighter and more compact than the original, and of improved optical quality. It was, however, tricky to build. 'As you know,' Keuffel & Esser informed the Navy, 'this is an entirely new design and it is not always possible to keep exact delivery dates when making a new instrument of this kind.' In March 1930 there were problems with the final adjustments of these instruments. In August the delivery of these instruments was 'delayed indefinitely'.[27] By 1932 Keuffel & Esser had introduced a new model (Navy designation Mark IV, Mod 1) that was more compact still, with the divided scale moved inside along with the optical train.[28]

The AIS improved sextant

The Aeronautical Instruments Section (AIS) of the National Bureau of Standards was established in 1918 and charged with collecting, evaluating and developing instruments for American use. By 1921 the AIS was said to be working on an 'improved aircraft sextant' that 'differs radically in form from the marine sextant'. This new instrument had a rotating mirror turned by a worm and wheel suitably graduated instead of the large divided scale used in marine sextants, a method of varying the size of the bubble to compensate for temperature changes, and electrical illumination of the bubble and scales for use in dark conditions.[29] Keuffel & Esser made the prototype.[30]

This AIS aircraft sextant was designed for the Navy's Bureau of Aeronautics and based, in large part, on the instruments that had been designed at the Royal Air Establishment (RAE) at Farnborough and used by the Royal Air Force.[31] Lionel Burton Booth and William Sidney Smith, both of the RAE, obtained a British patent for the British instrument in 1919, and Booth obtained an American patent in 1921.[32] Franklin L Hunt and Karl H Beij, both of the AIS, applied for a US patent for a similar instrument in 1921.[33] Hunt was a PhD physicist from MIT who had been sent to Europe in 1918 to examine and collect European instruments for the Bureau. Beij was a surveyor with a BS from Trinity College who would soon write a report on 'Astronomical methods in aerial navigation' for the National Advisory Committee on Aeronautics.[34]

The AIS began discussing their 'improved bubble sextant' in September 1923. Work was rushed in January 1924 as the Navy hoped to use this instrument for the polar flight of the *Shenandoah*, the first rigid helium airship built in the US. The sextant was delivered in July, but the *Shenandoah* was lost in a storm before the Arctic flight could occur.[35] The Smithsonian has two instruments of this sort, both marked 'BUBBLE SEXTANT / U.S. Navy / BUREAU OF STANDARDS / MODEL NO. 2 / 1924'. One (s/n 2) came from the Naval Observatory. The other (s/n 4) is shown in Figure 2 and came from Weems, who noted that he drew it 'from the storeroom in North Island, at the Naval Air Station, San Diego, and made numerous tests with it, along with Byrd, Lindbergh, Ellsworth, etc. etc.' Weems went on to say that this was one of six instruments made by the Bausch & Lomb Optical Co. in Rochester, New York, at a cost of $250 each,

*Figure 2 This bubble sextant was developed for the Navy by the Aeronautical Instrument Section of the National Bureau of Standards in 1924, and produced by the Bausch & Lomb Optical Co. (AF*59069-N). (Smithsonian Institution)*

and although Bausch & Lomb 'lost money on the deal', they 'naturally recuperated on later orders and on later models'. When Bausch & Lomb checked their figures several years later, they found that they had actually spent $650 apiece on these six sextants.[36]

Since the bubble was filled with a liquid hydrocarbon that tended to expand and contract with changes in temperature, Hunt and Beij patented a 'means for compensating for temperature changes affecting the leveling bubble'. Beij also patented an ergonomic version of the Bureau of Standards original that had filters to reduce the glare of sunlight and an electric light to provide illumination at night. These patents were issued to Hunt and Beij as individuals, but it was widely understood that they had been developed on government time, and thus government agencies could use them without paying royalties.[37]

Bausch & Lomb

In the late 1920s, having recently compiled his first star altitude curves that would simplify celestial navigation aloft, Weems was eager to assemble a package of related instruments and documents.[38] He favoured the Bureau of Standards bubble sextant, encouraged Bausch & Lomb to manufacture an improved model for commercial use, and convinced Charles Lindbergh and B F Mahoney (President of the firm that manufactured the *Spirit of St. Louis*) to join in the crusade.[39] In the mid-1930s, as the air sextant business began to look profitable, Bausch & Lomb signed a licence agreement with Hunt and Beij:

Bausch & Lomb would have exclusive rights to the three key patents, and the inventors would receive a royalty of 5 per cent of the net sales price.[40]

Bausch & Lomb brought out their Model B bubble sextant in 1929 and their Model C in 1930.[41] Weems helped design the Model C and described it as 'a good example of a modern instrument'. Lincoln Ellsworth thought it 'looks mighty crude to give such accurate results'. Lindbergh made good observations on his first attempt, noting that he could hold the sextant in one hand while piloting the plane with the other. Others were less enthusiastic. The Assistant Superintendent of the Naval Observatory reported that the Model B was 'being made with a view of getting it on the market, for commercial use', but was not being used by the Navy, and had been discarded by the Bureau of Aeronautics. The Observatory tested ten examples of the Model C and found them still wanting.[42]

The Model D of 1933 had a more stable bubble and a lower cost of manufacture. An improved method of bubble illumination and a built-in marking pad were introduced in 1937.[43] An improved bubble cell followed in 1938, and Bausch & Lomb deemed it 'the one outstanding virtue' of their sextants. Since this feature had caused them 'so much grief', they thought that 'it would be a hindrance rather than a help to deliberately offer the bubble element for use on any other make instrument'.[44] Edward F Flint, a Bausch & Lomb employee, patented bubble cells that were adjustable and temperature compensated in the early 1940s.[45]

The US Army began testing Bausch & Lomb bubble sextants around 1935, approved them for service use, and gave them the designation A-6.[46] Japan ordered 60 of these instruments in 1937 – a fact that Bausch & Lomb proudly advertised – and may have used some of them at Pearl Harbor.[47]

The Pioneer Instrument Co.

The Pioneer Instrument Co. joined the competition in 1931 with a compact and lightweight sextant designed in large part by Victor Carbonara (mentioned above in connection with Brandis).[48] This instrument had prisms rather than mirrors in its optical train. The bubble chamber was placed in the optical path and easily illuminated with ambient light. The dial was illuminated with radium paint, thus obviating the need for battery and electric light (the examples in Smithsonian storage are still 'hot'). The eyepiece was rotatable around the vertical axis, so that the navigator could easily take sights backwards as well as forwards. An astigmatiser elongated the image of the Sun, Moon or star, thus rendering observations more accurate. The unit cost was $350.[49]

Charles and Anne Lindbergh used a Pioneer sextant in 1933 when they flew the *Tingmissartoq* across and around the Atlantic, surveying air routes for Pan American Airways, and appreciated its 'compactness and mechanical construction'.[50] Fred Noonan used a similar instrument to navigate Pan American's *China Clipper* in 1935 and, although heavy cloud cover interfered with dead reckoning and drift observations, he was able to bring the airship from California to Honolulu 'within a short time of its scheduled arrival'.[51] He probably used it again when he navigated Amelia Earhart's ill-fated flight in 1937.

The Lindberghs reported that their instrument 'proved entirely satisfactory', except that 'the bubble element gave trouble'. Weems went on to say that 'the construction of a bubble element which will not leak has proved to be a problem for all bubble sextant manufacturers'.[52] Pioneer solved this problem by adopting a bubble similar to the one used in the Bureau of Standards instrument. As business increased, Bausch & Lomb argued that the design of Pioneer's bubble was covered by the Hunt and Beij patent, and forced Pioneer to pay royalties on all instruments sold for civilian use.[53] Pioneer also had access to the bubble patented by Richard Weniger of Brooklyn and assigned to the Bendix Aviation Corp., Pioneer's parent company.[54]

While civilian aviators captured media attention, military sales kept Pioneer in business. The Pioneer sextant received 'very favorable service comments' at an early date and Navy designation as the Mark III, Mod 1. This was soon followed by the Mark III, Mod 2 (Army designation A-5), the Mark III, Mod 3, the Mark III, Mod 4 and the Mark III, Mod 5 (Army designation A-7) in 1937 – these several iterations indicating a continuous effort to improve the instrument.[55] The civilian counterparts were advertised as small, rugged and highly accurate instruments that had been 'developed in collaboration with the United States Navy'.[56] As war approached and military demand increased, Pioneer reported that 'unexpected orders for unusually large quantities' meant that it could not quote delivery of instruments for civilian use 'of under six months'. The unit price at that time was $670.[57]

Developing the averager

The Pioneer Mark III, Mod 5 was not available to civilians 'without special permission from the Navy Department, inasmuch as it contains developments not common to sextants to be bought abroad or elsewhere'.[58] The development in question was undoubtedly an averager. By the mid-1930s, having discovered that the turbulence of the air and the unsteadiness of aircraft caused individual observations to be unreliable, aviators were routinely averaging several observations made in quick succession.[59] The next obvious step was to mechanise the process. Captain Julius Hellweg, Superintendent of the Naval Observatory, designed a mechanical averager for marine sextants, and Thomas L (Tommy) Thurlow, a creative, tenacious and fearless Army aviator, designed another for air sextants.[60] Weems was excited about the averager, deeming it 'extremely important' and seeing it as 'the next big advance in celestial navigation'. Thurlow's design, he said, 'saves the time, trouble, and possible errors in writing down each of several observations and then taking the average'.[61]

In May 1936, while arranging for a British edition of his *Air Navigation*, Weems mentioned Thurlow's work to Arthur J Hughes, the managing director of Henry Hughes & Son, the leading British firm manufacturing nautical and aeronautical instruments.[62] Hughes put his staff to work on the task and soon had a working model in hand. Years later, when Weems reminded Hughes that it was he who had suggested the averager to him, Hughes replied that this device 'cannot be traced to any particular individual'. Weems may have provided the spark, he said, but the heavy lifting was done 'in the Drawing Office and the factory'.[63] P F Everitt of Hughes filed an application for a British patent for the averager in August 1936, and another for an American patent on 2 August 1937.[64] Thurlow filed his American application on 3 August 1937.[65] After months of litigation, Thurlow conceded Everitt's priority and, with war on the horizon, Hughes agreed to give American manufacturers a free licence for instruments made for government use. S Smith & Sons, the British corporation that acquired Hughes' sextant patents in the postwar period, sued Bendix for patent infringement and received a judgment of $1,379,211 in 1956.[66]

Bausch & Lomb received an Army contract for an averaging sextant in early 1937: the model A-6-A was an A-6 equipped with a Thurlow averager that could handle eight consecutive readings.[67] Subsequent modifications led to the A-8 and A-8A, instruments that Bausch & Lomb produced in large numbers during the war.[68] In 1940, Bausch & Lomb obtained a licence from Fairchild (see below) to sell Thurlow averagers to civilian customers.[69]

The Army also provided funds so that Pioneer could equip their air sextant with a Thurlow averager. Thurlow received the first two examples in July 1938, just a few hours before he and Howard Hughes took off on their record-breaking flight around the world, and was able to 'obtain extremely accurate position fixes despite turbulent air'.[70]

Bausch & Lomb also produced an experimental model of the 'continuous integrating' averaging sextant designed by Captain Paul Gray of Pan American Airways. Charles L Bausch thought Gray's device 'may do a good job', but was 'too complicated' for actual use.[71] The same was true of the 'time and arc average recorder' that Weems proposed in 1938. Bausch opined that this 'complicated and delicate' mechanism would work 'if perfectly made' by 'a good custom mechanic with good clock-making experience', but it could not be manufactured at a reasonable cost.[72] There is no evidence that anything further became of either of these projects.

Bausch & Lomb's last air sextant was their model #61-90-04 (Army designation AN 5854-1 and Navy designation F.S.S.C. 88-S-375).

The firm donated an example to the Smithsonian in 1948, noting proudly that it had been 'patented and manufactured by them'.[73] Representatives from several aviation training commands conducted extensive tests with an instrument of this sort in September 1943 and recommended that it be 'considered for adoption as the standard sextant for the Army Air Forces'. It was rugged and compact, and easy to balance, and gave less trouble than any other sextant. It had an electric light for standard illumination and radium for low-intensity illumination. It also had a 15-shot median device that was simple and self-explanatory, and that offered 'a fool-proof visual average, which is easily understandable to the navigator'.[74]

The median device was a mechanism that determined the median rather than the arithmetical average of several observations. While the device itself was relatively simple, its origin is so complex that it is difficult to know who deserves credit for what. Weems and Thurlow were apparently inspired by an account of a French version published in 1938, and each man, working independently, worked out the details.[75] Bausch & Lomb made an example according to Weems' design and offered to apply for a patent in his name until a patent search revealed that Weems had been scooped by one Bart Diggins. Edwin Link thought that Weems' design resembled a device that had been suggested by an RAF officer named David Waghorn.[76]

As the US military was preparing for America's entry into the war, the Pioneer Instrument Division of Bendix Aviation (as the firm had become) made bubble sextants for the Navy and the Army. Both were modifications of the sextant that Pioneer had introduced in 1931. The Navy's Mark III, Mod 7 had a mechanism that averaged observations and the times at which they were made, and that had been designed by Lt Comdr Ira Hobbs of the Naval Aircraft Factory. The observations were recorded on a rotating cylinder covered with a pressure-sensitive paper.[77] The Mark III, Mod 7 also had a novel method of illuminating the bubble designed by Gregory Rylsky, an engineer employed by Pioneer.[78] The Mark IV, which followed in 1941, was similar in most respects.[79]

The Army's A-7 had a simple finger-activated pencil that made vertical marks on a piece of roughened grey paper. After a series of shots, these marks would be visually averaged and the average time of the series determined from a stopwatch.[80] Pioneer/Bendix received a contract worth $1,068,000 to make 2400 A-7s in January 1942.[81] By September the Army was boasting that an experienced navigator using an instrument of this sort could 'set his plane down at the end of a transoceanic flight within an error radius of only 15 miles, less than four minutes' flying time'.[82]

The AN 5851 (Army designation A-14, Navy designation Mark V), which followed in 1942, had a successful mechanical device that averaged 60 discrete altitude readings taken over a period of two minutes. The AN 5851-1 (Army designation A-15) was essentially similar, but could obtain average readings for any period of time up to two minutes. These instruments were heavy, and so were designed to be suspended from an arm installed in the centre of the astrodome. Many were still in use in the 1960s. Production was begun by Pioneer/ Bendix and continued by the Eclipse-Pioneer Division of the Bendix Aviation Corporation (as the firm then was).[83]

The Fairchild Aerial Camera Corporation

The same day in 1937 that Thurlow filed a patent application for his averager, he and his colleague Samuel M Burka filed another describing an optical system for an indirect-sighting bubble sextant that was 'more compact' than 'those heretofore employed'.[84] The Fairchild Aerial Camera Corporation acquired the rights to this instrument, 'lock, stock and barrel', and went after it 'in a big way'. Thurlow noted that 'Simplicity and ruggedness, small size, optical characteristics, and the averaging device (vernier type)' were the key features of the new design. Moreover, with the elimination of the precision worm, 'factory run machine work and optics may be used'.[85]

Weems visited the Fairchild factory in January 1938, had 'a good look' at the new sextant, and 'placed an order for the first commercial instrument they build for sale'.[86] Although Fairchild was a well-established firm that manufactured various technical devices, this instrument presented numerous unforeseen challenges. Thurlow reported in February 1940 that 'Fairchild had let him down and are starting all over again to design another sextant,' and later that 'Fairchild has made a perfectly atrocious mess of the sextant.'[87] By July 1941, however, he was sufficiently pleased with the new instrument to recommend Army designation.[88] The A-10, as this instrument was known, was actually a median sextant. The navigator pushed a plunger whenever he made a shot, making a series of marks on a white plastic disc. At the end of a series of shots, the disc would be removed and the median determined by eye.[89] The A-10-A (Figure 3) had an electrically operated timer such that observation marks were made once a second as long as the navigator held down the trigger. The Air Force was still using this instrument in the late 1950s.[90]

In March 1942, the Army signed a contract worth $2,682,618 under which Fairchild would produce some 8984 sextants, with a like number of adjustable bubble-chamber assemblies. The number represented the largest number of instruments that Fairchild could produce by the end of 1943. Since more air sextants were needed, the Army signed a similar contract with the Agfa-Ansco Division of General Aniline & Film Corp. in Binghamton, New York; this contract was worth $2,259,625 and included a $7500 payment to Fairchild for 'flow charts, material, specifications, bills of material, engineering aid, etc.'[91]

*Figure 3 The A-10-A bubble sextant was made for the US Army Air Forces in 1944 by the Fairchild Camera and Instrument Corporation. The navigator would push the plunger while making a shot, thus making a mark on the white plastic disc (AF*59062-N). (Smithsonian Institution)*

A third Army contract, this one with the Polarizing Instrument Co. in New York City, came to $2,289,890; the unit cost of these A-10 sextants was $201.03 (plus $23.96 apiece for jigs, dies, fixtures, etc.). Since no instruments bearing the name of this firm seem to have survived, they may never have been produced, or they may have been produced and sold under Fairchild's name.[92]

Although the A-10 was a fairly simple instrument, and although the Army established fine training facilities for pilots and navigators, personal attention was required. The Army informed Fairchild in June 1943 that navigators who met directly with Fairchild representatives 'were "sold" on the A-10 and therefore had the necessary confidence in it for successful operation'. But where the representatives did not visit, the navigators 'were not sure' they could rely on the instrument. That same summer, Fairchild conducted, at its own expense, a series of week-long courses covering the maintenance and repair of the A-10.[93]

Link Aviation Devices

Another army contract, this one with Link Aviation Devices in Binghamton, New York, covered the purchase of 6130 'Sextants, Spare Parts and Data' for a total cost of $1,115,387. The instruments in question were the A-11 and A-12 bubble sextants. The two were essentially identical, but the former was a single-shot instrument designed for training purposes, while the latter was a multi-shot instrument with a median device.[94] Theodore 'Dutch' Van Kirk, the navigator of the *Enola Gay*, used an A-12 on the long flight across the Pacific Ocean and back in August 1945.[95]

The story of these instruments began in April 1938, when Weems asked Edwin A Link to develop an inexpensive bubble sextant suitable for student use. Since the Army had recently issued an order for more than $26,000-worth of his Star Altitude Curves, Weems expected 'a big spurt in the celestial navigation business'.[96] In a letter to Thurlow, Weems said that if Link 'starts out to make an instrument at a low price, he might actually have an instrument that would be not only low-priced but good. It would probably not be quite as complete so far as averaging devices are concerned; on the other hand, I believe it would be a wonderful thing for fast training of navigators.' Moreover, Link 'is not only ethical but financially responsible, as well as being of mechanical genius'.[97]

Link was soon doing 'a large amount of playing around with a sextant under various conditions'. After finding that 'the main factor in getting good results is to take a large amount of observations very quickly', he made sketches of an averager and asked his attorney to search for patents describing instruments of this sort. On his next trip to London, Link 'met Mr. Henry Hughes on several occasions [...] and had some very interesting conversations with him'.[98] Since Hughes was the chief executive of Henry Hughes & Son, the subject of averagers must have come up. In the end, however, the Army asked Link to produce 'median sextants'.[99]

The basic form of the Link sextants was suggested by Edgar J Lesher, an assistant professor of aeronautical engineering at Texas A&M University. Lesher had sent an example of his 'new low-priced' instrument to Weems in early 1939, noting that he did not have a patent on the form, but he was sure that Weems and Link would treat him fairly.[100] Link planned to have these instruments manufactured by W & L E Gurley, an old line mathematical-instrument firm, and sell for under $100. When Gurley proved unable to do the job, Link began production in house. By November 1940, Thurlow had run the Link sextant through a number of tests and was considering putting through specifications for 500 examples.[101]

When production took longer than expected, Link and his colleagues redesigned the instrument so that it could be 'comfortably held without unnecessary strain' and easily serviced, even by the user.[102] The frame was made of aluminium and the recording drum was formed of a white plastic made by Plaskon.[103] The first examples of this new model were made in April 1941. In June these sextants were 'nearly in production'. In late August Link had 'hundreds of sextants about ready to go out, but as can be expected, there have been some manufacturing difficulties encountered when they are first put in production'. Over 600 sextants were 'nearly completed' in early October, but 'held up for one thing or another'. By the end of the month, production was under way. In mid-December, shortly after America's entry into the war, Link reported that 'the Air Corps has urgently requested that we send them every available sextant, as they have a shortage of sextants right now and need them for use on bombers'. By June 1942 Link was building sextants 'at the rate of 25 a day'. By October they were building 'several hundred units per week'. Five months later, however, Link were considering cutting their sextant production in half, as 'the government has brought in three or four other manufacturers, also building sextants, and does not have the demand for all the sextants they now have on order'. At this point, Link requested permission to obtain the necessary materials to produce air sextants for customers who were not affiliated with either the Army or the Navy but who, nonetheless, intended to use these instruments 'in connection with the war effort'. A new A-12 cost $262 in December 1941. By the fall of 1945, it was considered war-surplus, and available at deeply discounted prices.[104]

Not content to let well enough alone, Link patented and produced a horizon attachment for use with a bubble sextant that enabled the navigator to view the real horizon.[105] This design seems to have been technically successful, but it could not staunch the rapid decrease in military demand for air sextants.

Scattered evidence suggests that several other designs were developed on military contracts in the early years of the war. Link made a bubble sextant 'of the student type of design' that had 'three identical sealed tubes, the differing periods being obtained by the use of different liquids,' and could be 'read to the nearest minute of arc'.[106] Pioneer received a contract worth $6250 to develop an averaging sextant with 'a horizontal line of sight and incorporating a liquid-wedge type of horizontal reference'.[107]

With a pressurised cabin and an astrodome, navigators could take observations in safety and comfort. The downside was the necessity for a dome refraction correction to the calculations, and the fact that the astrodome interfered with the streamlining of the plane and was always in danger of blowing out.[108] Recognising that a periscope would eliminate these problems, Thurlow, Burka and another colleague patented a periscopic sextant in 1941.[109] Soon thereafter, the Army signed a $5940 research and development contract with Fairchild for a periscopic bubble sextant 'for experimental tests in comparison with similar instruments manufactured by Bendix'.[110] None of these instruments saw much service, if any, during the war. Similar work was done in Britain, and these sextants went into production in the late 1940s.[111]

The Kollsman Instrument Company

The Kollsman Instrument Company dominated the air sextant field from the late 1940s until the introduction of GPS in the 1980s made sextants all but obsolete. They made hand-held and periscopic instruments, some with pendulous-mirror artificial horizons and others with bubbles. Paul Kollsman was an immigrant engineer from Germany who worked briefly for the Pioneer Instrument Co., established his own firm in Brooklyn in 1928, and enticed Victor Carbonara and Charles Colvin of Pioneer to join this endeavour.[112] The firm became the Kollsman Instrument Division of Square D Co. in 1940, and the Kollsman Instrument Corporation a decade later.

Carbonara informed Weems in October 1935 that Kollsman had developed an averaging device for air sextants that 'is well on the way of being "a fait accompli"', and Bausch & Lomb understood that Kollsman was preparing to market an instrument that would 'embody a bubble cell similar to ours'.[113] As it happened, however, Kollsman did not produce any such instruments at that time. The historian Monte Wright believed that Kollsman found the engineering problems 'more perplexing than anticipated'.[114]

Kollsman introduced their first aircraft sextant in 1948, noting proudly that both Pan American Airways and KLM had installed these instruments in their transoceanic planes.[115] This instrument used a pendulous mirror and a periscopic mount designed by Carbonara.[116] It also had an integrator that produced a continuous moving average over any observation period up to two minutes.[117] This was based on the 'ball integrator' that had been patented by Richard Deimel and William A Black, and assigned to the General Time Instrument Corp. Deimal was a professor of mechanical engineering at the Stevens Institute of Technology who, during the war, was a consultant to Sperry Gyroscope and to Fairchild Aviation, and director of research at the General Time Instrument Corp. His co-inventor has not been further identified.[118]

Air sextants with gyroscopes

To round out this story, mention should be made of the air sextants that used a gyroscope as an artificial horizon. The French had been experimenting with instruments of this sort since the 1880s. The US Army adopted a gyroscopic instrument in 1922, designating it the A-1. The Sperry Gyroscope Company introduced another version in 1933.[119] The Navy joined the hunt in 1935, informing several instrument companies that they were interested in 'the possibility of developing a gyroscopic sextant for aircraft use'.[120] Navy Captain Harry Connor, the second navigator on the Hughes round-the-world flight in 1938, opined that the 'greatest single needed improvement is a gyroscopically stabilized octant'. An instrument of this sort, he said, 'will enable navigators to take accurate sights in rough air. And it won't be a simple job, either, to develop such a device. But it will be done soon, mark my words.'[121] Connor clearly understood the difficulty of developing such an instrument, but he was overly optimistic. The Pioneer Instrument Company had an Army contract to produce a 'Panoramic Sextant, gyro bubble type' in 1942.[122]

Summary and conclusions

Celestial navigation aloft was never a high military priority, but military demand was a key factor driving development and production of these instruments. This demand began in the First World War, and rose steadily in the interwar years. During this period, when the technology was not yet of critical importance, the military provided the steady employment and other resources with which talented innovators could develop new ideas, test the instruments as they became available, and provide feedback that contributed to their redesign.

The air sextants business in the 1930s might be seen as a vicious circle: small demand inhibiting the easy availability that might build a greater demand. When Weems told Bausch & Lomb about orders trickling in, the firm mentioned the 'prohibitive cost' of batch production. And when Weems asked Bausch & Lomb to make these instruments in batches of 50 to 100, the firm was reluctant to tie up the resources needed to maintain such a large inventory. In early 1940, despite orders in hand for 39 air sextants, Bausch & Lomb would not start production until they received a large order from the War Department.[123]

As the American military began gearing up for the Second World War, it faced the challenge of obtaining suitable instruments in sufficient quantities. In March 1941, nine months before Pearl Harbor, the military established specifications for, and began encouraging the manufacture of, small and lightweight air sextants equipped with an averager or a median device.[124] When Bausch & Lomb and Pioneer could not meet the demand, other firms were encouraged to enter the field. And when production was still behind schedule, the Air Inspector of the Army conducted an investigation 'with the idea of improving conditions in any way possible to expedite the delivery of these items of equipment very badly needed'.[125] To further improve the situation, a military navigation conference held at Fort Worth in May 1943 recommended the standardisation of sextants and listed the features desired.[126] The firms that manufactured air sextants for the military probably made money on these deals, but found themselves with unwanted equipment and excess inventory as the war drew to a close.

Major technological breakthroughs might make good stories, but the false leads and incremental developments of the air sextant better represent the norm. Moreover, while design changes in a mature technology often reflect attempts to hasten the obsolescence of otherwise still useful items, design changes in an evolving technology often reflect honest efforts to improve the product. Improvement is clearly a slippery concept, unless suitably circumscribed. The users of air sextants were especially concerned with accuracy and ease of handling. In this regard, the reliable and ergonomically satisfactory Bausch & Lomb and Pioneer instruments of the mid-1930s were clearly better than the clunky and error-prone instruments of the 1920s. The Army recognised that the quality of an air sextant was best judged by its actual performance. To this end, navigators were given sextants at the start of their training and expected to 'become familiar with their personal instruments through extensive use'.[127] Cost may have been a factor for student navigators, but for the military and for commercial airlines with transoceanic routes, the cost was trivial compared with the value of the aircraft, crew, armaments, cargo and passengers that the instrument was designed to protect. Finally, since ease of manufacture affected the bottom line, manufacturers struggled to design sextants that did not demand the special skills of a precision instrument maker.

Developmental challenges occurred in the process of manufacture as well as in the basic design. Edwin Link clearly understood the long hard slog that often separated clever ideas from reliable products: 'In my experience with inventions, which has covered a considerable number of years,' he said, 'I have found that there is a lot to be done between making something which just about works and possibly not too successfully, and getting something to work in a successful manner, and have found many inventions that have had to be abandoned due to this intermediate stage.'[128]

The air sextant story raises questions about the national identity of a rapidly evolving technology. How can this be defined when innovators from different countries are in frequent contact with one another, when inventors secure patents in several countries, and when the rights to these patents are cross-licensed? Another question concerns consequences that might have been anticipated. Why, for instance, were Bausch & Lomb eager to sell sextants to Japan in the late 1930s, and why did Weems extol the 'obvious efficiency of the Japanese night bombers, the Italian military flyers, etc.'?[129] Yet another concerns technological obsolescence. Aircraft sextants were always used in conjunction with compasses, ground-speed and drift meters, altimeters, calculators, radio and, eventually, other electronic aids, and the development of these several navigational technologies progressed at about the same pace. Thus, as the aircraft sextant improved, it became increasingly irrelevant.

One final issue concerns memory, and the efforts that some people make to ensure a favourable remembrance of some achievements. Weems, who organised his papers and donated his instruments to the Smithsonian so that historians would have the materials needed to tell the story of celestial navigation aloft, must clearly be seen in this light. So too must the American Institute of Navigation, which offers a Thurlow Award for contributions to the science of navigation. Weems received the Thurlow Award in 1955. Samuel Burka, who received it in 1957, was honoured as a PhD physicist who 'devoted a long and distinguished career' in the Air Corps to the 'research and development of air navigation equipment'.[130] The Institute of Navigation also gives a Burka Award for contributions to the advancement of navigation and space guidance, and a Weems award for individuals making continuing contributions to the advancement of navigation over a period of years.

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