

A Christmas Story about Celestial Navigation - December, 2007

Celestial Navigation; the end of a long era

Who knows when men first looked to the stars as an aid to guiding ships across seas? The ancient Polynesians did not keep records but they must have memorized star patterns to guide their twin-hulled canoes across thousands of miles of the Pacific to make repeated voyages to Hawaii about 500 A.D. It was not until the Portuguese found a way to determine latitude, by measuring the angular height of the sun at its zenith at midday, in the early 1500s that celestial navigation began to develop into a science. The solution for finding longitude had to wait for another 250 years. It was about 1765 before a small portable timepiece (a chronometer) was invented that could hold its accuracy for a long sea voyage. Accurate time and mathematics had finally solved the longitude problem. Celestial navigation remained the mainstay of seafarers for another two hundred years. This science was adapted to aircraft in the 1920s and 30s, further refined in the mid-20th century and was the primary method to navigate aircraft on ocean crossings and remote regions of the planet. Advanced electronics such as Inertial Navigation and Radar systems began to replace celestial navigation in the 1960's. Finally, by the end of the 1980s, the Global Positioning System (GPS), based on orbiting satellites, ended 500 years of reliance on celestial navigation. GPS can be used by almost anyone with a rudimentary knowledge of chart reading and dead reckoning. It is very fast and locates the ship or aircraft accurately within a few feet. It is inexpensive and hand held backups can be carried. These advanced electronics systems are automated and eliminate the need for a crew navigator.

A description of Celestial Navigation could fill a book but I'll attempt to outline the major aspects. It is the skill to determine one's position by sighting the stars or major planets at night or the sun and moon in daytime. There are 22 primary navigation stars (usually the brightest ones) but many additional stars can be used. Essential materials are the chart and plotting equipment, books of detailed tables printed by the Navy's Hydrographic Office, a sextant and an accurate watch (chronometer). Accurate time is essential because an error of 4 seconds of time is equivalent to one nautical mile of distance. A sextant is an optically precise instrument used to measure a star's angular height above the horizon in degrees and seconds of arc. Transoceanic transport aircraft, beginning with the Clipper types of the 1930's, were equipped with an astrodome, or Plexiglas bubble, on the upper surface of the fuselage through which the sextant sightings were taken. Experienced navigators knew the planets, the major constellations, the 22 primary stars and many more. When pressurized aircraft came on the scene in the 1940's, a mounting device which accommodated a "periscopic" sextant was designed into the fuselage instead of an astrodome. Aircraft navigators do not need to sight the horizon while observing a celestial body. Instead, the sextant has a leveling "bubble" which is optically arranged so that the star is superimposed in the bubble's center when the star's angle is measured correctly.

One sighting, together with the data required for a solution, produces a "line of position" or LOP. The navigator's position is located somewhere on that LOP. Another sighting on a different star, or an LOP derived from some non-celestial source, "fixes" the position at the point where the two LOPs cross. An LOP obtained from a star is plotted at right angles from the direction of the star. For instance, if you sight a star off to the right or left of the aircraft's axis then you will obtain an LOP parallel to your direction of movement. Such sightings are said to be "course checks". If you sight a star dead ahead or behind the tail you will obtain an LOP at right angles to your direction of movement. These sightings are "speed checks". An aircraft is not a stationary platform, often flying in rough air, so an aerial sextant sighting is usually measured over a two minute period with the measurement taken from the sextant's averaging mechanism. The time of the sighting is one minute after the sighting has begun. At night, the navigator selects three stars, roughly about 120 degrees apart in direction (azimuth), then picks the center of the triangle produced by the three plotted LOP's as the "fix". Aircraft move fast. Even the aircraft of the mid-1940s moved an average of about 3 nautical miles per minute. The first sighting advanced and the third sighting was retarded to the time of the second sighting. For daytime celestial, the sun is the only celestial body available much of the time although the moon is available at least 50% of daytime. The

planet Venus was available almost 25% of daytime. Venus could only be used if the sky above was cloudless and the planet was far enough from the sun. During morning and evening twilight the bright planets, Venus, Jupiter, Mars and Saturn, the brightest stars like Sirius and Canopus, and the moon when available, were used especially in high latitudes where twilight lingers for hours. No celestial was possible if the aircraft was in cloud or the sky above was overcast. This happened less often in the more advanced aircraft of the 50's which flew higher and topped more weather.

Navigators could determine the direction they were headed using celestial. Before the periscopic sextant they used a device called an astrocompass mounted in the astrodome.. In aircraft equipped with a periscopic sextant, the true heading was read on an azimuth scale while sighting a known star. Using these methods, navigators could check the accuracy of the aircraft's compass.

Celestial navigation was prone to human error. If the navigator was inexperienced or in a hurry, then he could make errors because the solution to each sighting involved extracting data from the tables plus several steps and calculations. He could sight the wrong star, use the sextant improperly, extract data from the wrong tables, use the wrong time or day, plot the LOP erroneously, make arithmetic errors or a host of other missteps. As the navigator gained experience and confidence and became master of his trade, he seemed to be "less busy", much less in a hurry and tracked the aircraft with modest effort. Modern GPS locates the holder within a few feet but "accurate" aerial navigation over the oceans in the 1950s was within about 10 miles and within 25 was acceptable. Shipboard celestial navigation was more accurate because the sightings are more accurate with a shipboard type of sextant. The slow movement of the ship gave the navigator much more time to eliminate errors. However, weather prevented shipboard celestial observations more often than in aircraft.

The way it was: The China Clippers

It's late September, 1939, a month past your 40th birthday. You are a passenger on Pan American Airlines China Clipper enroute to your newly assigned diplomatic post in Manila. You are on the last leg from Guam to Manila. After takeoff from San Francisco Bay and the 15 hour flight to Hawaii, your 35 fellow passengers and 8 crewmembers rested at the Royal Hawaiian in Waikiki. Next, the Clipper took 7 and ½ hours to fly to Midway Island. Two hours after touching down on the lagoon, the big seaplane was "on the step" with its four Wright "whirlwinds" at full throttle. It lifted off and the captain pointed its nose toward Wake Island. Seven hours later you were docked at the tiny spot in mid-Pacific and resting at the new Pan Am transient hotel. Another 9 hour flight put you on Guam, arriving at 1800 local. Then you were awakened at 5 a.m. for a 8 a.m. departure.

You checked your watch when the Clipper broke from the surface at Agana harbor. It was 0818 local. Light tailwinds were expected, the stewardess said, when she explained that flight time was forecast to be 8 and ½ hours to Manila for the 1,300 nautical mile flight. That was five hours ago and you wanted to visit the flight deck one last time. You had been forward several times in the last 4 days and had gotten to know the aircrew's first names. Most of all, you wanted to observe the navigator, especially since you had experience traveling on ships. After checking with the stewardess, you walked up the aisle and through the open door to the flight deck. The Boeing 317's flight deck was expansive. Only one pilot manned the cockpit, the other must be resting in the crew's closed sleeping compartment at the rear of the flight deck. The radio operator, seated on your left, is receiving weather reports. He is copying and sending Morse code. His fingers were a blur as he keyed an outgoing message at about 20 words per minute. A small group of instruments above the navigator's desk revealed that cruising altitude was 6,000 feet and indicated airspeed was 140 knots. The navigator had explained to you on the flight from Midway to Wake that this works out to be about 155 knots true, the seaplane's normal cruising speed. The navigator is taking a sun sight, his right eye peering through a sextant in the astrodome. You had watched him work several times on this trip and knew by now that he was taking a series of sights in rapid succession for 30 seconds and averaging them. Pan Am navigators used a state of the art sextant but

many more improvements would be made later in World War II. He stepped off his foot high stool, checking his chronometer simultaneously, subtracted 15 seconds, the time at the middle of the series, then wrote the time of the sighting on his celestial solution form: 2120 and 18 seconds (Greenwich time). His plotting chart was spread out over a desk that was at least 4 feet wide.

“Good Morning Sir”, he said.

You looked at your watch which was still on Guam time. It read 1:22 p.m. “Good afternoon Hank”, you replied, displaying your watch. However, Hank was right, it was still morning. You should have noticed that, with the airplane headed due west, Hank had been facing about midway between the left wing and the tail while sighting the sun. In other words, facing southeast, which meant that it was before noon in the northern hemisphere. Hank was an experienced navigator having worked for Pan Am since the South American flights in the early 30’s and was in on the initial survey flights in the Pacific in 1937. He took the time to explain some of his celestial navigation skills. “The sun’s direction from us will change rapidly while it is crossing our meridian around the time of local noon. This gives us a way to fix our position better”.

“Do you mean the sun’s direction changes rapidly at noon everywhere Hank”?

“It changes faster if you are in the lower latitudes - near the equator. Today we are about 14 degrees north latitude and it’s September 30th so the sun’s declination is about 3 degrees south. That means we are only 17 degrees from the sun (zenith distance) and that is close enough so that the sun’s direction from us is changing rapidly near noon.” Several minutes had passed since Hank had taken the sun sighting and he kept checking his watch. He said, “time for the noon sighting,” then again mounted the stool with sextant in hand, hung the sextant from a hook at the top of the astrodome and lined up the sun through the eyepiece.. He pressed on the sextant’s trigger several times during the series. The aircraft was not smooth and steady like the first sighting so Hank extended the series to one minute. He was facing off the left wing instead of behind the left wing as he had before. Hank stepped down, read the sextant’s averaging mechanism, subtracted 30 seconds from the end time and recorded data on his form. He plotted both sun LOPs, advancing the first one to the noon sighting. Hank went thru this routine again several minutes later. This time he was facing between the left wing and the nose. After climbing down from the astrodome, recording data and filling out the solution form for the 3rd time, he retarded the last sighting to the noon sighting, then plotted it. The first and third LOPs cut the noon LOP each by about a 35 degree angle, in opposite directions, and about 70 degrees with each other. Hank selected the center of this triangle which was about 10 miles on each side - a good quality fix. He then used dead reckoning from this fix to project the 2200 Greenwich position. He wrote this position on a note and handed it to the radio operator. The radio operator began sending this in Morse code but when finished he copied a message from the Pan Am operator at Manila of general interest to the passengers and crew: ***German and Russian armies have now occupied all of Poland. Polish organized resistance has collapsed. Exiled Polish government flees to Paris.***

You returned to your seat and relaxed while the stewardess served lunch of pineapple salad, scones and a choice of coffee or tea. As she did before every meal, the stewardess placed a white linen tablecloth on each passenger’s auxiliary tray. You had crossed the Pacific by ship and it had taken well over three weeks. This was your first airplane flight. It seemed almost impossible to span the Pacific in only 4 days. Hank had called his recent celestial work a “local apparent noon” fix. You were impressed. About half the passengers were going on to Hong Kong but when the pilot sighted the first Philippine Island, the stewardess served champagne. Everyone joined in to celebrate the successful crossing.

[The way it was: Crossing the North Atlantic](#)

Its mid-October, 1944 and you are an Army Air Corps navigator on the crew of a new Douglas C-54 (military version of the DC-4) returning from a supply run to Casablanca in French Morocco. You made a refueling stop at Lajes AFB, Azores, and are enroute to Harmon AFB, Newfoundland. You have limited experience. This is only your second round trip across the Atlantic after being designated an aerial navigator and 2nd lieutenant. Your training had been brief and the only celestial instruction you have

received was classroom work, using a sextant to sight the stars from the ground on the base, plus one 4 hour flight in a Twin Beech with three other student navigators. You took only one star sighting on that training flight and you never could get the LOP to fall on the chart, even after returning to the base in the quiet of your quarters. This was a letdown because you had used the latest aircraft sextant which was supposed to be more precise and incorporated a two minute averaging mechanism. This new sextant had been distributed to all long range military aircraft squadrons recently. You had imagined that, equipped with this precise instrument you would quickly master celestial navigation. However, this was World War II and air crew members were trained hastily. There were not enough navigators for the B-17s, B-24s and B-29s so you were on your own. You had actually gained more experience than you gave yourself credit for but the weather had been good on your ocean crossings so far. This flight was different. After almost 5 hours enroute you had not obtained an LOP that you trusted. Your C-54 had taken off from the Azores base about 1500 local (1700 Greenwich) on a 9 hour, 15 minute forecast time for the 1,500 mile flight to Harmon AFB with an acceptable weather forecast. Unknown to you and your pilot, however, bad weather would be trouble. Weather reporting in 1944 was nowhere near what it is in 2007. The last tropical storm of the season had missed the USA and was moving undetected northeast into the North Atlantic. Winds aloft were strong. Ships were now reporting the storm's effects but these reports were way too late for the forecaster at Lajes when you planned the flight. You now know the weather forecast was wrong because the C-54 encountered weather soon after you leveled off at 8,000 feet.

You lack confidence in your work. On previous flights, at no time did you go more than two hours without seeing the sky. You gained some confidence in your celestial navigation ability but you had made just about every mistake possible and expected to make more. You had tried to match the celestial data tables with the wrong star, made mathematical errors including subtracted when you should have added and vice versa, looked in the celestial data under the wrong latitude and even picked the wrong Greenwich date out of the Air Almanac. You did not have to explain your errors to the pilot in detail because he could not have understood them but he sensed that you were on shaky ground. In the C-54 you sat very close to the cockpit and, though he was not a navigator, he was not dumb. He observed that you were "too busy". Your plotting chart was usually under stacks of paper forms, celestial data books and general debris. Like you though, he was very young, about 23, and at that age he was fearless.

For the first hour after level off at 8,000 you could see the ocean through the driftsight. You lined up the grid just the way they taught you in nav school. Drift was more than predicted, about 12 degrees right instead of 3 right as planned. You altered heading to the left to correct but one hour later a cloud layer slid in under you and you could no longer see the whitecaps on the surface. Just before the surface was obscured, the drift had increased to 15 degrees and you corrected for that. You had no way to measure ground speed because you were under an overcast and could not see the sun. About 3 hours after level off darkness fell then you saw the moon thru a thin cloud layer above but no stars. You had not run into this situation or taken a moon sighting. Would it be okay to use the moon like that? Would a partial cloud layer distort the sighting? Nobody had offered anything on that at nav school. You decided to take a sighting and worry about the details later. When you looked through the sextant it was a half-moon positioned at a cocked angle. Intuitively you knew that you must "imagine" the center and aim for that so you did. Luckily you had a special form in your kit that reminded you of the parallax correction which only applies to moon sightings. You wanted to check on your ground speed for the first time since taking off but the moon was off your left wing and the LOP fell nearly parallel to your course. Furthermore, even though you had corrected heading to the left because of increased right drift, the moon LOP fell parallel to and about 50 miles to the right of planned course. You would have to correct your heading even further left. Did you have the confidence to do that? You rechecked your moon sighting data solution, making sure that there were no errors in time, data extraction from the tables, no math errors, even checked the sextant to see if you had made a mistake reading it. No errors but the pilot was getting nervous, four hours with no celestial fix, no drift, no nothing. You hunkered down, told him that all you had was one moon sighting and recommended that he alter heading to the left five more degrees. He looked at the flight plan and noted you were already more than 10 degrees left of planned heading and hesitated. He detected a lack of confidence in your voice and did not correct heading until you explained

what you had done.

Another hour had gone by since the moon sighting. The weather was worse, temperatures dropped and ice began to form on the props and wings. The C-54 bounced around some and St Elmo's fire streaked across the windshield, formed an eerie blue pattern circling each prop tip and snaked around the astrodome. The pilot had all the deicers turned on and had to add power to maintain airspeed. Within ten minutes he increased from cruise to climb power but airspeed dropped from 155 to 130 knots indicated. The C-54's fuel flow meters indicated that it was going through gasoline at twice the planned consumption rate!!

The C-54 was equipped with a new system of electronic navigation. It was called LORAN, acronym for Long Range Navigation. You had turned it on some time ago and you now scanned its cathode ray tube for signals. They had spent only an hour on LORAN during your training at Randolph AFB because it had just become operational a few months ago and none of the instructors had used it. It had been of no use between the Azores and Morocco because there were no stations. Even the first part of this flight was out of range of the stations but now you were close enough to receive them. You had tried to teach yourself about it by reading manuals and checking the equipment when you had gone eastbound on this trip but you were still mystified. You were beginning to understand it so you managed to receive station 1L3 but as near as you could tell the LORAN LOP that you plotted from it was nearly parallel to your course. It showed that you were tracking just to the right of planned course. This made you more confident of the heading corrections that you had given the pilot but you were still desperate for a check on ground speed.

Five and one half hours after take off, with indicated airspeed down to 125 knots, the throttles all the way forward, prop revolutions increased to 2,550 RPM, all forward facing surfaces coated with rime ice, the C-54 hit a couple of strong updrafts then popped out between layers in clear air. The night sky ahead blazed with stars.

You wasted no time taking two minute averaging sights on Vega, Aldeberan and Rigel Kentaurus as fast as you could write down the data and get the sextant ready for the next star. While you were doing the celestial work, the pilot was anxious to know his position and asked you for information before you were ready. It takes 6 minutes of sextant time to sight the stars for a 3-star fix. At least one minute between sightings to record the data and prepare the sextant for the next sight. About 5 minutes after the last sight to finish the data solution and plot the fix, around 13 to 15 minutes on average *if there are no mistakes*. This time you did everything right and your three LOPs plotted to a small triangle - a good fix which disclosed that you indeed were justified in your heading corrections earlier. However your ground speed was low, an average of only 140 knots since takeoff. With an average true airspeed of 175 knots cruising, that was an average headwind component of 35 knots for the first six hours of flight.

The results boosted your confidence and now that the weather was excellent you would "precompute" the next star fix, extracting data from the tables at planned times. When you completed the sightings it would take you only a couple of minutes to get the fix plotted and navigator's log complete. If your first fix was reliable then the C-54 was falling well behind flight plan and using too much fuel.

Forty -five minutes later you had the next 3-star fix on the chart. Headwinds had increased to 70 knots with your ground speed down to 105 even though the ice was mainly gone and the C-54 had regained cruising airspeed. As revealed by the celestial fixes, the wind direction had swung to almost dead ahead so you could take out the previous drift correction. You forecast that when you reached Newfoundland you would be over two hours behind flight plan and running low on fuel. You recommended to the pilot that he change his destination to Gander civil airport which was closer and would save an hour because Harmon AFB is on the west side of Newfoundland.

Eight hours after leaving the Azores, you had plotted yet another celestial fix, St John's radio beacon, on the eastern tip of Newfoundland, was indicating dead ahead on the radio compass and you could see lights below from fishing vessels working just off the coast. The C-54 was battling a strong west wind though, so you repeated your recommendation to the pilot that he refuel at Gander. During the last portion of the flight over the Atlantic, with the lights of St Johns becoming gradually brighter, you even had time to dial in the LORAN stations located in Newfoundland and Labrador. You studied the

dancing green traces on the cathode ray tube and plotted a few LORAN LOPs. Next flight across the Atlantic you would be able to use that new method but you had gained confidence in you ability to use celestial navigation and that would be the method you would trust most.

Joe Reeves

Retired U.S.Navy pilot & navigator

December, 2007