

Analysis of the navigation of the Earhart flight from Lae to Howland on July 2, 1937.

The purpose of this analysis is to illuminate the area where Earhart's aircraft is likely to be found if a proper search is conducted. I will go into the details of the analysis but the two opinions I have formed are:

1. Due to well known limitations in the methods of navigation being used, it is most likely that the plane ditched to the north of the destination, Howland island.
2. That the plane may have ditched much closer to Howland island than other researchers have postulated.

I. Basic facts.

The flight departed Lae New Guinea at 0000 Z, July 2, 1937 (10:00 am July 3rd local time) with 1,100 U.S. gallons of fuel on board. The planned true airspeed was 130 knots (150 m.p.h.) The direct line distance from Lae to Howland island is 2,222 NM (2,556 SM) so if there had been no wind the minimum flight time was 17:05. Since headwinds were forecast, the original estimate of flight time was 18 hours making the estimated time of arrival 1800 Z, approximately 15 minutes after sunrise at Howland island.

(For consistency, I will use nautical miles, knots and "Z" time (the same as GMT). The plane departed Lae at 10 in the morning, 0000 Z, encountered night at approximately 0718 Z and then observed sunrise at approximately 1800 Z. All headings and directions are "TRUE", referenced to true north, and Noonan would have made the appropriate corrections prior to directing Earhart to fly headings referenced to her magnetic compass.)

Radio contact was maintained with the departure airport until 0718 Z. Earhart transmitted two position reports. The first was at 0519 Z and was recorded as 150.7 E 7.3 S, making the latitude 7° 03' S but the longitude almost certainly contains a transposition error and should be 157° 00' E. The second report was at 0718 Z giving the position as 4° 33' S 159° 07' E. These two points are not on the direct course line from Lae to Howland so this slight dogleg added a small extra distance to be covered. The distance from Lae direct to the 0718 Z position at 4° 33' S 159° 07' E is 737 NM making the ground speed 101 knots if they had flown direct. The distance from Lae to the 0519 Z reported position is 597 NM producing a ground speed of 113 knots to that point. The distance from there to the 0718 Z position is 196 NM. The distance from Lae to the 718 Z position via the 0519 Z position is 793 NM making the overall ground speed to that point 109 knots. This dogleg adds only 56 NM to the route to Howland so the minimum distance becomes 2,278 NM. Earhart reported at 1912 Z that they must be at Howland and this would make the overall ground speed 119 knots. If they had flown direct to Howland then the ground speed would have been slightly less, 116 knots.

The Coast Guard cutter Itasca was located near Howland and heard from the plane:

1415 Z overcast
1515 Z overcast
1623 Z partly cloudy
1744 Z, wants bearing, about 200 miles out
1815 Z take bearing on us and report in/on half hour will whistle in mic about 100 miles out
1912 Z must be on you flying at 1,000 feet

"CANNOT SEE U BUT GAS IS RUNNING LOW"

"SEZ RUNNING OUT OF GAS ONLY 1/2 HOUR LEFT"

1927 Z circling, go ahead now or on /in half hour
1930 Z got your signal can't get minimum
2013 Z on the line 157-337 will repeat on 6210

No more transmissions were heard from the plane.

Some important definitions:

COURSE is the planned line to follow over the surface of the earth and is drawn on the chart.

TRACK is the path that the plane has actually followed over the surface of the earth.

HEADING is the direction the nose of the plane is pointed at any given moment. The HEADING is chosen to correct for any cross wind in an attempt to cause the TRACK to be the same as the COURSE.

II. General methods of navigation used in 1937

There were three methods of navigation in use on the flight from Lae to Howland. The first, and basic method, was dead reckoning. The second was celestial navigation and the third method was radio navigation and I will give a short introduction to each.

IIa. Dead reckoning

Dead reckoning is the method of determining your current position by allowing for the expected movement of your plane since its last known position or "fix." the way this is done, is to mark on your chart the last accurately known position. You then draw the line in the direction that you expect the aircraft to travel and mark a point along that line corresponding to the distance you expect the airplane travel based on the known winds. For instance if you mark on your chart that you're directly over the Empire State building and then you fly straight east for one hour at an expected 100 knot ground speed, you could place another dot on your chart exactly 100 nautical miles straight east from the Empire State building. However, in real life, you could never be that certain of the new, dead reckoned, position. Your knowledge of the winds is never perfect nor does any pilot fly a perfectly straight course. Due to these possible inaccuracies, an area of

uncertainty grows around the dead reckoning position as the length of the course line progresses. The normally accepted estimate of the uncertainty in a dead reckoning position is 10% of the distance traveled through the air since the last fix. In our example, we could draw a circle with a 10 mile radius around our dead reckoning position and be very confident that we're somewhere within that circle. Although it is possible to actually be outside of the circle, it is very unlikely. This example starts from a very accurately known position, but what happens if the starting position also has some uncertainty? You can never know your dead reckoning position more accurately than you do your starting position. So if we start from a position that also has some possible inaccuracy then that inaccuracy travels forward with us and is added to the growing uncertainty of the dead reckoning. If we start dead reckoning from a position this has a 10 mile uncertainty, represented by a 10 mile radius uncertainty circle around it, this circle travels forward with us because you could have actually been starting from anywhere within that circle. We then add to the original uncertainty circle the amount caused by the dead reckoning uncertainty. So, continuing with our example, if, instead of looking straight down on the Empire State building our starting position had been a fix, with the 10 mile radius of uncertainty, at the end of one hour there be the 10 mile uncertainty from the original fix plus an additional 10 miles of uncertainty due to dead reckoning possible errors making the uncertainty circle around the dead reckoned position now a 20 nautical mile radius. See post on TIGHAR for a more complete illustration. <https://tighar.org/smf/index.php/topic,696.msg15908.html#msg15908>

Iib. Celestial Navigation

Celestial navigation involves measuring the angle of celestial objects, the sun, planets, moon, and stars, above the horizontal and based on these measurements being able to determine a fix on the surface of the earth. Without going into the details of how this is accomplished, a navigator is able, after taking an observation and doing the appropriate computations, of drawing a line on his chart and being certain that he is located somewhere along that line. We call this line a "line of position," LOP, however, one line of position does not provide a fix because the aircraft could be anywhere along that line. In order to accurately fix a position a navigator needs to obtain two LOPs that cross each other, preferably at near a 90° angle. Since the aircraft must be located on each of these lines at the same time, the only possible position is at the intersection of the two lines of position. In everyday terms, having one line of position is knowing that you are on First Street. Obtaining a fix then means seeing another street sign showing that you are at the intersection of First Street and Main Street, this is a fix.

However, just as in the dead reckoning situation, there are uncertainties around each of these lines of position generally taken to be plus and minus 7 nautical miles. It is possible, even when doing everything right, to be off from the plotted line by seven nautical miles. It is possible, also, to be further out but this is unlikely. Because of the uncertainty in the two lines of position and where they cross the fix also has an area of uncertainty generally described by drawing a circle with a 10 mile radius around the fix position. The circle should encompass the actual position of the aircraft although it is possible to be outside this circle but it is unlikely.

Look now at the attached PDF file entitled "Track between fixes." The first image shows an initial fix, the second image shows a second fix and the third image shows the track followed between fix

one and fix two. This is the track line that the navigator would draw on his chart and use to determine his path and speed over the ground. The navigator measures the course and distance between these two fixes and uses this measurement to make corrections to his heading and estimated time of arrival. For example, say the two fixes are spaced 100 nautical miles apart and the course between the fixes is 090° , if the time between these two fixes was one hour then the navigator would know that his ground speed was 100 knots and his track was 090° . Based on this information he would determine any corrections necessary to his heading in order to stay on course to the destination.

IIC. Radio Navigation

Radio navigation involves using the radio direction finding equipment in the aircraft to determine the bearing towards the transmitting antenna. Again, without going into the actual details of the operation of this equipment, a pilot can determine in which direction he should point the nose of the aircraft in order to be heading directly towards the transmitting station. This was the plan of Ehrhardt and Noonan for finding Howland Island by determining when the nose of the aircraft is pointed directly at the Itasca which was transmitting a quote homing” signal. Unfortunately, there’s a problem with equipment or with Earhart’s use of the equipment that prevented her from “homing” in on the Itasca’s signal.

III FACTS AND INFERENCES

The facts necessary to determine the location of Earhart plane are contained in the radio logs of the Itasca. From these logged transmissions we can make reasonable inferences of what was occurring in the aircraft at the time.

Prior to 1623 Z the radio messages from Earhart indicated cloudy conditions, apparently precluding the opportunity for Noonan to obtain celestial observations. However, at 1623 Z the radio message stated the conditions as “partly cloudy.” A reasonable inference from this transmission is that at about 1623 Z Noonan would have been able to obtain a celestial fix.

At 1744 Z Earhart radioed that she wanted Itasca to take a bearing on her aircraft’s transmitter. This was contrary to the original plan for Earhart who would be taking bearings on the transmitter of the Itasca. From this we can infer that Earhart and Noonan had expected to be able to receive Itasca’s signal by that point, that they had been unable to do so, and that is why they were requesting the Itasca to take a bearing on them. However, the Itasca’s radio equipment was not capable of taking bearings on the transmitter frequency being used by Earhart.

The obvious plan was for the aircraft to fly within range of Itasca’s transmitter, using celestial navigation and dead reckoning, and once the signals were received from Itasca to then use the radio direction finder the “home” directly towards Itasca. By 1744 Z they recognized that this original plan would not work and logically proceeded with a backup plan, using celestial navigation alone to find Howland Island. The celestial technique being used by Noonan should have been sufficiently accurate to bring them within sight of Howland Island. This depended, however, on Noonan being able to take continuing observations of the sun as they approached Howland Island. They were not able to sight Howland Island so we can infer from this that

Noonan was prevented from taking continuing observations of the sun as required by the procedure.

Itasca reported clear skies in all directions except to the North and Northwest where they observed thick clouds approximately 40 miles away. If the aircraft had been flying in the clear area, there would've been nothing preventing Noonan from taking additional observations of the sun. From this we can conclude that the aircraft was located in the cloudy area 40 miles or more north of Howland. As additional support for this conclusion, on the radio transmission from Earhart at 1922 Z, she informed Itasca that they were flying at 1000 feet. From this we can conclude, again, that they were flying below the clouds located north of Howland Island. If they were in the clear area they would have flown at a higher altitude which would've provided a greater visibility range for spotting the island. The fact that they were at such a low altitude, which was not a desirable altitude for them, shows that they were compelled to be at that lower altitude by the heavy cloud cover to the north.

Also in the 1922 Z transmission, Earhart reported that her gas was running low and that she had only a half-hour of fuel remaining. This is the only direct evidence we have as to the fuel state of the aircraft at that time. Many people have made computations of what they believe the fuel should have been at that time however those are based on various assumptions but the only direct evidence we have is Earhart statement. Using Lockheed Report 487 fuel consumption and power required information one can, depending upon various assumptions, calculate an endurance for the aircraft of anywhere between 10 hours and 34 hours. Reasonable assumptions also provide the calculation of approximately 20 hours which comports with Earhart's statement and also the fact that no messages came from her aircraft after 2013 Z.

Earhart's transmission at 2013 Z said that she was on the line the position 157° - 337° . From this we can conclude that Noonan had been able to obtain at least one, and possibly several, observations of the sun as the 157° - 337° line of position can only be determined from such an observation.

IV landfall procedure

At 1744 Z the aircraft reported that it was approximately 200 miles from Howland island. As it is apparent from this transmission that they recognized that they would not be able to complete the flight as planned, using radio direction finder homing on Itasca, it is logical that Newton then commenced flying the standard "single line of position landfall procedure." Noonan described this method to Paul Manz as turning 10° to 20° away from the direct course towards the destination to ensure knowing which side of the destination the aircraft would be on when it intercepted the line of position. From the illustration of the course to Howland it is clear that the standard procedure would require turning to the left to intercept the 157° – 337° line of position to the north northwest of Howland Island. The normal method, when performing this procedure, is to take a series of observations of the sun until the observations and calculations reveal that you have reached the line of position at which point you turn to follow the line of position. The inbound course to follow to Howland was 078° . Using the method outlined by Noonan, he would have turned to 068° which, starting from 200 miles away, causes the plane to intercept the line of position approximately 36 nautical miles north northwest of Howland Island, a distance sufficient to ensure arrival at the LOP north north west of Howland Island. The original uncertainty was 72 NM, 36

NM to the left and 36 NM to the right of Howland. By aiming 36 NM to the left of Howland this uncertainty has also been shifted to the left so now it stretches the same 72 NM but now it runs from zero miles to the right of the island to 72 NM to the left of the island.

(For a more complete discussion of the standard “landfall procedure,” see navigation manuals showing this standard procedure available at:
<https://sites.google.com/site/fredienoonan/topics/landfall-procedure>)

If, on the way to intercepting the line of position, they were able to obtain radio bearings on Itasca they could have immediately turned towards Itasca and completed the approach by homing. If they were never able to obtain radio bearings they could complete the approach using the landfall procedure which would add only approximately 40 miles to the course length.

Look now at the second PDF file named “Explanation of navigation to Howland.” Illustration 1 shows the approach course to Howland Island which is 078° . Illustration 2 shows the 157° - 337° line of position that Noonan would be attempting to intercept in order to follow it to Howland Island. The direction of this line is determined by the azimuth of the sun since this line must run at right angles to the azimuth of sun. The sun’s azimuth for approximately an hour after sunrise remained at 067° thereby causing the line of position to run as illustrated.

Illustration 3 shows a hypothetical fix obtained at approximately 1623 Z. Depending upon the actual ground speed of the aircraft, the distance from the 1623 Z fix to Howland Island is somewhere between 325 and 335 nautical miles. The shorter distance is based on a ground speed of 116 knots and the longer distances based on a ground speed of 119 knots. The slower ground speed is based on flying a direct course from Lae to Howland Island and the slightly higher ground speed comes from the aircraft flying over Choiseul Island as is consistent with the 0519 Z position report. (The differences in these two ground speeds makes less than a 1 NM difference in this analysis so is not significant which route is the correct one.)

Illustration four shows a hypothetical second fix obtained that 1700 Z, approximately 6-10ths of an hour later. These two hypothetical fixes, for illustration purposes, show the aircraft on the direct course to Howland.

Illustration 5 shows the point at which the aircraft would have encountered civil twilight at approximately 1740 Z. The reason this is significant is that at this point the sky would be too bright to allow Noonan to take observations of stars to obtain a fix. In fact, for some time prior to that, it would have been very difficult for Noonan to take star sights and to obtain a fix.

Illustration 6 shows where an observation of the sun at 1822 Z, with the sun 6° above the horizon, the minimum altitude that could be measured by Noonan, would place the aircraft. Because Earhart announced that they were on the line the position, we know that Noonan took at least one observation of the sun and that observation would have been sometime between 1822 Z and 2013 Z. This illustration shows the earliest possible observation.

Illustration 7 shows the normal procedure being used to intercept the line of position north

northwest of Howland Island. I've illustrated this commencing at 200 miles out as we know from the radio transmissions that they had realized by that point that they had a problem with the RDF and would most likely have started the landfall procedure at that point, approximately 200 miles out. Using Noonan's stated method, I've illustrated the planned course of 068° , a 10° correction to the left. Although Noonan had not gone into detail in his conversation with Mantz, his stated method conforms with the standard "landfall" method. A navigator aims off to one side a distance that is at least as large as the maximum possible error in the dead reckoning from the last fix to the LOP. This ensures that the navigator knows for sure which side of the destination he is on when he intercepts the LOP. As illustrated, the example last fix was at 1700 Z, about 255 nautical miles from Howland. The expected dead reckoning error is 10% of the distance flown so the estimated error is 26 nautical miles. To this we add the original uncertainty in the fix of 10 nautical miles so the total estimated possible error in the position at the time of intercepting the LOP would have been 36 nautical miles, the same result using a ten degree course correction starting 200 nautical miles out. This is shown in illustration 8. But the total uncertainty at the time of intercepting the LOP is twice this amount since the error could be 36 NM to the right and also 36 NM to the left of the course, a total of 72 NM. This is why a navigator must fly twice the distance of the offset to ensure going far enough along the LOP to reach his destination. When Noonan aimed 36 NM NNW of Howland he knew that he might arrive at the LOP between zero nautical miles and 72 nautical miles to the NNW of Howland.

V. The mystery

The mystery, however, is why Newton was not able to follow this procedure and safely land at Howland Island. Turning 10° off course would cause the plane to intercept the line of position at 36 nautical miles north northwest of Howland Island at which point the aircraft would turn to 157° to follow the line of position for twice the distance of the interception setoff or approximately 72 nautical miles. The reason a navigator travels twice the distance of the offset is based on the possible dead reckoning error. Even though the aircraft was aimed approximately 36 nautical miles north northwest of Howland Island, Noonan would realize that it was possible that the aircraft could be twice that far away, or approximately 72 nautical miles north northwest of Howland. Therefore, the aircraft turned and flew to the south southeast for 72 miles to ensure that, even if they were at the maximum dead reckoning error distance to the North North West, they would still arrive at Howland Island. So even if the aircraft was under the cloudy area, approximately 40 miles north of Howland Island, traveling to the south southeast for approximately 72 miles should have caused them to end up in the clear, where Noonan could obtain additional solar observations which would have allowed him to find Howland Island. This is the mystery.

VI. A scenario

let's look now at a slightly different scenario. Illustration 9 also shows a fix at 1623 Z, this time however, approximately 9 miles north of the course. Illustration 10 shows a hypothetical fix at 1700 Z but this time, approximately 9 miles south of course. A navigator would then draw a line between these two fixes to determine the track that had actually been flown across the ground. He

would measure this direction with his plotter and determine that his actual track was 091° instead of the required course of 078° , illustration 11. Since they were flying a heading of 078° he would determine that the crosswind was blowing the aircraft off course to the right, illustration 12. Based on this determination, showing that their track was 13° off course, they would correct their heading to the left by the same amount, 13° , and now fly a heading of 065° and this should then cause the aircraft to parallel the desired course of 078° , illustration 13. Now, following the same standard landfall procedure, at the 200 mile point Noonan adjusts his heading 10° further to the left to intercept the line of position as before but corrects an additional 3° to allow for the starting position being 9 miles to the right of course, so the aircraft would then steer the heading of 052° and this should cause the airplane to intercept the line the position at the same point, 36 nautical miles north northwest of Howland, illustration 14, so, the mystery remains.

VII. A possible explanation

There is, however, an explanation for how this situation could occur that does not require any errors on the part of Noonan or any extraordinary problems in the navigation. Look now at the third attached PDF file entitled "More tracks between fixes." The first image shows an initial fix, the second image shows a second fix and the third image shows the track followed between fix one and fix two. This is the track line that the navigator would draw on his chart and use to determine his path and ground speed over the ground. The navigator measures the track and distance between these two fixes and uses this measurement to make corrections to his heading and estimated time of arrival. For example, say the two fixes are spaced 100 nautical miles apart and the track between the fixes is 090° . If the time between these two fixes was one hour then the navigator would know that his ground speed was 100 knots and his track was 090° . Based on this information he would determine any corrections necessary to his heading in order to stay on course to the destination.

However, each celestial fix has a 10 nautical mile radius "circle of uncertainty" surrounding it and these circles are illustrated. Since it is possible for the aircraft to be anywhere within the circle, there are actually an infinite number of tracks that can be drawn between two fixes. For example if the aircraft is actually 10 miles west of the position plotted for the first fix and then was actually 10 miles east of the plotted position for the second fix, the aircraft would have covered 120 nautical miles in that one hour and the ground speed would actually be 120 knots. I have illustrated a number of possible tracks between the two circles of position and each would have its own ground speed and track which would be different from the line drawn on the chart between the two plotted fix coordinates. In addition to determining an inaccurate ground speed, the track between the two fixes can also be in error. For instance, if the aircraft were actually 10 miles north of the first plotted fix and ended up 10 miles south of the second plotted fix this would show a 20 mile deviation in the space of only 100 miles which results in 11° error in the computed course. But a navigator has to choose so he must use the line between the two plotted fixes as the course made good and the measured ground speed even though he knows that there is some uncertainty, he has no other choice. He then uses this information to determine the wind and any necessary heading change. I believe this is the key to the mystery, that due to normal uncertainties in celestial fixes, Noonan determined an incorrect track for the aircraft and made adjustments to the heading based

on that erroneous information.

VII. A second scenario.

This second scenario follows the same sequence as the first scenario however, even though the 1623 Z fix and the 1700 Z fix each show the aircraft 9 miles off course, in fact the aircraft was still on the course line, illustration 15, since the course line passes within the normal 10 NM radius uncertainty circles surrounding each of the fixes. The aircraft is steering a heading of 078° and actually maintaining the course line of 078° , illustration 16. However Noonan, by using the same methodology as with the first scenario, determines his track is 091° and makes the same correction of 13° to the left to now steer a heading of 065° . He realizes that the new track indicated a shift in the wind direction but it was not such a large shift to be suspicious so that he could just reject it out of hand. This is still the best navigational information he had available and it would be irresponsible to ignore it. He also expects to take additional fixes and they will cure any error in this computation but, unfortunately, he never got those fixes due to the cloud cover and the arrival of twilight. He believes this change in heading will cause the aircraft to parallel the course line but in fact will now cause the aircraft to deviate to the left by 13° , illustration 17.. Then, at the 200 mile point, Noonan makes the same additional 13° correction to the left, illustration 18, expecting to hit the line the position at the same point, 36 nautical miles north northwest of Howland but instead, this time, actually aiming to intercept the line of position 103 nautical miles north northwest of the island, illustration 19, and he may possibly intercept the LOP as much as 133 nautical miles away from Howland based on the normally accepted estimate of dead reckoning errors, illustration 20. While still flying at 10,000 feet, above most of the clouds, he manages to get an observation of the sun (possibly only one such observation due to higher cloud cover), calculates his ETA at the point of intercepting the LOP through Howland and then descends down to 1000 feet to be below the clouds in order to be able to see the island, never to see the sun again. So when the aircraft reaches the ETA at the LOP it turns to 157° and flies approximately 72 nautical miles, the aircraft does not proceed far enough to come out from under the clouds which continued to obstruct further observations of the sun. After flying this distance Noonan would know that he had flown far enough to reach Howland even if he had been at the farthest possible dead reckoning error from Howland, 72 NM, at the point where he intercepted the LOP so he knew that he had missed the island. At that point it makes no sense to continue further to the south southeast but the sensible plan of action was to turn back to the north northwest and search back that way in an effort to find Howland. Noonan had no reason to suspect that the approach procedure had not worked out as planned, he had done everything right.

IX. Conclusion

So Noonan had done everything right and would have had no reason to suspect that the landfall procedure would not work out right and locate the island for them. He had taken two good fixes and neither had an exceptionally large error, just the normal limitation on the accuracy imposed by in-flight celestial navigation. He correctly computed the track and ground speed between those fixes and, based on this information, he made the correct heading change to ensure intercepting the LOP between zero and 72 NM to the NNW of Howland (most likely nearer to 36 NM). He took a normally accurate sun line observation and made the correct computation of the point to turn to 157° at the point that the plane should have intercepted the LOP. He then flew the correct distance

along the LOP, 72 NM, but still could not find the island so then did the appropriate thing and searched back to the NNW. In spite of all this he was prevented from landing on Howland by the capriciousness of the clouds that prevented additional fixes and sun lines.

Perhaps Judy Collins has the best solution for this mystery:

Bows and flows of angel hair and ice cream castles in the air
And feather canyons everywhere, I've looked at clouds that way
But now they only block the sun they rain and snow on everyone
So many things I would have done, **but clouds got in my way**

<http://www.youtube.com/watch?v=z8jGFu7ys64>