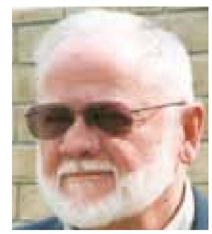
Introduction

The available evidence suggests that Amelia Earhart landed her Lockheed Electra on a particular section of the reef at Gardner Island (now Nikumaroro) and sent radio distress calls for several days before the aircraft was washed into the ocean leaving her and her navigator to survive as castaways on the uninhabited, waterless atoll. It's a hypothesis with a broad base of anecdotal and photographic support, but for it to be true the reef must be smooth enough and long enough to land on. Also, the reef must have been dry enough to permit a successful landing during the time Earhart could have arrived. Furthermore, for the radio signals to be genuine, the times of the credible signals must coincide with times when the water level on the reef was low enough to permit Earhart to run an engine to keep the the batteries charged. Those are specific, quantifiable, physical values that are not easy to determine for a location as remote as Nikumaroro and a point in time 75 years in the past. Bob Brandenburg's paper describes how we did it and what we discovered.



Time & Tide

Bob Brandenburg
TIGHAR #2286R

The Electra Landing Area

Pilots experienced in aircraft with tires similar to those on the Electra inspected the western reef during TIGHAR expedition Niku IIII[1] in September 2001. They found the surface dry at low tide, and suitable for landing the Electra in a strip (see photo previous page) about 50 meters wide,[2] bounded by the seaward edge of the reef, extending north from the wreck of the SS *Norwich City*, a ship that went aground there in 1929. They estimated the Electra could land safely with up to 0.15 meter (6 inches) of water on the surface. The reef immediately shoreward of the landing area was found too rough for landing, but suitable for taxiing the plane.

Tide Computation Considerations

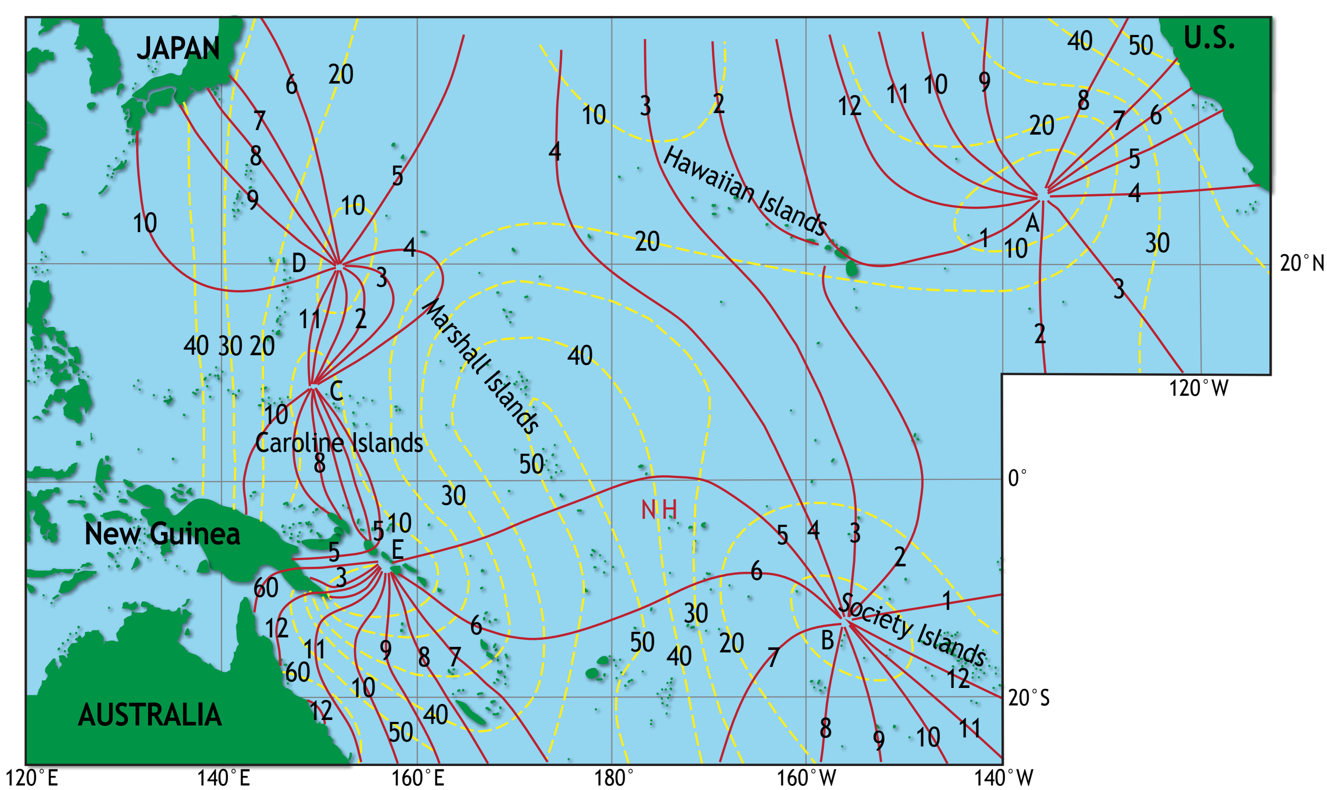
Tide tables are published for many places, and give tide height versus time of day. Tide height is the sum of the heights of harmonic constituent tides,[3] which are functions of harmonic constants derived from time series of hourly tide observations for at least 29 days. However, tide tables have never been published for Niku, and TIGHAR collection of the data needed for deriving harmonic constants would not be practicable. A feasible alternative would be to use a tide reference station for which July 1937 hindcasts are available, and find Niku tides by offsetting reference station tides, by an amount based on statistical correlation of tides at both places. This would require far fewer Niku tide observations than for deriving harmonic constants.

Tide Reference Station Selection

Hull Island (4°30´S, 172°10´W),[4] 143 nautical miles (nmi) east of Niku (4°40´S, 174°33´W), is the nearest island, and was selected as the tide reference station. Hull Island tide predictions and hindcasts are available from the UK Hydrographic Office (UKHO).[5]

The selection of Hull Island was informed by the work of Luther and Wunsch[6] on central Pacific harmonic constituent tides. Figure 2 is their chart of the lunar semi-diurnal (M2) constituent, the principal component of the Hull Island tide;[7] the solid curves are cotidal lines,[8] and the dashed curves are co-amplitude lines.[9] The chart is annotated for this paper to show the locations of Niku (N), and Hull (H), which are on about the same cotidal line, and slightly different co-amplitude lines, suggesting near-synchronous tides of similar heights.

Figure 2



Niku Tide Observations

Hull Island tide tables were used during Niku IIII to test the tide synchronicity suggested by Figure 2. Tides in the landing area were observed to occur at approximately the times predicted for Hull Island. Tide heights were not measured because it could not be assumed that the reef surface height, and thus tide height, everywhere in the landing area would be the same as at a single measurement point; and making concurrent measurements at multiple locations would not be practicable. Moreover, walking on the reef there is hazardous except near low tide. Post-expedition analysis of *Norwich City* engine photos found that the lowest tide during Niku IIII occurred at the time of lowest astronomical tide at Hull Island, confirming that Hull and Niku tides are synchronous.

Figure 3

It was decided that future expedition tasking would include data collection for correlating Niku tides with Hull Island tides, using a tide gauge at a convenient location, and a leveling survey to measure landing area reef heights relative to the gauge site. The collected data would be used in deriving an algorithm for offsetting the Hull Island tide to find the tide in the Electra landing area. The boat landing channel through the southwest reef (Figure 3) was selected as the gauge site; a gauge there could be read from the expedition ship's boat while carrying personnel to and from the island. Several tide heights were measured by hand at the gauge site during Niku IIII, near low tide, to confirm time agreement with Hull Island tide.

A float-type tide gauge was installed at the landing channel site during expedition Niku Vp in 2003.[10] However, it was found during post-analysis that the data collected were unusable, due apparently to anomalous gauge behavior not evident in the field. A second attempt, with a pole-type gauge during expedition Niku V in 2007,[11] was successful.

Tide Correlation

The landing channel tide heights collected during Niku IIII and Niku V were correlated with Hull Island tides by linear least squares regression (figure 4), yielding correlation coefficient $r = 0.981$, and regression line (Equation 1):

$$T_C = 1.156T_H - 0.6098$$

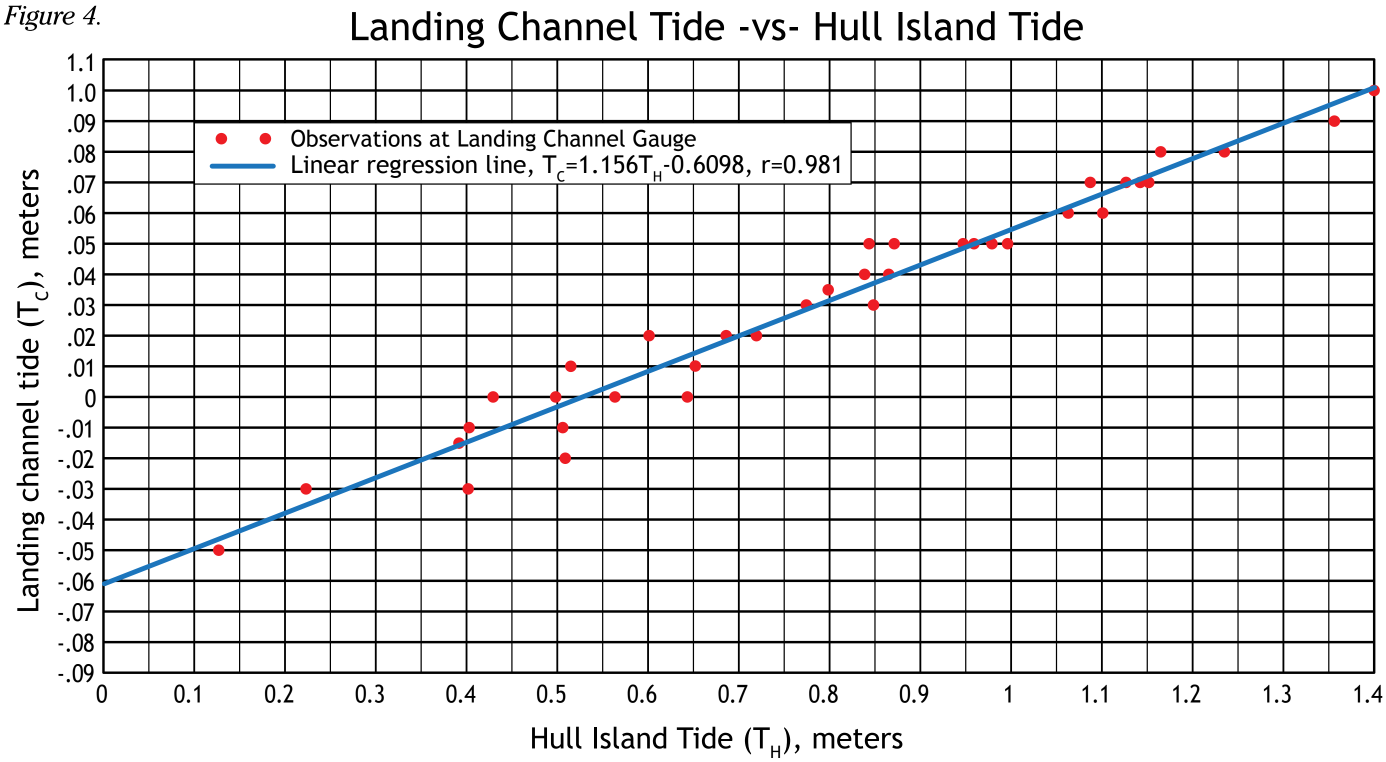
where T_C and T_H are the respective heights, in meters, at the landing channel and Hull Island. See Figure 4, next page.

Surveying the Reef

A leveling survey[12] during expedition Niku V measured Electra landing area reef heights relative to the landing channel gauge site. The survey was done in two phases because the landing channel site is not visible from the Electra landing area.

In phase 1, the survey instrument was sited on the southwestern shoreline, at a location with concurrent sight lines to the landing channel gauge site and a point, designated survey point A, at the *Norwich City* wreckage. The reef surface at point A was found to be 0.21m lower than at the gauge site, there-

Figure 4.



fore the point A tide is 0.21m higher than at the gauge site. Applying this difference to equation (1) gives the point A tide (TA), in terms of the Hull Island tide (equation 2):

$$T_A = T_C + 0.21 = 1.156T_H - 0.6098 + 0.21 = 1.1560\,T_H - 0.3998\text{m}$$

In phase 2, the instrument was sited on the shoreline east of the *Norwich City,* and reef heights relative to point A were measured. The results are shown in figure 5.

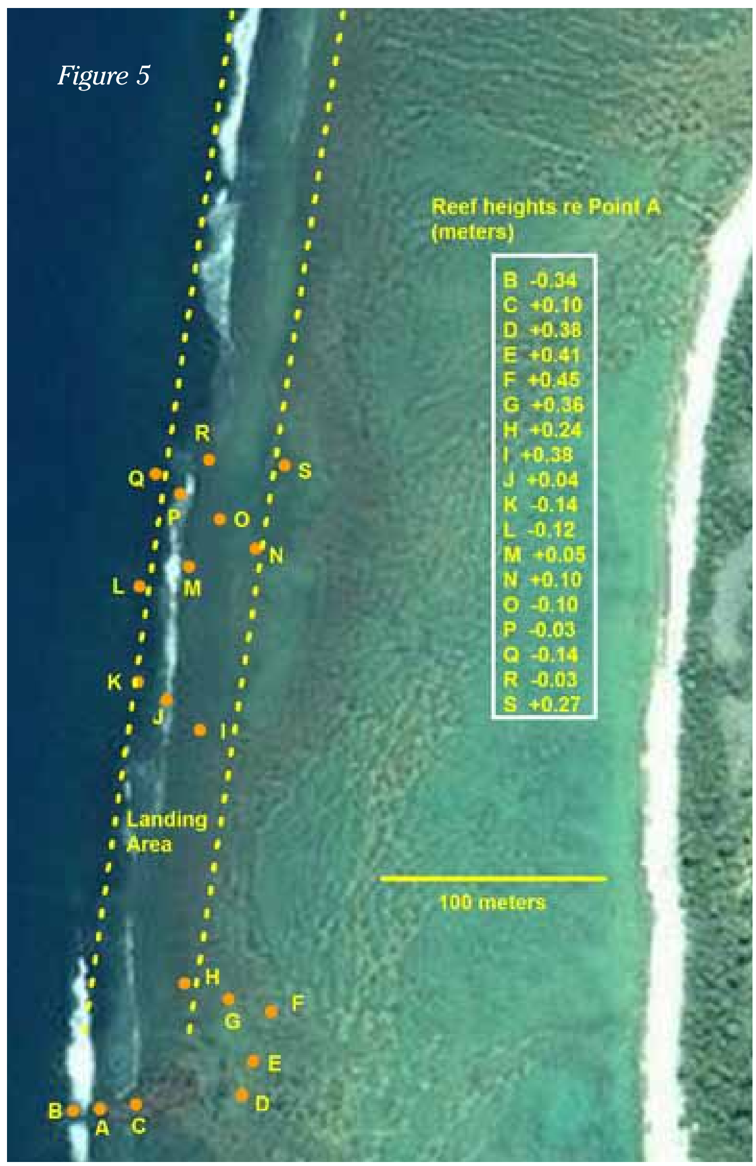


Figure 5

Hindcasting Tides in the Electra Landing Area

The tide height at a given point in the Electra landing area for a given date and time is found by solving equation (2) for the tide height at point A, and applying the reef height differential for the point of interest. For example, the reef surface at survey point I is 0.38m higher than at point A, hence the tide level at point I is 0.38m lower than at point A (Equation 3):

$$T_I = 1.156T_H - 0.3998\text{m} - 0.38\text{m} = 1.156T_H - 0.7898\text{m}$$

Testing the TIGHAR Hypothesis

The TIGHAR hypothesis[13] – that Earhart landed her Lockheed Electra 10E on the western reef of Niku on 2 July 1937, and sent radio signals[14] from there until 8 July 1937, when tide and surf forced abandonment of the aircraft[15] – relies on three implicit assumptions, each requiring satisfaction of a tide-governed constraint:

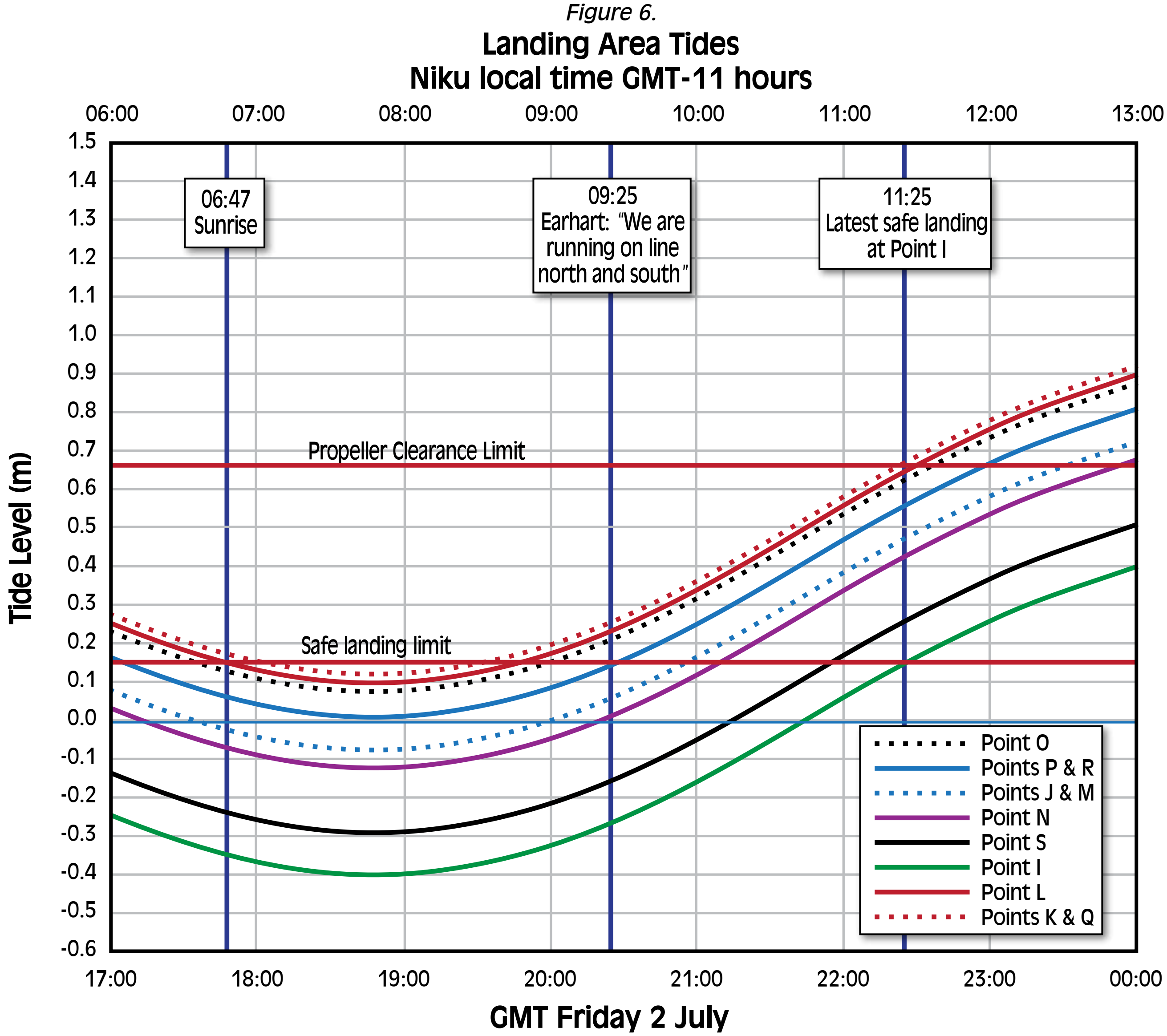
- the plane landed before the tide exceeded the 0.15m safe landing limit;
- the plane was parked where the radio transmitter was not subject to tidal flooding;
- tide allowed operating the plane's engine-driven generator for radio transmission and battery charging.

The hypothesis was tested with respect to each constraint, in the context of a northbound landing approach over the *Norwich City* wreck, as was flown by a helicopter[16] simulating an Electra landing during expedition Niku IIII. The hypothesis would be confirmed only if it was possible for all three constraints to have been satisfied, and would be false otherwise.

Time Zones. Niku local time is GMT-11 hours for this analysis, to agree with the UK Hydrographic Office zone time for Hull Island tides. Local time on the Coast Guard cutter *Itasca*, at Howland Island, was GMT-11.5 hours.[17]

The Landing Time Constraint. Figure 6 shows the tide versus time at each surveyed point in the Electra landing area the morning of 2 July 1937.

Figure 6.



The tide in the landing area was low at 07:43 Niku time and rising when the *Itasca* heard Earhart at 08:55[18] (09:25 Niku time), say "We are running on line north and south." Points S and I were above water then, and the tide was at or above the safe landing limit at points K, L, O, P, Q, and R. The limit subsequently was reached at Points J and M (09:52); point N (10:06); point S (10:55); and point I (11:25).

Table 1 shows landing times for various enroute speeds, given the 09:25 distance from Howland, if the Electra was on the 157°/337°[19] line of position through Howland Island. The times include a 15-minute search for a landing place after arriving overhead Niku.

Table 1

09:25 Niku Local Time		Landing time vs. Electra enroute speed			
Dist (nmi) Howland	Dist (nmi) Niku	87 kts (100 mph)	104 kts (120 mph)	113 kts (130 mph)	130 kts (150 mph)
0	350	13:41	13:01	12:45	12:21
20	330	13:27	12:50	12:35	12:12
40	310	13:13	12:38	12:24	12:03
60	290	13:00	12:27	12:13	11:53
80	270	12:46	12:15	12:03	11:44
100	250	12:32	12:04	11:52	11:35
120	230	12:18	11:52	11:42	11:26
140	210	12:04	11:41	11:31	11:16
160	190	11:51	11:29	11:20	11:07
180	170	11:37	11:18	11:10	10:58
200	150	11:23	11:06	10:59	10:49
220	130	11:09	10:55	10:49	10:40
240	110	10:55	10:43	10:38	10:30
260	90	10:42	10:31	10:27	10:21
280	70	10:28	10:20	10:17	10:12
300	50	10:14	10:08	10:06	10:03
320	30	10:00	9:57	9:55	9:53
340	10	9:46	9:45	9:45	9:44

Entering the speed columns of Table 1 with the limiting safe landing time at a point in the usable set (J, M, N, S, and I) gives the distances from Howland and Niku from which it was possible to arrive and land safely at the point. A single case is sufficient to show that it was possible to satisfy the landing time constraint: Earhart could land safely at point I before 11:25 if her 09:25 distance from Howland was at least 120 nmi, depending on enroute speed. This result is consistent with radio signal propagation analysis[20] suggesting Earhart likely was between 80 and 210 nmi from Howland at 09:25.

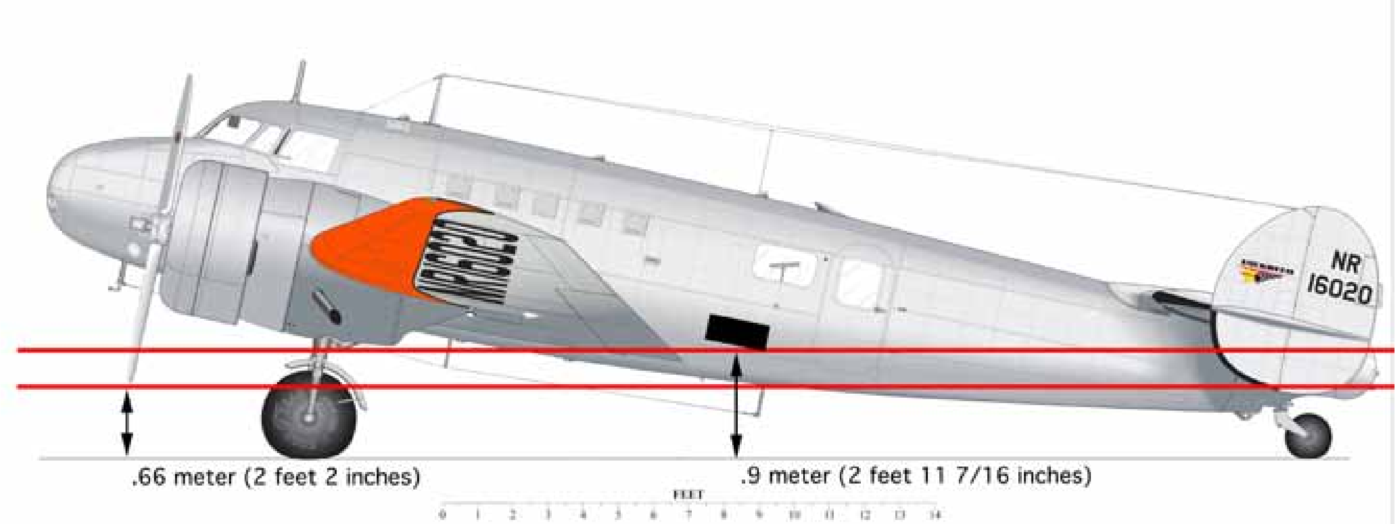
Figure 7 (next page) shows a possible scenario for landing at point I before 11:25, with touchdown at point I, followed by roll-out and taxiing to a parking place somewhere upslope where the transmitter would be dry and the engine-driven generator could be operated. The feasibility of the taxi, parking, and engine-operation components of the scenario, in relation to tide, is examined in the next section.

The Radio Transmission Constraints. The two post-arrival tide constraints – parking where the transmitter would not be subject to tidal flooding, and allowing operation of the plane's engine-driven generator – are interrelated, and will be treated together in this section. These constraints are illustrated[21] in figure 8 (next page).

The ***dry-transmitter constraint*** was due to the transmitter location, on the cabin floor behind the auxiliary fuel tanks, 0.9m above ground when the plane was parked.[22] Neither the cabin nor the transmitter was watertight, so if the tide height exceeded 0.9m sea water would enter the transmitter,[23] rendering it inoperable thereafter.

Figure 7.

Figure 8.



The actual Electra parking location is unknown, but the reef height there required by the dry-transmitter constraint can be derived. The highest Hull Island tide during the period 2-8 July was 1.5m, at 0545 (GMT-11) on 7 July. The landing area point A tide at that time is given by Equation 2:

$$T_A = 1.156T_H - 0.3998m = 1.156 \times 1.5m - 0.3998m = 1.334m$$

Therefore, in order for the tide at the parking place not to exceed 0.9m, the reef height there must be at least 1.334 - 0.9 = 0.432m greater than at survey point A. This is just 0.052m greater than at point I, and 0.162m greater than at point S.

At least one credible radio signal[24] was heard each day during the period 2-8 July 1937, suggesting the plane was parked where the transmitter was dry and operable. The reef height at survey point F – 0.45m greater than point A – shows it was possible for the required height to be found upslope of the landing area. The reef slope indicated by the survey data suggests the required parking area height could be found within 50 meters shoreward of the landing area. Clearly, Earhart had no way of knowing the reef height anywhere, but she could have found a suitable parking place merely by taxiing as far upslope as the reef surface permitted. Therefore, the evidence supports a conclusion that it was possible to satisfy the dry transmitter constraint by taxiing as shown in Figure 7.

The ***engine operation constraint*** was due to the Electra's propeller ground clearance, 0.66m (26 inches),[25] the low point of the arc described by the propeller tips during engine operation when the plane was taxiing or parked. Engine operation with a tide level above 0.66m would result in propeller impact with water, causing catastrophic engine damage.

Taxiing to the parking place after landing was possible only if the tide level was below the propeller clearance limit. The tide (Figure 6) was below the propeller clearance limit at points J, M, N, S, and I until well after 11:25, so it was possible for the plane to taxi in the landing area, and to a parking location upslope.

As in the case of taxiing, operation of the engine-driven generator for radio transmission and battery charging was possible only when the tide level at the Electra parking place was less than 0.66m.

The relationship between tide and radio transmissions evaluated as credibly having been sent from the Electra at Niku[26] is illustrated in Figures 9 through 14, which show the tide curve for each day 3-8 July 1937, with the dry transmitter and the propeller clearance limits, at any location where the reef height exactly satisfies the dry transmitter limit. If the plane was parked where the reef surface was higher, the tide curves would be correspondingly lower on the respective plots. Credible radio signals are shown as green bars; signal details are in the signal catalog.[27]

With the exception of one signal on 4 July (Figure 10), when the tide level was just at the propeller clearance limit, and two signals on 5 July (Figure 11), when the tide was at or above the propeller clearance limit, all credible signals were heard when the tide level was below the limit. Those signals could have been transmitted on battery power, without operating the engine-driven generator. However, if the plane had been parked where the reef height was only 0.1m higher than required for the transmitter to be dry, the tide would have been below the propeller clearance limit for those signals, allowing engine operation. The evidence supports a conclusion that it was possible to operate the engine-driven generator for radio transmissions, and between transmissions for battery charging.

Conclusion

Application of tide hindcasting has shown that it was possible for Amelia Earhart to land her Lockheed Electra 10E on the western reef of Niku on 2 July 1937, and send radio signals from there until 8 July 1937. If future research requires hindcasting tides at reef locations other than those discussed herein, the only additional information needed would be the results of a leveling survey to find the associated reef surface heights. ◆

These illustrations plot the credible post-loss radio signals against the tidal rise and fall of the water level on the reef for July 2-8, 1937 for anywhere the reef surface is 0.43m higher than reference point A. The Electra, parked at such a location, could transmit as long as the water level did not exceed the "Radio transmitter dry limit" and could run an engine any time the water level was not above the "Propeller clearance limit." Note that the water level is never high enough to flood the transmitter. The credible radio signals occur almost exclusively during hours of darkness at Nikumaroro and only at times when the water level is low enough to permit engine operation to keep the batteries charged.

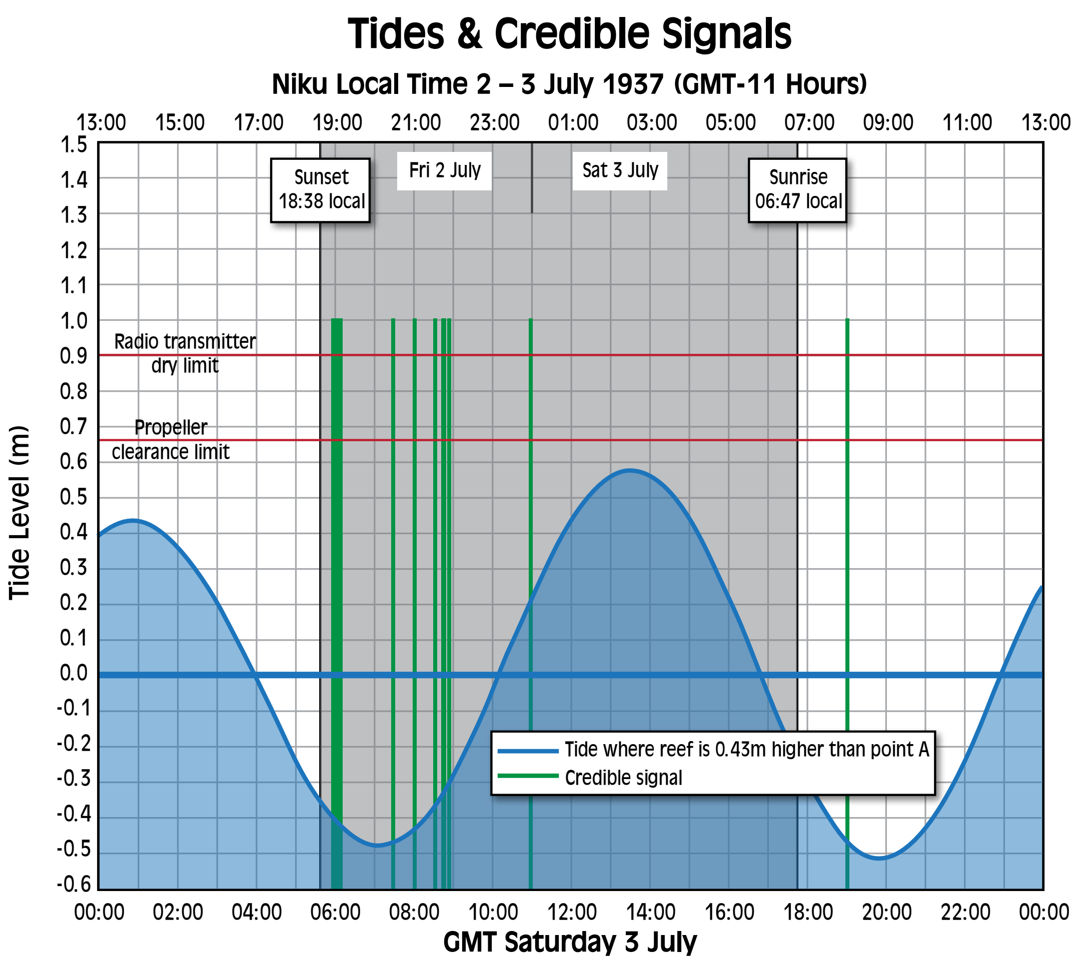


Figure 9

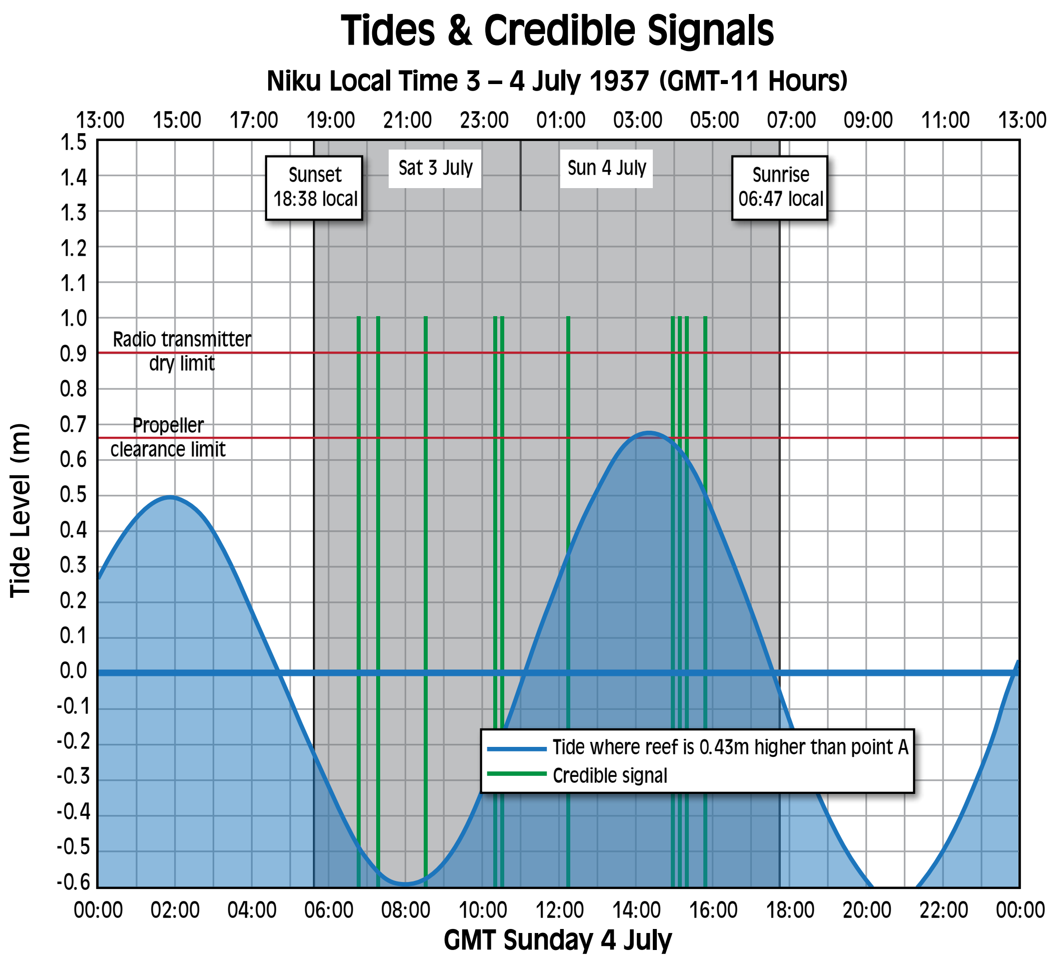


Figure 10

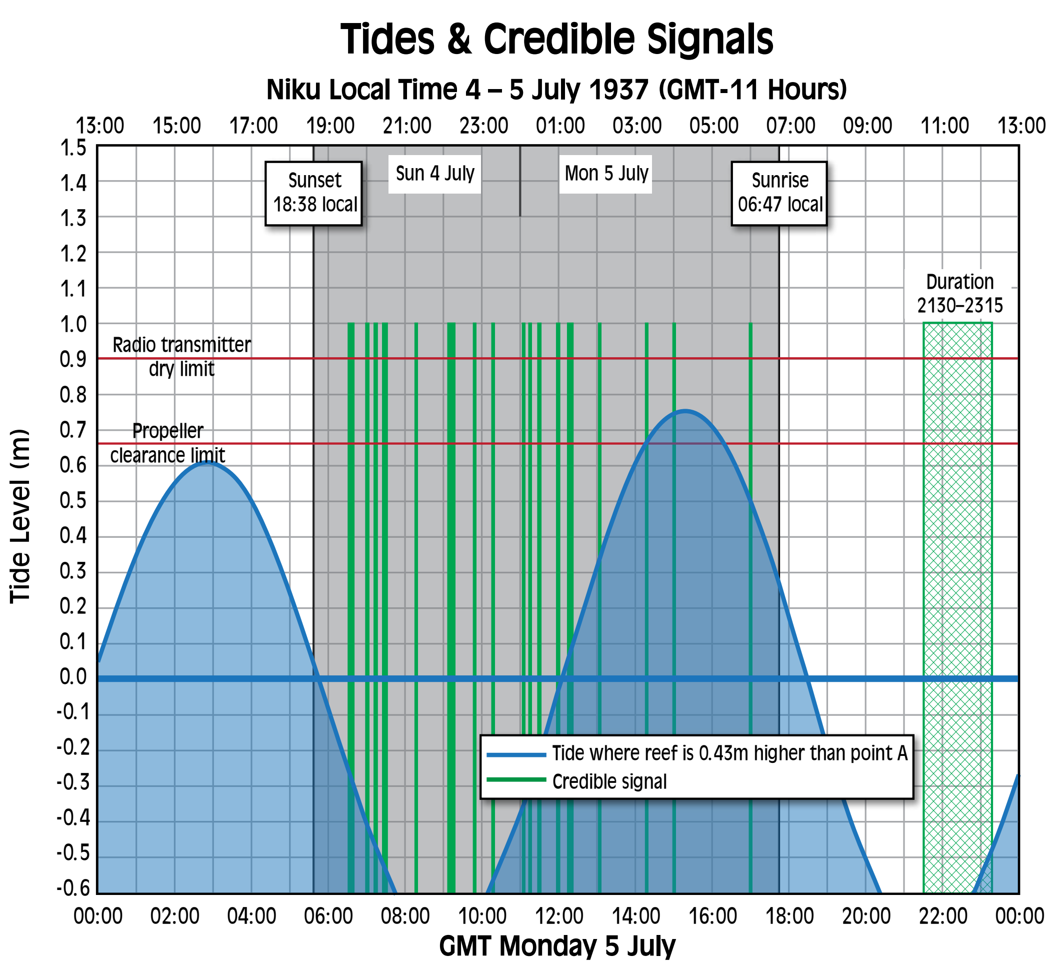


Figure 11

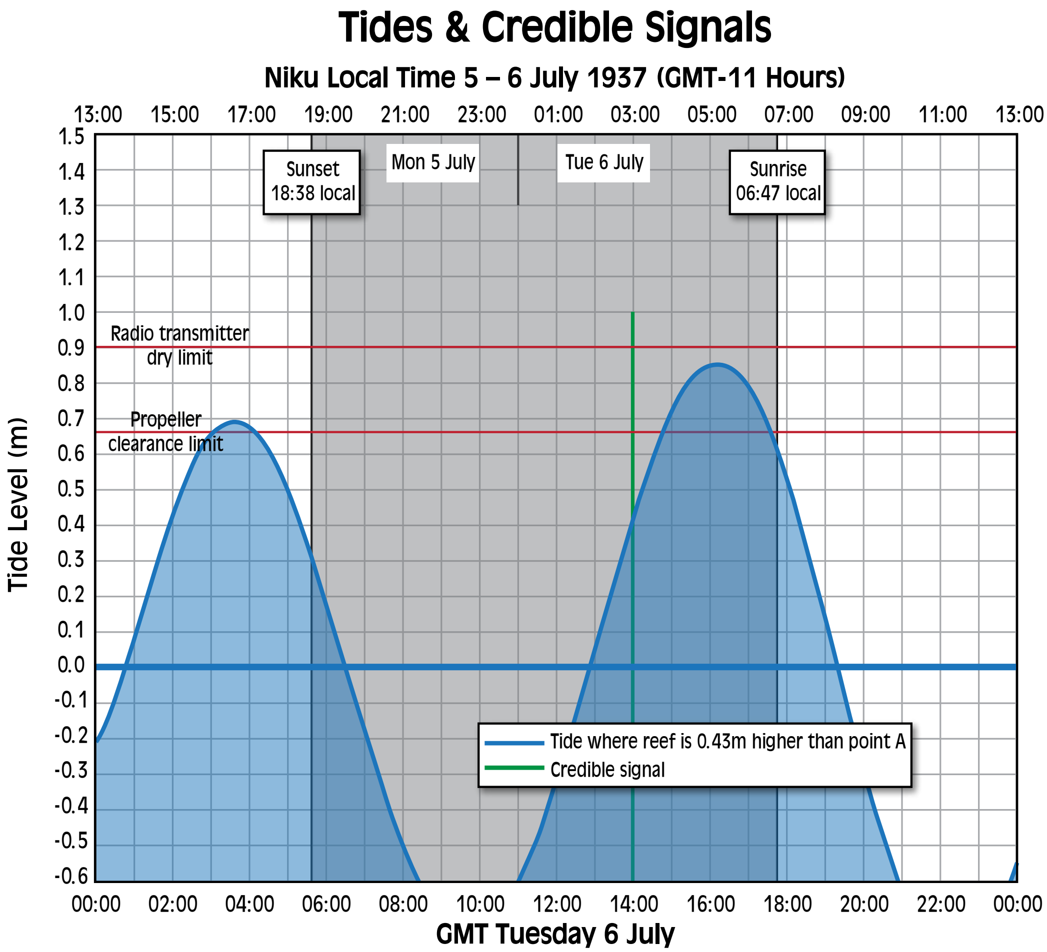


Figure 12

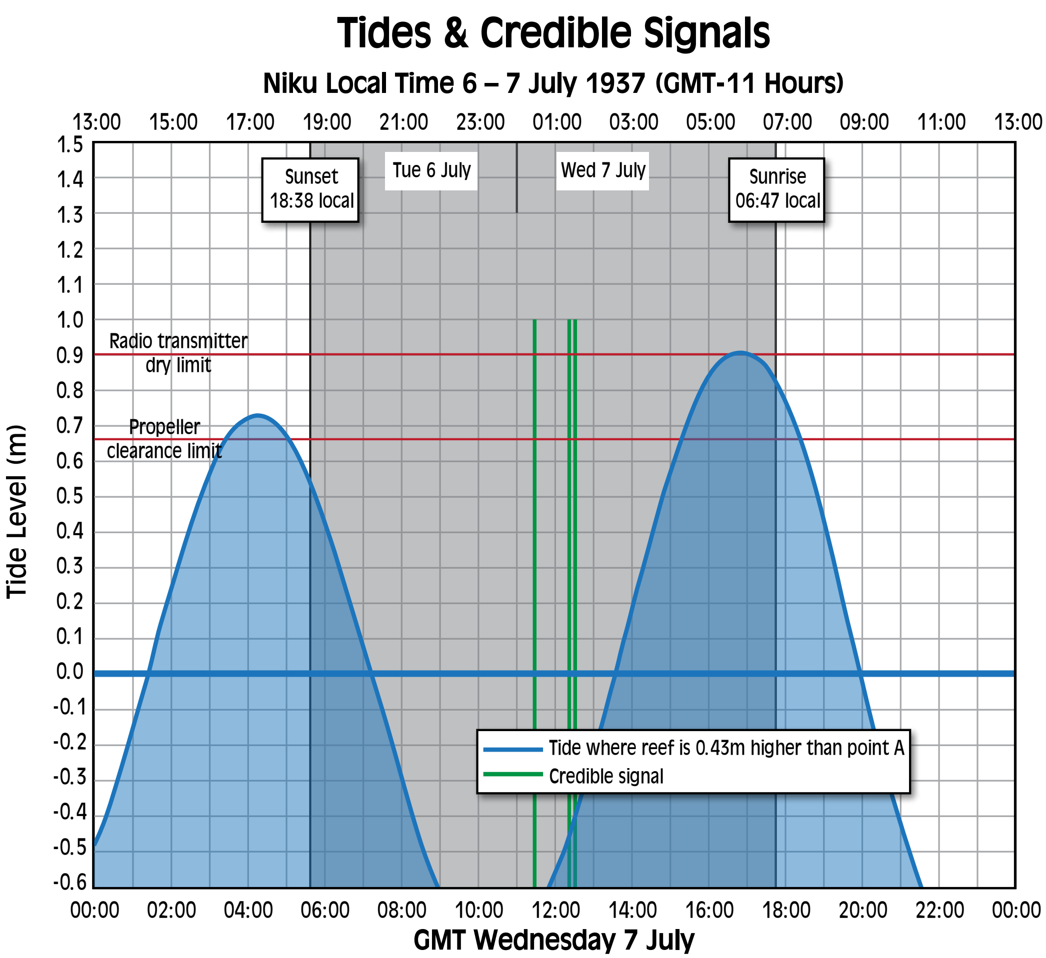


Figure 13

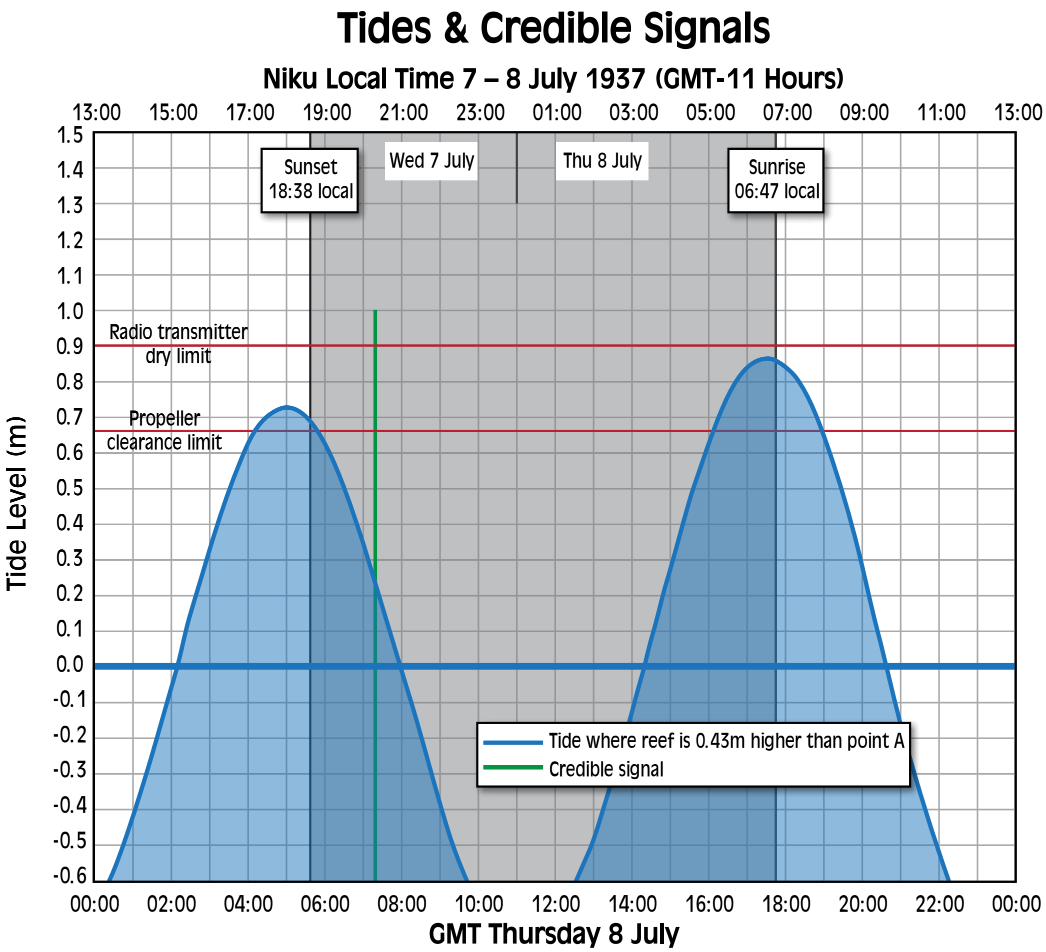


Figure 14

Notes

1 tighar.org/TTracks/2001Vol_17/1707.pdf

2 Ric Gillespie, TIGHAR Executive Director, personal correspondence.

3 Schureman, Paul. 1941. *Manual of Harmonic Analysis and Prediction of Tides*, U.S. Department of Commerce, Coast and Geodetic Survey, Special Publication No. 98. Washington: U.S. Government Printing Office, reprinted 1958 with corrections.

4 British Admiralty chart 184, "Plans of the Phoenix Islands," November 1991.

5 easytide.ukho.gov.uk. UKHO tide tables give the times and heights of low water and high water. Heights at intermediate times for TIGHAR research were computed by the author, using cosine interpolation.

6 Luther, Douglas S., and Carl Wunsch. 1975. "Tidal Charts of the Central Pacific Ocean." *Journal of Physical Oceanography* 2 (April): 222-230.

7 Luther and Wunsch, Table 1. The M2 tide accounts for 56% of the composite tide at Hull Island.

8 High water occurs simultaneously everywhere on a co-tidal line. Each line shows the Greenwich epoch (G), the phase lag in solar hours to high water after moon passage over the Greenwich meridian.

9 Amplitude (half the tide range), shown in centimeters, is the same everywhere on a co-amplitude line.

10 tighar.org/Publications/TTracks/2003Vol_19/NikuVp.pdf

11 tighar.org/Publications/TTracks/2007Vol_23/2303.pdf

12 With a Sokkia SRX Total Station, courtesy Instrument Sales & Service Co., Wilmington, Delaware.

13 tighar.org/Projects/Earhart/Overview/AEhypothesis.html

14 tighar.org/Projects/Earhart/Archives/Research/ResearchPapers/Brandenburg/signalcatalog.html

15 tighar.org/Projects/Earhart/Archives/Documents/Lambrecht's_Report.html. USS *Colorado* aircraft did not see the Electra during an aerial search of Niku on July 9.

16 Video CD, "An Aerial Tour of Nikumaroro," narrated by Ric Gillespie, available at tighar.org/store.

17 Time Zones section of the Jacobson Database at tighar.org/Publications/Books/FindingAmeliaNotes.

18 tighar.org/Projects/Earhart/Archives/Research/Bulletins/49_LastWords/49_LastWords.html.

19 "The 3105 Donut" tighar.org/publications/TTracks/2008Vol_24/1008.pdf.

20 Ibid.

21 Courtesy Ric Gillespie.

22 William F. Harney drawings of Earhart's Electra, TIGHAR.org/store.

23 Suggested by Ric Gillespie, personal correspondence.

24 See footnote 14.

25 Harney drawings of Earhart's Electra.

26 See footnote 14.

27 See footnote 14.