A Uniquely “Serendipitous” Total Solar Eclipse 2016 Observation Flight Opportunity: <u>Intercepting the Moon’s Shadow from AS Flight 870</u>

Dr. Glenn Schneider[1]*, Ph. D.*

(24 October 2015)

The opportunity under consideration, to view the soon upcoming total solar eclipse (TSE) on March 9, 2016 UTC (March 8 AKST/HST) from high altitude on an Alaska Airlines (AS) B737-800 aircraft, is truly exciting and should be pursued with vigor. “Eclipse flights” are no longer rare (though no other is being planned for TSE 2016), but when undertaken are typically done with dedicated research or charter flights arranged exclusively for that purpose. E.g., most recently for the 20 March 2015 TSE over the Norwegian Sea including (also) a B737-800 aircraft (provided by Air Berlin, along with two other aircraft) for which I had developed the eclipse-intercept flight plan. Those were (completely successful) charters designed from the start with the sole objective of optimally positioning that B737-800 aircraft for the very best and longest possible view of the total phase of the eclipse. In this case, a very rare opportunity presents itself to advantageously make use of a regular scheduled Alaska Airlines flight, AS 870 from Anchorage to Honolulu, as has already been advocated by Joseph Rao. Indeed, the AS 870 nominal flight routing and schedule would naturally bring the aircraft very close in both location and time to where it could easily cross exactly through the center of Moon’s umbral shadow as the aircraft is approaching Honolulu from the north.

With only a relatively minor modification to its regular flight plan, AS 870 on March 8, 2015 HST, could fly right through the “bull's eye” at the center of the path of totality just at the instant that the Moon’s shadow comes racing by. This is truly an amazing happenstance, and would enable a spectacular high-altitude view of the TSE for passengers on the “sun side” of the aircraft. This, of course, requires collaborative preplanning with Alaska Airlines, but is readily achievable with modern aircraft flight management systems and piloting with that objective in mind.

Such an eclipse-modified flight plan, at a high level, can be conceptualized with the inclusion of an additional short leg called the “Totality Run” (TR), preceded by a heading realignment maneuver (turn) to place the aircraft on the requisite heading for the TR track. The end-to-end flight plan can then be described as: (1) take-off (wheel's up), (2) airport pattern departure and ascent to cruise, (3) outbound cruise, (4) turn onto totality run, (5) totality run, (6) inbound cruise, (7) descent and pattern approach, (8) landing; where (1 – 3) and (6 – 8) are as usual, but here with (5) and (6) augmenting the usual plan with the inclusion of a “time critical” eclipse-observation Totality Run.

---

[1] Contact: Dr. Glenn Schneider
Astronomer and EXCEDE Project Principal Investigator
Steward Observatory and the Department of Astronomy
933 North Cherry Avenue
The University of Arizona
Tucson, Arizona 85721, USA
Telephone: 520-621-5865
Email: gschneider@as.arizona.edu
URL: http://nicmosis.as.arizona.edu:8000

The TSE 2016 Path of Totality

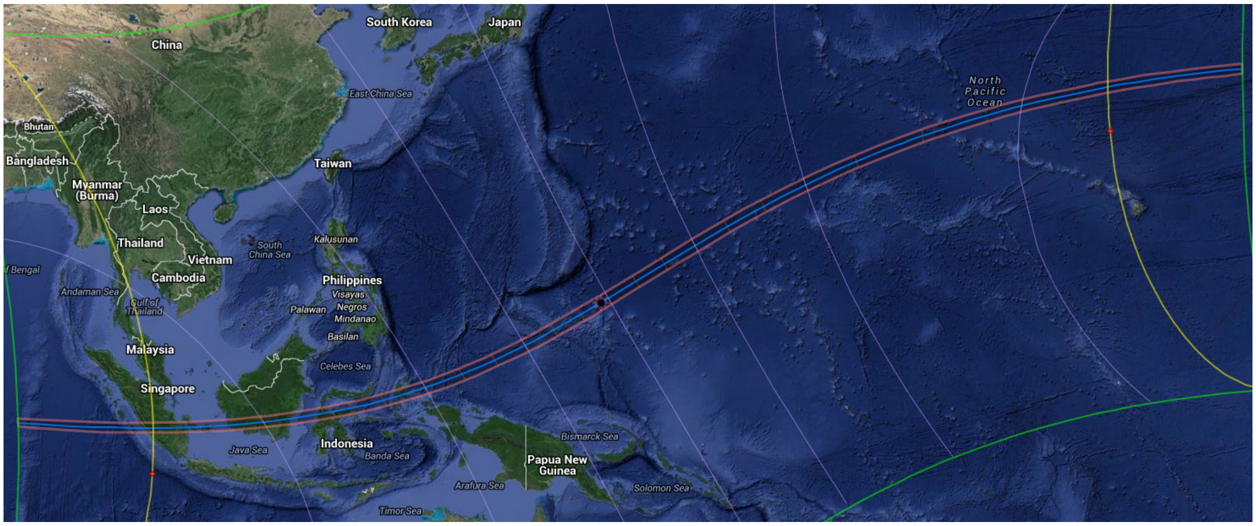

Fig 1. TSE 2016 path of totality from sunrise to sunset over the Pacific Ocean.

The long, but relatively narrow, "path of totality" is the region of (or flying above) the Earth from where (and only where) the eclipse will be seen as total. For TSE 2016 this is the region between the parallel red curves in Figure 1 that depict the northern and southern limits of the path of totality. The total phase of the eclipse is optimally viewed from the (depicted blue) "centerline" mid-way between the red-lined northern and southern path limits. The TSE 2016 path of totality traverses several thousand miles of the Pacific Ocean from Indonesia (at sunrise locally on March 9) to northeast of Hawaii (at sunset locally on March 8); see Figure 1. In order to see the eclipse as total (i.e., "totality") – a truly amazing and awe inspiring celestial phenomenon like no other – one must be within the path of totality that Moon's shadow traces out as it sweeps over that small sliver of the Earth's surface.

The location of the path of totality is dictated by the inexorable laws of celestial mechanics that heed no geographical boundaries. An observer located within the path of totality, at the right moment in time will be enveloped by, and immersed within, Moon's umbral shadow for the fleeting few minutes of its passage. The width of the narrow path is defined by its northern and southern limits, outside of which the eclipse will be seen only as partial, or not at all. The very center of the Moon's shadow, which traces out the centerline of the path of totality, is where (for any location along the path) the totality duration is longest, the sky darkest, and the view of totality is optimal. From centerline north of Hawaii, an observer will have a view of totality for just under two minutes. The "trick" is to be exactly at the right place, at the right time, which over the vast expanse of the Pacific Ocean is enabled with only a minor "tweak" to the AS 870 flight plan as it begins its approach to Honolulu.

Alaska Airlines Flight 870 – The Right Place at the Right Time

The centerline of the path of totality, for all practical purposes, may be expressed as a time-correlated set of way points (latitude, longitude) that maps out the central position of the Moon's umbral shadow as it traverses the Earth. Totality may be well seen anywhere along that path, but AS 870's regular flight plan (*ideal* for intercepting the lunar shadow) guides us to select a "best" location in concert in conformance with normal aircraft scheduling and operations.

Serendipitously, the latter portion of AS flight 870's takes the aircraft it **directly though** the TSE 2016 path of totality (on a heading close to due south approximately along longitude 156° W) soon before its decent for a landing (nominally at about 6:51 PM HST) in Honolulu. From recent historical records, we see that 48% of AS 870 flights *crosses the path of totality* (at latitude appx +31° N) within ±0.5° of longitude 156°W (and 90% within ± 1.5°) *and* (by very good luck) also very close to the time that the Moon's shadow will arrive at that location on March 8, 2015 (HST). This, obviously, is the time and region within to plan the TSE 2016/AS 870 mid-eclipse intercept, having the least impact on the regular flight routing and schedule while providing a spectacular view of the total eclipse.

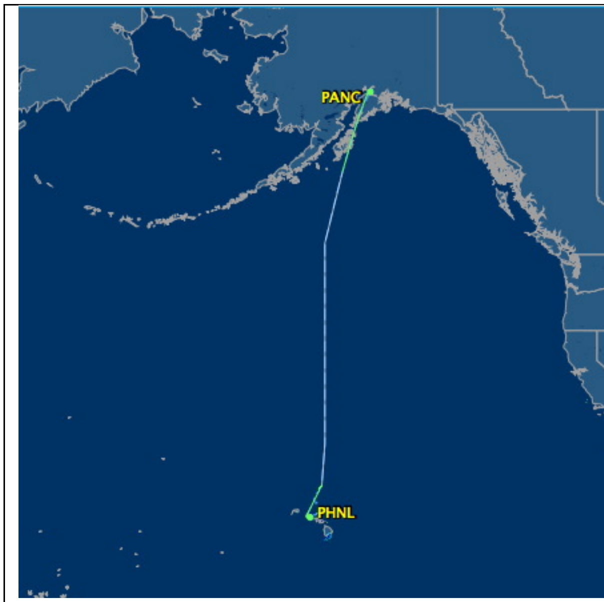

Fig. 2. Typical AS 870 (Schematic) Flight Plan

MID-ECLIPSE INTERCEPT (MEI) - Time and Location

In detail, the location of the path of totality (and its centerline) predictably shifts in position at different heights above mean sea level. Given the aircraft type (B737-800) and historical flight record, **for baseline planning** FL350 (35,000 ft., or 10,668 m AMSL) is assumed for the aircraft altitude for eclipse-viewing and thus for the computation of the "at altitude" path of totality.

The AS 870 centerline crossing (“Mid-Eclipse Intercept”; MEI) at precisely 03:36:00 UTC is:

MEI(35,000 ft.) = [Latitude: +31.30356°, Longitude: -156.15476°] @ 03:36:00 UTC

This time-correlated point of **mid-eclipse intercept is the key waypoint** in position and time to “hit” as precisely as possible, and about which the rest of the flight is planned to achieve that goal.

(Note of detail: If the aircraft is actually assigned a different flight level ± a few thousand feet from FL350 for the eclipse viewing portion of the flight, there is no need to recompute this, as the difference in the geometrical and temporal circumstances of the eclipse will be acceptably small).

This MEI is exactly where and when the aircraft must be located to be centrally within the Moon's shadow to view totality with minimal impact to normal schedule and flight plan.

AIRCRAFT HEADING AT MEI

At MEI (and throughout the totality run flanking it for several minutes before and after) the aircraft must be flying on a heading that will allow viewing of the eclipse out the passenger windows on one side of the aircraft. Ideally, with a line-of-sight “straight out” the windows; i.e., with the aircraft on a heading 90° ± the solar azimuth angle at MEI. At MEI the solar azimuth angle will be 258.5° (east of north), and thus for viewing considerations (alone) the aircraft then could be flying a heading of either 168.5° (so the Sun will be viewed out the right side of the aircraft) or 358.5° (with the Sun out the left side windows). It is advantageous to doing this **on a**

heading of 168.5° (sun on the right side of the aircraft), for several reasons.

First, with the aircraft's speed (discussed below), the 168.5° heading will increase the duration of totality to 1m 53.5s (assuming a ground-speed of 447.4 nm/hr; see below), whereas flying in the opposite direction would result in a shorter, 1m 40.2s of totality. I.e., with a 168.5° heading, a net increase of 13.3s of precious totality viewing duration is realized – every second counts! Second, an initial heading for the approach to the MEI of 168.5° is very close to the otherwise "nominal" due south direction for the flight at this point, so requires only a very small (-11.5°) change in course at the start of the totality run. Third, after totality, this will leave the aircraft very close to the heading it will need to resume for an approach and subsequent landing in Honolulu.

The "TOTALITY RUN" - Boundary Conditions/Assumptions

The MEI time, location, and heading, are then used to define the overall Totality Run, the time-correlated set of waypoints that will take the aircraft through the center of the Moon's shadow at the right time. The TR run begins prior to the aircraft entering into the Moon's shadow while in straight-and-level flight, right after making a small heading alignment change (as needed) to 168.5°. Thereafter, no change in heading (except as may be needed for wind compensation) should be made during the totality run itself, as following the time-correlated key waypoints that define the start, middle, and end, of the totality run (as would be loaded into the aircraft FMS) would take the aircraft optimally through the Moon's shadow. We suggest (from prior experiences) that the TR should begin 9 minutes prior to mid-eclipse (allowing minor navigational corrections for windage, if needed, and viewing the approach of the Moon' shadow (see Appendix A visualizations). I.e., for this baseline plan with an MEI at 03:36:00 UTC the entry (initial) waypoint for the Totality Run Start (TRS) is computed for 03:27:00 UTC. Similarly the exit (final) waypoint for the Totality Run End (TRE) is computed for mid-eclipse plus six minutes, i.e., 03:42:00 UTC.

The key time-correlated TR boundary waypoints, TRS, and TRE will depend upon the aircraft's ground speed during the totality run (MEI does not, as that is the immutable anchor for the TR). *For baseline planning purposes* (without further input at this point from AS flight planning services[1]), *we assume no wind* (so ground-speed = true airspeed) though this may not be the most likely scenario. In any case, to maintain the time-correlated TR (ground) track with wind, the pilot (and/or FMS/CDU) should compensate winds aloft within the allowable Mach range of the aircraft.

[1] If Alaska Airlines can (please) advise as to the most likely statistical winds aloft at approximately the MEI location for early March we can factor this into a recomputation of the baseline TR plan for higher precision and accuracy.

Also, for baseline planning purposes, we assume for the B737-800 aircraft at FL350 cruise a True Air Speed (TAS) = Mach 0.78 (without further input at this point from AS flight planning services[2]) = 447.4 kts (assuming a standard atmosphere model); and with a no-wind assumption TAS = ground speed.

[2] If Alaska Airlines can (please) advise as an alternate TAS for baseline planning (if not Mach 0.78) we can also factor this into the baseline TR plan for higher precision and accuracy.

During the TR itself, the pilot using *in situ* actual winds-aloft should adjust (to the extent possible) the true airspeed and heading to maintain the ground-track of the baseline totality run.

The Baseline "TOTALITY RUN" - Key Waypoints

The three key time-correlated waypoints (that are very close to a short great circle arc segment) that define the totality run by its start (TRS), middle (MEI) and end (TRE) are as follows:

Totality Run Waypoint	UTC (hh:mm:ss)	Aircraft Longitude	Aircraft Latitude
TRS	03:27:00	-156.41882°	+32.39963°
MEI	03:36:00	-156.15476°	+31.30356°
TRE	03:42:00	-155.98211°	+30.57244°

N.B.: The geodetic reference datum for all coordinates is WGS 84.

The Baseline "TOTALITY RUN" – Informational Details

Details (*information only!*) of the TR are provided (with one minute time granularity) in the table below, from which the above three key time-correlated waypoints above to be used in flight planning were extracted. The top section provides information about the intercept planning and the resulting eclipse visibility. The bottom section provides minute-by-minute information on the progression and geometry of the Moon's shadow, and of the aircraft track throughout the totality run.

The top left section of the header gives the key parametric inputs for the TR flight segment that are: the UTC of MEI, the aircraft flight altitude AMSL, the true heading at MEI (computed here to put the Sun straight out the right side windows), the aircraft TAS, and the assumed wind vector for the totality run (here assumed no wind.).

The top right section gives: the duration of the total phase of the eclipse as seen from the moving aircraft, the angular depression of the apparent horizon in degrees with respect to the astronomical horizon, and the eclipse circumstances for Contacts 2 and 3 (the start and end of totality) as seen from the aircraft. The UTCs, latitude, and longitude of contact 2 and contact 3 given are not inputs, but are computed based upon the totality run geometry.

The bottom section, for each UTC minute throughout the TR, gives information of the center of the lunar umbral shadow, and for the aircraft. For times after 03:37:00 UTC the Moon's shadow has left the Earth and those entries would have no meaning (so are not tabulated for those UTCs). For the center of the umbra, its UTC correlated lat/lon, the width of the path of totality, the speed of the shadow as projected onto a surface 35,000 ft AMSL, and the Sun's azimuth and altitude from those corresponding positions. (Note how the shadow velocity accelerates toward sunset and will be moving 18,500 km/hour at the time it overtakes the aircraft).

For the aircraft, most importantly, the UTC-correlated lat/lon waypoints for the TR are given. Only the first, middle and last need to be programmed into the aircraft FMS for execution. The column labeled MidΔT is the time in seconds from the UTC of MEI. The column labeled MidΔD gives the distance in nm the aircraft is from the MEI location. (These are useful numbers to watch on a FMS display in the run-up to totality and mid-eclipse). The column labeled LOS, is the line-of-sight deviation angle of the vector out the right-side windows to the sun (which is zero at MEI). The column labeled Brng is the aircraft bearing (true, not magnetic), and Azm, Alt is the azimuth and altitude angles of the Sun.

```
UTC Intercept: 03:36:00.0 | Totality Duration: 1m 53.5s (gain of 0m 01.4s with limb profile correction)
Flight Altitude:  35000ft | Horizon Dip: +3.3° (w.r.t. astronomical horizon, with atmospheric refraction)
True Heading:  168.45 deg | Cnt  hh:mm:ss.s  Alt°  Azm°    P°    Cnt  hh:mm:ss.s  Alt°  Azm°    P°
True Air Speed:  447.4 kt | 2nd  03:35:01.2 +10.5 258.3  54.8   3rd  03:36:54.7 +10.1 258.6 235.0
Wind Speed:        0.0 kt | Latitude:   31° 25' 09.4" N         Latitude:   31° 11' 16.2" N
Wind Direction:   0.0 deg | Longitude: 156° 10' 56.4" W         Longitude: 156° 07' 38.1" W
```

UTC	Umbra_Center						Aircraft							
Time HHMMSS	Longitude °	Latitude °	Width km	Speed km/h	Azm °	Alt °	Longitude °	Latitude °	MidΔT s	MidΔD nm	LOS °	Brng °	Azm °	Alt °
032700	-171.45207	+28.31022	121.4	6747.9	249.2	25.7	-156.41882	+32.39963	-540	-67.1	+1.6	168.31	256.8	12.1
032800	-170.31625	+28.59490	120.3	7136.5	250.0	24.4	-156.38917	+32.27788	-480	-59.7	+1.4	168.33	257.0	11.9
032900	-169.10503	+28.88640	119.1	7591.4	250.7	23.1	-156.35959	+32.15612	-420	-52.2	+1.3	168.34	257.2	11.7
033000	-167.80487	+29.18577	117.8	8133.5	251.5	21.8	-156.33010	+32.03436	-360	-44.7	+1.1	168.36	257.4	11.5
033100	-166.39762	+29.49448	116.5	8794.2	252.4	20.3	-156.30069	+31.91258	-300	-37.3	+0.9	168.37	257.6	11.3
033200	-164.85811	+29.81450	115.0	9623.4	253.4	18.7	-156.27135	+31.79079	-240	-29.8	+0.7	168.39	257.7	11.1
033300	-163.14954	+30.14875	113.4	10706.3	254.4	17.0	-156.24209	+31.66900	-180	-22.4	+0.5	168.40	257.9	10.9
033400	-161.21420	+30.50174	111.5	12203.9	255.5	15.1	-156.21291	+31.54719	-120	-14.9	+0.4	168.42	258.1	10.7
033500	-158.95170	+30.88132	109.4	14469.4	256.8	12.9	-156.18380	+31.42538	-60	-7.5	+0.2	168.43	258.3	10.5
033600	-156.15476	+31.30356	106.8	18500.4	258.5	10.2	-156.15476	+31.30356	+0	+0.0	-0.0	168.45	258.5	10.3
033700	-152.21167	+31.81571	103.3	29224.1	260.7	6.6	-156.12581	+31.18173	+60	+7.5	-0.2	168.47	258.6	10.1
033800	----.-----	---.-----	---.-	----.-	----.	--.-	-156.09692	+31.05989	+120	+14.9	-0.3	168.48	258.8	9.9
033900	----.-----	---.-----	---.-	----.-	----.	--.-	-156.06811	+30.93804	+180	+22.4	-0.5	168.49	259.0	9.6
034000	----.-----	---.-----	---.-	----.-	----.	--.-	-156.03937	+30.81618	+240	+29.8	-0.7	168.51	259.1	9.4
034100	----.-----	---.-----	---.-	----.-	----.	--.-	-156.01071	+30.69432	+300	+37.3	-0.9	168.52	259.3	9.2
034200	----.-----	---.-----	---.-	----.-	----.	--.-	-155.98211	+30.57244	+360	+44.7	-1.0	168.54	259.5	9.0

N.B.: See - Appendix A Baseline "TOTALITY RUN" Visualizations to assist in understanding the geometry of the eclipse path and aircraft intercept for this Totality Run.

***Minimum* (with No Wind) Time (Duration) Estimation from Take-off to TRS:**

With the totality run defined, we can now look at what take-off ("Wheel's-up", not pushback) UTC is required (without suggested **necessary additional margin**) from Anchorage to assure a critically on-time transition from the outbound cruise phase of the flight to the start of the TR. We make several informed assumptions here, but may be better constrained or informed with information that could be provided by Alaska Airlines flight planning services. Our estimations (detailed below) should be assessed and reviewed in that light.

(a) The *minimum* (great circle) distance from Anchorage (61.1742° N, 149.9983° W) to TRS (32.39963° N, 156.41882° W) is 1745.5 nm.

(b) We *estimate* the initial portion of the (end-to-end) length of that track, and the duration in time, for airport pattern departure and ascent (climb-out) to at-altitude cruise from recent historical flights as typically about 130 nm in 22 minutes.

(c) Thus, *after* an initial 22 minutes from "wheels up" (covering 130 nm) the at-altitude outbound cruise phase is appx 1615.5 nm to TRS.

(d) During the 1615.5 nm outbound cruise phase, to the TRS point, we assume a nominal TAS of Mach 0.78 (447.4 kts) as "typical" for a B737-800 at high-altitude cruise[3].

[3] If Alaska Airlines can (please) advise as an alternate TAS for baseline planning (if not Mach 0.78) we can also factor this into the baseline outbound cruise estimation for higher precision and accuracy.

(e) We do not know the historical winds during the outbound cruise. *We make a baseline planning assumption* here (which may not be a very good one, see important note on margin and contingency) of a net average "no wind" condition. With that assumption…

(f) The estimated 1615.5 nm outbound cruise at 447.4 kts would take 3.611 hours.

(g) to that we add the initial 22 minutes (0.367 hours) for PANC airport departure pattern and climb-out, for a total of 3.977 hours from take-off to reach the totality run start point.

(h) *N.B.*: prior to the initiation of the TR at the TRS, the aircraft will need to make a small (~ 12 degree) heading alignment maneuver (as a constant radius turn). We estimate this will appx 20 seconds.

(i) Thus the TOTAL *minimum* time, for a net "no-wind" condition throughout the outbound cruise then is 3.983 hours.

This would put the **latest** take-off (not pushback) time, ***without any margin*** for a possibly unfavorable wind, at 03:27:00 UTC - 3.983 hours = 23:28:02 UTC (March 8) or **2:28 PM AKST**

MARGIN and CONTINGENCY for Winds-Aloft and/or Take-Off Delay

The time-critical nexus of this flight is the start of the totality run at the time-correlated TRS waypoint, and with that following the time-correlated path TR path hitting waypoints MEI and TRE at the requisite times. The take-off UTC required to arrive at TRS at 03:27:00 UTC was estimated above assuming an exact (i.e., not delayed) take-off time with also a net no-wind condition during the outbound cruise. However, planning for such a "time-critical" take-off, ***without* contingency margin for either a take-off delay or unfavorable outbound winds aloft is most strongly *NOT* recommended**.

With either a take-off delay *OR* with an unfavorable (head) wind (slowing the aircraft ground speed beyond the range that could be compensated by increasing TAS), the aircraft could arrive at the TR start point (TRS waypoint) too late in UTC and thus miss the eclipse; I.e., the with Moon's shadow already having passed by before the aircraft reaches the path of totality. For either of these possible cases, a take-off **earlier** in UTC than a no-margin time-critical 23:28 UTC **must** be planned. This would then program into the outbound cruise phase a "buffer" to be utilized should either case arise. How much earlier needs to be discussed with Alaska Airlines, and in part would depend on what statistical variation in winds-aloft might be expected, but likely on the order of half an hour to 45 minutes. With a take-off time moved earlier than time-critical with no margin:

(1) In the case of a late take-off, any delay less then the margin added (by setting the planned take-off time earlier than critical), would then not put the eclipse intercept in jeopardy.

(2) In the case of unfavorable (head) winds aloft, the "extra" time allotted (to its limit) with an earlier take-off time can be used to allow the aircraft to reach the TRS waypoint at the requisite time.

Conversely, in the case of a "tail" wind, pushing the aircraft faster along its ground track to reach TRS too early (equally to be avoided!) either:

(1) the aircraft could simply slow down during outbound cruise to compensate, and/or

(2) deviate from a minimum distance path during outbound cruise with a longer distance to TRS to arrive at the requisite time.