Falcon Heavy's Maiden Launch Opens An Interplanetary Superhighway

The Falcon Heavy's inaugural launch from Kennedy Space Center LC-39A featured a novel payload described in the pertinent SpaceX press kit as follows.[1]

> The payload for Falcon Heavy's demonstration mission is SpaceX CEO and Lead Designer Elon Musk's midnight-cherry Tesla Roadster. Demonstration missions like this one typically carry steel or concrete blocks as mass simulators, but SpaceX decided it would be more worthwhile to launch something fun and without irreplaceable sentimental value: a red Roadster for the red planet. Following launch, Falcon Heavy's second stage will attempt to place the Roadster into a precessing Earth-Mars elliptical orbit around the sun.

The nature of "a precessing Earth-Mars elliptical orbit around the sun" started to become clear when Elon Musk supplied a heliocentric trajectory plot reproduced in Figure 1.

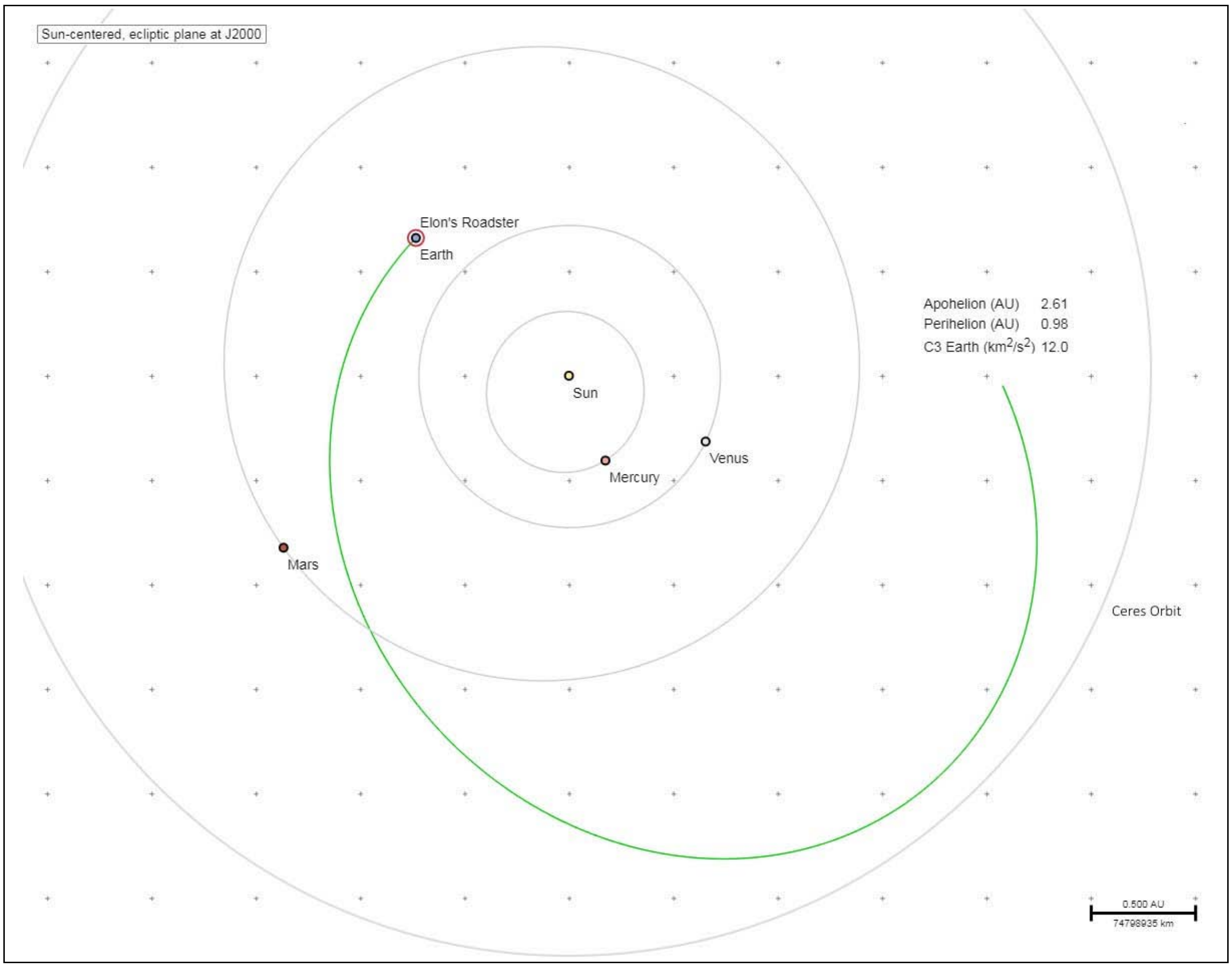

Figure 1. Although this SpaceX heliocentric trajectory plot was made public after Falcon Heavy's launch, the Tesla Roadster payload's trajectory (in green) is inconsistent with the *C3* = 12 km^2/s^2 annotation and only approximates the as-flown orbit after Earth departure.

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[1] Reference "Falcon Heavy Demonstration Mission", downloadable at http://www.spacex.com/sites/spacex/files/falconheavypresskit_v1.pdf, (accessed 10 February 2018).

This paper summarizes results from an effort to reconstruct the Roadster payload's as-flown trajectory following Falcon Heavy launch. Milestones associated with this reconstruction appear in Table 1.

Table 1. Major trajectory events for Falcon Heavy's demonstration mission are listed in chronologic order. The two reconstructed second stage burns, called "apogee adjust" (AA) and "deep space injection" (DSI), are simulated as impulsive events in which a change-in-velocity of magnitude Δv is instantaneously applied. Orbit apsis heights above a spherical Earth with radius 6378 km are annotated "HA x HP". The mission elapsed time (MET) column displays time in hh:mm:ss since launch for each event.

2018 Feb 6-7 UT	MET	Event
20:45:00	00:00:00	Launch
20:53:31	00:08:31	Parking orbit insertion: HA x HP = +183 x +183 km
21:13:46	00:28:46	AA: Δv = 1.227 km/s, burnout HA x HP = +6949 x +183 km
22:36:19.402	01:51:19	Two-line-elements (TLE) epoch T_{TLE}
02:29:50	05:44:50	DSI: Δv = 2.743 km/s

Launch UT is obtained from the Roadster trajectory description posted to JPL's *Horizons* ephemeris server[2] with a revision date of 9 February 2018. Parking orbit insertion UT is inferred from MET = 00:08:31 appearing in the SpaceX press kit previously cited.

Critical to reconstruction of all remaining Table 1 events are the following TLE obtained from https://www.space-track.org for epoch T_{TLE}.

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1 43205U 18017A   18037.94189123  .00000283 -50857-6  00000+0 0  9991
2 43205  29.0185 287.3580 3404246 180.0270 180.5840  8.75540848    00
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The foregoing data associate epoch T_{TLE} with an orbit count $n = 0$. If the launch epoch is defined as having $n = 1$, T_{TLE} is immediately after the Roadster's first post-launch ascending node on Earth's equator (geodetic latitude at T_{TLE} is 0.142° N) such that n is actually 2. With the TLE argument of perigee $\omega = 180°$, T_{TLE} is also near the first post-AA apogee (inertial flight path angle $\gamma = -0.172°$ at T_{TLE}).

When the osculated TLE are coasted[3] backward in time to the first perigee, the associated epoch is assumed to be that of the AA impulse. This assumption is corroborated by the SpaceX press kit. It shows the AA burn arc nominally beginning at 00:28:22 MET and ending at 00:28:52 MET with the Table 1 AA impulse a satisfactory 80% into this interval with respect to its start.

The backward coast to AA also produces an orbit height of +183 km. This is assumed to be the circular orbit height between parking orbit insertion and AA, as documented in Table 1. That

[2] Reference https://ssd.jpl.nasa.gov/?horizons (accessed 10 February 2018).
[3] Before and after DSI, a Roadster orbital coast is simulated with the GEM10 gravity model truncated to 7th degree and order, together with third body gravity accelerations from the Moon and Sun. No atmospheric drag accelerations are simulated.

assumption produces a purely prograde estimate for AA Δv in Table 1. Figure 2 plots the Roadster's ground track in this circular orbit from the launch site through the AA impulse to half an orbit past T_{TLE}.

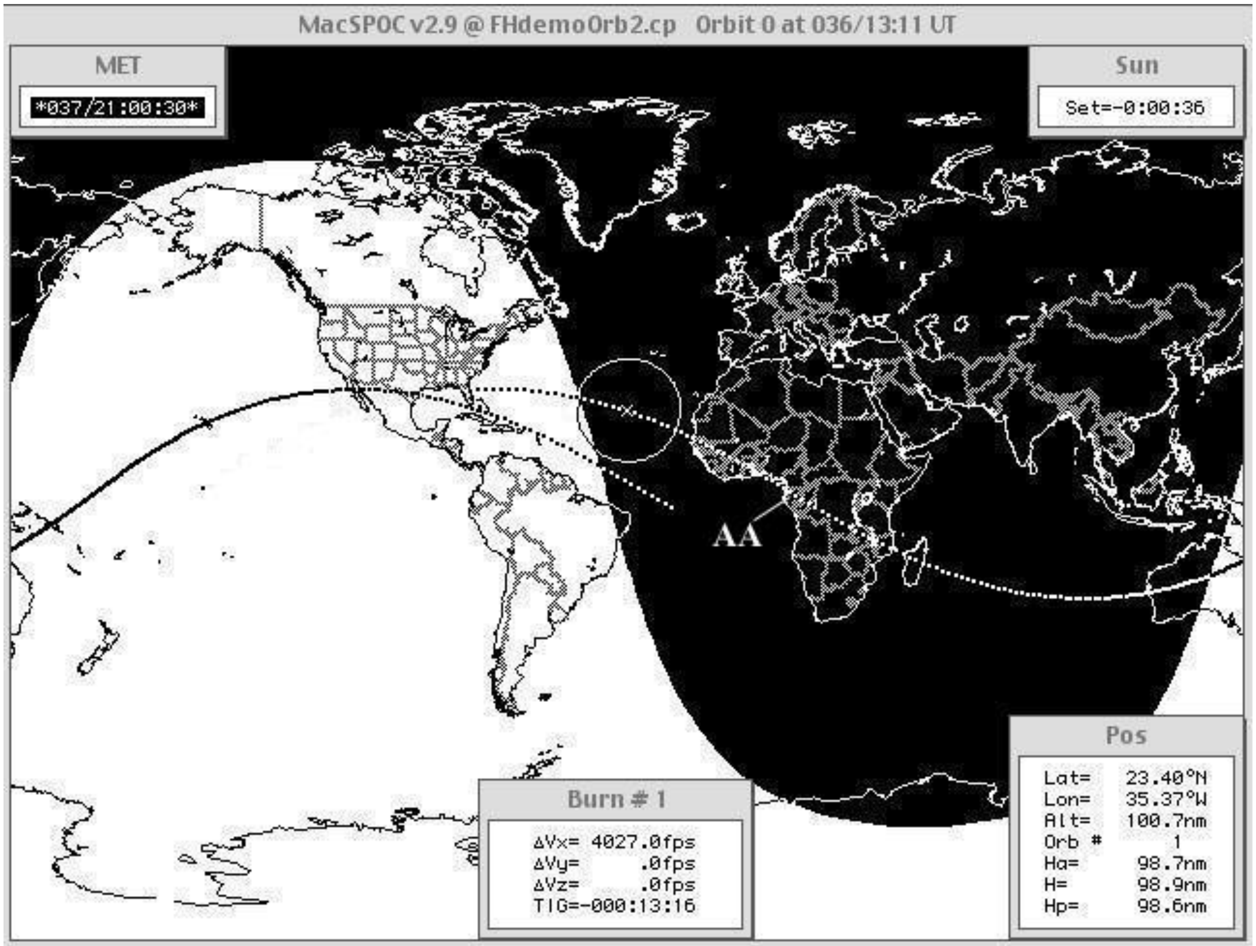

Figure 2. The Roadster ground track is plotted with two-pixel-square markers at 30-s intervals from launch through the Table 1 AA impulse and for a half-orbit thereafter. Note how these markers merge over the Pacific Ocean in the vicinity of apogee and T_{TLE}. All digital displays are synchronized with the "current" Roadster nadir denoted by a small "X" off the West Africa coast. This nadir location is circumscribed with a circle confined to the East Atlantic Ocean and corresponding to the Roadster's current Earth horizon. As indicated by reverse-field white-on-black world map features, the current nadir is also on Earth's nightside. Note the "MET" window is configured to display UT in DOY/hh:mm:ss format, with DOY = 037 corresponding to 6 February.[4]

Reconstruction of the DSI impulse begins with the statement "a third burn by the second stage was completed at approximately 02:30 UTC Feb 7" appearing in the previously cited Roadster trajectory description on *Horizons*. This trajectory is based on "128 ground-based optical astrometric measurements spanning 2018 Feb 8.2 to 9.5" called "tesla_s5", and it commences

[4] Day-of-year (DOY) is an ordinal count of days in a particular calendar year beginning with 001 on January 1 and ending with 365 on December 31 (or 366 in a leap year).

with epoch T_2 on 7 February 2018 at 02:58:50.815 UT. Iterative coasts forward in time from T_{TLE} to plausible impulsive DSI epochs T_1 are then performed to establish boundary values for a perturbed Lambert solution best estimating DSI burnout velocity. After the DSI impulse, each such solution is required to coast and intercept tesla_s5 position at epoch T_2 within 0.001 km.

An ideal perturbed Lambert solution for DSI burnout velocity would have $\Delta v = 0$ when coasted to T_2 and compared with tesla_s5 velocity at that epoch. For the Table 1 T_1 = 02:29:50 UT, this Δv residual at T_2 is nearly minimal at 0.068 km/s. The ground track resulting from this reconstruction before and after the DSI impulse appears in Figure 3.

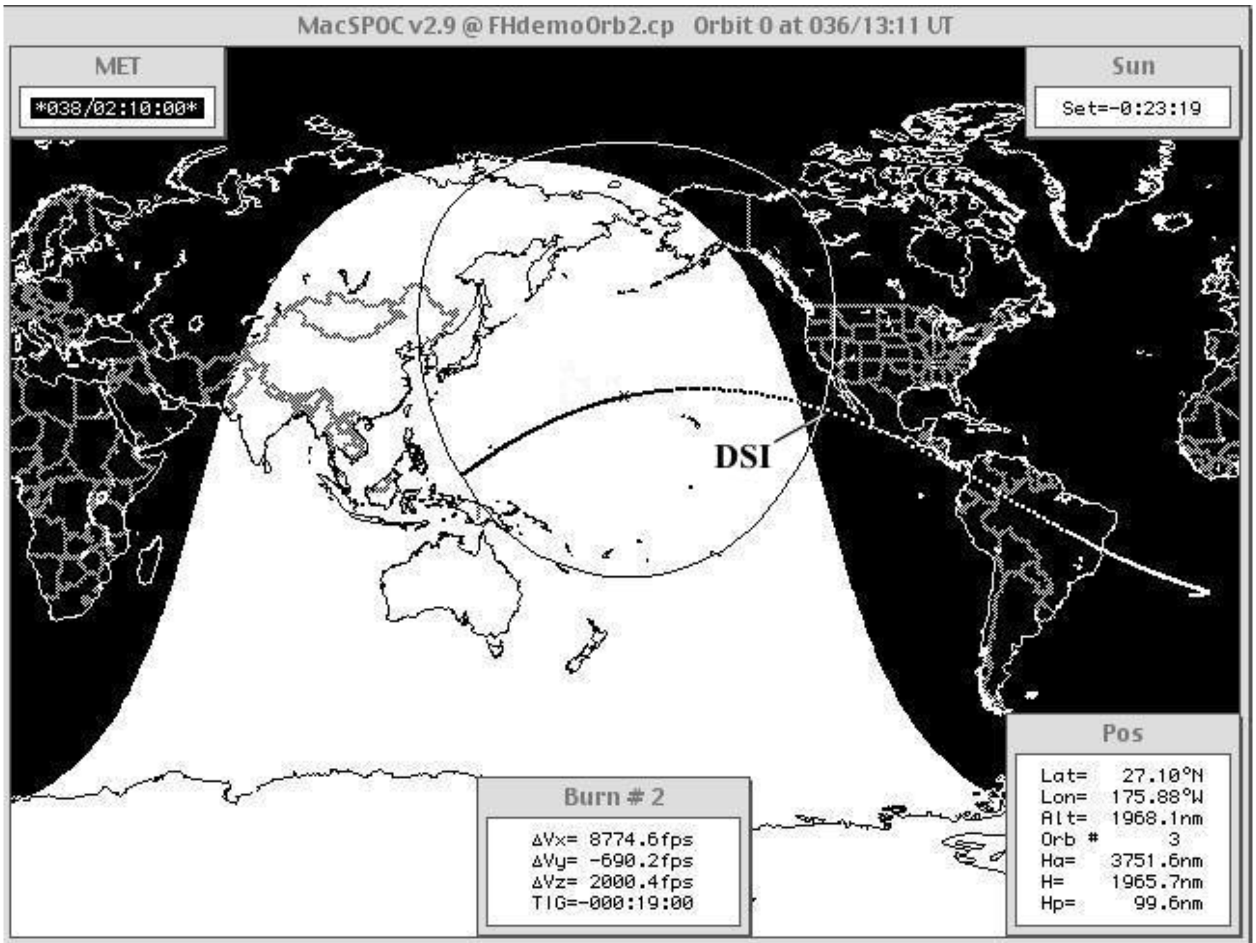

Figure 3. Note the greatly increased post-AA altitude in the "Pos" window, and its affect on the Roadster's horizon locus, with respect to Figure 2's current Roadster position. After the DSI impulse, the Roadster's eastward motion over the South Atlantic Ocean reverses as the payload recedes into deep space.

A coast from T_{TLE} to T_1 = 02:29:50 UT indicates DSI is performed significantly prior to perigee at a γ = -14° (a no-DSI coast reaches n = 3 perigee at 2:42:48 UT). The impulsive approximation also contains appreciable out-of-plane (0.211 km/s northward) and radial (0.376 km/s downward) velocity-to-be-changed components. These departures from a theoretically ideal prograde impulse at perigee are attributable to TLE orbit determination errors, TLE osculation errors, coast modeling errors, the impulsive approximation of a finite burn arc, DSI steering errors, and a presumed desire to accommodate short DSI ignition delays by planning the burn prior to its optimal time.

Earth departures for Mars and other superior planets tend to be in the direction of our planet's heliocentric motion. The Moon lies nearest this direction when at last quarter, and that phase falls on 7 February 2018 at 15:54 UT.[5] Figure 4's geocentric plot of the tesla_s5 trajectory posted to *Horizons* shows the Roadster does indeed depart Earth in roughly the Moon's direction.

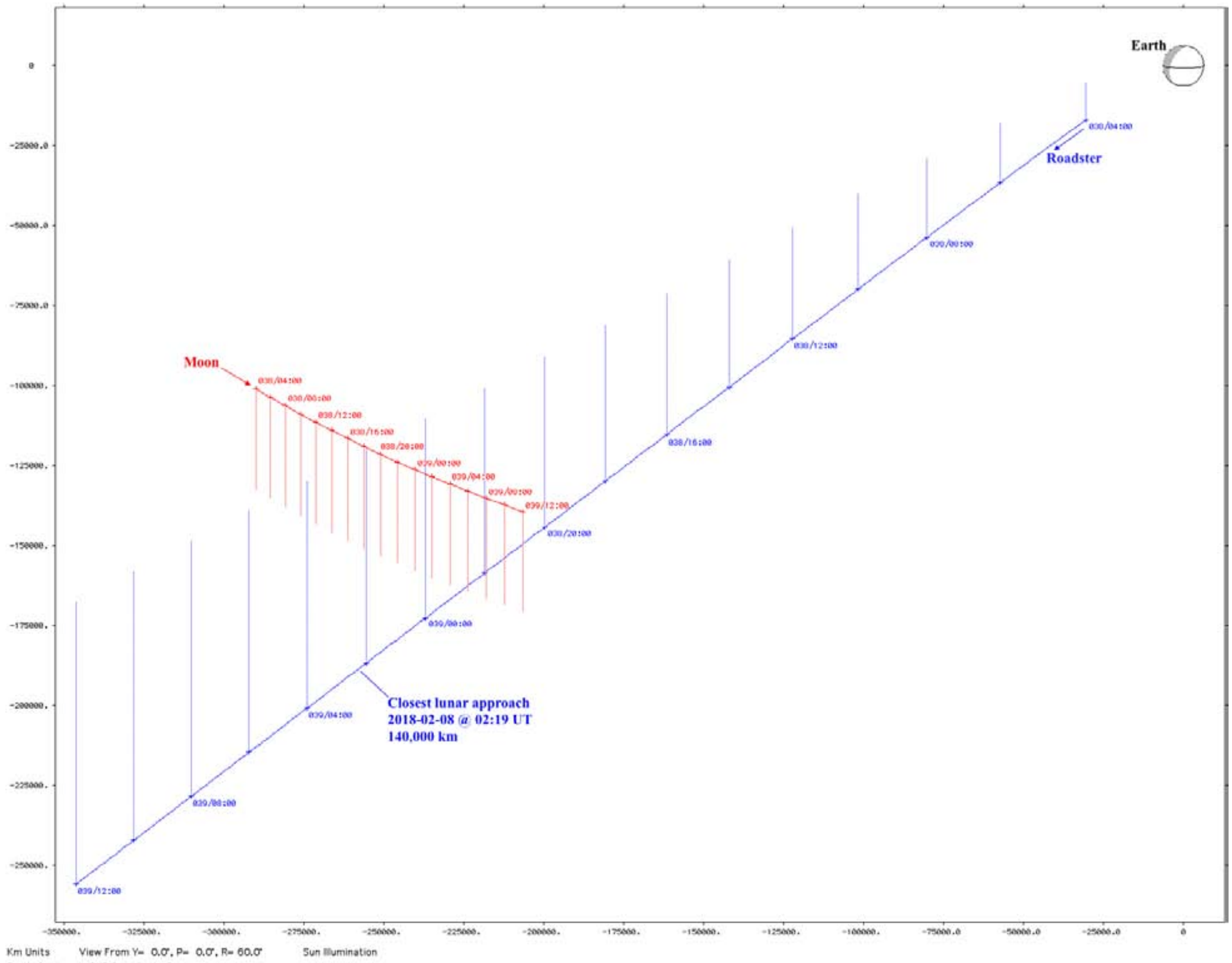

Figure 4. Roadster geocentric motion during Earth departure (blue) is plotted together with that of the Moon (red). Time ticks ("+" markers) appear at 2-hour intervals and are annotated with UT in DOY/hh:mm format every 4 hours (DOY = 038 is 7 February). Dotted lines are projections onto the ecliptic plane, and the shaded area on Earth is its nightside.

The tesla_s5 geocentric state vector at epoch T_2 has an asymptotic Earth departure speed of 3.454 km/s. Squaring this speed produces $C3$ = 11.927 km^2/s^2, 99.4% of the corresponding SpaceX value annotated in Figure 1. Sampling a heliocentric state vector from the tesla_s5 ephemeris in late 2018, when the Roadster is far from any planet's perturbations to its solar orbit, shows its

[5] Reference the calculator at http://aa.usno.navy.mil/data/docs/MoonPhase.php (accessed 11 February 2018).

first aphelion will be at a heliocentric distance of 1.6637 AU, only 63.7% of the corresponding SpaceX value annotated in Figure 1. An authoritative explanation for the apparent inconsistency between Figure 1's *C3* and aphelion annotations is beyond the scope of this paper, but it is thought to arise from computing Roadster aphelion using a heliocentric state vector less than two hours after DSI. This computational error's implications are illustrated in Figure 5.

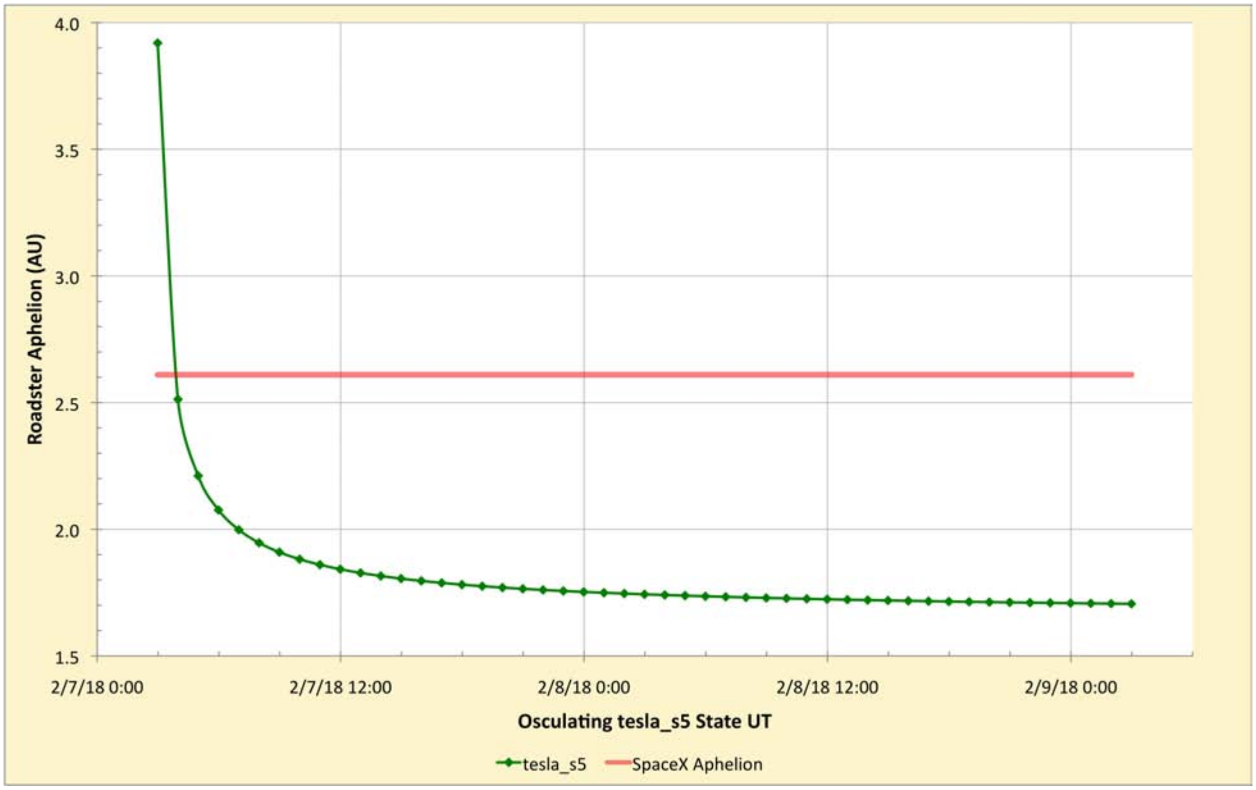

Figure 5. Osculating Roadster aphelion is rapidly decreasing (green) in the hours after DSI as Earth's gravity significantly retards heliocentric motion. The Figure 1 aphelion value (red) likely was computed from a heliocentric Roadster state vector at a UT where the two lines cross less than 1.5 hours after DSI. This computation would achieve far greater accuracy with the Roadster in interplanetary space weeks or months after DSI, as described in the narrative's previous paragraph.

Figure 6 is a heliocentric plot of the Roadster's tesla_s5 ephemeris ending in July 2019 near completion of its first 557-day solar orbit. Heliocentric motion of Mars and the Earth during this interval are added to Figure 6 for scale and to facilitate comparison with Figure 1.

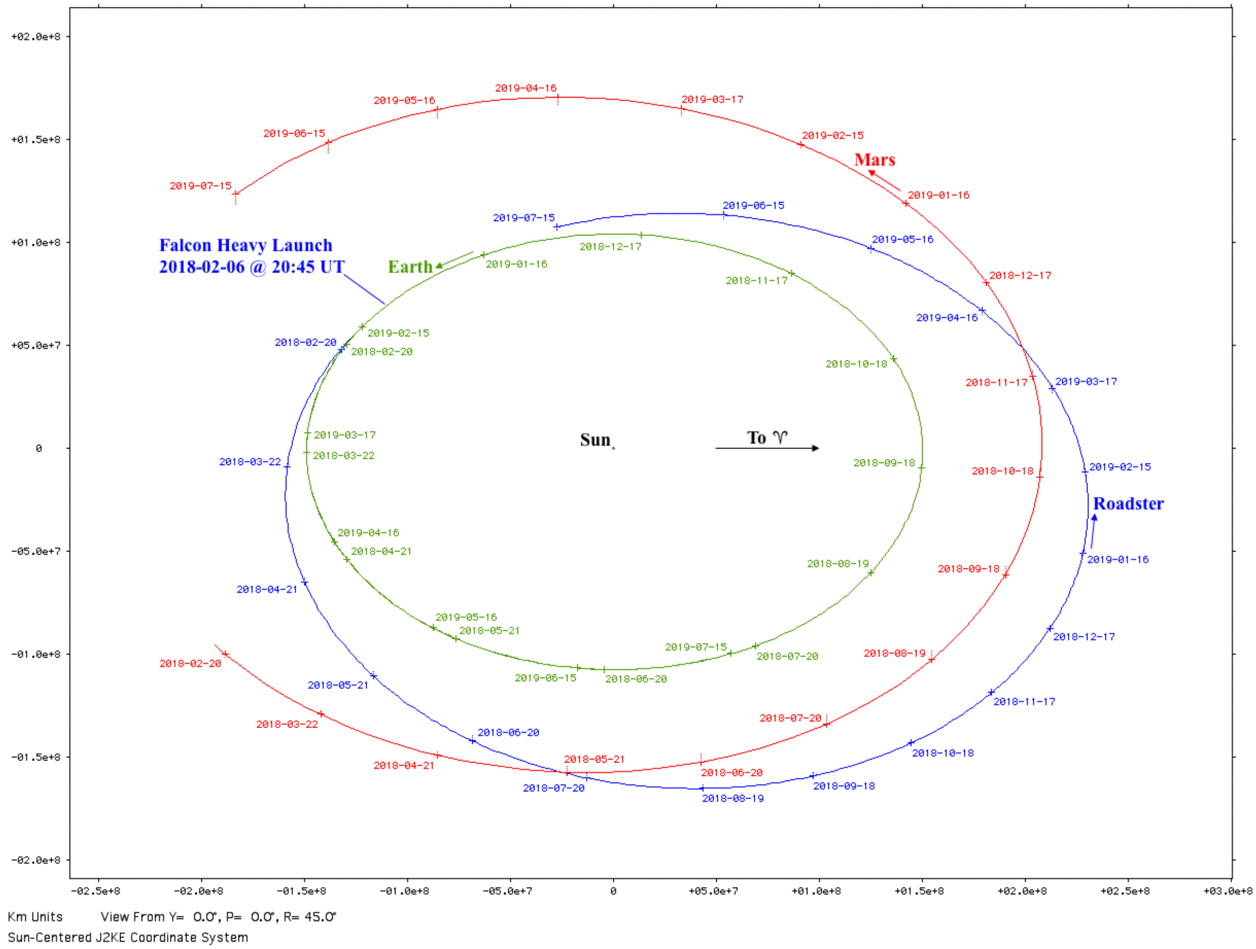

Figure 6. Roadster heliocentric motion during its first 17 months in solar orbit (blue) is plotted along with that of Earth (green) and Mars (red). Orbit shapes in the plot appear "squashed" in the vertical direction by a perspective 45° from normal to the ecliptic plane.[6] This perspective reveals dotted projection lines onto the ecliptic plane from each position marker at 30-day intervals. The shortness of these projections on this scale indicates the three orbits are nearly coplanar. Roadster inclination to the ecliptic is 1.08° and that of Mars is 1.85°. Position markers are at 00:00 UT for the corresponding annotated date in YYYY-MM-DD format.

Horizons processing of the tesla_s5 ephemeris for Roadster planetary approaches closer than 0.1 AU before 2048 produces Mars encounters on 7 October 2020 and 22 April 2035, together with an Earth encounter on 11 January 2047. Due to the short Roadster observation arc associated with tesla_s5, these encounters are highly uncertain, and others not reported may arise with further orbit determination refinement. Continued observations with the most sensitive Earth-based telescopes may be possible into April 2018, but the Roadster tallies very nearly 2

[6] The "To ♈" direction in Figure 6 points toward ecliptic longitude zero. Perspective in Figure 6 is from a viewpoint at ecliptic longitude 270° (reckoned as a counterclockwise rotation from the ♈ direction) and 45° ecliptic N latitude.

heliocentric orbits in the same time Earth makes 3.[7] Prospects for additional orbit refinement are therefore poor until early 2021.

Due to the nearly coplanar geometry among orbits plotted in Figure 6, collisions between the Roadster and Earth or Mars cannot be ruled out. The Roadster and attached Falcon Heavy second stage would likely be totally incinerated by entry into Earth's atmosphere and pose no threat to lives or property on our planet. But the threat to hypothesized extant life on Mars posed by an impacting Roadster could be an incalculable disaster to astrobiology and humanity's stewardship of our planetary neighbor. Was the Roadster subject to planetary protection protocols requiring decontaminating before launch? Why was it necessary to launch the Roadster so close to the ecliptic plane? At $C3$ = 12 km^2/s^2, it would be possible to achieve ecliptic inclinations up to 6.6°. A draft paper published 14 February 2018 and titled "The Random Walk Of Cars And Their Collision Probabilities With Planets"[8] finds higher inclinations "are more likely to escape the terrestrial planet zone" and thereby evade collisions with these bodies.

When the Space Age dawned, humanity failed to anticipate the proliferation of artifacts in Earth orbit only a few decades afterward, together with collision threats these objects pose to each other and every new launch. Falcon Heavy's first launch may be setting a poorly informed interplanetary precedent in this regard. The "fun" SpaceX associates with "a red Roadster for the red planet" in the press kit quote at the start of this paper is undeniable. But with fun in space operations also comes responsibility. Responsible space operations require bearing in mind Ian Malcolm's admonition from the *Jurassic Park* movie (italics added for emphasis): "Your scientists were so preoccupied with whether or not they *could*, they didn't stop to think if they *should*."[9]

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[7] This orbit motion resonance is evident in Figure 6. As the Roadster nears perihelion in July 2019, note how Earth is across the solar system from it, having made 1.5 orbits since Falcon Heavy launch.
[8] This draft can be downloaded at https://arxiv.org/pdf/1802.04718.pdf (accessed 16 February 2018).
[9] Reference https://www.rottentomatoes.com/m/jurassic_park/quotes/ (accessed 12 February 2018).