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2018 MARS INSIGHT TRAJECTORY RECONSTRUCTION AND PERFORMANCE FROM LAUNCH THROUGH LANDING

Fernando Abilleira[*], Allen Halsell[†], Gerard Kruizinga[‡], Eugene Bonfiglio[§], Robert Grover[**], Min-Kun Chung[††], Ken Fujii[‡‡], Eric Gustafson[§§], Yungsun Hahn[***], David Jefferson[†††], Eunice Lau[‡‡‡], Julim Lee[§§§], Sarah Elizabeth McCandless[****], Neil Mottinger[††††], Jill Seubert[‡‡‡‡], Evgeniy Sklyanskiy[§§§§], Mark Wallace[*****]

The InSight mission successfully launched to Mars on an Atlas V 401 launch vehicle from the Western Test Range (WTR) at Vandenberg Air Force Base (VAFB) at 04:05:00 PDT on May 5th, 2018 and landed in the Elysium Planitia Region on November 26th, 2018. Data confirming nominal touchdown was received at 11:52:59 AM PST. This paper summarizes in detail the actual vs. predicted performance of the InSight spacecraft and all associated assets in terms of launch vehicle events, injection performance, DSN performance, cruise performance, and Entry, Descent, and Landing events.

INTRODUCTION

The Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport (InSight) Mission has the primary objective of placing a science lander on the surface of Mars followed by the deployment of two science instruments onto the Martian surface to investigate the fundamental processes of terrestrial-planet formation and evolution.

A nominal injection imparted by the Atlas V launch vehicle, small maneuver execution errors, and accurate orbit determination solutions were critical to precisely deliver the InSight spacecraft to the correct Mars atmospheric Entry Interface Point (EIP) for a safe landing within ~14 km from its intended target.

LAUNCH PERIOD

The InSight launch period extended from May 5th, 2018 through June 8th, 2018. The launch/arrival strategy was developed to provide Entry, Descent, and Landing communications from entry to the landing target located in the Elysium Planitia region via Direct-To-Earth (DTE) and the Mars Reconnaissance Orbiter (MRO) using the Ultra High Frequency (UHF) link. The launch period was optimized to keep MRO's node

[*] InSight Deputy Mission Manager, Fernando.Abilleira@jpl.nasa.gov
[†] Navigation Team Chief, Charles.A.Halsell@jpl.nasa.gov
[‡] InSight Deputy Navigation Team Chief, Gerhard.L.Kruizinga@jpl.nasa.gov
[§] InSight EDL Systems Engineer, Eugene.Bonfiglio@jpl.nasa.gov
[**] InSight EDL Team Lead, Myron.R.Grover@jpl.nasa.gov
[††] InSight Maneuver Analyst, Min-Kun.Chung@jpl.nasa.gov
[‡‡] InSight Mission Planning Lead, Kenneth.K.Fujii@jpl.nasa.gov
[§§] InSight Orbit Determination Lead, Eric.D.Gustafson-133274@jpl.nasa.gov
[***] InSight Maneuver Analyst, Yungsun.Hahn@jpl.nasa.gov
[†††] InSight Orbit Determination Analyst, David.C.Jefferson@jpl.nasa.gov
[‡‡‡] InSight Orbit Determination Analyst, Eunice.L.Lau@jpl.nasa.gov
[§§§] InSight Orbit Determination Analyst, Julim.Lee@jpl.nasa.gov
[****] InSight Orbit Determination Analyst, Sarah.E.McCandless@jpl.nasa.gov
[††††] InSight Orbit Determination Analyst, Neil.Mottinger@jpl.nasa.gov
[‡‡‡‡] InSight Orbit Determination Analyst, Jill.Tombasco@jpl.nasa.gov
[§§§§] InSight EDL Trajectory Analyst, Evgeniy.Sklyanskiy@jpl.nasa.gov
[*****] InSight Trajectory Lead, Mark.S.Wallace@jpl.nasa.gov
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

close to its nominal Local Mean Solar Time (LMST) node of 3:00 PM (ascending) at the time of arrival (note that the actual LMST target submitted to MRO was 2:52 PM to further improve EDL communications). Other primary constraints in the design included the maximum hyperbolic excess at arrival (V_∞). The launch/arrival strategy is shown in Figure 1. The arrival date on November 26, 2018 (UTC) was maintained constant for all launch days and the actual entry time only varied ~15 min across the launch period. This strategy provided good UHF relay communications support during EDL via MRO. UHF DTE 8 kbps tones were available through landing.

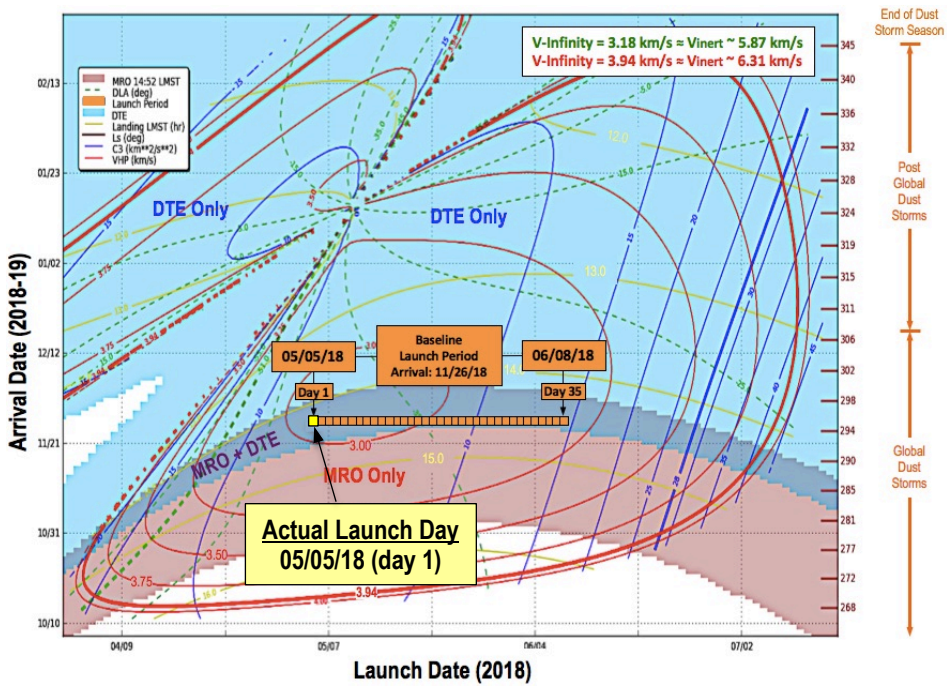

Figure 1. InSight Launch/Arrival Strategy

LAUNCH WINDOW AND LIFTOFF TIMES

The launch window is a continuous, finite period of time during which the launch vehicle can liftoff and deliver the spacecraft to the desired targets. The variable declination of the departure asymptote, the location of the launch site (latitude = 34.446 deg), a fixed launch azimuth of 158.0 deg, launch vehicle ascent trajectory capabilities, and available launch vehicle performance were the primary factors for determining the duration of the launch window

The available propellant for the trans-Mars injection burn by the Centaur upper stage was limited by propellant reserves to account for lower-than-expected launch vehicle performance, launch vehicle weight uncertainties, and environmental variation effects. For InSight, the Flight Performance Reserve (FPR) propellant reserved was 157 kg whereas the Launch Vehicle Contingency (LVC) expendable propellant allocated also was 157 kg. The daily launch windows were dependent upon the selected launch strategy (fixed azimuth, variable azimuth, upper stage trajectory shaping, etc.). Determination of the daily launch window defined the liftoff time for a given launch opportunity. The right ascension of the launch asymptote (RLA) was the primary determinant of liftoff time. Launch opportunities occurred every five minutes, with window middle chosen as the whole minute at the zero or five-minute mark closest to the optimal launch time (i.e. window middle was within 2.5 minutes of the optimal launch time).

For InSight, the launch window analyzed for each day consisted of a maximum of 25 instantaneous launch opportunities spread across a 2-hour window. Those opportunities were analyzed and the ones that did not meet all requirements were excluded. For InSight, all days in the launch period had between 23 and 25 instantaneous launch opportunities spread across a 115 - 120 min launch window.

Launch vehicle rollout occurred on May 4th at 11:37 PM PDT in preparation for the open of the launch period. InSight successfully launched on May 5th at 4:05 AM PDT (11:05 UTC) which corresponded to the

launch window open time on launch day 1. Table 1 and Figure 2 provide the final launch times and launch windows for each day in the launch period. Note that launch windows for all days were calculated assuming a spacecraft mass of 700.5 kg; although, the final spacecraft mass was 688.6 kg

Table 1. Launch Windows, Launch Times, and Launch Window Duration

Universal Time Coordinated (UTC)			United States Daylight Savings Local Time				Total Window Duration (hh:mm)	Launch Opps
			PDT (UTC -7 hours)		MDT (UTC- 6 hours)			
Window Open Date (2018, mm/dd)	Open	Close	Open	Close	Open	Close		
	(hh:mm)		(hh:mm)		(hh:mm)			
05/05	11:05	13:05	4:05	6:05	5:05	7:05	2:00	23
05/06	10:55	12:55	3:55	5:55	4:55	6:55	2:00	24
05/07	10:50	12:50	3:50	5:50	4:50	6:50	2:00	25
05/08	10:40	12:40	3:40	5:40	4:40	6:40	2:00	25
05/09	10:35	12:35	3:35	5:35	4:35	6:35	2:00	25
05/10	10:30	12:30	3:30	5:30	4:30	6:30	2:00	25
05/11	10:20	12:20	3:20	5:20	4:20	6:20	2:00	25
05/12	10:15	12:15	3:15	5:15	4:15	6:15	2:00	25
05/13	10:10	12:05	3:10	5:05	4:10	6:05	1:55	24
05/14	10:00	12:00	3:00	5:00	4:00	6:00	2:00	25
05/15	9:55	11:50	2:55	4:50	3:55	5:50	1:55	24
05/16	9:45	11:45	2:45	4:45	3:45	5:45	2:00	25
05/17	9:40	11:40	2:40	4:40	3:40	5:40	2:00	25
05/18	9:35	11:30	2:35	4:30	3:35	5:30	1:55	24
05/19	9:25	11:25	2:25	4:25	3:25	5:25	2:00	25
05/20	9:20	11:20	2:20	4:20	3:20	5:20	2:00	25
05/21	9:10	11:10	2:10	4:10	3:10	5:10	2:00	25
05/22	9:05	11:05	2:05	4:05	3:05	5:05	2:00	25
05/23	9:00	11:00	2:00	4:00	3:00	5:00	2:00	25
05/24	8:50	10:50	1:50	3:50	2:50	4:50	2:00	25
05/25	8:45	10:45	1:45	3:45	2:45	4:45	2:00	25
05/26	8:40	10:40	1:40	3:40	2:40	4:40	2:00	25
05/27	8:35	10:35	1:35	3:35	2:35	4:35	2:00	25
05/28	8:30	10:30	1:30	3:30	2:30	4:30	2:00	25
05/29	8:25	10:25	1:25	3:25	2:25	4:25	2:00	25
05/30	8:20	10:20	1:20	3:20	2:20	4:20	2:00	25
05/31	8:10	10:10	1:10	3:10	2:10	4:10	2:00	25
06/01	8:05	10:05	1:05	3:05	2:05	4:05	2:00	25
06/02	8:00	10:00	1:00	3:00	2:00	4:00	2:00	25
06/03	7:55	9:55	0:55	2:55	1:55	3:55	2:00	25
06/04	7:50	9:50	0:50	2:50	1:50	3:50	2:00	25
06/05	7:45	9:45	0:45	2:45	1:45	3:45	2:00	25
06/06	7:40	9:40	0:40	2:40	1:40	3:40	2:00	25
06/07	7:35	9:35	0:35	2:35	1:35	3:35	2:00	25
06/08	7:30	9:30	0:30	2:30	1:30	3:30	2:00	25

Notes:
- Launch window duration constrained by launch vehicle performance except where noted below.
- 05/05 (11:50 UTC and 11:55 UTC) and 05/06 (11:45 UTC) have window cutouts due to Centaur mandatory coverage violations.

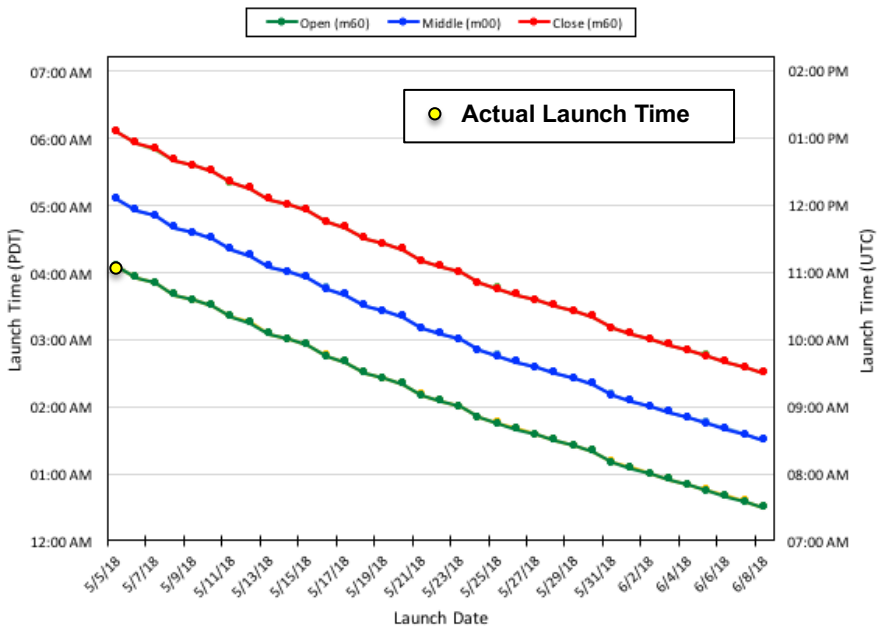

Figure 2. Launch Windows and Launch Times

LAUNCH VEHICLE EVENTS

On the ground, the RD-180 engine system (a single set of turbo machinery with 2 thrust chambers) was ignited to provide thrust for liftoff. Booster flight continued in this closed-loop phase until sensors detected propellant depletion which occurred ~244 sec after liftoff. Centaur separation occurred ~6 seconds after Booster Engine Cutoff (BECO). Both Common Core Booster (CCB) ascent and Centaur separation were nominal. A nearly eight-minute burn by the Centaur put the spacecraft into the desired 185 km altitude, 64 deg inclination parking orbit. After the ~66 min coasting period, a second burn of the Centaur RL-10 engine injected the spacecraft into the interplanetary transfer trajectory. Spacecraft separation took place 540 sec after this second burn once the Centaur maneuvered into the spacecraft separation attitude. The flight performance of the launch vehicle was outstanding and the InSight spacecraft separated within one second of the nominal time. Table 2 shows the expected vs. the actual event time from Go-Inertial command to spacecraft separation.

Table 2. Planned vs. Actual Launch Vehicle Time Events

Event	Expected Time (sec)	Actual Time (sec)	Actual Time (min:sec)	Delta (sec)
Guidance Go-Inertial	-7.960	-7.960	-7.960	0.000
T-Zero	0.000	0.000	00:01.070	0.000
Liftoff (T/W > 1)	0.000	0.000	00:01.070	0.000
BECO	244.280	244.680	04:04.680	0.400
Atlas/Centaur Separation	250.280	250.688	04:10.688	0.408
MES1	260.260	260.680	04:20.680	0.420
Payload Fairing Jettison	268.260	268.700	04:28.700	0.440
MECO1	796.103	798.620	13:18.620	2.517
Burn-1 Duration	535.843	537.940		2.097
MES2	4736.780	4738.320	18:58.320	1.540
MECO2	5059.733	5060.460	24:20.460	0.727
Burn-2 Duration	322.953	322.140		-0.813
InSight Separation	5599.760	5600.500	33:20.500	0.740
MarCO-A Separation	5633.760	5634.531	33:54.531	0.771
MarCO-B Separation	5681.760	5682.531	34:42.531	0.771

Notes:
- T/W = Thrust/Weight ratio. BECO = Booster Engine CutOff. MES-1 = Main Engine Start #1.
MES-2 = Main Engine Start #2. MECO-1 = Main Engine CutOff #1; MECO-1 = Main Engine CutOff #2
MarCO = Mars Cubesat One spacecraft

INJECTION ACCURACY

The injection targets specified as twice the hyperbolic injection energy per unit mass (C3), declination of the launch asymptote (DLA), and right ascension of the launch asymptote (RLA) at the Targeting Interface Point were generated using open-loop entry trajectories targeted to the center of the E09 ellipse located in the Elysium Planitia region (areocentric latitude = 4.460 deg, East longitude = 135.970). These targets were held constant across each daily launch window and are shown in Table 3. The injection targets also satisfied two planetary protection requirements: (1) The probability of impact of Mars in the next 50 years by the launch vehicle shall not exceed 10^{-4} and (2) the probability of non-nominal impact of Mars due to failure during the cruise and approach phases which shall not exceed 10^{-2}. This was achieved by biasing the injection aimpoint and using Trajectory Correction Maneuvers (TCMs) during cruise to remove the injection bias. Due to the good injection imparted by the Centaur, and small maneuver execution and orbit determination errors, a combined TCM-1/TCM-2 optimization strategy was able to remove all the injection biasing.

Table 3. Injection Targets

Launch Day	Launch Date (2018, UTC)	Earth Centered EME2000		
		C3 (km^2/s^2)	DLA (deg)	RLA (deg)
1	05/05	8.197	-40.829	328.132
2	05/06	8.063	-40.427	326.878
3	05/07	7.942	-39.899	325.471
4	05/08	7.856	-39.286	324.213
5	05/09	7.795	-38.749	323.070
6	05/10	7.752	-38.274	321.945
7	05/11	7.727	-37.846	320.817
8	05/12	7.720	-37.447	319.683
9	05/13	7.731	-37.069	318.548
10	05/14	7.762	-36.706	317.416
11	05/15	7.813	-36.353	316.297
12	05/16	7.882	-35.958	315.186
13	05/17	7.974	-35.571	314.139
14	05/18	8.085	-35.237	313.071
15	05/19	8.215	-34.863	312.067
16	05/20	8.375	-34.670	311.139
17	05/21	8.543	-34.350	310.231
18	05/22	8.727	-34.036	309.367
19	05/23	8.925	-33.729	308.545
20	05/24	9.138	-33.432	307.765
21	05/25	9.365	-33.143	307.022
22	05/26	9.606	-32.864	306.315
23	05/27	9.851	-32.457	305.563
24	05/28	10.130	-32.334	305.007
25	05/29	10.415	-32.089	304.412
26	05/30	10.719	-31.871	303.869
27	05/31	11.042	-31.743	303.402
28	06/01	11.350	-31.930	302.705
29	06/02	11.651	-31.447	301.593
30	06/03	12.035	-30.998	301.152
31	06/04	12.436	-30.715	300.728
32	06/05	12.856	-30.473	300.297
33	06/06	13.297	-30.247	299.874
34	06/07	13.763	-30.029	299.466
35	06/08	14.255	-29.817	299.079

The maximum launch energy (C3) was ~14.3 km^2/s^2 and occurred at the close of the launch period. The declination of the launch asymptote (DLA) ranged from a maximum value of ~ -29.8 deg at close of the launch period to a minimum value of ~40.8 deg on launch day 1. The targets assumed a spacecraft mass of 700.5 kg. Note that the targets were specified at the Target Interface Point (TIP), which was defined at 20 min (1,200 sec) after MECO-2.

Historically, planetary missions have used a variety of methods to assess injection accuracy. A commonly- used method simply compares the actual C3, DLA, and RLA errors to the individual maximum allowable values or tolerances. Other methods would evaluate the magnitude of the post-launch ΔV to target to the desired atmospheric entry aimpoint or to target back to the desired biased injection point and compare them to the maximum allowable values. These methods are commonly used for orbiter missions that carry large propellant margins or spacecraft that use planetary flybys or large Deep Space Maneuvers (DSM), which can offset a significant amount of the injection error. InSight just like the Mars Science Laboratory (MSL) which carried a limited amount of cruise propellant, which translated into potentially small cruise propellant margins; hence, large cruise ΔV to correct injection errors could have been catastrophic. In order to account for the effects of injection errors on cruise propellant usage, MSL developed an error ellipsoid probability method that included the effects of injection errors mapped to the Mars B-plane by accounting for corrections of C3, DLA, and RLA errors and worst-case cruise propellant usage at the 99.0% probability level (3.36σ for a 3-dimensional distribution)[1]. This method was dependent on the Injection Covariance Matrices (ICMs) and accounted for effects of injection errors on Mars impact probability in order to satisfy planetary protection requirement.

Table 4 shows the injection accuracy results in terms of C3, DLA, and RLA at TIP in EME2000 coordinates, the 1σ uncertainties based on the InSight Navigation Team's orbit determination solution, expected 1σ dispersions, and the sigma levels of the errors with respect to the expected 1σ dispersions. The expected dispersions were derived from the ICM for a launch on May 5th, 2018 at the optimal minus 60 min launch (T-Zero = 11:05:00 UTC).

Table 4. Injection Accuracy Assessment

Parameter	Achieved	Target	Error	OD Uncertainty (1σ)	Expected Dispersion (1σ)	Error σ Level
TIP Epoch (UTC)	05/05/18 12:49:19.78					
C_3 (km^2/s^2)	8.204	8.197	0.0070	2.74E-05	3.03E-02	-0.23σ
DLA* (deg)	-40.824	-40.829	0.0050	2.39E-04	4.98E-02	-0.10σ
RLA* (deg)	328.098	328.132	-0.0330	4.50E-04	5.44E-02	0.61σ
*EME2000 coordinate system.						

With respect to the principal axis injection error ellipsoid defined by the ICM corresponding to the actual launch time, the injection errors corresponded to 1.22σ (31.5% probability error), which easily satisfied the 3.36σ injection accuracy requirement (99.0% probability error).

MARS B-PLANE PARAMETERS

Table 5 shows the effects of injection errors propagated to the Mars B-plane. The table includes achieved values, targets, errors (achieved minus target), 1σ uncertainties, expected 1σ dispersions, and the sigma levels of the errors with respect to the expected 1σ dispersions. The achieved values and 1σ uncertainties are taken from the InSight Navigation Team OD solution. The targets are obtained by propagating the TIP state in the Near-Earth Trajectory System (NETS) file to the Mars B-plane. The expected 1σ dispersions are obtained by propagating to the Mars B-plane the unscaled Best Estimate Trajectory (BET) ICM for launch on May 5th, 2018 at the optimal minus 60 min launch time (T-Zero = 11:05:00 UTC).

Table 5. Injection Errors Mapped to the Mars B-Plane

Parameter	Achieved	Target	Error	OD Uncertainty (1σ)	Expected Dispersion (1σ)	Error σ Level
B.R* (km)	-28239.4	-14988.0	-13251.4	501.1	44214.4	-0.30σ
B.T* (km)	-30838.8	14155.3	-44994.1	1198.4	136976.8	-0.33σ
TCA** (11/26/18), hh:mm:ss, UTC)	11:27:03.0	19:28:34.2	-08:01:31.2	00:18:27.8	21:10:04.0	-0.38σ
*Mars Mean Equator and Equinox of Epoch coordinate system. **TCA = Time of Closest Approach.						

SEPARATION ACCURACY ASSESSMENT

Separation (SEP) accuracy results in terms of the right ascension and declination of the spacecraft $+Z_M$ axis and angular rate per axis are shown in Table 6. The SEP time is the actual event time reported in the SEP Orbital Parameter Message (OPM). The table lists the estimated values, the required values, the errors (estimated minus desired), and the required accuracy. The estimated values are based on post-separation spacecraft telemetry. Considering the uncertainties in the estimates for the separation attitude and spin rate, the attitude and spin rate errors easily satisfy the accuracy requirements.

Table 6. Separation Accuracy Assessment

Parameter	Estimated	Required	Error
Separation Epoch (UTC)	05/05/18 12:38:20.56		
$+Z_M$ Axis Right Ascension[1] (deg)	229.160	229.157	0.003
$+Z_M$ Axis Declination[1] (deg)	7.570	7.566	0.004
$+Z_M$ Pointing Error (deg)	1.26	≤2.0	N/A
$+X_M$ Angular Rate (deg/s)	0.19	±3.0	N/A
$+Y_M$ Angular Rate (deg/s)	0.21	±3.0	N/A
$+Z_M$ Angular Rate (deg/s)	-0.10	±0.75	N/A
[1] EME2000 coordinate system.			

Note: Z_M = Spacecraft mechanical frame or "M" has its origin located along the spacecraft/launch vehicle centerline, is centered at the spacecraft separation plane, and goes through the center of the heat shield.

The achieved separation conditions in terms of spacecraft attitude and spin rate following separation from the Centaur upper stage were very close to the desired values; hence, the separation accuracy requirements are satisfied. The performance of the trans-Mars injection and spacecraft separation by the Centaur upper stage were outstanding.

SAFE MODE ENTRY AND SLEW TO INITIAL ACQUISITION ATTITUDE

Three breakwires were used to indicate separation of the spacecraft from the Launch Vehicle Adapter Assembly. Separation was acknowledged by the flight system when at least two breakwires indicated that separation had occurred. When the separation monitor detected separation, the fault protection software commanded an entry into Safe Mode. Upon entry into Safe Mode in the "Launch" mission phase, the Safe Mode Executive (SME) performed a series of actions to configure the spacecraft. Within seconds of separation, flight software, fault protection, attitude control, and telecommunications were configured. SME flight software also removed small residual rates caused by the separation from the launch vehicle. Once rate

damping was completed and following a small delay to allow any post-deployment rate damping transients to settle, the star tracker acquired attitude. A nominal SME execution assumes that the star tracker provides inertial reference immediately. On InSight, the sun sensors determined the sun location first and the spacecraft began coning until the inertial reference was established. At that point, the spacecraft slewed to the initial acquisition attitude. At this point, the spacecraft was in a power and thermal safe configuration, and the telecom subsystem was properly configured for initial acquisition through the 34-meter Deep Space Network (DSN) tracking stations at Goldstone.

Figure 3 shows the nominal InSight ground track, main launch vehicle events, and ground station rise/set events. During actual flight, Goldstone Deep Station 26 (DSS-26) antenna acquired the InSight downlink signal about one minute after the InSight spacecraft started transmitting. Goldstone achieved solid telemetry lock ~20 sec after carrier lock. Table 7 shows the expected and the actual carrier/telemetry lock times. Rise times, spacecraft separation, and spacecraft transmitter times are also shown for reference. There were no frame gaps after the initial Goldstone pass and DSN performance was nominal. The initial acquisition telemetry confirmed that the spacecraft had achieved a thermally stable, positive energy balance, and commandable configuration.

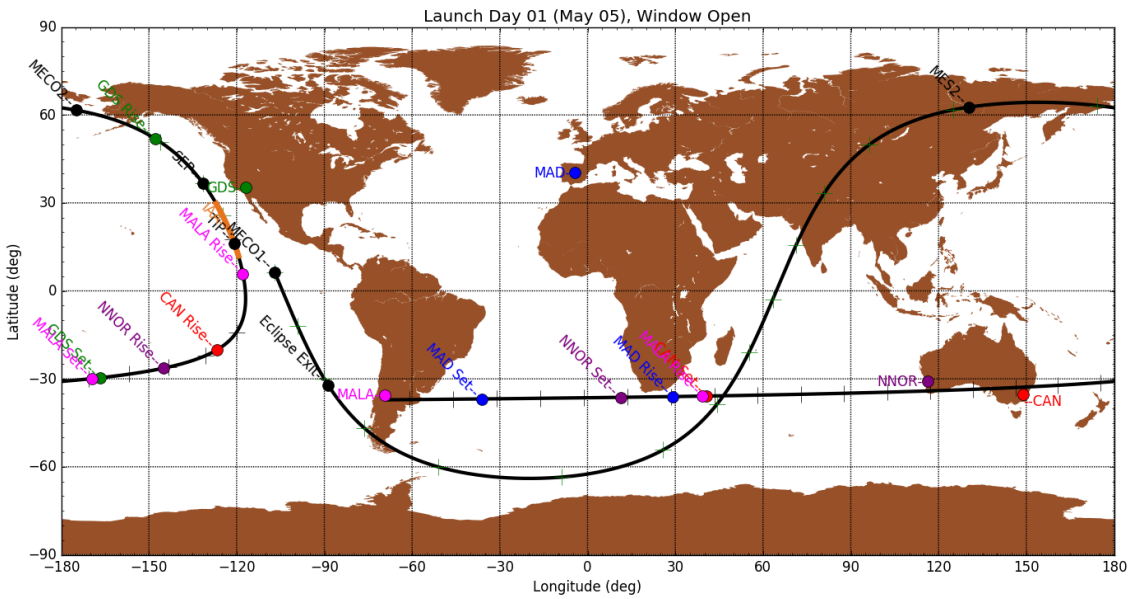

Figure 3. Launch Trajectory Ground Track – 05/05/2018 (launch window open: 11:05 UTC)

Table 7. DSN Rise Times and Carrier/Telemetry Lock Times

Event	Expected Time relative to Event	Expected Time (UTC, hh:mm:ss)	Actual Time relative to Event	Actual Time (UTC, hh:mm:ss)	Delta
Goldstone Rise (DSS-26)	-	12:32:00	-	12:32:00	-
Spacecraft Separation	-	12:38:20	-	12:38:21	1 s
Spacecraft Transmitter ON		12:38:41	-	12:38:43	2 s
Goldstone (DSS-26) Carrier Lock	Transmitter ON + 5 s	12:38:46	62 s from Transmitter ON	12:39:45	59 s
Earliest time to Achieve Initial Acquisition Attitude	SEP + 30 s	12:38:50	-	-	-
Goldstone (DSS-26) Telemetry Lock	Carrier Lock + 20 s	12:39:00	19 s from Carrier Lock	12:40:04	64 s
Intermediate time to Achieve Initial Acquisition Attitude	SEP + 210 s	12:41:50	-	-	-
Spacecraft arrived at the Initial Acquisition Attitude	-	12:42:50	-	12:50:34	464 s

INTERPLANETARY CRUISE AND MARS APPROACH

The cruise phase started with the first commanding of the spacecraft (No-Op) following initial acquisition on May 5, 2018. The Approach sub-phase began on September 27, 2018 (60 days prior to Entry). Up to six nominal trajectory correction maneuvers (TCMs) were planned during cruise. Figure 4 shows a heliocentric view of the InSight trajectory and the TCM execution dates. TCM-1 and TCM-2 were designed to remove most of the planetary protection-required aimpoint bias and correct launch vehicle injection errors. TCM-3 was the first maneuver designed to deliver InSight to its intended EIP defined at a radius of 3,522.2 km. During the cruise phase, the team executed TCM-1 (05/22, delayed by a week to assess higher-than-expected outgassing activities after spacecraft separation from the launch vehicle) and TCM-2 (07/28), carried out the thruster calibration activity (06/26), performed camera (06/11 and 06/14), pyro mechanisms (06/27), radar (07/09), and UHF (07/10) checkouts, transitioned to the late cruise attitude (07/12), and completed the science instrument checkouts (07/16 and 07/19). Communications transitioned from the Low-Gain Antenna (LGA) to the Medium Gain Antenna (MGA) on 08/07 and the descent engine vent activity was completed on 08/09 which was the first significant event in preparation for EDL. The EDL thermal checkout (08/28), the Small Deep Space Transponder (SDST) calibration (09/14), and two battery cell balancing activities (08/21 and 09/25) took place prior the start of the Approach sub-phase. In the last two months before atmospheric entry, three additional maneuvers were executed, TCM-3 (10/12), TCM-5 (11/18), and TCM-6 (11/25). TCM-4 originally scheduled for 11/11 was canceled due to expected large maneuver execution errors which would have warranted another maneuver. During the Approach sub-phase, a second checkout of the radar (10/11), UHF (10/15), and POP/Pyro (10/31) were completed. During this period, two additional battery cell balancing activities were executed (10/16 and 11/11). The Pre-EDL cold reboot was completed on 10/29 and the EDL sequence started on 11/22. Note that TCM-5 was sufficient to meet all Navigation and EDL safety requirements; nevertheless, the Project decided to execute TCM-6 to retire the small risk of landing in the northeast corner of the landing ellipse. This region featured undesirable ridged terrain and had not been characterized using High Resolution Imaging Science Experiment (HiRISE) imagery. TCM-6 execution was nominal and moved the atmospheric entry interface point closer to the desired EIP.

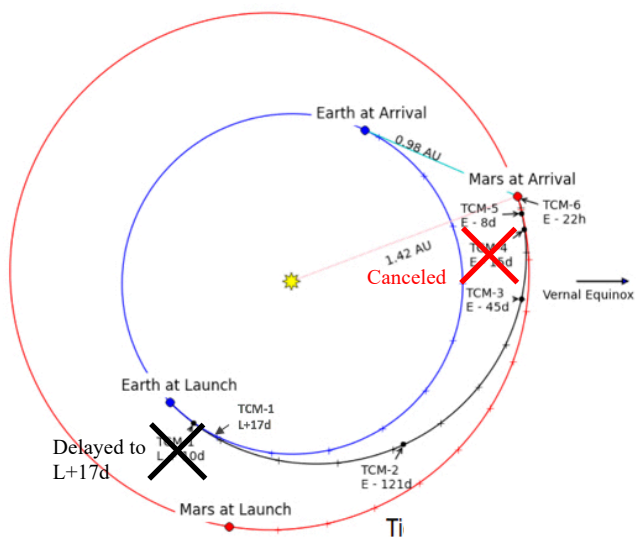

Figure 4. Interplanetary Trajectory

TRAJECTORY CORRECTION MANEUVER PERFORMANCE

Navigation accuracy and precise quantification maneuver execution errors were critical for a precise delivery of the spacecraft to the desired atmospheric entry point. Unlike other systems which have separate propulsion systems (and propellant tanks) for cruise and EDL, InSight featured a single propulsion system (and a single set of propellant tanks) used for all cruise activities that require thrusting (TCMs and attitude control) as well as EDL. In order to ensure that enough propellant was available for EDL, the maximum ΔV for TCMs was constrained to 30 m/s. Small launch vehicle dispersions, small force accelerations well within

predicted models (except for the short-lived outgassing small force acceleration which was ~25 times the predicted response), and good maneuver executions resulted in very low TCM and Attitude Control System (ACS) propellant consumption during cruise. Table 8 shows the planned ΔV, estimated ΔV, and magnitude and pointing errors for each maneuver. The actual total TCM ΔV of 6.1 m/s had extremely healthy margins against the 30 m/s requirement. Note that since TCM-6 occurs so close to entry, reconstruction based on radiometric data is sensitive to effects such as Mars ephemeris error and OD modeling.

Table 8. TCM Maneuver Performance

Event	Pre-launch Date (2018, UTC)	Actual Date (2018, UTC)	Planned ΔV (m/s)	Est.ΔV (m/s)	Mag. Error (%, sigma*)	Point. Error (deg)
TCM-1	05/15 18:00:00	05/22 18:00:00	3.777	3.761	0.42 (0.61σ)	0.175
TCAL	06/26 15:00:00	06/26 15:00:00	0.472	0.492	4.24	N/A
TCM-2	07/28 18:00:00	07/28 18:00:00	1.498	1.503	0.33 (1.25σ)	0.68
TCM-3	10/12 18:00:00	10/12 18:00:00	0.167	0.160	4.19 (0.83σ)	1.47
TCM-4	11/01	Canceled				
TCM-5	11/18 18:00:00	11/18 18:00:00	0.057	0.063	10.53 (0.93σ)	8.42
TCM-5X	11/21	Not Needed (TCM-5 was executed)				
TCM-6	11/25 21:39:00	11/25 21:39:00	0.085	0.091	7.06 (2.53σ)	4.29
TCM-6X	11/26 11:40:00	Not Needed (TCM-6 was executed)				

* Sigma errors include magnitude and slew errors.

CRUISE MAINTENANCE ACTIVITY PERFORMANCE

Due to the intrinsic nature of a 3-axis stabilized vehicle with unbalanced thrusters such as the InSight spacecraft, the ACS thrusters autonomously fired on a daily basis to maintain early (50 deg off-Sun) and late cruise attitude profiles (2 deg off-Sun) with [X,Y,Z] deadbands of [10,10,7.5] deg and [4,4,4] deg respectively. The average daily propellant consumption for ACS was typically between 2 and 3 grams/day. Besides trajectory correction maneuvers and attitude maintenance events during cruise and approach, other activities such as the thruster calibration, the slew to the late cruise attitude, the descent engine vent, the cold reboot, and the final turn to entry contributed to a total propellant consumption of ~3.6 kg. The propellant mass usage, based on the spacecraft team's trending analysis, due to major cruise and approach events are shown in Table 9. Other unplanned activities such as the slews to alternate attitudes to effectively force any remaining outgassing also required some small propellant consumption and are shown in the total propellant consumed in Figure 5 below. These two outgassing activities took place on 05/29 and 05/31. The total propellant load at launch was 66.1 kg (63.29 kg usable) and the estimated amount of usable propellant for EDL at Entry was ~59.7 kg. Based on pre-launch EDL analysis, the maximum propellant usage for EDL (99-percentile) was ~45 kg so propellant margins were very healthy. The entry mass (wet) after jettisoning of the 79.4 kg cruise stage was 605.6 kg.

Table 9. Cruise/Approach Propellant Consumption

Event	LV Sep	TCM-1	Thruster Cal.	TCM-2	TCM-3	TCM-5	TCM-6	Entry
Date (2018)	05/05	05/22	06/26	07/28	10/12	11/18	11/25	11/26
Propellant Mass Used (kg)	N/A	1.179	0.529	0.507	0.078	0.062	0.065	0.078
Cumulative Use (kg)	N/A	1.559	2.275	2.912	3.245	3.446	**3.536**	3.614
Spacecraft Wet Mass After Event (kg)	688.6	687.041	686.325	685.688	685.355	685.154	685.064	605.6

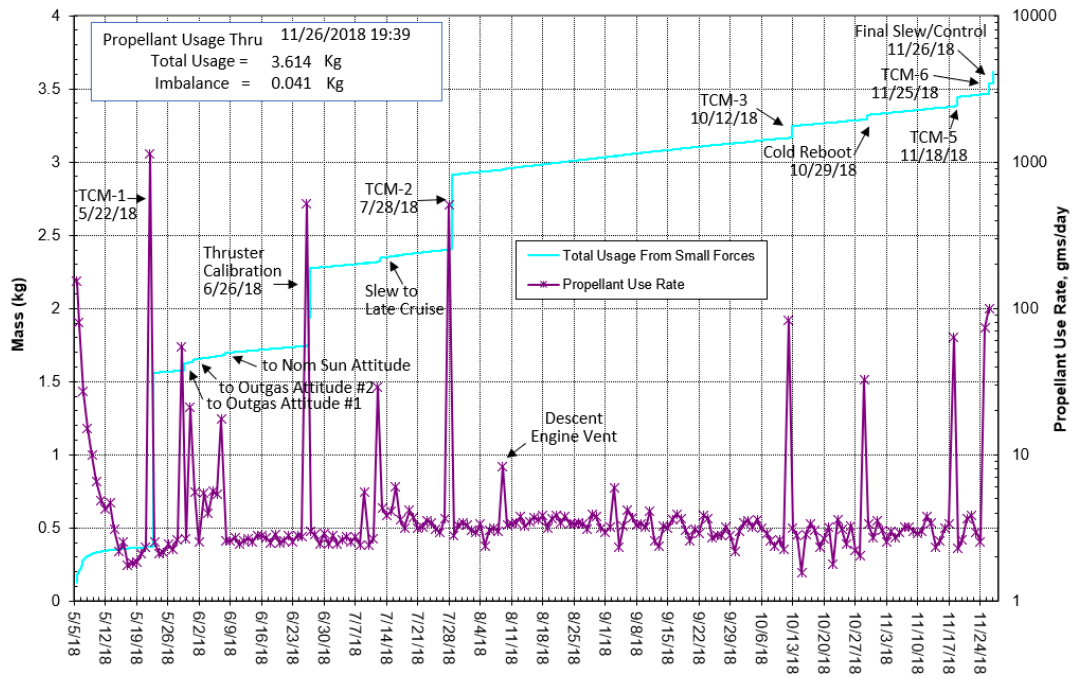

Figure 5. Cruise Propellant Mass Utilization

ATMOSPHERIC ENTRY DELIVERY

The navigation delivery requirement stated that the entry vehicle shall be delivered to the specified atmospheric entry conditions to achieve an Entry Flight Path Angle (EFPA) of -12.0 deg ± 0.21 deg (3-sigma) at the atmospheric EIP defined at a Mars radius of 3,522.2 km. Based on a post-landing trajectory reconstruction using all the data and calibrations leading up to atmospheric entry, the actual EFPA was well within the 3-sigma requirement being estimated as 0.046 deg steeper than the -12.0 deg EFPA target. EPU-E was the final EDL parameter update and was uplinked 22 hours prior to entry. This entry state was off by 14.17 km in position and 8.17 m/s in velocity from the post-landing reconstructed entry state. Figure 6 shows the evolution of the Orbit Determination (OD) solutions from the last OD prior to TCM-5 through the last OD (OD106) solution based on a Data Cut-Off (DCO) at Entry-12 min (OD-133). Figure 7 shows the location of the entry target, the estimated entry point prior to TCM-5 (OD106) and TCM-6 executions (OD116), the location of EPU-E (OD112), and the estimated entry point (OD133). The difference between the OD used to generate EPU-E and OD119 and OD124 used to generate EPU-F and EPU-FX, respectively, was less than 12.0 km and 10.7 km; hence, EFU-F and EPU-FX were not needed. The distance between the EIP of the TCM-6 target and the actual EIP based on OD133 was ~4.5 km. The distance between the actual EIP location and the EPU-E location (on-board state) was only of ~14.2 km. The B-Plane coordinates for TCM-6 and OD133 are shown in Table 10.

Table 10. B-Plane locations for TCM-6 Target and OD133

Event	B ▪ R (km)	B ▪ T (km)	DCO (UTC)
TCM-6 Target	266.360	6660.316	24-NOV-2018 18:38:00 UTC
OD133	269.195	6659.182	26-NOV-2018 19:27:00 UTC

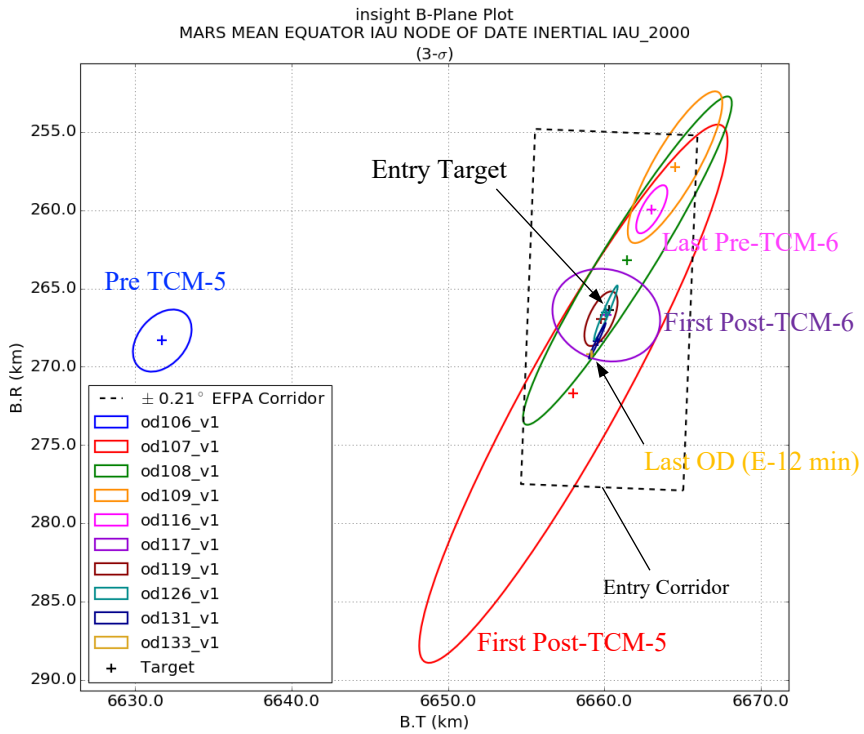

Figure 6. Evolution of Orbit Determination Solutions from Last OD prior to TCM-5 through EIP

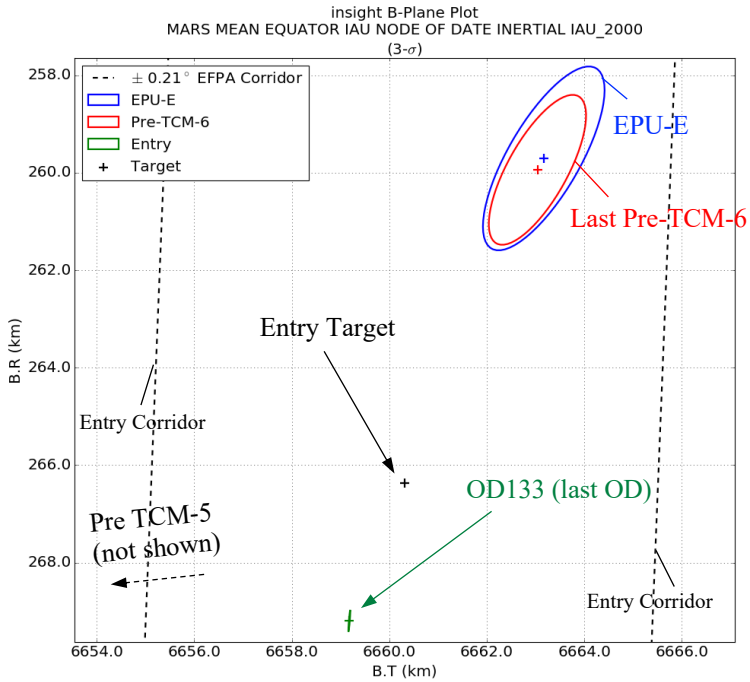

Figure 7. Location of Estimated Entry Points at Relevant Times during Final Approach

ARRIVAL GEOMETRY AND EDL COMMUNICATIONS

MRO served as the primary EDL coverage asset and recorded the telemetry data stream in open loop. EDL data was on the ground within 1.5 hours from landing and post-processing of the data was completed ~2 hours later. The two MarCO (Mars Cubesat One) spacecraft, which launched on the same Atlas V vehicle and flew independently to Mars, captured telemetry in unreliable mode (the spacecraft would not request a retransmission from the lander if it detected a missing frame) and via its bent pipe capabilities, retransmitted the data back to Earth, providing near real-time (minus the one-way light time delay of about 8 minutes) monitoring of the spacecraft health during EDL. In addition to the assets at or near Mars, the radio telescopes at Green Bank (West Virginia) and Effelsberg (Germany) were configured to detect the UHF signal. Green Bank detected carrier from Entry through landing. Due to the low Signal to Noise Ratio (SNR), Effelsberg carrier detection was limited to before entry and immediately after landing. Figure 8 illustrates a close-up of the arrival geometry. The InSight Navigation team and the MRO and MarCO Navigation teams continuously exchanged trajectory predicts which were evaluated to adjust the asset positioning as necessary.

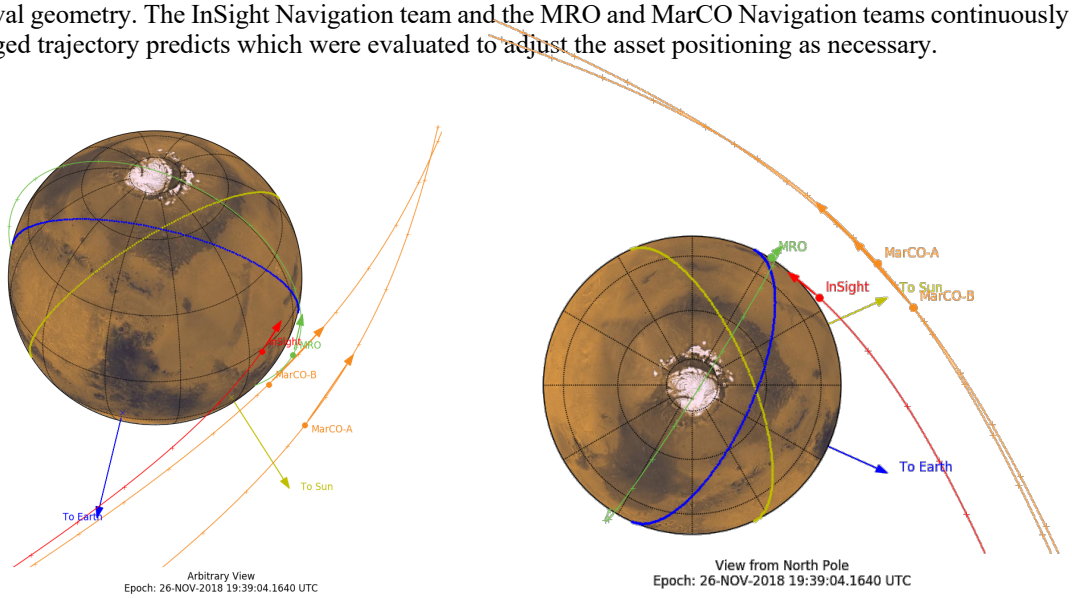

Figure 8. Arrival Geometry

MRO executed several maneuvers to achieve an optimal geometry at the time of atmospheric Entry consistent with a target request of 2:52 PM LMST. The first maneuver, orbit change maneuver (OCM-3), was executed on 03/22/17 and arrested MRO's upward LMST drift in order to achieve the LMST target. MRO also executed two orbit synchronization maneuvers on 08/22/18 and 10/24/18 to remove timing phasing errors. Note that even though the original target was 2:52 PM LMST, InSight link performance was marginally better at slightly earlier LMSTs so InSight accepted the achieved LMST of 2:50:40 PM post OCM-3 and designed subsequent on-orbit phasing targets accordingly. These targets were specified in the EDL Relay Target Files (ERTF), which in the case of MRO took the form of the latitude, and LMST to be achieved at the InSight Entry epoch. Figure 9 shows the phasing offset as a function DCO time with respect to EDL. The final phasing targets delivered at Entry minus 40 days were provided in ERTF #15. Subsequent ERTF deliveries did not levy any new requirements and were used for reference purposes only in order to track the evolution of the targets and trajectory predictions. The MRO team was expected to achieve its EDL relay targets within ± 30 s. The final phasing error was less than 9 sec and well within the on-orbit phasing requirement[7]. The MarCO phasing strategy was based on evaluation of the link budget. They did not carry enough propellant to enter Mars orbit by design, so they flew by Mars as they were relaying the InSight EDL data. Due to the chute-can null in the InSight antenna pattern, one MarCO spacecraft targeted the North side of the InSight orbit plane whereas the other one targeted the South side. MarCO attitude was such that it would produce the highest UHF margin while keeping the MarCO HGA boresight pointed to Earth. During cruise, the MarCO team executed several TCMs to bring both spacecraft closer to their respective flyby targets. The MRO and MarCO spacecraft strategies produced link margins from Entry through Landing plus 1 minute of not less than 4.4 dBm and 1.9 dBm (1% low) respectively[8].

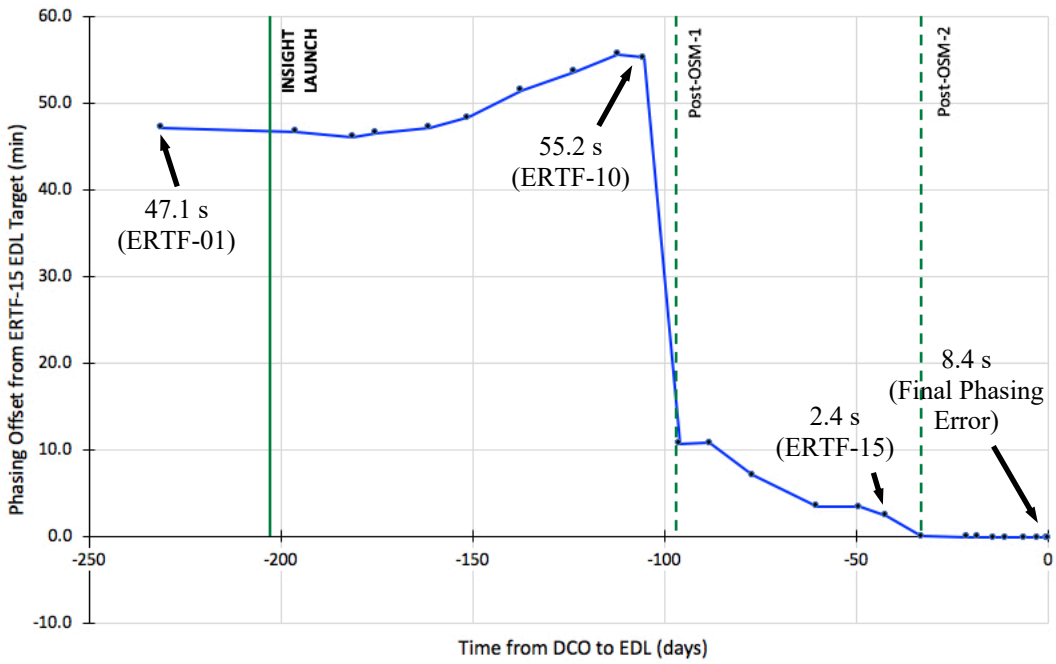

Figure 9. MRO Phasing Offset with respect to DCO Time to EDL

EDL TRAJECTORY PERFORMANCE

At the time of compilation of this paper, a significant EDL reconstruction effort was ongoing; hence, the results shown in this section and in the Landing Accuracy section should be considered preliminary. Figure 10 shows a graphical timeline of the different EDL events from the last opportunity for an EDL Parameter update through landing.

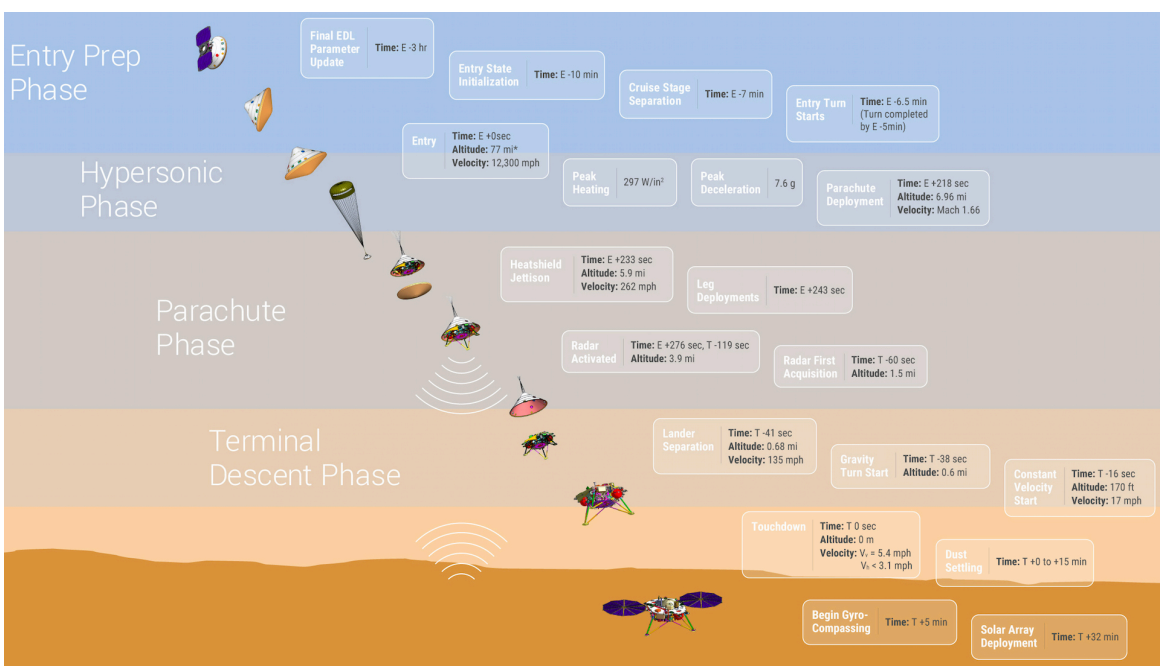

Figure 10. EDL Timeline

Based on the current information available, EDL performance was nominal. Table 11 shows the predicted (based on OD133) and the as-flown times. Note that the change in entry time of 1 sec is due to the difference between the on-board entry epoch based on EPU-E (OD112) and the actual entry epoch (OD133). The EDL sequence was about 40 sec shorter than the nominal case. Parachute deployment and backshell separation occurred about 10 sec and 43 sec earlier than predicted. The differences between the expected nominal and actual flight performance are under study as part of the EDL reconstruction effort.

Table 11. Predicted Vs. Actual EDL Event Timeline

Event Name	Predicted (OD133)		Actuals		Delta (s)	Actual Spacecraft Time (11/26/2018, PST)	Actual Earth Received Time (11/26/2018, PST
	Time from Entry (s)	Time from Landing (s)	Time from Entry (s)	Time from Landing (s)			
Entry Interface Point	0.0	387.3	0.0	348.2	-1.0	11:39:04 AM	11:47:11 AM
Parachute Deploy	216.9	170.4	208.3	139.9	-9.6	11:42:32 AM	11:50:39 AM
Heat Shield Separation	232.0	155.3	223.4	124.8	-9.6	11:42:47 AM	11:50:55 AM
Backshell Separation	345.8	41.5	304.1	44.1	-42.7	11:44:08 AM	11:52:15 AM
Gravity Turn	348.8	38.5	306.7	41.5	-43.1	11:44:10 AM	11:52:18 AM
Constant Velocity	371.4	15.9	332.4	15.8	-40.0	11:44:36 AM	11:52:44 AM
Touchdown	387.3	0.0	348.2	0.0	-40.1	11:44:52 AM	11:52:59 AM

LANDING ACCURACY

On 12/06/18, MRO acquired HiRISE and Context (CTX) images which showed the final location of the InSight lander, the backshell/parachute, and the heat shield. Table 12 shows the planetocentric coordinates and elevation with respect to the Mars Orbiter Laser Altimeter (MOLA) geoid of the original E09 target, the TCM-6 target, and the actual InSight lander location. The lander is about 13.8 km away from the target used in late operations (based on OD133), but well within the landing ellipse. The heat shield is located 0.762 km down-track (northeast) from the lander and the backshell/parachute is located 0.553 km in the southeast direction.

Table 12. Target Vs. Achieved Landing Location

Landing Location	Latitude (deg)	Longitude (deg)	Elevation (m)
Target (E09)	4.5100°N	135.9900°E	-2,655
TCM-6 Target	4.5004°N	135.9514°E	-2,652
OD133	4.4558°N	135.8427°E	-2,657
Actual	4.5023°N	135.6234°E	-2,613

Figure 11 shows the actual landing location with respect to the original E09 landing ellipse, the pre-TCM-6 (OD115) ellipse, the TCM-6 target ellipse, and the final post TCM-6 ellipse (OD133)

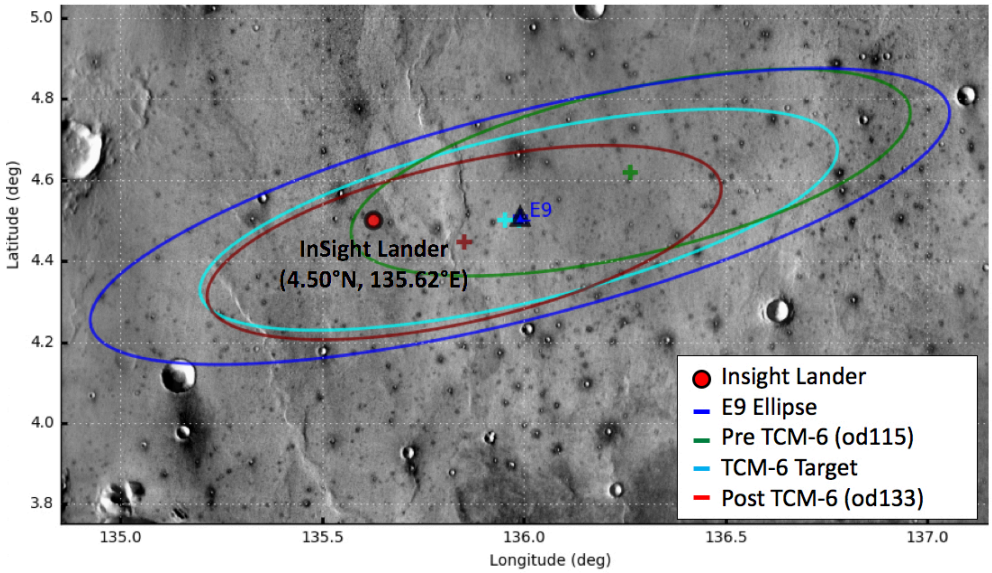

Figure 11. Actual Landing Vs. E09 and TCM-6 Ellipses

CONCLUSION

The performance of the InSight spacecraft and all associated assets including the launch vehicle, the Deep Space Network, and the relay assets was outstanding and culminated in the successful touchdown of the InSight lander in the Elysium Planitia region within ~14 km of the desired target. With a launch period open of May 5th, 2018, InSight had 869 available launch opportunities across its 35-day launch period. The Atlas V 401 carrying the InSight spacecraft and the two MarCO cubesats launched on day 1 at the open of the launch window (first opportunity across the entire launch period) which resulted in the first interplanetary launch from the West Coast. All launch vehicle events (including separation of the three spacecraft) occurred within 1 sec from the expected times. The trans-Mars injection burn had small errors (1.22σ) which helped to keep the TCM propellant usage low. InSight separation from the Centaur upper stage in terms of direction, pointing error, and tipoff rates was near perfect. The DSN locked on the carrier one minute from the transmitter ON event. Telemetry lock was achieved within 20 s from carrier lock. Both activities occurred within nominal DSN support. Due to the 3-axis stabilized nature of the InSight spacecraft, five trajectory correction maneuvers were necessary to ensure a safe delivery of the lander to the surface of Mars. The last maneuver, executed only 22 hours prior to Entry, was the TCM with the latest execution time with respect to Entry in the history of Mars Exploration. Propellant usage during cruise was very small leaving about 59.8 kg available for EDL resulting in ~15 kg of propellant margin for the powered descent phase. MRO and both MarCO-A and MarCO-B spacecraft captured telemetry. The MarCO cubesats enabled near real-time telemetry monitoring back on Earth by bend-piping the UHF signal. MRO open loop data record was downlinked within 1.5 hours from landing. Direct-to-Earth UHF carrier detection was also successful at Green Bank Observatory from Entry through landing. Due to low SNR, carrier detection at Effelsberg radio telescope was limited to right before Entry and immediately after landing. The EDL trajectory was nominal although some notable differences in the event timeline with respect to the nominal case have been observed and they are currently under study. The InSight landing is another tremendous achievement for human kind and promises to increase our knowledge of planetary formation and evolution of terrestrial planets in the upcoming years.

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