(Preprint) AAS 19-213

INSIGHT ORBIT DETERMINATION

Eric D. Gustafson,[*] C. Allen Halsell,[†] David Jefferson,[‡] Eunice Lau,[‡] Julim Lee,[‡] Sarah Elizabeth McCandless,[‡] Neil Mottinger,[‡] and Jill Seubert[‡]

The InSight mission relied on accurate deep-space navigation for a successful Mars landing on November 26, 2018. In this paper, we discuss the role of the cruise Orbit Determination team, whose responsibilities included determining the spacecraft state, predicting the future trajectory, and quantifying the uncertainty associated with those estimates. In particular, we will focus on spacecraft dynamic modeling, small forces due to attitude control, radiometric tracking data, filter strategies, uncertainty quantification, and responses to unexpected flight situations. We will also provide analysis of reconstructed maneuvers, small forces, and delivery accuracy at Mars arrival.

INTRODUCTION

The InSight Orbit Determination (OD) team had the responsibilities of determining the spacecraft state, predicting the future trajectory, and quantifying the uncertainty associated with those estimates. This paper details the planning, processes, tracking data, improvements, and results of InSight OD, as well as how OD fits in with overarching navigation goals.[1,2]

The most recent spacecraft to land on Mars before InSight, the Mars Science Laboratory (MSL) (with the Curiosity rover) was spin-stabilized during cruise, and therefore very dynamically quiescent.[3] In contrast, InSight proved to be dynamically exciting in ways both expected and surprising.

MISSION OVERVIEW

On May 5, 2018, InSight launched from Vandenberg Air Force base on an Atlas V-401 launch vehicle. The deep space navigation and OD tasks concluded on November 26, 2018 with a successful landing on Mars' Elysium Planitia region. Unlike MSL, InSight did not have guided entry capabilities, so its landed delivery accuracy was driven by events occurring on approach to Mars. The focus of MSL OD during approach was knowledge—identifying the position and velocity of the spacecraft at a given time—because MSL could actively guide itself through the Martian atmosphere using that information. In contrast, the last opportunities for InSight to actively control its landing sight were maneuvers on final approach. Therefore, the focus of InSight approach OD was

[*]InSight Orbit Determination Lead, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.
[†]InSight Navigation Team Chief, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.
[‡]InSight Orbit Determination Analyst, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.
© 2019 California Institute of Technology. Government sponsorship acknowledged.

delivery, which is how accurately we can actually control the spacecraft state before it reaches the atmosphere.

InSight's cruise stage physical properties were very similar to the Phoenix mission (mass, size, shape, thrusters), as shown in Figure 1*. The operational approach for OD, however, was significantly different than Phoenix in several ways.[4] The most notable of these is the treatment of the Attitude Control System (ACS) small forces. The ACS of InSight is actuated solely by four unbalanced Reaction Control System (RCS) thrusters. Without reaction wheels or other momentum management hardware, these thrusters alone must maintain the spacecraft attitude within specified deadbands. Each time they fire, there is a net change in velocity of the spacecraft. The modeling and prediction of these small forces was a major challenge to the OD team.

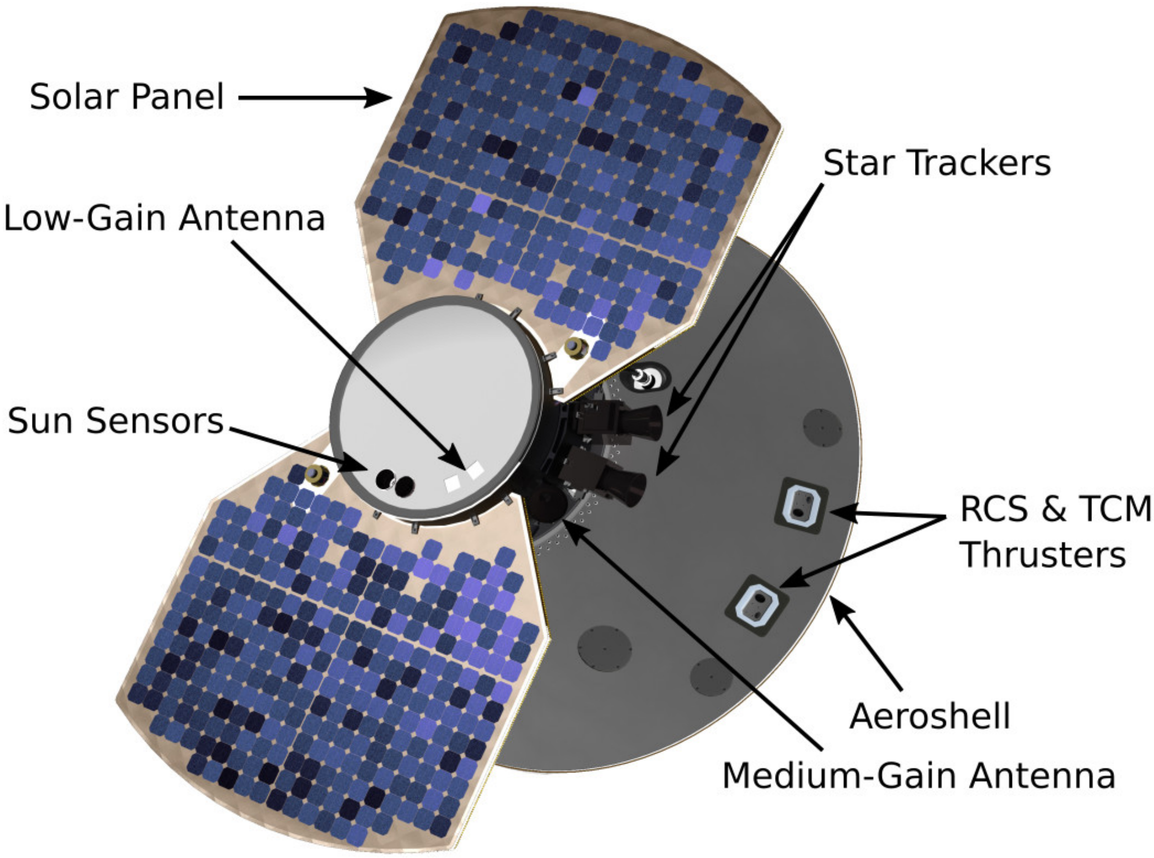


Figure 1: InSight cruise stage

InSight had six scheduled Trajectory Correction Maneuvers (TCMs), and a Thruster Calibration (TCAL) activity.[5] The two main purposes of the first TCM, TCM-1, were to correct for launch vehicle injection errors and remove intentional biasing for planetary protection.[6] The remaining TCMs were planned as statistical corrections. TCM-4 was canceled even though a correction was required to meet delivery requirements because the correction needed was too small with respect to expected execution errors.

The InSight cruise stage has repeatedly exhibited strong outgassing when surfaces were exposed

*https://mars.nasa.gov/resources/22007/insight-cruises-to-mars-artists-concept/

to sunlight for the first time. This outgassing creates a net force and torque on the spacecraft that must be countered by the RCS thrusters. In the days immediately after launch, the RCS thrusters fired approximately 25 times more frequently than expected.

To ameliorate the impact of RCS thruster firings on the mission, InSight included spacecraft thruster and attitude telemetry in the OD process. This was a major process improvement over the Phoenix mission, which simply fit batch stochastic accelerations of various durations without regard to actual spacecraft activity.[4] While this worked adequately, we were able to obtain a much cleaner fit to tracking data and predict the spacecraft trajectory much better using this new approach. The detailed modeling of spacecraft attitude also necessitated the modeling of antenna motion to fully capture the available information in the high-quality Deep Space Network (DSN) data.

In response to the strong outgassing and resulting increased rate of RCS thruster firing after launch, the schedule regarding TCM-1 was shifted during operations. The pre-launch plan was to have the Data Cutoff (DCO) on a launch-relative date of L+5 days, and execution at L+10 days. In reality, the DCO was shifted to L+10 days (May 15, 2018), and the execution to L+17 (May 22, 2018). Furthermore, TCM-1 and TCM-2 were optimized jointly instead of the pre-launch plan of having TCM-1 target the entry point directly.

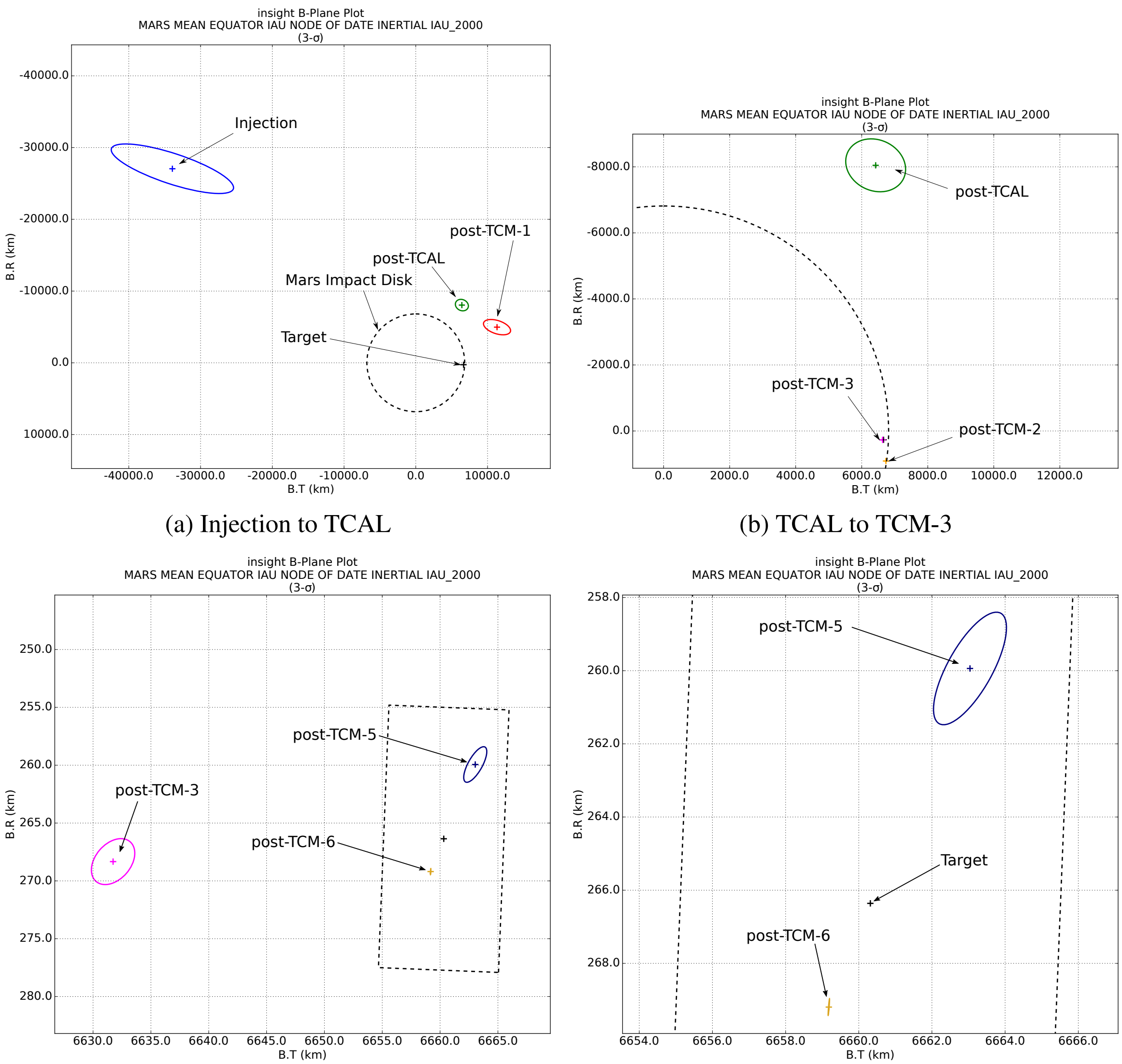
In order to minimize corruption of the TCAL or TCM-2 from the outgassing perturbative accelerations, an unplanned in-flight bakeout was performed. The spacecraft was rotated to the first of two of the TCAL attitudes on 29-May and the newly sun-facing components were allowed to outgas for two days. On 31-May, the spacecraft was rotated to the second attitude, which was then held to force outgassing for 7 days. The spacecraft was rotated back to its nominal early cruise attitude on 7-June. This activity effectively ensured that any outgassing experience during the TCAL would be at a low enough level as to not trigger unexpected RCS thruster firings that would disrupt the calibration.

The high-level goal of the TCAL was to minimize uncertainty in small force propagation by calibrating the RCS thrusters in-flight. This is particularly important in TCM design and quantification of future uncertainty. The TCAL analysis and results are summarized in a separate paper.[7] There was no calibration activity specific to the TCM thrusters; the TCMs themselves served that purpose.

The progression of OD solutions in the B-plane is shown in Figure 2. Each event label corresponds to the best estimate of the state after that event, projected forward in time to entry. For example, in Figure 2a, the label "Injection" is the last OD before the execution of TCM-1. The "post-TCM-1" label shows the last OD before execution of the TCAL. TCMs-2 and on were all designed to hit the target, shown as a black plus sign. The dashed black box visible in Figures 2c and 2d is a region in the B-plane that is nominally acceptable to the project, if the OD solution center is within the box. Its half-width (B·T) is computed from the 0.21°, 3-σ Entry Flight Path Angle (EFPA) requirement and its height (B·R) was chosen to 24 km based on a reasonable cross-track allowance of 12 km on the ground.

RADIOMETRIC DATA AND TELEMETRY

Two kinds of data were critical to the success of the OD process: radiometric data and spacecraft telemetry. There were three types of radiometric tracking data used for InSight OD: two-way coherent Doppler, two-way coherent sequential ranging, and Delta-Differential One-way Range (ΔDOR). Doppler and range data give line-of-sight measurements of velocity and position, respectively. ΔDOR data gives a measure of plane-of-sky angular distance between InSight and nearby quasars.



(a) Injection to TCAL

(b) TCAL to TCM-3

(c) TCM-3 to entry (post-TCM-6)

(d) TCM-5 to entry

Figure 2: InSight B-plane evolution.

In addition to radiometric data, the OD team routinely processed spacecraft telemetry. During DSN tracking passes, the spacecraft would downlink channelized data—realtime data from various sensors onboard. Of particular interest to the OD team were the attitude (quaternions) and angular rates. Any time a thruster fired, a non-channelized data packet was also created and stored onboard, then downlinked when possible. These small force packets contained the time of the firing, thruster valve on-times, a computed estimate of the net Delta-Velocity (ΔV), and the quaternion at the time of firing. Therefore, throughout cruise, we had a logging of every thruster firing (with attitude data), and additional channelized data interspersed when possible.

A critical part of InSight's success came from detailed modeling of spacecraft attitude and RCS thruster firings. During Phoenix operations, the OD team received periodic deliveries of Small Force Files (SFFs) containing information about thruster firings as well as quaternions at the time of firing. In contrast, the InSight OD team developed the ability to directly query the Ground Data Systems (GDS) telemetry servers and access this information directly. This largely alleviated the team's reliance on external periodic deliveries of products like SFFs because the latest data could be queried at any time. Additionally, it gave visibility into all available channelized telemetry such as onboard attitude (between thruster firings), temperatures, pressures, etc. Spacecraft attitude was modeled by interspersing channelized attitude telemetry with the attitude available at the time of thruster firings, linearly interpolating between available telemetry. Attitude modeling was important because full antenna motion was used within the OD filter. Each and every RCS thruster firing was modeled in the OD solution, with over 60,000 minimum-impulse-bit-equivalent firings accumulated throughout cruise.

ORBIT DETERMINATION PROCESS AND RESULTS

As the mission evolved through various stages, the OD filter strategies were adapted to best serve the changing goals. Right after launch, the primary navigation and OD goal is to enable the DSN to track the spacecraft. This requires quick response and low-fidelity models due to the tight time constraints and lack of data available for dynamical modeling. On the other extreme, during the leadup to final maneuver design, the goal is to completely understand spacecraft dynamics, and be able to determine as accurately as possible both the current and future spacecraft state in order to achieve the best delivery accuracy. This section will step through the events and stages of the mission and describe the pertinent filtering approach and results.

All OD and other navigation work was performed using JPL's navigation software, MONTE.[8]

General Orbit Determination Approach

The baseline filter configuration is summarized in Table 1. The *a priori* spacecraft position and velocity uncertainties shown refer to late cruise initialization; immediately post launch and during early cruise, the filter was initialized with uncertainties of 1000 km and 1 m/sec, respectively. Doppler and range data weights were empirically determined for each individual pass, with the minimum allowable values referenced in the table. Several dynamic model parameters were estimated in addition to the spacecraft state: TCM main burn and slew errors, solar radiation pressure (SRP) model errors, and the effective thruster direction and magnitude for each RCS thruster. Numerous sources of measurement and dynamic model error were considered (i.e., not estimated): ionosphere- and troposphere-induced radiometric signal delays, Earth polar motion and UT1 errors, ground station antenna and quasar locations, and relevant gravitational parameters and ephemeris errors. The main driver of InSight's delivery accuracy capability was propulsion system uncertainty, both in

TCM executions and RCS attitude control. The onboard knowledge capability was predominantly limited by ΔDOR measurement and media calibration accuracy.

Table 1: Baseline Filter Configuration

Error Source	Estimation Model	*A Priori* Uncertainty	Comments
Spacecraft Position	Dynamic	1,000 km	Sun-centric EME2000
Spacecraft Velocity	Dynamic	3 m/sec	Sun-centric EME2000
2-way Doppler noise	-	$\geq$ 0.05 mm/sec	
2-way Range noise	-	$\geq$ 1 m	
ΔDOR noise	-	60 ps	
2-way Range Bias	Stochastic	2 m	Uncorrelated per-pass
TCM & TCM Slews	Bias	Requirement Gates Model	
Thrust Direction Y Offset	Bias	3°	
Thrust Direction Z Offset	Bias	3°	
ΔV Magnitude	Bias/Stochastic	3%/15%	Uncorrelated per-firing
SRP Scale Factor	Bias	10%	
SRP Spherical Harmonics	Bias	1 m^2	Early & late cruise biases
Ionosphere Day/Night	Consider	55/15 cm	Per DSN complex
Troposphere Wet/Dry	Consider	1/1 cm	Per DSN complex
Earth Polar Motion (ΔX/ΔY)	Consider	1/1 cm	
UT1 Bias	Consider	2 cm	
DSN Station Locations	Consider	2003 Covariance	Reference 9
Quasar Locations	Consider	1 nrad	
Mars Gravitational Parameter	Consider	2.8×10^{-4} km^3/sec^2	
Earth Gravitational Parameter	Consider	1.4×10^{-3} km^3/sec^2	
Moon Gravitational Parameter	Consider	1.0×10^{-4} km^3/sec^2	
Earth-Mars Ephemeris	Consider	DE423 Covariance	Reference 10

The Solar Radiation Pressure (SRP) model used for InSight was both simpler and more flexible than that used for Phoenix. Phoenix followed a traditional approach of modeling spacecraft components and their surface properties like specular and diffuse reflectivity coefficients. This model has the benefit of having some level of intuition, but has drawbacks such as not modeling complicated effects like shadowing, component-to-component radiative effects, or having clear degrees of freedom for estimation. The approach taken for InSight was purely empirical. The model was implemented as four coefficients of a spherical harmonics expansion per axis. While this moves away from first-principles modeling, it is more able to capture arbitrarily complex SRP forces due to the available degrees of freedom.

A comparison of OD solutions utilizing various dynamic models, filter configurations, and measurement combinations was provided by executing what are referred to as "filterloops." Filterloops are variations on the baseline filter configuration that provide insight into the OD solution sensitivity and consistency across a wide trade space, and are useful in assessing strengths and weaknesses of various models and data content. The filterloops were executed as part of the daily OD assessment during final approach.

Various data arc lengths were utilized throughout cruise in order to optimize OD filter performance while reducing processing time. The starting epochs for all data arcs are shown in Table 2. The starting epochs were typically chosen to exclude specific TCMs or other spacecraft events from the OD solution, or as in the case for the D arc, to shorten the data arc and thus reduce the run time. Multiple data arcs were often executed for the same DCO as an indication of solution consistency, and as a means to quantify solution sensitivity to TCM execution errors and measurement errors.

Table 2: Starting epoch of the data arcs

Arc label	Arc start epoch	Comment
A	05-MAY-2018 12:38:20 UTC	Launch
B	08-JUN-2018 23:58:51 UTC	Post-bakeout
C	29-JUL-2018 00:00:00 UTC	Post-TCM-2
D	11-SEP-2018 07:00:00 UTC	Late cruise "quiet" period
E	12-OCT-2018 18:58:51 UTC	Post-TCM-3
F	18-NOV-2018 19:00:00 UTC	Post-TCM-5

The DCO of a given maneuver is the point in time at which no new tracking data is incorporated for the maneuver design process. In the time between the DCO and maneuver execution, new data is obtained and new OD solutions are computed, but they are simply monitored for any shifts that would cause problems should the maneuver be executed in the current situation. Another spacecraft action with an associated DCO are the opportunities to upload Entry Parameter Updates (EPUs). These are the team's chance to update parameters pertinent to Entry, Descent, and Landing (EDL) such as entry states and parachute timers.

Entry State Files

The primary method of transferring information about OD solutions to the EDL team is through Entry State Files (ESFs). All information is conveyed at a very specific event, known as "entry". The entry event is defined when the spacecraft distance from the center of Mars is 3522.2 km.

ESFs contain dispersed delivery and knowledge samples, which answer two different questions about the OD uncertainty. Informally, the delivery solution answers the question

> "How accurately can we target a specified entry point?"

On the other hand, the knowledge solution answer the question

> "How accurately do we know the actual spacecraft entry point?"

Said another way, a delivery state represents a specific realization of the spacecraft state at entry, and the corresponding knowledge state represents the OD filter's *estimate* of the spacecraft state at entry. These two questions are tightly related to each other because a dispersed delivery state sample and its corresponding knowledge state sample are correlated, as we'll see in the following mathematical definition. In the context of EDL simulations, a delivery state is taken as the truth state, and the associated knowledge state is used as the on-board state estimate.

The algorithm used in all previous missions to create knowledge states has long been know to be an approximation, valid in the limit of "good knowledge." For missions such as MSL with quiescent dynamics and small maneuver execution errors, this approximation was extremely accurate and caused no concern. InSight, because of perturbing small forces and larger maneuver execution errors, needed something better. A mathematically correct algorithm was developed and used on InSight. This updated algorithm will also be used on future missions.

For the mathematically correct definition, consider three slices of time denoted with indices 0, 1, and 2 as shown in Figure 3. Time 0 is the DCO for the last planned TCM, time 1 is the DCO for the last EPU, and time 2 is the entry time.

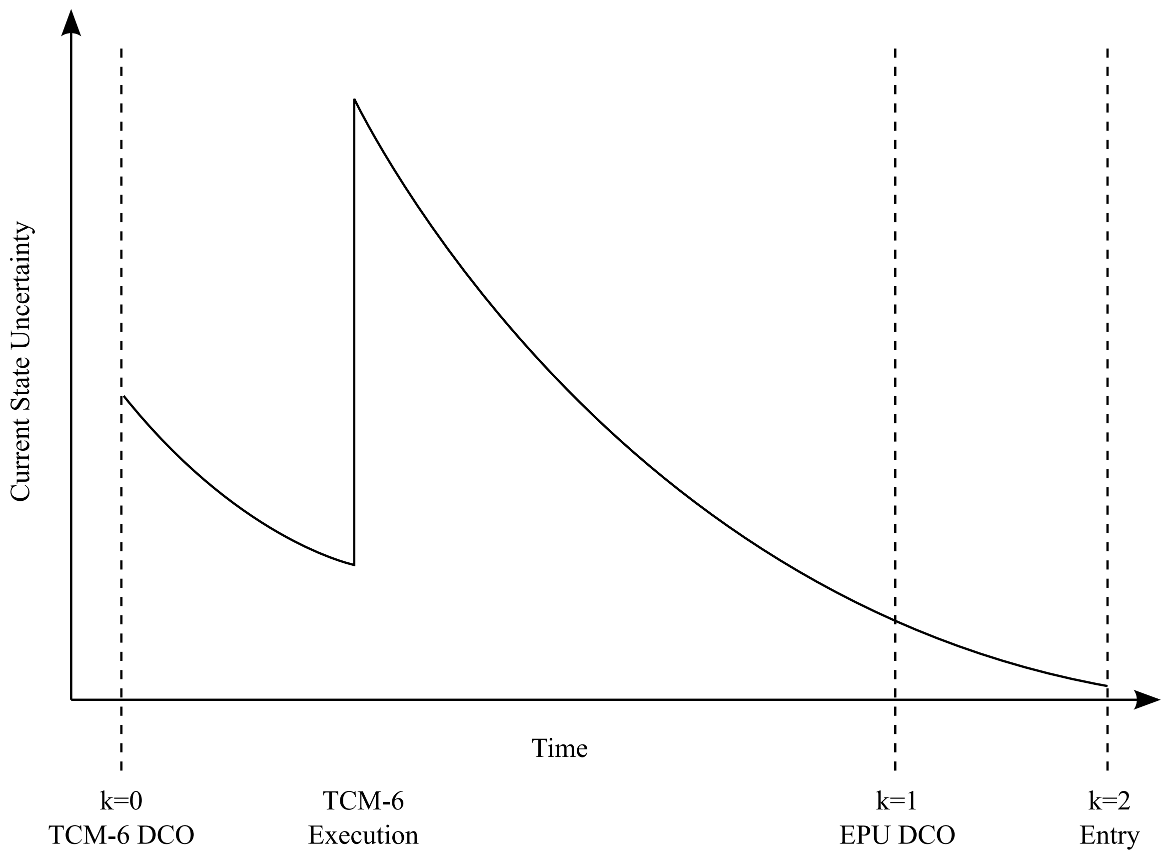


Figure 3: Schematic of uncertainty vs. time for key events

The delivery samples are **d** and the knowledge samples are **k**; $\mathbf{x}_{\text{nom}}$ is the nominal entry state. There are three covariance matrices involved. The considered delivery covariance is denoted as C_d. The estimated delivery and knowledge covariances are C_{de} and C_{ke}, respectively.

Let $\mathbf{x}_k$ be the truth state at time k. Let $\hat{\mathbf{x}}_{k|j}$ be the filter estimate at time k, given information up to and including time j. Let $P_{k|j}$ be the considered covariance of $\hat{\mathbf{x}}_{k|j}$, and $P_{e\,k|j}$ be the estimated covariance of $\hat{\mathbf{x}}_{k|j}$. Both $\mathbf{x}_k$ and $\hat{\mathbf{x}}_{k|j}$ are random variables.

In terms of these definitions, we can now formally define delivery and knowledge states. For a given realization, the delivery state, $\mathbf{d}$ is $\mathbf{x}_2$—the truth state at entry. The knowledge state associated with that realization, $\mathbf{k}$ is $\hat{\mathbf{x}}_{2\,|\,1,\mathbf{x}_2=\mathbf{d}}$—the filter estimate at entry conditioned on two pieces of information:

1. all information up to the EPU DCO
2. the truth state at entry, $\mathbf{x}_2$, is $\mathbf{d}$

Note that $\hat{\mathbf{x}}_{2\,|\,1,\mathbf{x}_2=\mathbf{d}}$ is a random variable even though the truth state at entry is given because it still depends on the measurements and stochastic dynamics, neither of which are deterministic.

The considered covariances C_d and C_k are formally defined as $C_d = P_{2\,|\,0}$ and $C_k = P_{2\,|\,1}$. The estimated covariances C_{de} and C_{ke} are $C_{de} = P_{e\,2\,|\,0}$ and $C_{ke} = P_{e\,2\,|\,1}$.

The old algorithm can be summarized as follows. Repeat for each delivery/knowledge sample pair:

1. Draw $\mathbf{d}' \sim \mathcal{N}(0, C_d)$
2. $\mathbf{d} = \mathbf{x}_{\text{nom}} + \mathbf{d}'$
3. Draw $\mathbf{s} \sim \mathcal{N}(0, C_k)$
4. $\mathbf{k} = \mathbf{d} + \mathbf{s} = \mathbf{x}_{\text{nom}} + \mathbf{d}' + \mathbf{s}$

This algorithm treats delivery states correctly. However, there is a major shortcoming regarding the knowledge states. They are not treated as state estimates from the OD filter. Instead, they are simply noise on top of delivery states. This causes the dispersion of the knowledge states relative to the nominal to be larger than it really is. Also, there is too much cross-correlation between delivery and knowledge states, and no distinction between considered and estimated covariance is made.

The new algorithm is as follows:

1. Draw $\mathbf{d}' \sim \mathcal{N}(0, C_d)$
2. $\mathbf{d} = \mathbf{x}_{\text{nom}} + \mathbf{d}'$
3. Draw $\mathbf{n}' \sim \mathcal{N}(0, DC_{ke})$
4. $\mathbf{k} = \mathbf{x}_{\text{nom}} + D\mathbf{d}' + \mathbf{n}'$

The matrix D may be obtained by solving a linear equation:* $C_{de}D^{\mathrm{T}} = C_{de} - C_{ke}$. Alternatively, if directly inverting the matrix C_{de} isn't objectionable, then D can be computed directly as $D = I - C_{ke}C_{de}^{-1}$.

*For example, in Python this could be performed as: `D = np.linalg.solve(Cde, Cde - Cke).T`

Launch and Early Operations

As with most missions, the primary objective for OD during the launch phase is to do everything possible to ensure successful acquisition at the DSN complexes beyond initial acquisition. The first DSN complex to provide radiometric tracking data was Goldstone, which had a 1.5 hour pass of two-way Doppler and range data. However, this wasn't enough time or data to produce an update for Canberra before InSight was scheduled to rise there. Fortunately, the injection error was low and Canberra was able to acquire signal based on pre-launch predicts. Therefore, the remaining OD work was to process data from Goldstone and Canberra and deliver an updated trajectory to the DSN before transitioning to Madrid.

The initial filter setup used polynomial accelerations to account for RCS thruster firings instead of discrete impulse burns to provide robustness to any GDS telemetry issues. Nonetheless, estimates of C3, and the direction of the outgoing asymptote (declination and right ascension) converged quickly and were stable as more data was included in the solution as show in Table 3 and Figure 4.

Table 3: Launch Performance vs DCO

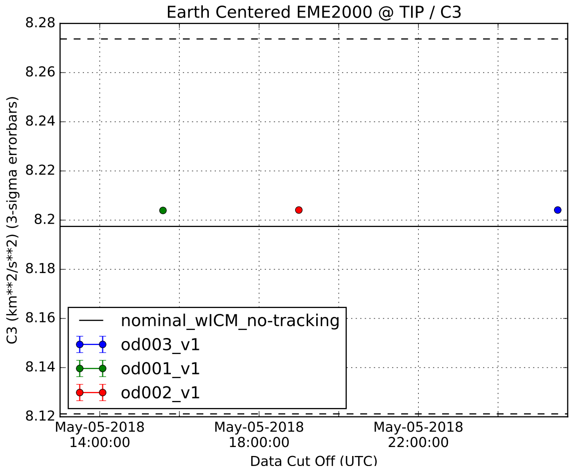
Data Cut-Off	C_3 (km^2/s^2)	RLA (deg)	DLA (deg)
05-May-2018 15:35:14 UTC	8.203929	328.096323	-40.824669
05-May-2018 18:59:54 UTC	8.204097	328.096943	-40.824463
06-May-2018 01:29:54 UTC	8.204104	328.097549	-40.824772

Within several hours of launch, it became clear that significant non-gravitational accelerations were detectable. Switching to actual small force modeling with telemetry provided better fits and prediction, however, residual effects were still clear. Once our models were refined to respond to this, we estimated an acceleration with exponential decay as shown in Figure 5. The spike in accelerations on May 6 at about 17:00 was the transition from launch initial acquisition attitude to the early cruise attitude. This change in geometry exposed new spacecraft components to the sun, resulting in a new trend in outgassing acceleration.

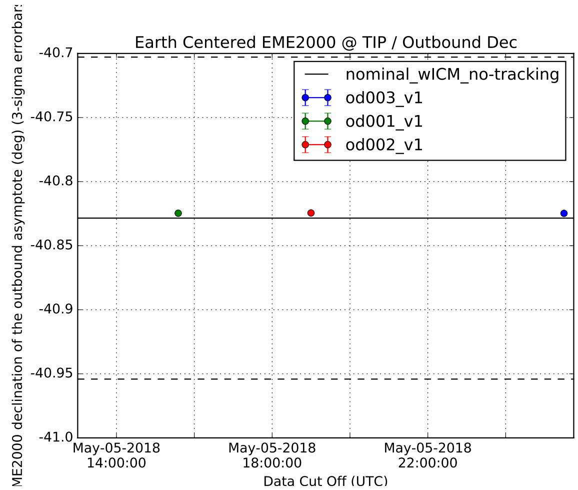
Early Cruise

In early cruise, much effort was devoted to characterizing the outgassing and refining models and processes. The spacecraft team at Lockheed Martin developed the hypothesis that outgassing from the interior of the cruise stage was venting to space through a vent hole where the solar panel joins the cruise stage. This geometry not only imparts a translational force on the spacecraft, but also a torque with a lever arm of about one meter. This torque must be countered by the RCS system, causing the RCS thrusters to fire about 25 times more than expected.[7] The attitude deadbands for the X, Y, and Z axes were 10°, 10°, and 7.5°, respectively, during early cruise.

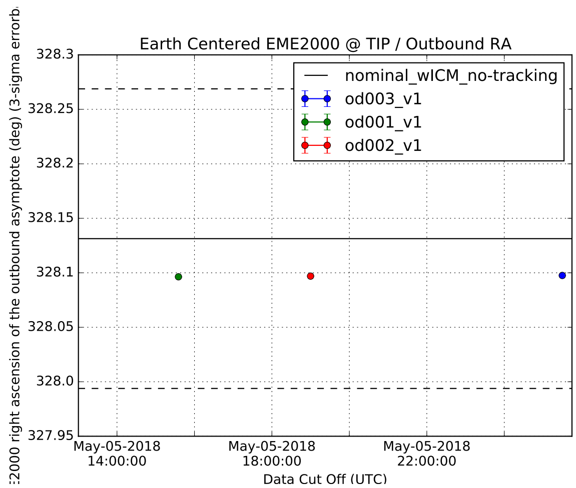
Another important activity in early cruise was the TCAL.[7] This activity was performed to characterize the RCS thruster behavior by firing individual thrusters in various attitudes to allow full line-of-sight visibility from the Earth line. Results from the TCAL were used to update *a priori* values for the thruster directions and magnitudes.



(a) Launch energy



(b) Declination of outbound asymptote



(c) Right ascension of outbound asymptote

Figure 4: Estimates of C_3, DLA, RLA vs DCO shortly after launch

Late Cruise

The transition to the late cruise attitude with solar panels pointing nearly directly at the sun occurred on July 12, 2018. Along with the attitude change, the deadband limits were reduced to 4° in all axes.

Beginning in late cruise, filterloops were utilized to assess the OD solution's sensitivity to variations in data types, data weights, data arcs, dynamic models, and filter configurations. The filterloops are flexible and extensible, and allow the OD analysts to quickly assess the impact of changes to the baseline, such as excluding a specific ΔDOR session or increasing the predicted RCS thruster acceleration uncertainty. By final approach, a total of 34 filterloops were executed along with the baseline OD solution.

Figure 6 presents a selection of data variations (Figure 6a) and dynamic model/filter configuration variations (Figure 6b) for a DCO of 17-November (one day prior to execution of TCM-5). The data

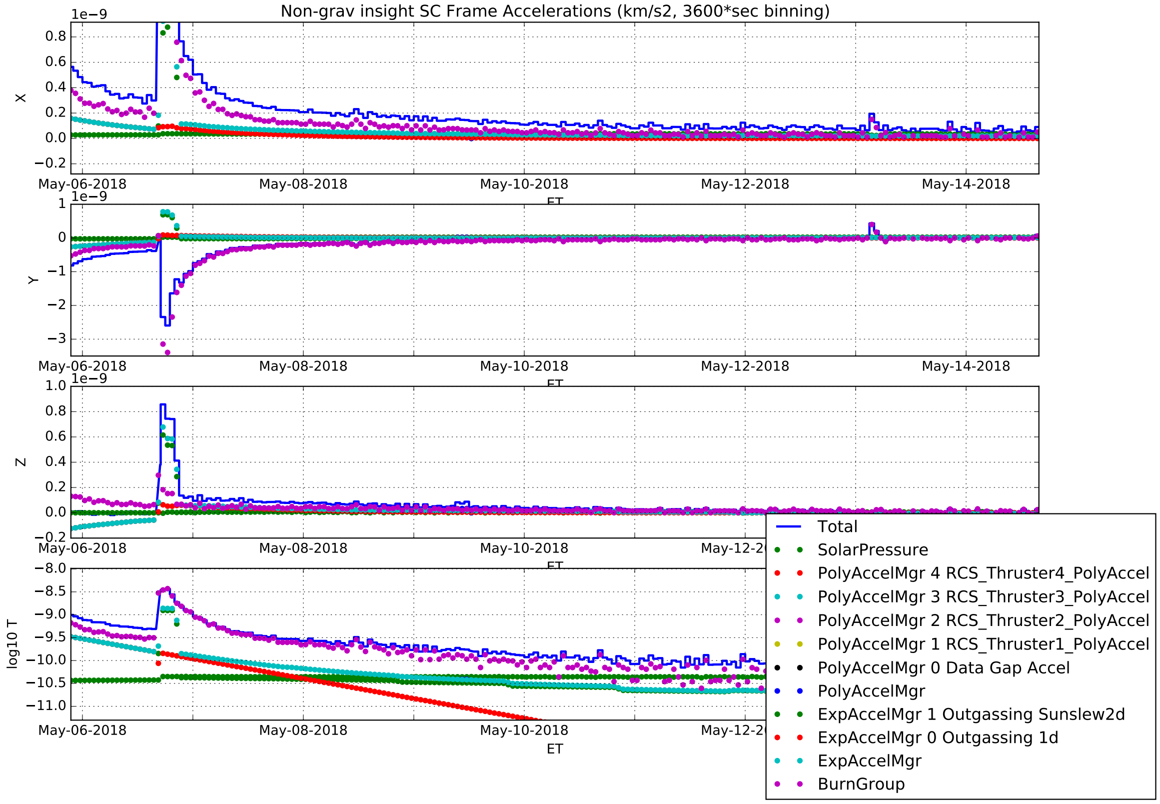
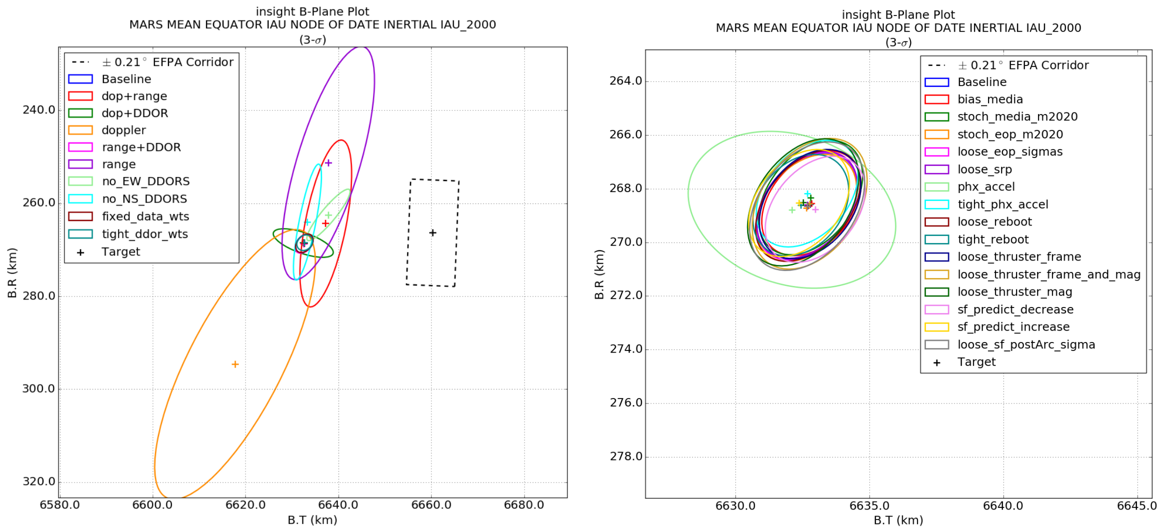


Figure 5: Non-gravitational accelerations clearly showing outgassing

variation filterloops make no changes to the baseline dynamic models or filter configuration, but adjusts the processed data types or data weights. Figure 6a compares the baseline 3-σ B-plane ellipse with those produced via all data types combinations, including the removal of East-West or North-South ΔDOR measurements. Additional filterloops shown process all available data types but assume conservative, fixed Doppler and range noise levels ("fixed_data_wts") and decreased ΔDOR noise levels ("tight_ddor_wts"). The data variation filterloop results are statistically consistent with one another, which increases confidence that no one data type is incorrectly driving the OD solution. Furthermore, the data variation filterloops provide great insight into the information content of the individual measurement types (including ΔDOR baselines) as mapped to the entry B-plane.

In contrast to the data variation filter loops, the dynamic model and filter configuration variations (Figure 6b) make no changes to the baseline data set or data weights, but adjust the dynamic and filter models. The model variations explored generally included variations to the estimation of media effects and Earth Orientation parameter errors, tight and loose maneuver execution errors, increased uncertainty in solar pressure, increased uncertainty in the RCS thruster parameters, and adjusted predicted small force accelerations. Figure 6b shows a selection of model filterloops executed at the 17-November DCO; all model variations are consistent, indicating that the OD solution is not sensitive to the variations explored. With less than 9 days until entry, the entry point dispersion and uncertainty across all model variations is small due to the relatively short propagation time. Earlier in cruise, the filterloops showed much more sensitivity to variations in the small force modeling and estimation strategies.[7]



(a) Select data variations (b) Select model variations

Figure 6: Late cruise filterloops (DCO = 17-November)

On October 29, 2018, the spacecraft was commanded to perform a "cold reboot," the purpose of which is to get the spacecraft avionics into a known, clean state before EDL. As with most spacecraft, InSight boots into safe mode. For this spacecraft, that means that the RCS thrusters are guaranteed to fire autonomously, with the amount of firing depending on the specific attitude at the time of the reboot. Therefore, the ΔV from the cold reboot activity is not well-predictable. In the unlikely worst case, it was possible the spacecraft could have not quickly acquired attitude as expected and gone into sun-coning. This would have resulted in nearly continuous thruster firing. The Guidance, Navigation, and Control (GNC) team gave a more realistic expectation that the ΔV would range between 10 mm/s and 30 mm/s. The actual estimate from the OD solution was about 21 mm/s, directed almost entirely along the spacecraft +X axis as expected.

The OD solution remained stable throughout cruise, with a substantial improvement in solution uncertainty provided by implementing the higher-fidelity small force and attitude modeling strategy (see Figure 6b, "Baseline" versus "phx_accel"). At the DCO for TCM-4, a comparison of the propagated OD solution with and without TCM-4 (and its associated requirement-level execution errors) (Figure 7) showed a non-trivial probability that executing TCM-4 could actually move the spacecraft further from the target. In contrast, with only one week between TCM-5 execution and Mars entry for maneuver execution errors to propagate, even a 3-σ TCM-5 would move the spacecraft closer to the target. Therefore, the decision was made to cancel TCM-4 in favor of executing TCM-5.

Final Approach

The OD and navigation goals for final approach are focused entirely on delivering the spacecraft accurately to the entry target at Mars.

To achieve an accurate landing on the surface, atmospheric dynamics must be modeled as well as possible. During final approach, the Council of Atmospheres delivered daily updates on Martian atmospheric profiles. Each of these deliveries results in a different EDL trajectory from the top of the

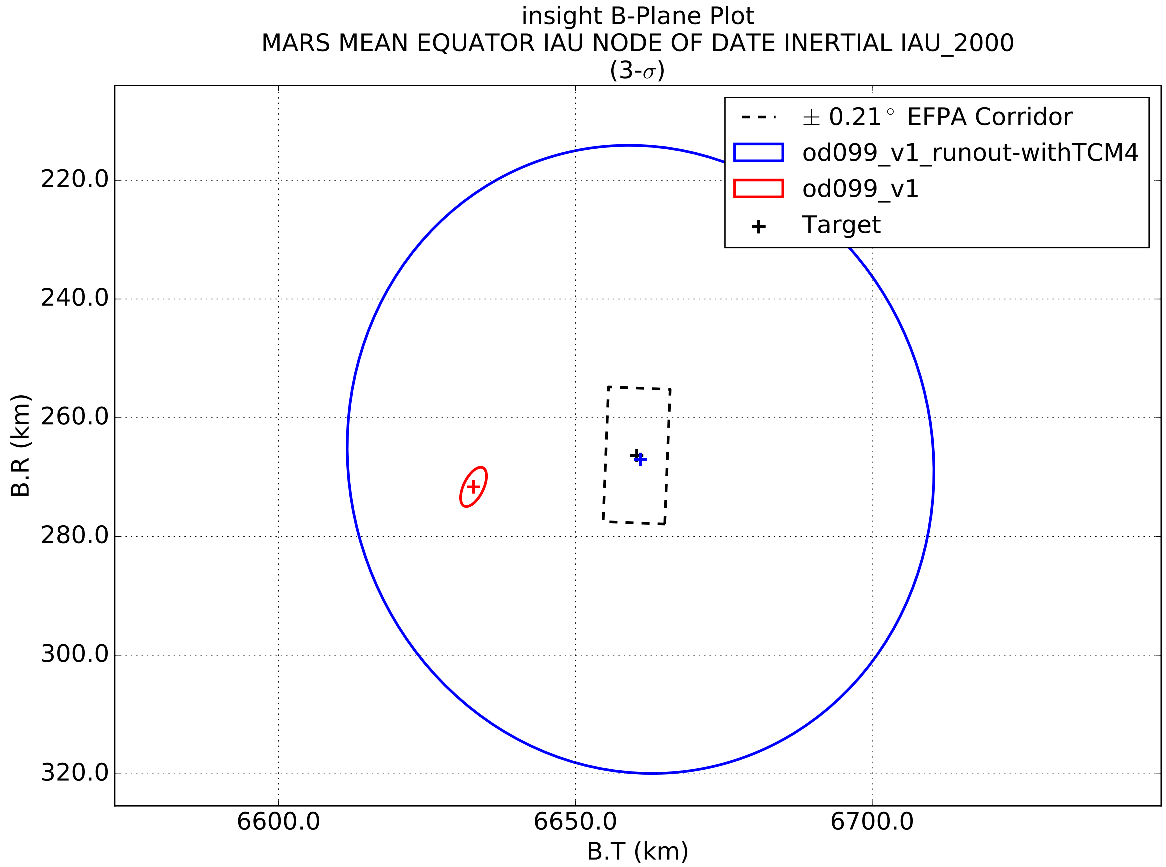


Figure 7: TCM-4 OD and delivery solutions

atmosphere to the surface. Using the final planned maneuver, TCM-6, to directly target the original landing site in response to a shift in atmosphere has the potential to require a large maneuver. To alleviate this concern, the targeting strategy allowed for a 0.15° tolerance in our EFPA target.[11] In other words, although our nominal EFPA target was -12.0°, it was acceptable to the project to target a range from -12.15° to -11.85°. This is distinct from the navigation delivery requirement of 0.21°, 3-σ.

Throughout the mission, tracking data residuals for Doppler and range were very much aligned with expectations: near-zero mean, no discernible signature remaining, and expected values of standard deviation. The residuals for ΔDOR data, shown in Figure 8, were also well within expectations, even though the data doesn't fit as nicely as Doppler and range. The data weight used for ΔDOR in the OD filter was that suggested by the tracking team. Testing done by the OD team revealed that the standard deviation of the ΔDOR residuals could be reduced by tightening the data weight, but that approach was not taken in our baseline solutions to avoid over-weighting the data and being misled by potential systematic effects.

InSight transmitted radiometric navigation data until seven minutes before entry, when the cruise stage separated from the entry vehicle and took the Medium-Gain Antenna (MGA) with it. After Cruise Stage Separation (CSS), depicted in Figure 9*, InSight continued transmitting a Ultra-High

*https://mars.nasa.gov/resources/22115/illustration-of-insight-cruise-stage-separation/

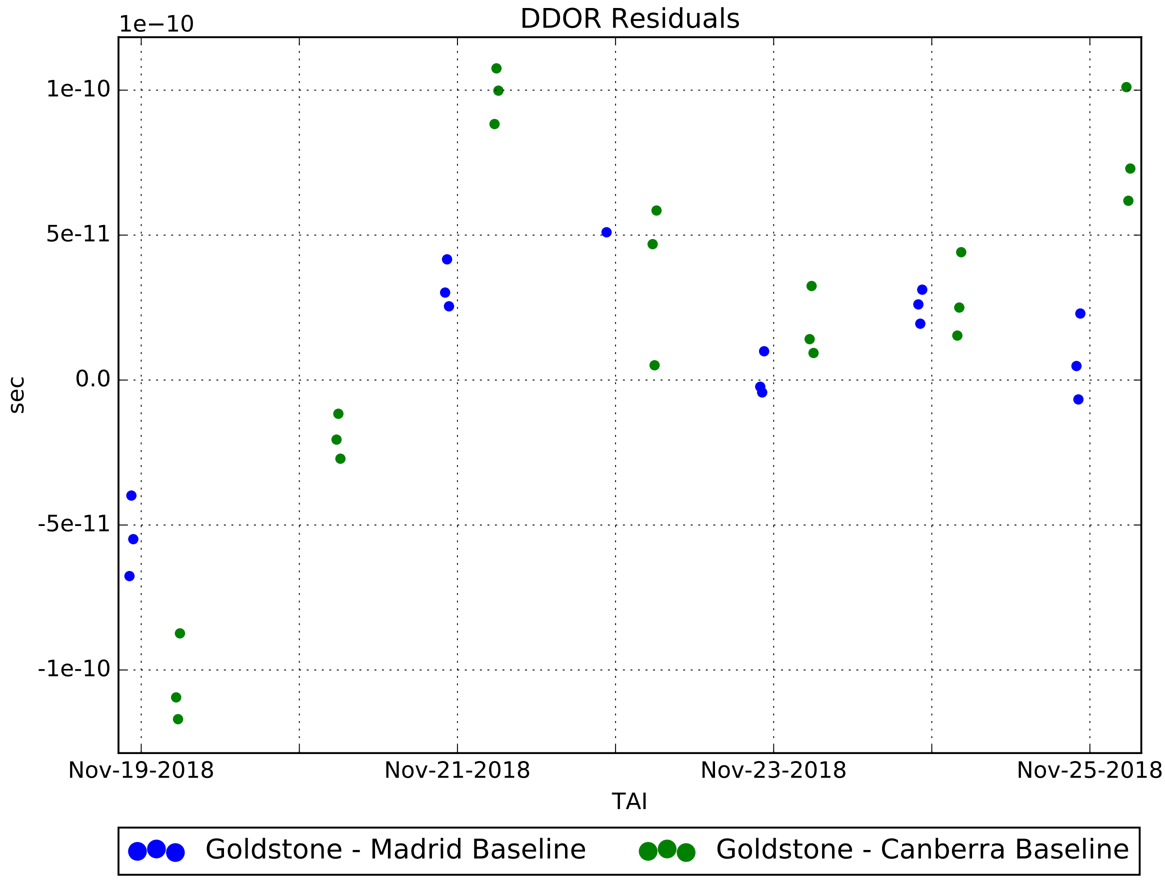


Figure 8: Late cruise ΔDOR residuals

Frequency (UHF) signal received by Mars Reconnaissance Orbit and the MarCO CubeSats, among others.

SUMMARY

InSight orbit determination successfully worked in concert with other navigation subsystems to accurately deliver the InSight lander to its entry target at Mars. Many process improvements and new capabilities were developed and described including the treatment of small forces, SRP, and ESF algorithms. During flight, the unavoidable coupling between attitude control and trajectory dynamics was constantly monitored. The OD approaches adapted as necessary to continue smooth operation of the spacecraft. All OD and navigation requirements were met with ample margin throughout cruise.

ACKNOWLEDGMENTS

The orbit determination team would like to thank the InSight maneuver team, EDL team, spacecraft team (especially GNC), Tim McElrath, Gerard Kruizinga, Jim Border, system administrators, Navigation Advisory Group (NAG) members, the DSN, and K.J. Lee.

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

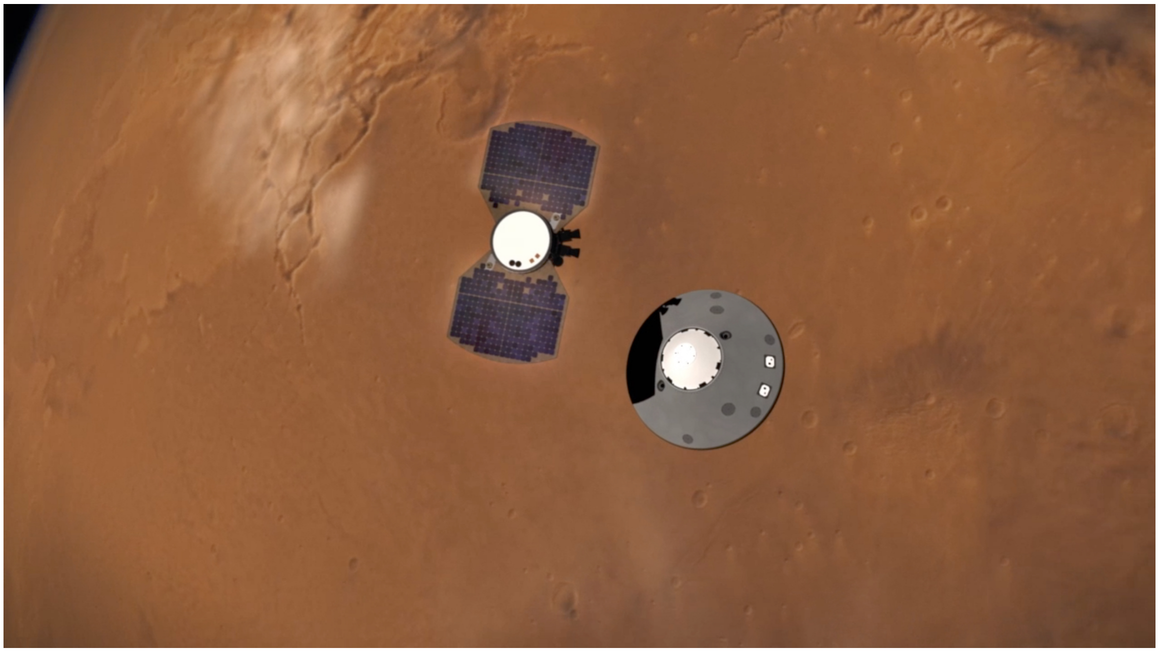


Figure 9: Illustration of InSight shortly after cruise stage separation

REFERENCES

[1] C. A. Halsell, M.-K. Chung, E. Gustafson, Y. Hahn, D. Jefferson, G. Kruizinga, E. Lau, J. Lee, S. E. McCandless, N. Mottinger, J. Seubert, E. Sklyanskiy, and M. Wallace, "Navigation Performance Of The 2018 InSight Mars Lander Mission," *29th AAS/AIAA Spaceflight Mechanics Meeting*, 2019.

[2] F. Abilleira, C. A. Halsell, M.-K. Chung, K. Fujii, E. Gustafson, Y. Hahn, M. Johnson, T. Kennedy, J. Lee, S. E. McCandless, N. Mottinger, J. Seubert, G. Signori, E. Sklyanskiy, and M. Wallace, "Navigation Performance Of The 2018 InSight Mars Lander Mission," *29th AAS/AIAA Spaceflight Mechanics Meeting*, 2019.

[3] G. Kruizinga, E. Gustafson, P. Thompson, D. Jefferson, T. Martin-Mur, N. Mottinger, F. Pelletier, and M. Ryne, "Mars Science Laboratory Orbit Determination," *23rd AAS/AIAA Spaceflight Mechanics Meeting*, 2013.

[4] M. S. Ryne, E. Graat, R. Haw, G. Kruizinga, E. Lau, T. Martin-Mur, T. McElrath, S. Nandi, and B. Portock, "Orbit Determination for the 2007 Mars Phoenix Lander," *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, 2008.

[5] M.-K. Chung, Y. Hahn, C. A. Halsell, S. E. McCandless, E. Sklyanskiy, and M. Wallace, "Maneuver Design Overview of the 2018 InSight Mars Lander Mission," *29th AAS/AIAA Spaceflight Mechanics Meeting*, 2019.

[6] M. S. Wallace, "A Massively Parallel Bayesian Approach to Planetary Protection Trajectory Analysis and Design," *AAS/AIAA Astrodynamics Specialist Conference*, 2015.

[7] J. Seubert, E. D. Gustafson, C. A. Halsell, D. Howell, T. Kennedy, J. Lee, and S. E. McCandless, "InSight Attitude Control System Thruster Characterization and Calibration for Successful Navigation to Mars," *29th AAS/AIAA Spaceflight Mechanics Meeting*, 2019.

[8] S. Evans, W. Taber, T. Drain, J. Smith, H.-C. Wu, M. Guevara, R. Sunseri, and J. Evans, "MONTE: The Next Generation of Mission Design and Navigation Software," *CEAS Space Journal*, Vol. 10, March 2018, pp. 79–86.

[9] W. M. Folkner and C. S. Jacobs, "DSN Station Location Update for MER," JPL Internal Office Memorandum, October 2003.

[10] W. M. Folkner, "Mars ephemeris uncertainty for Mars Science Laboratory navigation," JPL Internal Office Memorandum, August 2010.

[11] E. P. Bonfiglio, M. Wallace, E. Gustafson, E. Sklyanskiy, M.-K. Chung, and D. Kipp, "Atmospheric Impacts On EDL Maneuver Targeting For The Insight Mission And Unguided Mars Landers," *29th AAS/AIAA Spaceflight Mechanics Meeting*, 2019.