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ATMOSPHERIC IMPACTS ON EDL MANEUVER TARGETING FOR THE INSIGHT MISSION AND UNGUIDED MARS LANDERS

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Early in operational testing for the InSight mission to Mars, it was discovered that the final maneuver to target the entry-interface point (EIP) was unexpectedly sensitive, in both magnitude and direction, to planned atmosphere model updates that would be based on real-time measurements of the Martian atmosphere by Mars Reconnaissance Orbiter (MRO). Upon investigation, the team realized that the Phoenix mission also discovered this sensitivity during its operational testing. A further investigation identified that maneuver sensitivity to real-time atmosphere updates was a result of the fact that both the EFPA and ground target were being held fixed, constraining the maneuver in a way that forced the entry time to change in order to compensate for changes to the nominal trajectory from updating the atmosphere model. The final maneuver occurs 22 hours prior to entry, at which point it is very expensive to change entry time. The study also revealed that any unguided Mars entry, descent, and landing (EDL) mission would be impacted by this sensitivity if it used real-time atmosphere observations to model the nominal expected atmosphere used for maneuver targeting of the EIP. This paper discusses the results of that investigation and presents a number of mitigations as well as the consequences of ignoring the sensitivity.

INTRODUCTION

The Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport (InSight) Mission launched on May 5, 2018. The InSight entry, descent, and landing (EDL) system had the primary objective of placing a science lander on the surface of Mars. The primary science of the mission is supported by the deployment of two science instruments (SEIS and HP3) onto the Martian surface to investigate the fundamental processes of terrestrial-planet formation and evolution. The lander will also perform radio science (RISE) to understand the nutation of Mars' pole and will also monitor weather with the TWINS instrument package. The InSight mission successfully executed entry, descent, and landing on November 26, 2018, following a direct entry into the atmosphere from its interplanetary trajectory to Mars. The EDL event was relayed to Earth 'live' via two

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CubeSats called Mars Cube One (MarCO)[1] which launched alongside InSight and were timed to fly by Mars during the InSight EDL event. InSight EDL was also viewed by the Mars Reconnaissance Orbiter (MRO), whose orbit was phased specifically to record the EDL event and play it back to Earth at a later time[2].

The InSight entry vehicle is a 'build-to-print' version of the successful Phoenix Mars lander[3], which was the sister spacecraft of the Mars Polar Lander (MPL), albeit with significant modifications made to improve on the MPL design[4]. Some of the more notable modifications made to InSight relative to Phoenix were a thicker thermal protection system (TPS) to accommodate a more stressing heating environment and the potential for dust ablation associated with dusty atmospheres, larger solar arrays, strengthening of key components to account for a slightly higher lander mass and larger snatch loads at parachute deploy, and a new payload.

The InSight mission arrived at Mars during dust-storm season.[5] This is the time of the Martian year when there is a higher risk of regional and global dust storms forming. In fact, one of the largest Martian global dust storms on record began in June of 2018, a little more than six months prior to InSight arrival.[*] Because of the uncertainty in the type of atmosphere InSight would experience on landing day, the EDL system was required to accommodate any one of four different types of atmospheres: background (expected seasonal conditions), a regional dust storm, a global dust storm, and a decaying (from global conditions) dust storm. Each atmosphere type had structural differences that impacted the EDL system in different ways; thus, the team required independent models for each type.

EDL, NAVIGATION, AND TARGETING

The EDL and Navigation systems have a unique relationship that binds them together and can create non-intuitive interdependencies. This is particularly true for an unguided system such as InSight which cannot correct for navigation errors and uncertainties in the aerodynamic forces after entry. The Navigation team must guide the spacecraft from its initial injection orbit at Earth to the entry-interface point (EIP) at the Martian atmosphere. It must also enter the atmosphere at a specific entry flight path angle (EFPA) at the EIP. This EIP has been arbitrarily defined by previous missions as the point when the entry vehicle is at a radius of 3522.2 km from the center of Mars. From that point, the Spacecraft and EDL team must design, test and simulate a system that safely lands on the ground. The entry-interface point is quite literally where the entry capsule is handed off from the Navigation system to the EDL system.

The Navigation team uses an in-house tool called Monte[6] for trajectory propagation, maneuver targeting, and associated analyses. The EDL team uses a tool called DSENDS[7], also developed at JPL, for the EDL trajectory simulation. Both tools have Python-based scripting interfaces, allowing the EDL and Navigation team to seamlessly automate the iterative process of designing a maneuver to target the desired entry conditions. While the DSENDS tool has the capability to perform high-fidelity EDL trajectory simulation and estimate EDL system performance, for expediency and operational simplicity, the InSight DSENDS simulation only includes models which significantly affect the landing location. Flight software was not integrated into the InSight DSENDS simulation, nor did it contain sensor models of the IMU and radar.

On InSight, EDL system performance was evaluated using high-fidelity simulations in the Program to Optimize Simulated Trajectories 2 (POST II)[8] by Langley Research Center, another POST II simulation operated by engineers at Lockheed Martin, and a third simulation in a tool called LanderSim, developed and operated at Lockheed Martin. POST II is a trajectory simulation

[*] https://mars.nasa.gov/weather/storm-watch-2018/

tool originally developed at Lockheed Martin. The EDL landing dispersions on the ground covered a landing ellipse footprint of up to 130 km x 27 km, depending on what atmosphere was being used.

EDL System

The InSight vehicle is an unguided entry, descent, and landing system consisting of a 2.65 m diameter heatshield, an 11.7 m disk-gap-band parachute system[9,10], an IMU to estimate attitude and aerodynamic deceleration, a radar to determine ground-relative altitude and velocity, and twelve pulse-width modulated 300 N thrusters which execute a gravity turn starting at about a kilometer above the ground. The entry vehicle is three-axis stabilized until entry at which point attitude control is effectively disabled, via large attitude-control deadbands[11], until the gravity-turn phase. Touchdown is targeted at a vertical velocity of 2.5 m/s and a horizontal velocity of 0 m/s. Figure 1 gives an overview of the nominal EDL scenario for an inertial entry flight path angle of -12.0°.

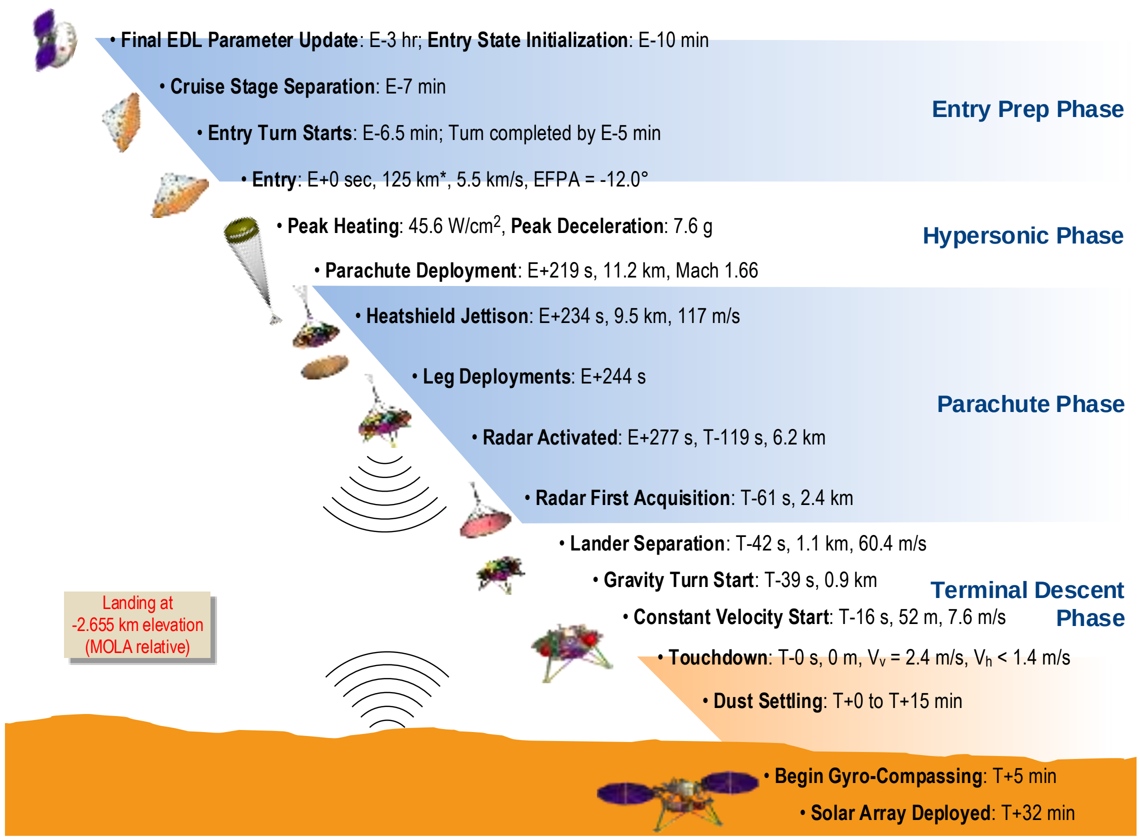

Figure 1. Overview of the InSight Entry, Descent, and Landing timeline (times and altitudes correspond to a nominal scenario with an EFPA of -12.0°)

Navigation System

The *InSight Navigation Plan*[12] contained six trajectory correction maneuvers (TCMs), along with two contingency maneuvers, to target the desired entry state at Mars such that the targeted entry flight path angle results in the nominal trajectory landing at the desired latitude and longitude (ground target). The nominal EFPA target requirement for InSight was originally defined as -12.0° ± 0.21° (3σ). The nominal landing target (also referred to as 'E9' on the project) was modified post launch to be -4.51° latitude and 135.99° longitude. Table 1 provides the schedule for TCMs from the *InSight Navigation Plan*. The 'X' version of maneuvers in this table represent contingency maneuvers in the event that the nominal maneuver could not be executed or had unusually large execution errors.

Table 1. TCM schedule for the InSight mission

Event	Trajectory-Relative Time	Date
TCM-1	Launch + 17 days	22 May 2018
TCM-2	Entry – 121 days	28 Jul 2018
TCM-3	Entry – 45 days	12 Oct 2018
TCM-4	Entry – 15 days	11 Nov 2018
TCM-5	Entry – 8 days	18 Nov 2018
TCM-5X	Entry – 5 days	21 Nov 2018
TCM-6	Entry – 22 hours	11/25/18 21:40 UTC
TCM-6X	Entry – 8 hours	11/26/18 11:40 UTC

EDL Targeting

It is the job of the Navigation team to target the correct EIP such that the nominal trajectory will touchdown on the surface at the desired ground target. This requires a trajectory to be propagated to the Martian EIP at a particular time and at the desired EFPA. Next, the entry state is handed off to an EDL trajectory simulation tool (DSENDS) that models the aerodynamics and the EDL system (parachute, thrusters, etc.) and propagates the trajectory to the ground. The miss-distance on the ground from the initial propagation is calculated and then the entry time and entry state that the Navigation team should target is corrected and updated accordingly. This process is repeated until the miss-distance on the ground is within an acceptable tolerance (typically a few meters). Through the entire process, the EFPA target and the ground target are kept constant.

This iterative process is referred to as EDL targeting and once it has converged, the Navigation team has an entry state that can be targeted with maneuvers that will meet the EFPA-target and ground-target requirements of the EDL system. The EDL simulation that is used in the iterative process of EDL targeting is a single EDL trajectory (i.e., it is not a Monte Carlo) and uses nominal flight conditions for parameters such as aero coefficients, atmospheric density, winds, etc. Since the EDL trajectory used for targeting always uses the same nominal inputs, it means that, for a given EFPA, the arc flown through the atmosphere from the EIP to the ground *is always the same*. This arc is commonly referred to as the central angle (the angle made by the EIP, the center of Mars, and the landing location). If the EFPA (e.g. -12.0°) is unchanged, the central angle in the EDL trajectory will also be unchanged if all other nominal simulation parameters are the same.

The entry epoch essentially defines the sub-Martian latitude and longitude when the interplanetary trajectory intersects the atmosphere (i.e., the EIP). If the entry vehicle arrives at a later entry epoch, Mars will rotate a little more and the EIP will move westward. If the vehicle arrives at an earlier entry epoch, Mars won't have rotated as much and the EIP will move eastward. All of this means that if the entry epoch and the central angle do not change, the nominal trajectory will always go to the same point on the ground. The role of the nominal trajectory profile in the EDL targeting process is illustrated in Figure 2. The blue 'x' in Figure 2 is defined by the sub-Martian latitude and longitude at the point of entry, thus it is labeled the entry epoch.

The nominal trajectory approximately defines the center of the EDL landing ellipse on the ground and the Monte Carlo performed for EDL uncertainty analyses defines the size of the landing ellipse which is also shown in Figure 2. This means that wherever the nominal trajectory moves on the ground, the center of the landing ellipse will move with it.

Having defined the entry target through this process, the Navigation team is able to perform covariance analyses to determine the worst-case propellant required to meet the EFPA accuracy requirements (-12.0° ± 0.21°). Included in this analysis are orbit determination uncertainties, maneuver execution errors and other uncertainties associated with navigating interplanetary spacecraft (e.g., solar radiation pressure and small forces that are imparted to the spacecraft while maintaining the desired attitude in space).

Hidden in the targeting process is an assumption that the nominal EDL trajectory used to target TCM-1 and TCM-2 to the desired ground target is the same nominal trajectory used to target TCM-5 and TCM-6 to the desired ground target. In other words, it's assumed that there is no variation to be accounted for in the nominal EDL trajectory when the Navigation team calculates worst-case propellant needed to meet EFPA requirements. It turns out that, for InSight, this assumption is not strictly true if the EFPA target and ground target remain fixed.

InSight's plan as the project approached the EDL event was to start using measurements from the Mars Reconnaissance Orbiter instrument Mars Climate Sounder (MCS) to estimate the actual EDL atmosphere the capsule would experience on landing day. Starting at about 2-3 weeks out, MCS measurements would be used by atmospheric scientists to forecast the EDL atmosphere. Atmospheric scientists would deliver updated atmosphere models to the EDL and Navigation teams. Prior to these measurements being made, all maneuvers are targeted using the nominal background atmosphere. The same process was used on Phoenix as well[13].

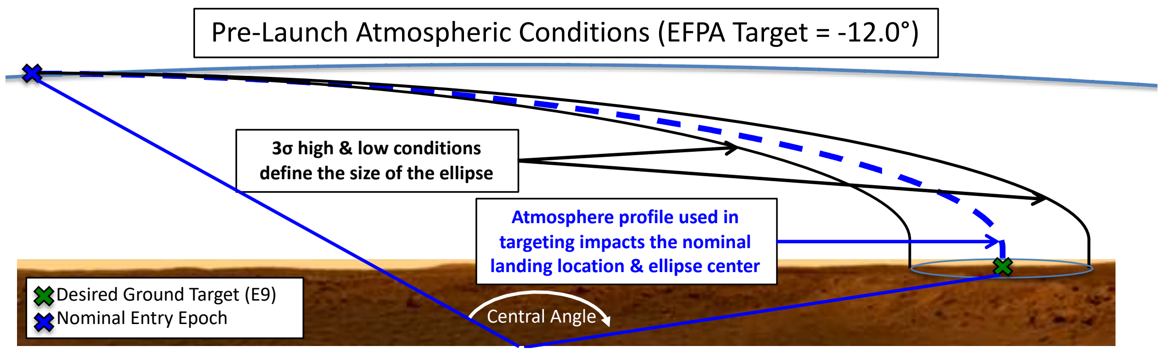

Figure 2. Illustration of the how the nominal trajectory is used for EDL targeting.

The newly delivered atmosphere violates the assumption that nothing in the nominal trajectory profile changes between the time when targeting is performed at TCM-1 and then again at TCM-6. The atmosphere used to target TCM-1 is the nominal background atmosphere. The atmosphere used to target TCM-5 and TCM-6 is whatever atmosphere model is delivered to the team prior to entry. This new atmosphere changes the central angle of the nominal trajectory which means that entering at the same entry epoch with the same EFPA will no longer put the lander at the same nominal landing location on the ground.

One way or another the new atmosphere model needs to be considered in the targeting process. If the new atmosphere is used for EDL targeting, either the entry epoch, the EFPA, or the ground target needs to change to allow the EDL targeting process to converge. If the atmospheric update is ignored in EDL targeting then when the EDL team evaluates EDL system performance, the new atmosphere model will move the landing ellipse on the ground away from the location targeted by the Navigation team. Therefore, an analysis needs to be performed to understand the effect of the changing atmosphere on the placement of the ellipse on the ground, and if the resulting ellipse displacement is acceptable from a landing safety perspective.

Even within the background atmosphere model used by InSight there is significant variability in just how much ground shift of the nominal trajectory can occur. Additionally, because of the uncertainty in the landing-day dust conditions, having MCS measurements was particularly important for InSight. As discussed earlier, there was a major global dust storm that began just six months prior to landing, although it subsided to background conditions by landing day.

IMPACT OF MODIFYING NOMINAL TRAJECTORY ON TARGETING

Figure 3 provides an illustration of what happens to the nominal trajectory used for EDL targeting when the atmosphere model is updated. Clearly the central angle has changed and the nominal trajectory will no longer intersect the surface at the desired ground target.

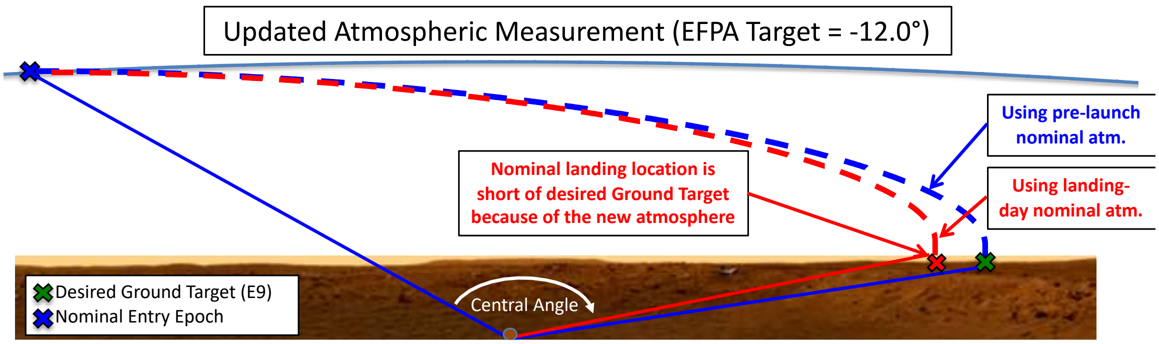

Figure 3. Illustration of the how updating the atmosphere impacts the nominal trajectory used for EDL targeting.

There are three feasible options to accommodate this issue, each of which will be discussed in the following sections, along with the associated costs:

1. Allow the entry epoch to change, keeping the EFPA target and ground target constant.
2. Allow the desired ground target to move, keeping the EFPA and entry epoch constant.
3. Allow the EFPA target to change, keeping the entry epoch and ground target constant.

Option 1: Allow the Entry Epoch to Change

One option to accommodate the updated atmosphere is simply to allow the entry epoch to vary freely. This option also does not restore the central angle to what it was with the pre-launch background atmosphere but allows the entry epoch to change and moves the entry-interface point relative to the ground. With a new ground-relative EIP, the nominal trajectory is able to intersect the ground at the desired ground target with the new atmosphere. This option is illustrated in Figure 4.

There are a few costs that are important to consider with this option. First, the partial of miss-distance on the ground with respect to entry epoch shift is relatively small. A 10 km shift on the ground requires an entry time change of 40 seconds. Furthermore, this time shift is *not* a function of the time-to-go until entry. Once TCM-1 and TCM-2 target a particular entry epoch, a change to the nominal trajectory that is used in EDL targeting will result in the same entry epoch shift regardless of which maneuver makes the correction (TCM-5 or TCM-6). This is because changing entry epoch does not restore the central angle and the only way to get back to the target is to move the entry-interface point (i.e., allow Mars to rotate by the appropriate amount of time to enter at the correct longitude). Allowing entry epoch to change could negatively affect EDL communications because the relay satellites and orbiters that are timed specifically to record the EDL event.

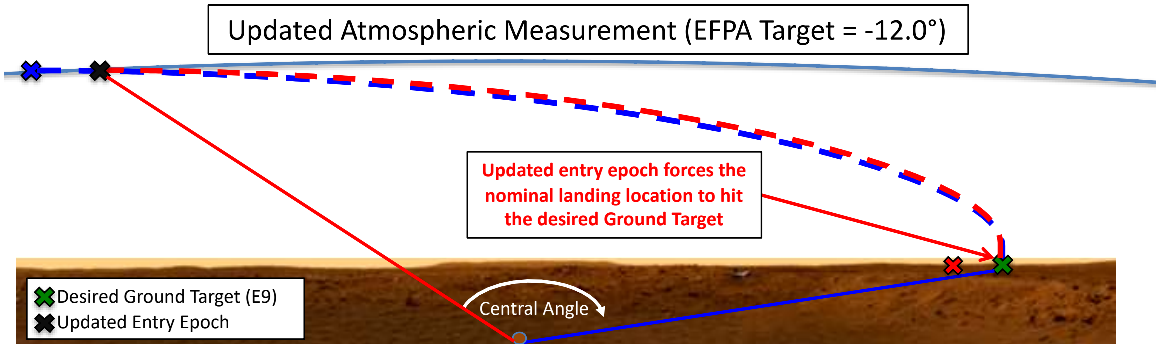

Figure 4. Illustration of the how updating the entry epoch accommodates the impact of the new atmosphere to the nominal landing location.

The other cost associated with this option is that changing the arrival time can quickly increase the size and direction of the maneuver. Fortunately, this *is* a function of time-to-go until entry so changing the entry time at TCM-5 (E-8 days) is not very expensive. However, if the targeted entry epoch needs to be changed at TCM-6 (E-22 hours), the maneuver size can grow dramatically. Changing the entry epoch by 40 seconds at TCM-6 could result in a maneuver that is 3-5 times larger than the largest TCM-6 the Navigation team had planned to execute. In addition to not accounting for the propellant in the worst-case analyses, the larger maneuver execution errors could preclude meeting the ± 0.21° EFPA requirement and increases the size of the EDL landing ellipse.

EDL targeting was initially architected to use this option for both Phoenix and InSight. The quickly-escalating cost of TCM-6 was how both Phoenix and InSight independently discovered this issue (the lesson was learned on Phoenix and subsequently forgotten by the time the InSight project started). In fact, the issue was discovered in the *exact same way* on both missions. During an operational readiness test on Phoenix, an atmospheric update was delivered prior to a simulated TCM-6 and the team was surprised by how much the new atmosphere changed the maneuver size and direction. This happened again on InSight, thus initiating the analysis that is the subject of this paper. When the issue was discovered on Phoenix it was only about six months prior to landing. On Insight the issue was discovered prior to the two-year mission delay so there was time to investigate it and develop a formal policy for how to handle atmospheric updates in EDL targeting.

Option 2: Allow the Desired Ground Target to Change

A second option is to allow the ground target used in EDL targeting to vary freely. The InSight team refers to this as ‘ground-target tolerance’. This option does not restore the central angle to what it was with the pre-launch background atmosphere and doesn’t change the EFPA target or the targeted entry epoch. This option is essentially the same as targeting with the old (pre-launch background) atmosphere in the nominal trajectory with the original desired ground target. (When the EDL performance Monte Carlo is subsequently run with the newly delivered atmosphere the landing ellipse shifts away from the original desired ground target.) Option 2 is illustrated in Figure 5.

The cost for this option is clear: the size of the region required to accommodate the landing ellipse grows by however much ground-target tolerance is required to accommodate the atmospheric shift. For example, the EDL landing ellipse for InSight was on the order of 130 km. If atmospheric shifts can move the nominal trajectory 10 km uptrack or downtrack, the safe landing area required to accommodate a 130 km ellipse is more like 150 km. This impacts landing safety calculations and potentially limits the number of suitable landing locations that can be identified.

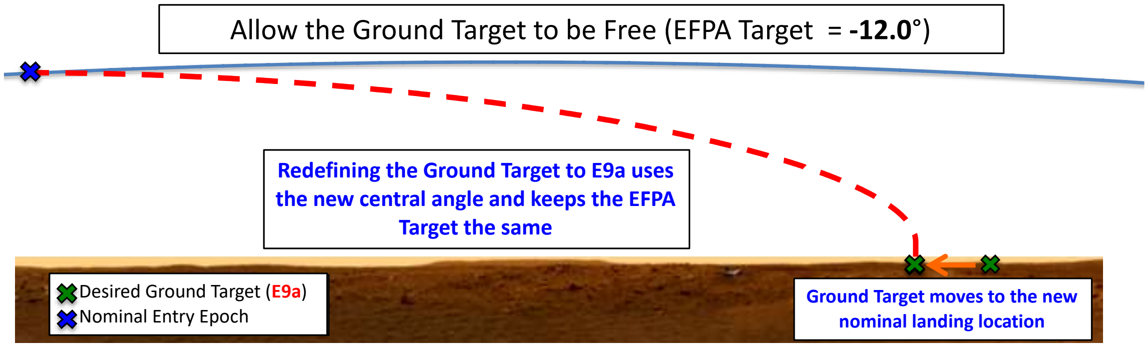

Figure 5. Illustration of the how freeing the ground target used in EDL targeting accommodates the impact of the new atmosphere to the nominal landing location.

Option 3: Allow the EFPA Target to Change

The final option is to allow the EFPA targeted by the maneuver to vary freely. The InSight team refers to this as 'EFPA-target tolerance'. This option allows the central angle to be restored while keeping the ground target and entry epoch constant. Option 3 moves the landing location of the nominal trajectory back to the original desired ground target *because* the central angle is restored. For example, if the nominal EFPA target is -12.0°, the EFPA-target tolerance is ±0.15°, and the delivery accuracy requirement is ±0.21°, it means the maneuver can target an EFPA between -11.85° and -12.15°. The delivery accuracy of the new EFPA that is targeted must be within ±0.21°. Note that this is *not* the same as saying the navigation requirement is -12.0° ± 0.36°, as the ellipse size associated with a ±0.36° delivery error is significantly larger than one associated with a ±0.21° delivery error. Requirements associated with option 3 would be written something like: "The Navigation team shall use an EFPA-target of -12.0° ± 0.15° in maneuver design and shall deliver the entry vehicle to within ±0.21° of the selected EFPA target." Option 3 is illustrated in Figure 6.

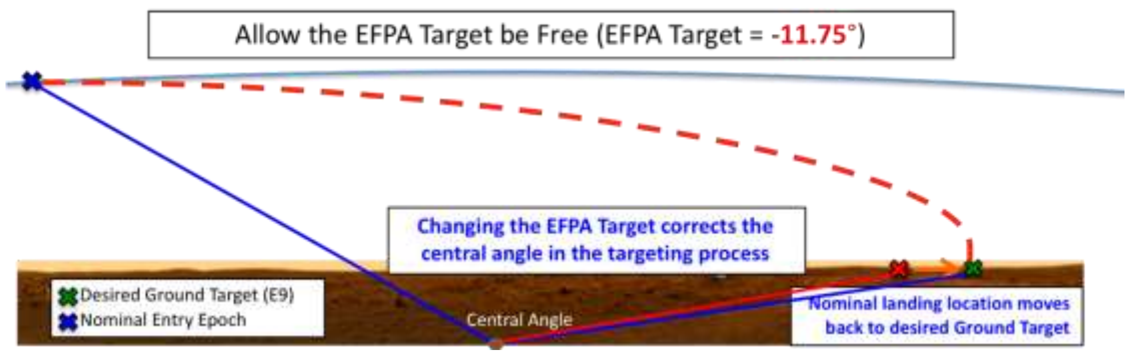

Figure 6. Illustration of the how freeing the EFPA target accommodates the impact of the new atmosphere to the nominal landing location.

There are a few costs associated with EFPA-target tolerance, but they are not necessarily significant. One potential cost is to EDL performance. The EDL system is designed and tuned for a specific EFPA target and modifying that target changes the carefully-chosen balance of margins. Fortunately, changing the EFPA target is a particularly effective method of accommodating ground shift. A ground shift of 10 km can be accommodated by a small change in EFPA of just 0.05° (this is the partial for the -12.0° nominal EFPA associated with the InSight trajectory). A small amount of EFPA-target tolerance would likely cover most background atmosphere variation.

Another cost is the propellant required to retarget to a new EFPA, although an analysis performed by InSight suggests the cost is minimal and is much smaller than the worst-case propellant requirements. Figure 7 provides a plot from this analysis which puts an upper bound on additional propellant required to target to a new EFPA. The figure shows the ΔV required (y-axis) to hit the ground target *and* retarget to a new EFPA target (different colored contours) from -12.0° as a function of miss-distance from the desired ground target (x-axis). The minimum of each contour defines the upper bound on ΔV if EFPA is allowed to optimized while the ground target is held fixed. For example, the minimum value on the green v-shaped contour for -12.10° is about 0.025 m/s and corresponds to about an 18 km ground shift (downtrack miss distance). This means that if the new atmosphere shifts the nominal trajectory (which has an EFPA of -12.0 degrees) to miss the target by 18 km downtrack, changing the EFPA to -12.10° would shift the landing location of nominal trajectory back to the desired ground target and the ΔV to make the change would only cost about 2.5 cm/s. As expected, the -12.0° contour shows a ΔV of 0 m/s for a miss-distance of 0 km. The red dashed line is the limit at which the Navigation team would not be able to meet EFPA accuracy requirements. The minimum point for each contour is well below this limit and the figure demonstrates that the propellant cost to fix EFPA is relatively small.

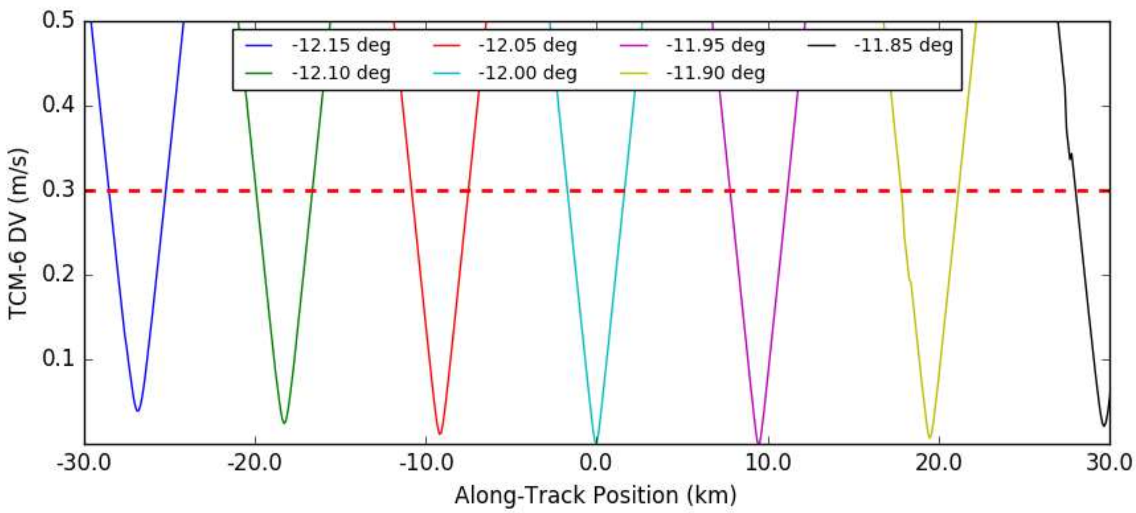

Figure 7. ΔV required to hit the desired ground target *and* change the EFPA target from -12.0° as a function of along-track miss-distance.

Figure 7 is an attempt to provide an upper bound of the ΔV required to retarget the EFPA so the nominal trajectory lands at the desired ground target. There would certainly be scenarios where prior maneuver execution errors made it less expensive to target a new EFPA. A better way to assess the propellant cost would be to perform a statistical analysis (e.g., Monte Carlo). In this analysis the entire iterative targeting process would be modeled and the atmosphere used in the nominal trajectory would be allowed to vary. InSight didn't have the time or tools to easily perform this type of analysis although it was sufficient to show that the worst case met our requirements.

Finally, there's no reason why any combination of the three options couldn't be used as well, with tolerances applied to each parameter (EFPA, ground target, and entry epoch). Depending on the tools being used for EDL targeting, vehicle performance, and terrain safety and suitability for science, some combination of tolerances might make the most sense. InSight ultimately decided to use a combination of EFPA-target and ground-target tolerance. Of course, the more combinations that are used, the more complicated the EDL targeting process becomes.

STATISTICAL ANALYSIS OF RANGE OF INSIGHT ATMOSPHERES

The InSight EDL system was required to accommodate atmospheres ranging from expected background conditions to a globally-encompassing dust storm. The EDL team and atmospheric scientists agreed to analyze and assess EDL performance against four distinct types of atmospheres as noted previously. The models that were delivered contained a nominal atmosphere as well as a dispersed set of atmospheres, which represented the full 3-sigma set of atmospheres that could be present on landing day *and* that could be delivered to the team based on measurements by MRO.

As discussed earlier, early TCMs would target the entry-interface point assuming a nominal background atmosphere on landing day. This meant that whatever atmosphere was present on landing day would represent a shift relative to the background case and would impact the EDL targeting accordingly. In order to understand the size of the ground shift of the potential landing day atmosphere relative to the background, the team ran Monte Carlos of the EDL simulation that only dispersed the atmospheres and left everything else nominal – as would be the case in the nominal trajectory used for targeting. The landing point distribution on the ground would inform the team as to how much atmospheric shift could be expected. The landing points distribution of an atmosphere-only Monte Carlo is a very narrow and long ellipse as can be seen in Figure 8. A more visually-appealing version of this figure will be presented and discussed later. The important aspect of Figure 8 is how long and narrow the ellipses are.

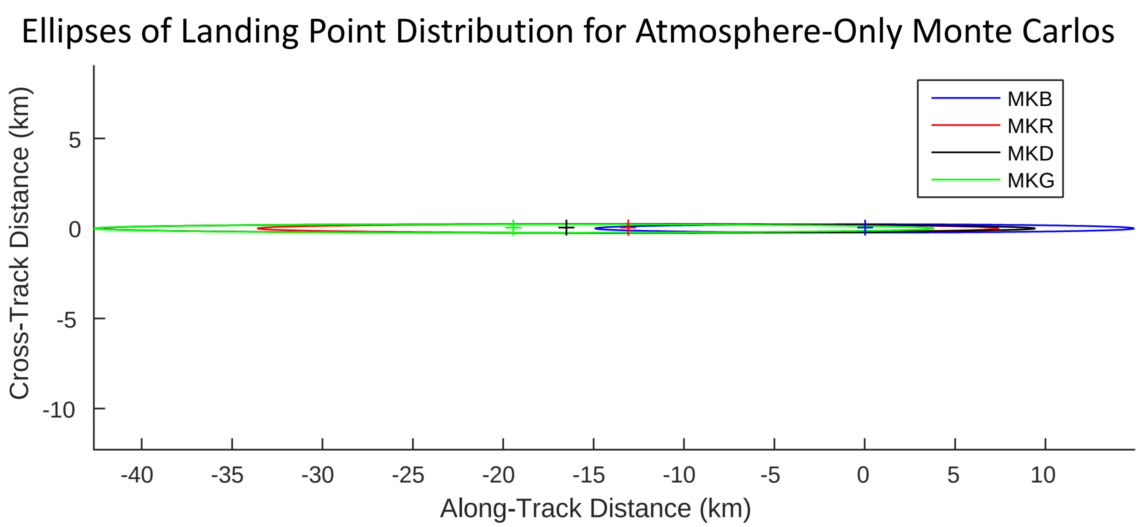

Figure 8. 99% Ellipses from atmosphere-only Monte Carlos (ellipse azimuth ignored). (The legend uses the abbreviations identified in Table 2)

Because the distribution is very narrow and almost exclusively in the along-track direction (i.e., the direction of the flight path of the entry vehicle), the distribution can be approximated as one-dimensional for this analysis and cross-track movement can be ignored. The size of the distribution and its mean relative to the nominal background atmosphere are given in Table 2 which also contains the project abbreviations for each atmosphere type. These abbreviations are used as labels in some of figures in this paper. With a statistical representation of the movement of the nominal landing location as a function of atmosphere type, the team was able to perform an analysis to quantify the actual cost of the three options mentioned earlier. Using the 1-D simplification, Figure 9 contains an illustration that makes it straightforward to visualize the full range of nominal trajectory ground shift that is attributable to atmospheric variation. The length of each colored bar is sized consistently with a distribution that contains 99% of the corresponding atmospheric ground shift. The bars are also placed at the correct location relative to each other, with the blue 'target' label placed at the location of the nominal background atmosphere. A 99% worst-case global dust storm could shift the nominal landing location by up to 41 km uptrack. Even a 99% worst-case regional storm could shift the nominal trajectory by up to 33 km on the ground, which is significant even compared to the expected EDL landing ellipse of 130 km that InSight designed to. Note that the uptrack side of the ground shifts are labeled 'UPTRACK/SHALLOW' because the EFPA would have to be shallowed to move a nominal landing point on that side back to the target.

Table 2. Size of 1-D distribution and offset from the nominal background atmosphere.

Atmosphere Type	Project Abbreviation for Atm. Type	Along-Track Distribution Length (99%; 2.6σ)	Offset Relative to Nominal of the Background Atm.
Background	MKB	25 km	0 km
Regional Storm	MKR	40 km	13 km
Decaying Storm	MKD	49 km	13 km
Global Storm	MKG	44 km	19 km

InSight Policy for Accommodating Atmospheric Changes Prior to Entry

With this issue in mind, the EDL and landing safety team performed analyses to understand and better quantify technical margins available for ground-target and EFPA-target tolerance. The landing safety team is the team that assesses the risk that a terrain feature (rocks, craters, slopes, etc.) can cause a failure at touchdown. Ultimately, the InSight project decided on the following policy to account for atmospheric shifts to the nominal landing location:

- The landing safety team will define separate ground-target tolerances in the downtrack ($Xtol_{DT}$) and in the uptrack direction ($Xtol_{UT}$).
- The EDL systems team will define an EFPA-target tolerance (γ_{tol}) that can be applied about the nominal EFPA of -12.0°.
- In operations, the EDL and Navigation teams will assess the nominal landing location shift caused by the new atmosphere.
    - The Navigation team will use the ground-target tolerance (Xtol) first to define a new ground target to be used in EDL targeting.
    - If Xtol is not large enough to account for the shift to the nominal landing location, the Navigation team will set the ground target at the Xtol limit and allow the EFPA target to optimize (i.e., minimize the maneuver) to within the range of -12.0° ± γ_{tol}. (Note that this keeps the ground target of the maneuver at the Xtol limit while the EFPA is optimizing)
    - Finally, if the optimized EFPA target hits the γ_{tol} limit, the Navigation team will then allow the new ground target to move outside the Xtol limit.
        - *The probability of this occurring is the 'accepted risk'*

The policy described above accounts for any shift that can be imposed on the nominal landing location. The *accepted risk* is the risk that the ground-target tolerance and the EFPA-target tolerance are not large enough to accommodate the shift to the nominal landing location. The reason the project decided to use ground-target-tolerance first is because the heatshield had already been sized and built and the project was less comfortable giving up margin on the heatshield versus landing terrain safety. The other reason for using ground-target tolerance first is because allowing the ground target to move around is essentially the same as ignoring the atmosphere model update when targeting the entry-interface point. Particularly for small changes in the atmosphere that only move the landing location a handful of kilometers (compared to a landing ellipse that is 130 km!), it might not make sense to let what may amount to measurement noise move around the targeted EFPA. Clearly judgement would be used in operations and the policy stated above does not need to be hard and fast. Still it was important to have a policy that would account for any outcome and that the project be aware of any risk that was being assumed.

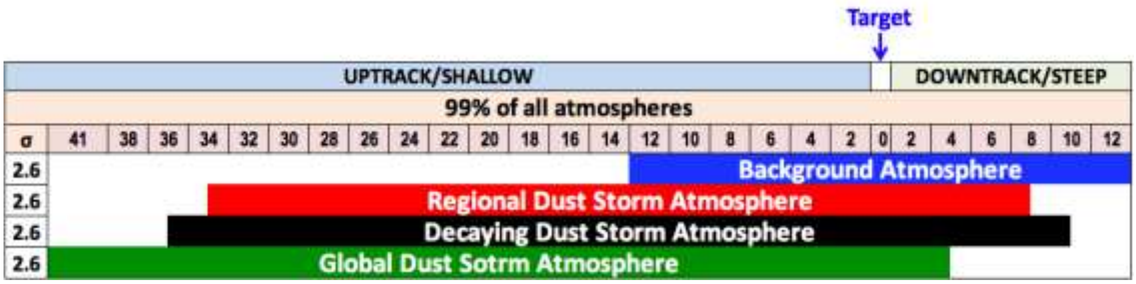

Figure 9. Graphical illustration of the 1-D atmospheric distributions relative to each other.

Figure 10 provides a graphic of how the policy adopted by InSight might accommodate shifts to the nominal landing location due to atmospheric changes. In this scenario, the probability density function (PDF) of ground shift was calculated assuming a 75% probability of a background atmosphere and a 25% probability of one of the dusty atmospheres. The PDF curve was created by sampling Gaussian distributions consistent with the means and standard deviations listed in Table 2. The background distribution was sampled 75% of the time, regional 12.5% of the time, and the remaining 12.5% of the samples were split evenly between the global and decaying dust storm distributions.

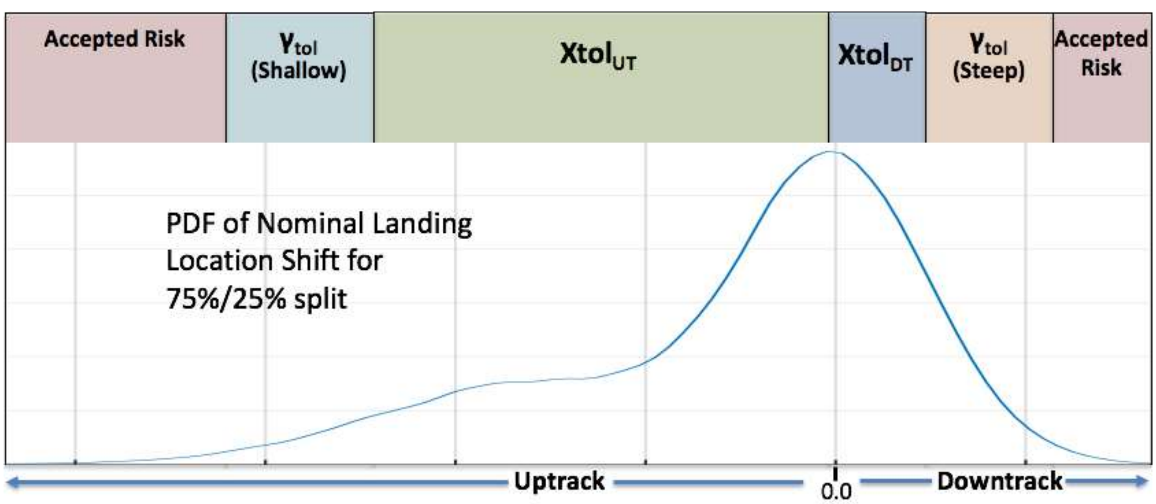

Figure 10. Illustration of how ground-target and EFPA-target tolerances might accommodate shifts to the nominal landing location. PDF assumes a 75% probability of a background atmosphere and a 25% probability of a dusty atmosphere.

Not surprisingly, the peak of the distribution in Figure 10 occurs near a 0 km ground shift. The uptrack and downtrack ground-target tolerances (purple and green) can account for much of the shift and then the EFPA-target tolerance (light blue and orange) accounts for most of the remaining shift. The small percentage that is not covered by these tolerances, is the accepted risk (pink region) by the project. It should be noted that this is an example only and specific numbers were intentionally left off the chart. The actual tolerances agreed to by the InSight project will be discussed in the next section.

INSIGHT OPERATIONS PLAN AND AS-FLOWN ATMOSPHERIC IMPACTS

After launch, the landing safety team performed a final assessment of the increased terrain risk as a function of allowing ground-target tolerance. The results of this study are summarized in Figure 11. The analysis used 99% ellipses that correspond to the landing points distribution of each atmosphere type and the navigation EFPA accuracy requirement of ±0.21°. The largest of these ellipses was approximately 130 km x 27 km. Using these ellipses, the landing safety team calculated the combined probability of landing in acceptable terrain. The team also assessed terrain safety corresponding to a smaller ellipse of 95 km x 24 km, which was the size of the landing ellipse the team expected to have by the final TCM-6 Go/No-Go decision meeting.

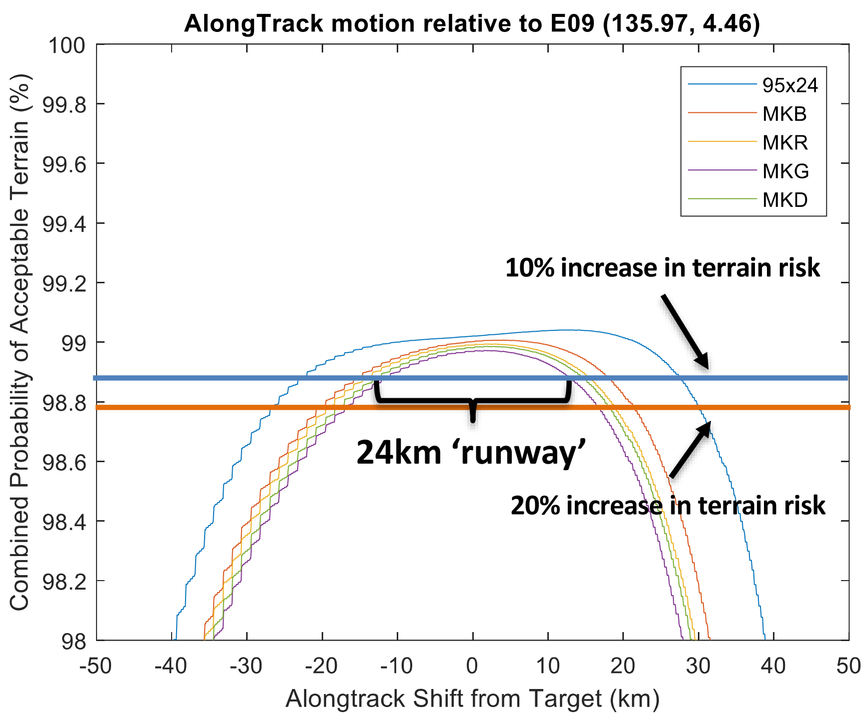

Figure 11. Post-launch analysis of probability of increased terrain risk as a function of ground-target tolerance. (The legend uses the abbreviations identified in Table 2)

The calculation of the probability of acceptable terrain is based on high-resolution (30 cm/pixel) imaging of the InSight landing region performed by the MRO instrument HiRISE. While there is less confidence in the absolute values of the probability of a particular terrain location being acceptable, there is high confidence in the relative safeness of one terrain location compared to another. For example, if location ‘A’ is calculated at a 99% acceptability (1% risk) and location ‘B’ is at a 98% acceptability (2% risk), the landing safety team is confident that location B is twice as risky as location A, even if they can't say with high confidence that the acceptability of location B is exactly 98%.

The metric used for determining ground-target tolerance was a 10% increase in terrain risk relative the background atmosphere (MKB) scenario. The background atmosphere scenario has a maximum combined probability of acceptable terrain of about 99% (or a 1% risk). Using the 10% criteria, the limit for defining the acceptable risk associated with ground-target tolerance is about 1.1%. If the risk increased beyond that, the team was not comfortable shifting the ground target any further. The blue horizontal line in Figure 11 marks the 10% threshold used to determine how much along-track tolerance could be allowed to the ground target. The orange line of 20% increased risk is included as a reference but was not used to determine ground-target tolerance. Figure 11 was actually created using the pre-launch desired ground target of 135.97° longitude and 4.46° latitude. At that location, the acceptable ground-target tolerance was calculated to be 24 km. An outcome of the post-launch analysis was to move the desired ground target slightly to 135.99° longitude and 4.51° latitude. This increased the total ground-target tolerance to 29 km (not shown in Figure 11).

Ground-Target and EFPA-Target Tolerances from InSight Operations

Since dusty atmospheres tend to push the nominal landing location uptrack, the team split the ground-target tolerance asymmetrically, applying 10 km tolerance in the downtrack (less dusty) direction and 19 km in the uptrack (dusty) direction. Additionally, the team determined the EDL system could accommodate an EFPA-target tolerance of ±0.15°. The tolerances agreed to by the project are listed in Table 3. The EFPA-target tolerance corresponds to about a ±27 km shift on the ground which means that between the two tolerances, the team could accommodate a 37 km ground shift in downtrack and a 46 km ground shift in uptrack. Using these tolerances, the project was able to reduce the accepted risk to an inconsequentially small number. This can be seen visually in Figure 12. To make the figure more readable, the orange bars which represent EFPA-target tolerance do not extend the full 27 km that the InSight tolerance actually accommodated.

Table 3. Tolerances ultimately agreed to by the InSight project for operations.

Tolerance Type	InSight Ops Setting
Downtrack Ground-Target Tolerance	10 km
Uptrack Ground-Target Tolerance	19 km
EFPA-Target Tolerance	± 0.15°

Once the tolerances were agreed to, the project formally changed not only the corresponding requirements, but the wording of the requirements since the concept of EFPA-target and ground-target tolerances had not been considered when the requirements were originally written. The new EFPA requirement specified that "The Insight Project Shall:

- Nominally target the atmospheric entry-interface point of EDL with an inertial entry flight path angle (EFPA) of -12.0°.
- Accommodate an EFPA-target tolerance during maneuver targeting of ±0.15° about the nominal EFPA target of -12.0° (i.e., the EFPA targeted by a maneuver can range from -11.85° to -12.15°).
- Be compliant with a delivery uncertainty no greater than ±0.21°, 3-sigma, centered about the selected EFPA target."

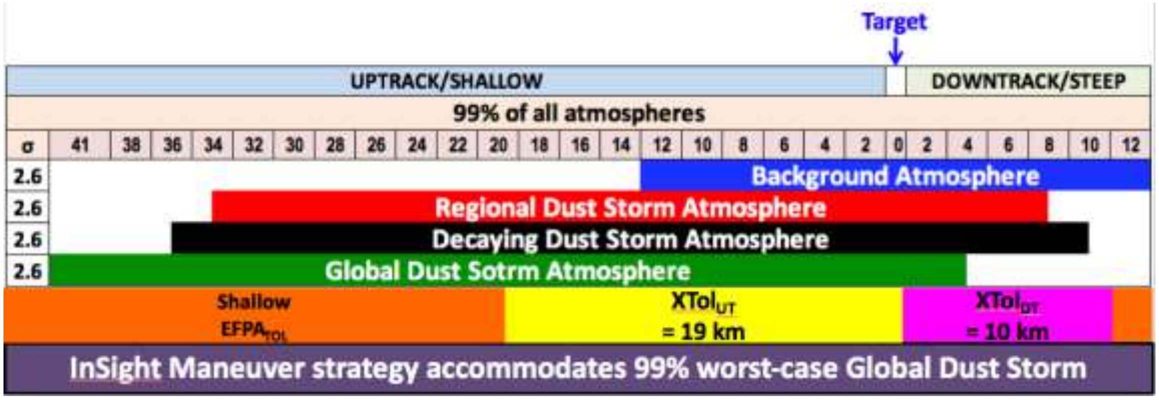

Figure 12. Visualization of the atmospheric impact to the nominal landing location alongside the final tolerances used for flight.

InSight Operations and Atmospheric Impacts

Relative to the analysis required to assess this issue, the models of the expected landing-day atmosphere that were delivered to the EDL and Navigation teams in flight were benign. All of the deliveries kept the ground shift well within the ground-target tolerance and required no adjustment to the entry flight path angle target. Table 4 lists the two deliveries that were made in flight and the corresponding shift of the nominal landing location relative to the E9 ground target (135.99, 4.51°). The initial flight delivery moved the nominal landing location 2.22 km uptrack from the desired target and the final delivery used in flight moves it another 130 meters uptrack. Deliveries were made to the team on a daily basis starting from E-15 days until touchdown but most of them were not used because they were indistinguishable from the flight deliveries listed in Table 4. The shifts from the atmospheres relative to E9 are also shown on a Themis map in Figure 13.

Table 4. History of ground shift to nominal landing location in flight

Atmosphere Model	Ground Shift Relative to E9 Landing Target	Shift Direction	Date Released
Background	0 km	N/A	Pre-Launch
E15	2.22 km	Uptrack	11/12/2018
E7	2.35 km	Uptrack	11/20/2018

All of this is not to say that the analysis and tolerances were unnecessary. Weather prediction on Mars is very difficult. This is particularly true when atmospheric scientists are creating a model many years ahead of an actual flight that will occur in the middle of dust storm season on another planet. The atmosphere model used by both the Spirit and Opportunity rovers was updated late in operations due to the effects of a dust storm that reached its maximum in December of 2003.[14] In the case of InSight, Mars experienced a planet-smothering global dust storm in the summer of 2018, with conditions only subsiding to background levels about a month or two prior to landing. Had an event like that occurred closer in time to EDL, and at the InSight landing site, the system was designed to successfully land in the conditions but the policy outlined in this paper would have become much more relevant.

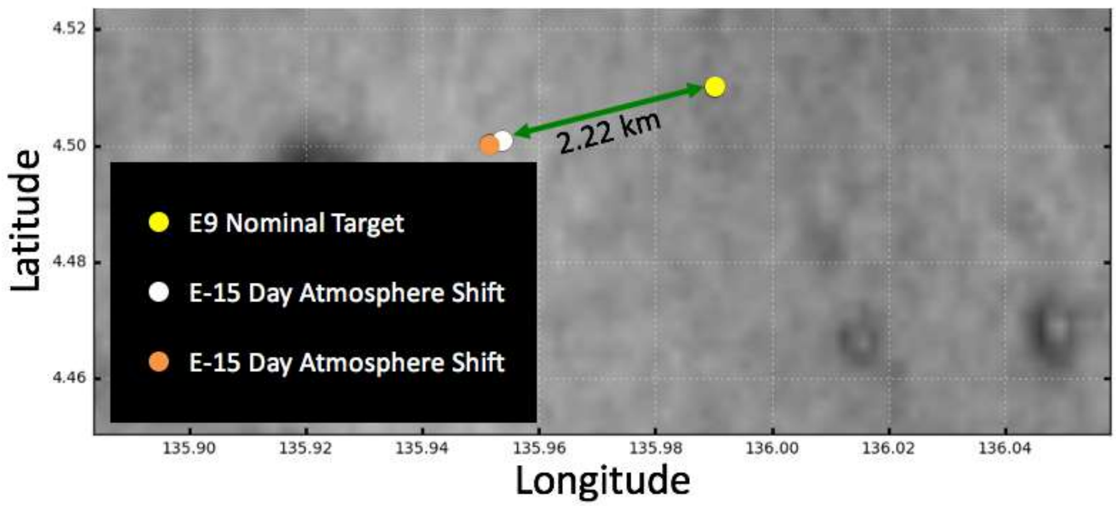

Figure 13. Ground shift of nominal landing location during InSight flight operations plotted on a Themis image

Extensive work to determine to determine exactly where in Figure 12 a global dust storm like the one from 2018 would have shifted the nominal landing location has not been performed. The best guess is that it would have been in the range of a 90 to 99 percentile regional event on the dusty side of the model. A storm such as that one could have shifted the nominal landing location by up to 30 km uptrack and, if a plan hadn't been in place, the project certainly wouldn't have been ready for the size of the maneuver and the change in entry epoch it would have caused. With the policy InSight had in place, a 30 km shift would have put the new ground target at the tolerance limit of 19 km (uptrack) and changed the EFPA target to be something between -11.95 and -11.9 degrees. The entry epoch would have stayed consistent with what MarCO and MRO had targeted and the maneuver size would have easily been in a range consistent with what the Navigation team had predicted.

CONCLUSIONS

The impact to EDL targeting from landing-day atmosphere changes is a real effect that cannot be ignored. The effect was discovered independently by two different projects (InSight and Phoenix) and was never fully assessed on Phoenix due to time constraints of when the dependency was discovered. It was only because of InSight's two-year launch delay that the team had the time and resources to investigate this concern. Phoenix's plan essentially amounted to using ground-target tolerance and then retargeting if the shift got too large, but the team hadn't had a chance to understand the impact to entry epoch, EDL communications, and maneuver size had they decided to retarget.

InSight chose to address this issue in a two-tiered fashion, defining both ground-target and EFPA-target tolerances. This made the solution more complicated and, although there were ways the two-tiered solution could have been made less complicated, had the problem been identified early and written into requirements, it likely could have been addressed and simplified by using one of the options rather than both. Not only does using one method make the targeting problem easier, having a single method for addressing it makes the plan much more obvious and intuitive to other members of the project.

The InSight mission was the first mission to really study this issue in detail. Future Mars missions that do not use guidance to correct for atmospheric uncertainties need to consider this issue and decide early on how it will be addressed. Once that is decided, the plan should be clearly stated in project requirements.

As with many studies of worst-case scenarios on flight projects, things ended up playing out in a fairly nominal way and, fortunately, the policy created by InSight had little impact on actual landing day operations. Of course, had the Martian global dust storm of 2018 started 2-3 months later than it did, that would not have been the case. With this analysis and policy in place, however, the mission would have been prepared to deal with it.

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