

InSight Entry, Descent and Landing Post-Flight Performance Assessment

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On November 26, 2018, the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander successfully touched down on the surface of Mars. NASA Langley Research Center’s (LaRC) Program to Optimize Simulated Trajectories II (POST2) was used during both project development and flight operations to assess the Entry, Descent and Landing (EDL) vehicle performance against related requirements across the expected range of possible environmental and spacecraft conditions. During flight operations, these analyses were used to evaluate the need for updating flight software EDL parameters and the effects of executing a trajectory correction maneuver (TCM). Therefore, the NASA LaRC POST2 simulation had a critical role during the cruise, approach and ultimately EDL phases of the mission. This paper presents results of the final pre- and post- EDL flight performance assessments. A summary of the reconstructed “as-flown” trajectory with a comparison of key EDL metrics to the nominal and three-sigma bound pre-EDL predictions is also provided. Emphasis on the trajectory between entry interface and parachute deploy is provided as this is the period during which deviations from the pre-EDL prediction occurred. The post-flight assessment provides important verification of the POST2 models and analysis techniques used for InSight, providing critical feed-forward information to future lander missions.

I. Introduction

On November 26, 2018, the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander successfully touched down on the surface of Mars. Selected for flight from NASA’s Discovery Program, development of this mission began in 2012 with an original launch date in 2016. This mission leveraged the Phoenix lander mission, utilizing a spare hardware and a proven architecture to reduce risk and cost. NASA Langley Research Center (LaRC) joined the InSight Entry, Descent and Landing (EDL) team at the start of the project’s Phase B. One of the responsibilities of the LaRC EDL team was to provide end-to-end EDL performance assessments of mission and project requirements and the establishment of EDL system margins. This task made use of the LaRC Program to Optimize Simulation Trajectories II (POST2) simulation, with heritage from an earlier version used for the Phoenix mission EDL analyses, and integrated InSight mission specific models. Several simulation campaigns were completed during project development to assess system performance against key EDL metrics[1].

The EDL analyses performed in support of flight operations followed a process similar to the simulation campaigns used during development, providing the EDL team with a very familiar way to assess “real-time” vehicle performance and provide inputs to operational decisions. After the successful landing, the spacecraft team delivered the recorded Inertial Measurement Unit (IMU) flight data which was used to estimate the “as-flown” EDL trajectory. With this estimate, a comparison was made to the pre-landing predictions to assess the robustness of the pre-flight and operational EDL assessments.

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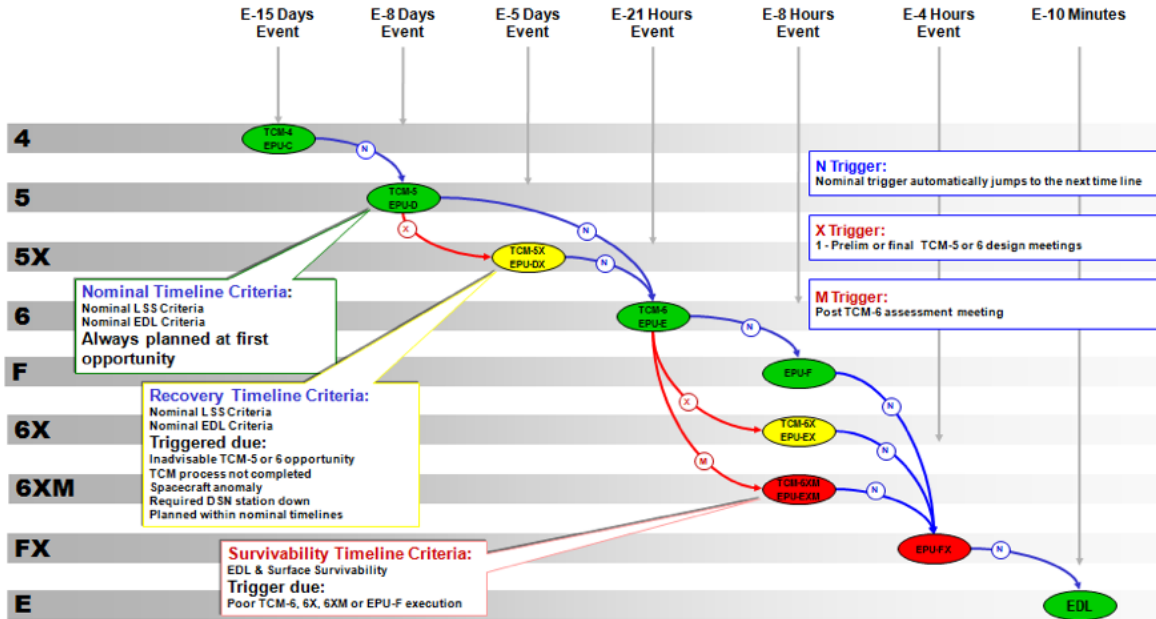


Figure 1. Final Approach EPU Cycle Nominal and Contingency Timelines
(credit: Jet Propulsion Laboratory / California Institute of Technology)

timeline, both nominal (EPU-C/D/E/F) and back-up or contingency (EPU-DX/EX/EXM). Each EPU cycle consisted of the same Monte Carlo analysis framework used during the project development simulation campaigns, but with a couple of notable differences.

The first difference involved the atmosphere model. As the InSight lander approached Mars, the atmospheric science team was provided more current atmospheric measurements near the landing site from the Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (MCS) instrument. This information was used to develop and provide a specific “day-of” atmosphere model which represented the best estimate for landing day conditions given the latest observations. Therefore, it was not necessary to run analyses covering the wide range of possible dust conditions as a single condition was then assumed for landing day.

The second notable difference between simulation campaigns and operations analyses was the type of cases considered. Instead of the four atmosphere dust variations, each EPU opportunity (or “cycle”) required the EDL team to consider four other possible scenarios. The first (referred to as “OnBoard/NoBurn”) considered the current spacecraft state and navigation performance and provided the set of performance metrics if nothing was (or could be) done to the spacecraft. The second scenario (“OnBoard/Burn”) considered a model of the TCM execution (including estimated errors) but did not update the EDL flight software parameters to account for the effect of the maneuver or the latest navigation data. The third scenario (“Update/NoBurn”) did not consider the TCM but did provide the EDL flight software an update based on the latest navigation data. And finally, the fourth scenario (“Update/Burn”) considered execution of the TCM and updating of the EDL flight software parameters. These four cases were run for each EPU cycle (except for the last, EPU-F/FX, where performing a TCM was not an option, therefore, only the “NoBurn” cases needed to be considered) and the performance summary provided in the same format as the simulation campaigns (Table 2). As time allowed, this set of analyses was repeated multiple times during a single EPU cycle, utilizing updated navigation data as it became available to the EDL team.

IV. Reconstruction

Reconstruction of the InSight as-flown trajectory began with the use of real-time IMU telemetry provided by the lander, relayed through the Mars Cube One (MarCO) cubesats and recorded by the Mars Reconnaissance Orbiter (MRO) for delayed playback[2]. Although the data was provided at a slower rate than the data being recorded onboard the lander (up to 2 Hz versus 200 Hz), this data allowed the EDL team to track the lander in “real-time” (considering one-way light time delays) through the EDL mission phase itself and make initial assessments of the entire trajectory flown by the lander[3,4]. In the days following landing, the high-rate IMU telemetry recorded onboard the lander was sent back to Earth to provide for a more detailed examination of the as-flown EDL performance.

middle of final predicted ranges. First, the peak deceleration exceeded 8 g, slightly exceeding the predicted maximum limit (but still well within the design requirement). Second, the time from entry to touchdown was more than 35 s faster than predicted, near the predicted lower limit. Finally, the vehicle landed over 10 km from the center of the final predicted landing ellipse (up-track and to the north).

As additional data was received, the comparison of the initial assessment of the EDL trajectory to the final pre-EDL prediction was made. Table 3 provides a summary of the comparison of critical EDL metrics between the reconstructed trajectory and final pre-EDL prediction (nominal, 1%-tile and 99%-tile). Figure 2 shows the landing location compared to the predicted landing footprint four hours prior to entry (od124) and for the final pre-EDL prediction at one hour before entry (od133). Although there were exceptions (as described above), for the most part, EDL performance was as predicted. Those metrics which were at, or exceeded, predicted limits appeared to indicate some off-nominal behavior occurred between the time of entry and parachute deploy. Once on the parachute, EDL performance was near nominal.

Table 3. End-to-End EDL Performance

EDL Metric	Reqmt	Units	Flight	Pre-Flight Predicts			
			Reconstructed Value	Nominal	1%-tile	99%-tile	
Loads							
Peak Deceleration	< 13	Earth G	8.1	7.6	7.1	8.1	← 0.5 g higher peak deceleration
Parachute Inflation Load Indicator	< 15	1000 lbs	10.1	12.0	9.2	14.2	
Parachute Deploy State							
Time from Entry	NA	sec	208.4	217.4	204.5	234.7	← 9.0 sec early to chute deploy
Deploy Mach	1.1 to 2.1	Mach	1.5	1.7	1.5	1.9	
Deploy Dynamic Pressure	300 to 750	Pa	546.0	521.4	477.4	572.0	
Total Angle of Attack	< 9.7	deg	3.1	1.6	0.1	6.5	
Total Angle of Attack Amplitude	< 9.7	deg	8.5	2.1	0.4	7.7	
Altitude at Deploy	NA	km	8.5	10.9	7.8	14.8	← 2.4 km low on chute deploy altitude
Parachute Phase Events							
Attitude Rate Amplitude at Heatshield Se	< 100	deg/s	19.8	49.6	20.4	88.9	
Attitude Rate Amplitude at Leg Deploy	< 100	deg/s	27.0	40.9	18.7	72.1	
Radar Activation Altitude (MRD_INIT)	2497 to 10051	m	5383	5796	4217.1	8862.2	
Lander Separation State							
Time from Parachute Deploy	NA	sec	95.5	126.4	88.3	193.3	← 30.9 sec shorter duration on chute
Altitude at Lander Sep	NA	m	1257	1046	935.3	1412.1	
Attitude Rate Amplitude at Lander Sep	< 60	deg/s	8.5	22.9	14.5	41.3	
Touchdown Conditions							
Time from Lander Separation	NA	sec	44.2	39.8	37.7	45.9	← 4.4 sec longer during terminal descent
Vertical Velocity	1.4 to 3.4	m/s	2.4	2.7	2.0	2.8	
Horizontal Velocity	< 1.4	m/s	0.3	0.2	0.03	0.58	
Overall Metrics							
Maximum Attitude Rate	< 375	deg/s	105.1	93.1	44.4	175.7	
Duration of EDL	NA	sec	348	384	341.5	458.7	← 35.5 sec early to landing

B. Atmosphere Reconstruction

As previously mentioned, since no atmospheric instrumentation was flown on the InSight vehicle, separating the effects of atmosphere from those of aerodynamics is not possible. However, an initial estimate of the as-flown atmospheric conditions can be made assuming the vehicle aerodynamics were nominal. In this way, aerodynamic forces and moments are assumed to be caused by atmospheric effects and a density profile as a function of altitude is generated. From this, a pressure profile is also estimated using the hydrostatic equation, and a temperature profile from the ideal gas law.

To accomplish this for InSight, the LaRC New Statistical Trajectory Estimation Program (NewSTEP) was used[5]. With an initial and final state, the IMU data is passed through an iterative extended Kalman filter and assuming nominal aerodynamic coefficients, an atmospheric density profile can be generated.[6] Figure 3 shows that when compared to the atmosphere model used in the final prediction (Kass v4.24), the reconstructed density profile has a consistently lower density above 10 km altitude (near parachute deploy). Although this could account for the shortened EDL timeline, it is not consistent with the higher than expected entry loads or the up-track landing location.

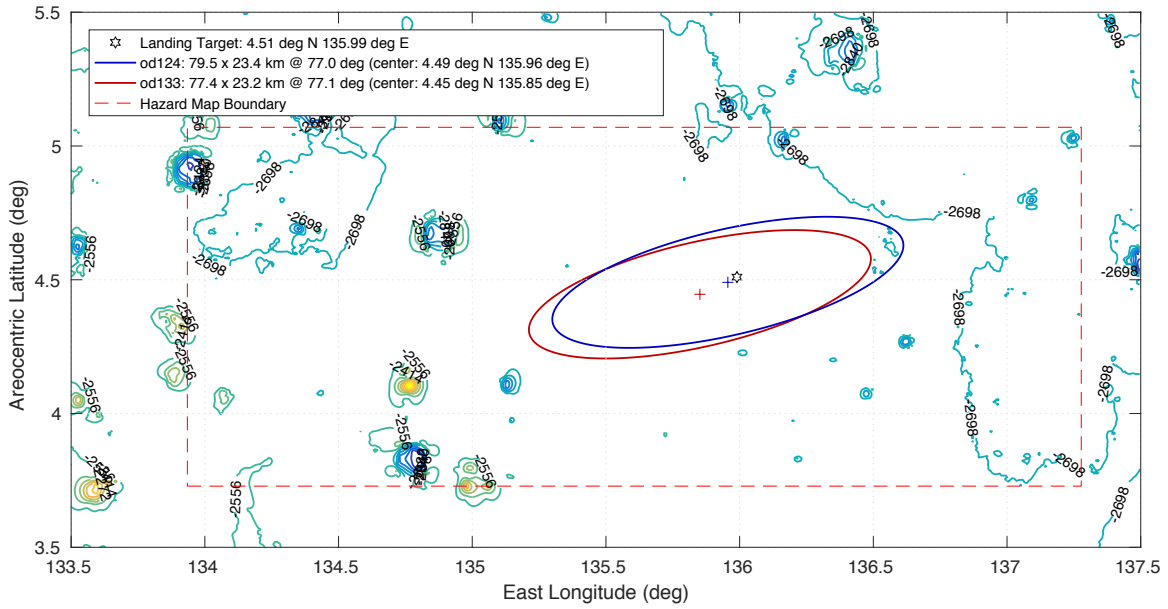


Figure 2. Final Predicted Landing Footprints (EPU-FX)

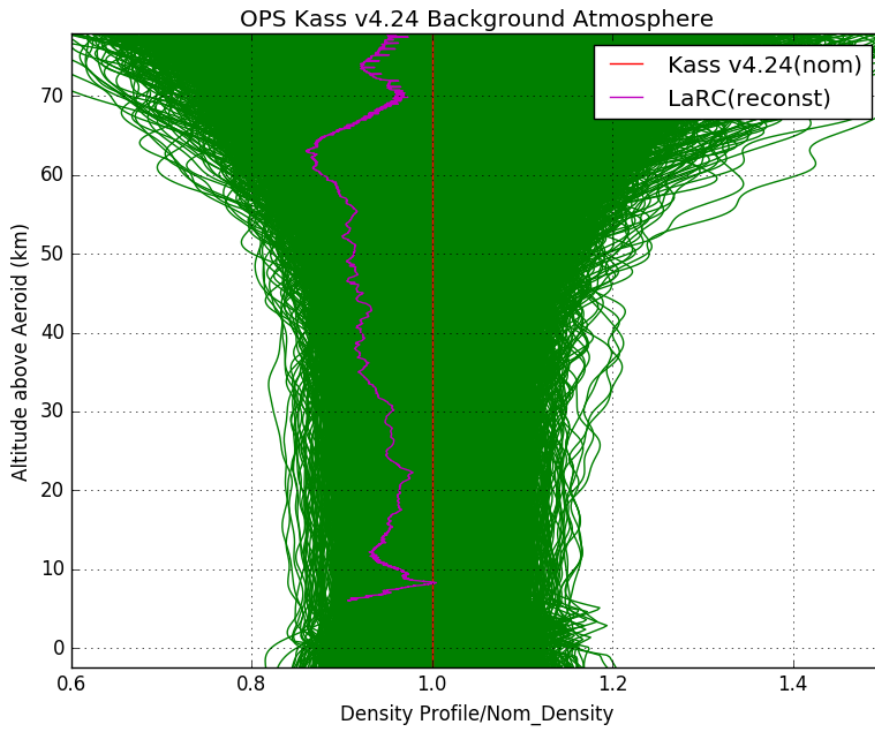


Figure 3. Reconstructed Atmospheric Density Profile

C. Aerodynamic Reconstruction

Again, due to the lack of EDL instrumentation on InSight, only an initial assessment of the aerodynamic performance can be made[7]. One advantage InSight did have was that its entry shape was identical to that of Phoenix and used the same aerodynamics database in pre-flight predictions. Because of this, a comparison to the Phoenix aerodynamic reconstruction[8] can also be made.

With the exception of the difference in atmospheric conditions, the similarities of the Phoenix and InSight vehicles prompted the expectation that the aerodynamic profiles would also be similar. Figure 4 below shows the comparison between the angle-of-attack and angle-of-sideslip profiles of the two missions (where BET indicates the best estimated trajectory from reconstruction). As expected, the shapes of the profiles are very similar, however, there are a couple of noticeable differences. First, while the Phoenix lander trimmed to a “lift-up” profile (positive angle-of-attack and bank of 180°), InSight trimmed to a “lift-down” (negative angle-of-attack and bank of 180°). Although this could be result of differences in the atmosphere and/or aerodynamics, one additional possible explanation could be a shift in the center-of-mass location between the two vehicles.

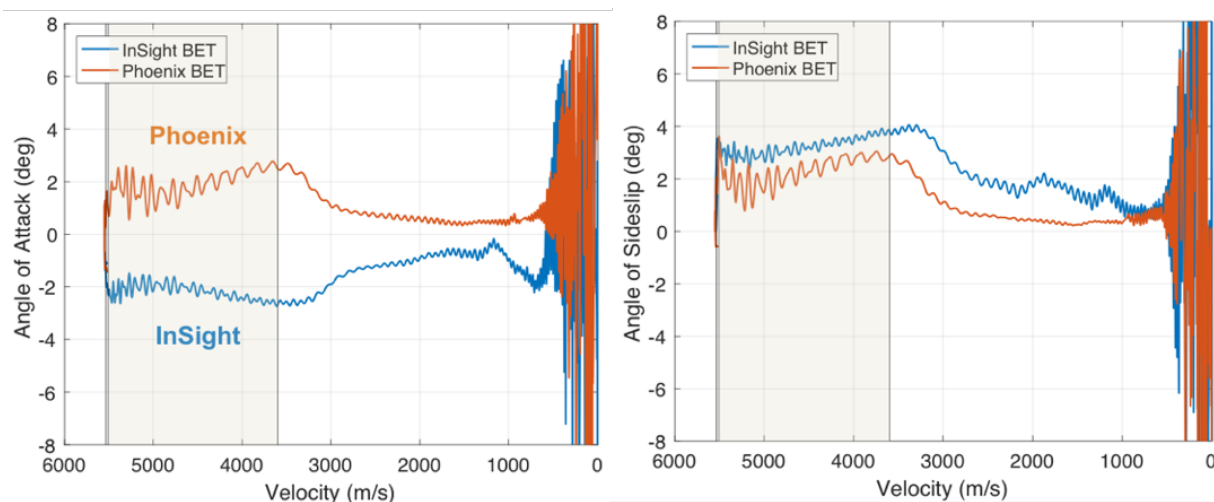


Figure 4. Reconstructed Aerodynamic Profile Comparison

Likewise, the profile for the angle-of-sideslip also compares well with Phoenix, however, the magnitude of the angle is almost doubled. As with angle-of-attack, these differences could be due to atmospheric and/or aerodynamic effects, but another possible explanation is a difference in mass properties between the two vehicles.

D. Vehicle Roll and Landing Location

Another interesting behavior observed from the InSight EDL reconstruction was a reversal in the vehicle roll direction which occurred early in the entry phase. As dynamic pressure began to build, the vehicle began a slow clockwise roll (as seen from behind). However, just after maximum dynamic pressure, the roll reversed to a counterclockwise direction, as can be seen in Fig. 5. This role reversal can also be seen in the Phoenix data, however, it appears to have occurred much earlier in the dynamic pressure pulse (so much so that the initial clockwise roll is almost unnoticeable).

This roll reversal behavior is something which was not seen in the pre-flight simulation analyses for either mission. Being the only unguided (no spin) ballistic entries at Mars, it is possible that these characteristics are what drive this type of behavior. Without flight instrumentation, however, the exact cause is likely to remain unknown.

For InSight, since this unmodeled clockwise roll continued through peak dynamic pressure, the vehicle lift had a large component in the cross-track (e.g. north) direction as seen in Fig. 6. This roll, coupled with the large sideslip angle (and lift-down profile), is likely the main contributor to the miss distance in the landing location. In fact, if the final pre-flight prediction had assumed a similar roll profile (including the reversal), the predicted landing location would have been centered very near the actual landing location. This is illustrated in Fig. 7, with the results using the pre-landing prediction one hour prior to entry (od133) compared to the same analysis repeated but with only the reconstructed attitude rates prescribed to the vehicle.

It should be noted that by forcing the vehicle to fly one particular attitude profile, the simulation essentially removes the uncertainties modeled in the atmosphere and aerodynamics (resulting in the smaller landing ellipse). These results are only meant to be illustrative. They are not meant to suggest that the cause of the roll and/or roll reversal behavior is independent of other trajectory dispersions. In fact, it is very likely that the cause (and effect) of this phenomenon scales with some trajectory and/or vehicle attribute (e.g. dynamic pressure, center of gravity, etc.).

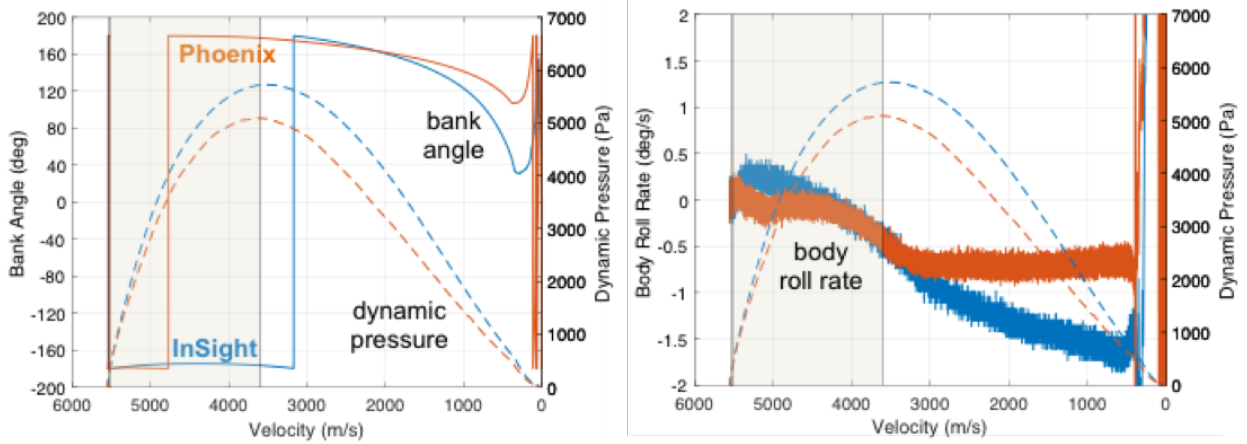


Figure 5. Reconstructed Bank Angle and Roll Rate Profile Comparison

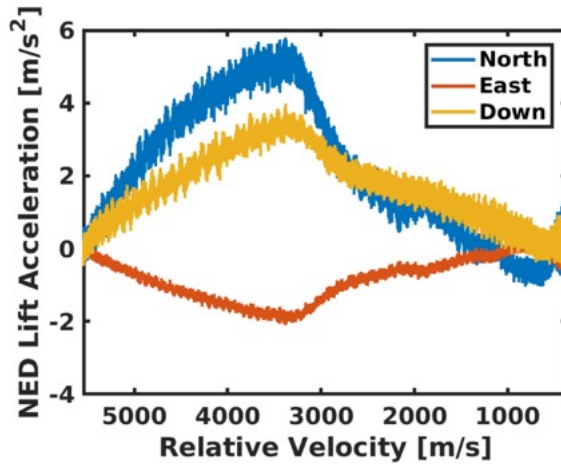


Figure 6. Reconstructed Lift Direction

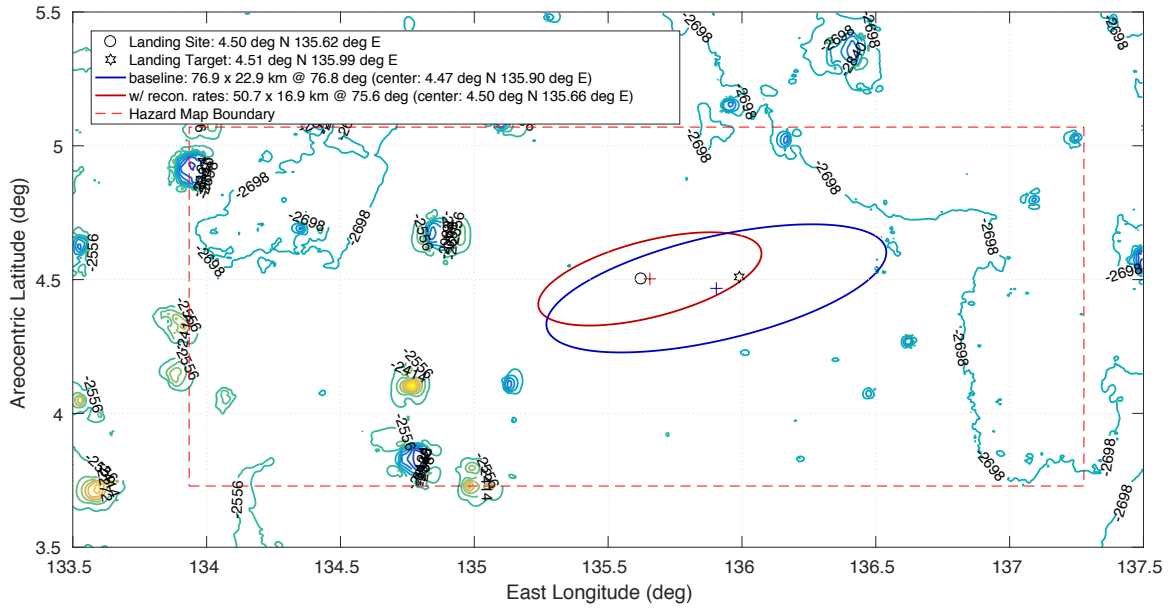


Figure 7. Effect of Reconstructed Attitude Rates on Landing Footprint

V. Conclusions

The reconstruction of the InSight EDL trajectory shows that fully understanding all of the intricate components of vehicle flight through an atmosphere (particularly an unknown atmosphere) is a significant challenge. EDL at Mars is far from routine. Although the final reconstructed trajectory did fall within the predicted pre-flight limits, phenomenon remain to be modeled that could have further improved these predictions. This work also emphasizes the value of flight instrumentation, such as the Mars EDL Instrumentation (MEDLI) suite which flew on the Mars Science Laboratory (MSL) mission and MEDLI2 which is set to fly on the Mars 2020 mission. These types of systems can be used to collect data to be used in the reconstruction effort to further understand not only what occurred, but also why. Understanding the cause of the roll / roll reversal behavior of uncontrolled ballistic entries may be moot as future lander missions are more likely to use various forms of guidance and perform precision landings. In fact, if InSight were even spin stabilized, this behavior would likely not have been observed. However, understanding this particular behavior may remain only an academic interest, further understanding of any new or formally unobserved phenomenon could provide information crucial in improving EDL predictions of future missions.

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