InSight Entry, Descent and Landing Pre-Flight Performance Predictions

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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. Over its seven-plus year development, NASA Langley Research Center's (LaRC) Program to Optimize Simulated Trajectories II (POST2) was used to assess the mission's Entry, Descent and Landing (EDL) vehicle system performance against related requirements across the full range of possible environmental and spacecraft conditions. Much of the simulation code was derived from the Phoenix mission, for which this vehicle is very similar. The InSight six degree-of-freedom simulation included models for Mars atmosphere, gravity and digital elevation maps of the landing location. Additionally, vehicle specific aerodynamic, parachute, engine, navigation sensor, flight software and landing radar models were also included. A set of dispersions for each model, as well as for additional simulation input parameters, were also included in order to provide a statistical, Monte Carlo prediction of the EDL system performance. An overview of the pre-flight performance assessments completed, including the various simulation campaigns used, will be provided. Ultimately, this work was critical in the assessment of readiness for InSight launch. A brief description of the use of this simulation in support of flight operations is also discussed.

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 over eight years ago with an original launch date planned for 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, as it prepared for the completion of the preliminary design. One of the responsibilities of the LaRC EDL team was to provide end-to-end EDL performance assessments against mission and project requirements and the establishment of EDL system margins. This included the use of the LaRC Program to Optimize Simulation Trajectories II (POST2) simulation integrated with various mission specific models.

The overall EDL performance assessment for InSight included a wide range of analyses, including trade space investigations, sensitivity and stress testing, and model variability effects. As compared to its predecessor, Phoenix, the number of EDL simulation analyses completed for InSight increased by at least an order of magnitude, with the number of individual trajectories run well into the millions. This increase in the number of analyses was made possible due to improvements in cluster computing capabilities and resource availability. For InSight, these analyses were phased into what the EDL team referred to as "simulation campaigns", with each focused on a particular goal and/or area of interest. Analyses through the use of these simulation campaigns continued through the project's development, including a "hiatus" period following the decision to delay the launch date until 2018. The later simulation campaigns not only took into account the effects of the launch slip to overall EDL performance, but also allowed the team to gain a deeper understanding of the vehicle behavior and the flight performance of the EDL phase of the mission.

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II. POST2 Simulation Development

POST2 development began in the mid-1990's in an effort to update the software architecture and expand the modeling capability of the original POST computer code developed through the 1970's and 1980's[1,2]. POST2 has been used successfully to solve a wide variety of atmospheric ascent and entry problems, as well as exo-atmospheric orbital transfer problems. The versatility of the program is evidenced by its multiple vehicle, multiple phase simulation capability that features generalized planet and vehicle models. POST2 also contains many vehicle and environment models while maintaining modularity in the code structure. As a result, the user has substantial flexibility to modify existing models, or include mission specific models of varying fidelity, such as vehicle specific aerodynamic data, planetary (e.g. gravity) and atmosphere models, vehicle and sensor models, and even onboard flight/mission specific software. POST2 has become an industry standard trajectory simulation and optimization tool that has been transferred to hundreds of organizations throughout government, industry, and academia, where it is used to evaluate, design, develop, test, and operate numerous current and future aerospace systems.

Developed for the 2007 mission, the Phoenix POST2 simulation provided a logical starting point in the development of the InSight EDL simulation. The software was first updated to the current version (at the time) of the POST2 core software, version 3.0. The InSight simulation took advantage of all bug fixes and new capabilities of POST2 until the time the InSight simulation was "locked down" to provide a smooth transition between development and mission operations support in the project's Phase D (late 2015).

With the core InSight POST2 software in place, mission specific model updates were integrated, including the flight software and vehicle models (e.g. mass properties, thrusters, sensors, etc.). Although the same flight software (with a few minor exceptions) and vehicle model libraries used for the Phoenix mission were delivered by Lockheed Martin Space Systems (the spacecraft provider) for InSight, both required updates due to the new vehicle configuration and landing location. These libraries were linked directly into the POST2 simulation using the same software interface developed for the Phoenix EDL simulation.

Since the InSight entry vehicle geometry was identical to that of Phoenix, the same aerodynamics database was integrated into the simulation. However, while Phoenix relied on a simplified multi-body model of the parachute, InSight utilized a higher fidelity multi-body parachute model developed originally for Mars Science Laboratory[3]. This provided a significant improvement in the characterization of the vehicle behavior, particularly the dynamics, while descending on the parachute.

Another significant difference between the Phoenix and InSight EDL simulation was the atmosphere model[4]. Not only was the landing location different (Phoenix landing near the north pole and InSight near the equator), InSight was the first Mars mission to land during the Mars dust storm season. The increased range of uncertainty in the atmospheric conditions during EDL required a new atmosphere model for InSight. This new model (both density and associated winds) was integrated into the InSight POST2 simulation and included the option to select one of four dust conditions representative of "background" dust, a regional dust storm, a decaying dust storm, or a global dust storm. Each dust condition would generate a unique set of dispersed atmospheric density profiles for use by the simulation.

Selection of the InSight landing location was based primarily on landing safety with soil characteristics for science also a consideration. Although largely a flat area, the location was not completely free from slopes or large rocks that could damage the lander or prevent successful science data collection. Therefore, a landing safety assessment map, or hazard map, was incorporated in the POST2 simulation. Using data from the Mars Reconnaissance Orbiter's CTX (context camera) and HiRISE (High Resolution Imaging Science Experiment) imagers, a digital elevation map (DEM) was generated that characterized patches of the various terrain types found within the landing area. Each trajectory simulation would query the hazard map to determine which terrain type (each with its own predetermined safety value) the lander was likely to encounter and simulate that terrain as what landing radar would observe during descent.

The POST2 simulation, with the InSight specific models and flight software, provided the simulation framework to perform both design and development assessments in the early phases of the mission as well as detailed landing predictions during operations, which emphasized key EDL metrics which will be described in the following section.

III. EDL Metrics and the Scorecard

EDL analyses, particularly the POST2 Monte Carlo analysis which consists of thousands of individual trials, generated a very large amount of useful data. For InSight, this data was collected at key points along the EDL trajectory, including cruise stage separation, atmospheric entry, parachute deploy, heatshield separation, landing radar activation, lander separation (from the parachute and backshell) and touchdown itself. Although useful in understanding the flight mechanics and overall performance of the vehicle, there were no specific mission requirements to which much of this data could be quantitatively compared. To make quick assessments of the various EDL analyses, a list of key EDL metrics was identified to generate an analysis "scorecard". This allowed the EDL team to capture the quantitative performance (e.g. margin against a mission requirement) and provide a way to qualitatively compare performance between similar analyses (e.g. those assuming different atmospheric dust conditions). As the EDL development process matured, new trends observed and new areas of interest identified, the scorecard was adapted as needed.

For those "critical" metrics that represented a mission requirement, the EDL team also selected and tracked a "desired margin"[5]. Therefore, these metrics were not simply measured in binary terms (i.e. does or does not meet the requirement), but also tracked relative to a margined "target value". The list of InSight EDL metrics, their respective requirement, desired margin, and target value, are shown in Table 1.

Table 1. InSight EDL Metrics

EDL Metric	>, <, =	Requirement Value	Desired Margin	Target Value	Units	Type
Monte Carlo						
Number of Successful Cases (out of 8001)	>=	8001	1%	7920	[ ]	Size
Propellant Consumption						
Propellent Used During Hypersonic	<	1.0	1.0	0.0	%	% of Cases
Usable Propellent Remaining @ TD	>	0	1.6	1.6	kg	1%-tile
Aeroheating (Sutton-Graves)						
Heat Rate Indicator	<	51.8	0	51.8	W/cm^2	99%-tile
Total Angle of Attack at Peak Heating	<	10	0	10	deg	99%-tile
Integrated Heat Load Indicator	<	3200	0	3200	J/cm^2	99%-tile
Heat Pulse Duration	<	232.24	3.64	228.6	sec	99%-tile
Loads						
Peak Deceleration	<	13	0.35	12.65	Earth g's	99%-tile
Parachute Inflation Load Indicator	<	15	0	15.0	1000 lbs	99%-tile
(Alternate) Parachute Inflation Load Indicator	<	15	0	15.0	1000 lbs	99%-tile
Parachute Deploy Conditions						
High Deploy Mach	<	2.3	0.115	2.185	[ ]	99%-tile
Low Deploy Mach	>	1.1	0.055	1.155	[ ]	1%-tile
High Deploy Dynamic Pressure	<	750	37.5	712.5	Pa	99%-tile
Low Deploy Dynamic Pressure	>	300	15	315	Pa	1%-tile
Total Angle of Attack	<	9.7	2.2	7.5	deg	99%-tile
Low Altitude at Parachute Deploy					m	1%-tile
High Altitude at Parachute Deploy					m	99%-tile
Heatshield Separation						
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile
Mach	<	0.8	0	0.8	[ ]	99%-tile
Leg Deploy						
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile
MRD Init						
High Altitude	<	10051.0	631.5	9419.5	m	99%-tile
Mean Altitude					m	Mean
Low Altitude	>	2496.9	1263.0	3759.9	m	1%-tile
MRD Init Altitude Spread (99%-1%)	<	7554.1	1894.5	5659.6	m	Nominal
Number of Cases with MRD Init @ 35 sec					[ ]	Size
Low Time from Parachute Deploy for MRD Init					sec	1%-tile
High Time from Parachute Deploy for MRD Init					sec	99%-tile
Lander Separation						
High Altitude					m	99%-tile
Low Altitude					m	1%-tile
Attitude Rate Amplitude	<	60	5.3	54.7	deg/s	99%-tile
Landing Accuracy						
99%-tile Landing Ellipse Major Axis	<	150	0	150	km	Nominal
99%-tile Landing Ellipse Minor Axis	<	35	0	35	km	Nominal
Touchdown Conditions						
High Vertical Velocity (wrt ellipsoid)	<	3.4	0.1	3.3	m/s	99%-tile
Low Vertical Velocity (wrt ellipsoid)	>	1.4	0.1	1.5	m/s	1%-tile
Horizontal Velocity (wrt ellipsoid)	<	1.4	0.08	1.32	m/s	99%-tile
Attitude Rate (RSS pitch/yaw)	<	11.3	1.64	9.66	deg/s	99%-tile
Overall Probability of Safe Landing	>	95	3.9	98.9	%	Mean
Number of Cases Off Hazard Map					[ ]	Size

IV. EDL Simulation Dispersions

Based on the level of uncertainty expected in various simulation inputs and models, Monte Carlo analyses were used as the primary source of the EDL team's performance assessments. Individual inputs were dispersed across an uncertainty range to provide a statistical base by which each metric (and its margin) could be assessed. For the InSight POST2 simulation, these dispersions included:

- initial vehicle state (and attitude)
- separation dynamics (i.e. tip-off rates)
- atmosphere (density and winds)

- aerodynamics (including various vehicle configurations, jettisoned components, parachute, etc.)
- mass properties (including initial propellant mass)
- parachute deployment
- sensor performance (e.g. alignment and biases), and
- thruster pointing and performance.

Typically, each Monte Carlo analysis used a set of 8001 dispersed values (including a nominal) for each of these simulation inputs.

V. Simulation Campaigns

As previously mentioned, the large number of individual InSight EDL analyses were grouped into "simulation campaigns", with each campaign having a specific focus or area of interest. In this way, overall assessments were made within the context of a single simulation campaign and results between simulation campaigns were tracked in order to understand larger scope trends or sensitivities. This section focuses on only those simulation campaigns completed for the 2018 launch opportunity (although many were also completed for the 2016 opportunity). Most simulation campaigns also included analyses for each of the four atmospheric dust conditions available in the atmosphere model to ensure acceptable performance across the range of possible conditions on landing day.

Early in the project, many of these analyses were also completed at more than one day within the planned launch period in order to understand the effects of launch date on the EDL metrics. Although a fixed arrival date of November 26th was always assumed, varying the launch date did effect arrival geometry and ultimately, the vehicle entry conditions. These early analyses were also run using an intermediate fidelity landing radar model. Many of these were later repeated using a higher fidelity radar model (with significantly increased computation time) to verify that the intermediate model captured the EDL performance during terminal descent with sufficient fidelity.

A. "First Look" / Baseline Entry Flight Path Angle (EFPA) Simulation Campaign

The "First Look" or Baseline EFPA simulation campaign was the initial set of InSight EDL analyses performed following the decision to delay launch from 2016 to 2018. It focused on understanding the EDL system performance across a range of candidate EFPA values, which are typically tuned to help control the expected maximum heat rate (which is critical to the design of the thermal protection system), target the parachute deploy conditions and provide some control over the full EDL timeline. Since EFPA can drive so many aspects of EDL, this campaign was crucial to inform the selection of the nominal EFPA for the new 2018 launch opportunity.

These analyses used a "locked down" InSight POST2 simulation as it was established prior to the decision to slip the launch date. Likewise, this simulation campaign used the atmosphere (density) model originally developed for the 2016 launch/arrival opportunity. Although the launch slip resulted in a slight shift in the Mars solar longitude at arrival (from 230º to 295º), it was felt that the difference did not warrant a new atmosphere model for this first assessment of the 2018 arrival date. The overall EDL system performance was not expected to change significantly from the 2016 assessments, however, the 2018 opportunity di present a change in the expected entry velocity (from 6.2 km/s to 5.8 km/s), which made it even more important to establish a new benchmark for 2018 EDL performance assessments.

For each EFPA value studied (between -11.0º and -13.0º), a set of dispersed entry states was generated based on the navigation and targeting assumptions. A summary of the scorecard results for this campaign is provided in Table 2. Here, green cells denote values which meet the desired margin (or do not have a specified requirement value), yellow cells values meet the mission requirement but not the desired margin, and red cells values do not meet the mission requirement. In addition, MKB denotes the "background" dust conditions while MKG denotes the global dust storm conditions. Based on these results, the nominal EFPA for the 2016 opportunity, -12.5º, was shallowed to -12.0º for the 2018 launch date, which resulted in a decrease of the expected peak heat rate. This change also allowed for taking further advantage of the lower entry velocity and resulting total heat load for which the thermal protection system was sized, while also adding margin to the overall EDL timeline.

B. Hiatus Simulation Campaigns

The InSight project "hiatus" was a period of "down time" following the decision to slip the launch date from 2016 to 2018. During this period, which lasted for just over one year, the EDL team was able to make additional assessments of the EDL performance associated with the 2018 landing date. As with the "First Look" Simulation Campaign, only the 2016 opportunity atmosphere model was available for use in these analyses.

The Hiatus simulation campaign consisted of several separate analyses, including: (1) an assessment of the new 2018 entry conditions when launching across the selected launch period, (2) another providing an initial look at expected aeroheating (both heat rate and heat load) sensitivities, (3) another examining EFPA sensitivity and parachute

Table 2. "First Look" / Baseline EFPA Simulation Campaign Scorecard (Launch Period Open)

						EFPA=-11.5°		EFPA=-11.75°		EFPA=-12.0°		EFPA=-12.5°		EFPA=-13.0°	
EDL Metric		Requirement Value	Desired Margin	Target Value	Units	MKB	MKG	MKB	MKG	MKB	MKG	MKB	MKG	MKB	MKG
Monte Carlo															
Number of Successful Cases	>	2001	1%	7920	[ ]	8001	7996	8001	8001	8001	7999	8001	8000	8001	8001
Landing Accuracy															
99%-tile Landing Ellipse Major Axis	<	150	0	150	km	132.40	135.09	120.46	127.01	110.14	116.15	93.33	102.94	84.28	90.94
99%-tile Landing Ellipse Minor Axis	<	35	0	35	km	25.97	28.08	25.00	27.62	23.46	26.00	21.70	24.78	20.62	22.96
Touchdown Conditions															
High Vertical Velocity	<	3.4	0.1	3.3	m/s	2.79	2.79	2.79	2.79	2.78	2.78	2.78	2.78	2.78	2.77
Low Vertical Velocity	>	1.4	0.1	1.5	m/s	1.94	1.92	1.95	1.94	1.95	1.95	1.95	1.95	1.95	1.95
Horizontal Velocity	<	1.4	0.1	1.3	m/s	0.51	0.55	0.52	0.53	0.51	0.53	0.52	0.52	0.51	0.52
Attitude Rate (RSS pitch/yaw)	<	11.3	1.7	9.6	deg/s	6.47	6.41	6.49	6.62	6.53	6.50	6.37	6.49	6.50	6.33
Max Attitude Rate During EDL	<	200	40	160	deg/s	192.35	163.97	188.45	161.87	185.79	159.82	171.54	155.24	161.61	151.66
Overall Probability of Safe Landing						98.96	98.64	99.17	98.90	99.22	99.06	99.28	99.17	99.30	99.26
Propellant Consumption															
Propellent Used During Hypersonic	<	1.0	1.0	0.0	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Usable Propellent Remaining @ TD	>	0	1.6	1.6	kg	11.38	11.97	11.37	11.98	11.42	12.01	11.43	12.04	11.36	12.02
Aeroheating															
Heat Rate Indicator	<	64.6	0	64.6	W/cm^2	45.22	42.51	46.40	43.42	47.42	44.32	49.37	45.98	51.17	47.53
Total Angle of Attack at Peak Heating	<	10	0	10	deg	2.03	2.04	1.99	2.03	2.02	2.02	2.00	2.05	1.99	2.01
Integrated Heat Load Indicator	<	3497	0	3497	J/cm^2	2967.61	3079.80	2881.45	3007.17	2808.34	2944.42	2679.04	2835.56	2576.48	2739.28
Loads															
Peak Deceleration	<	13	0.4	12.6	Earth g's	7.19	6.20	7.64	6.54	8.06	6.86	8.85	7.46	9.62	8.06
Parachute Inflation Load Indicator	<	15	0	15	1000 lbs	14.52	14.90	14.62	14.94	14.69	14.99	14.80	15.06	14.88	15.12
Parachute Deploy Conditions															
High Deploy Mach	<	2.3	0.115	2.185	[ ]	1.94	1.86	1.94	1.85	1.93	1.85	1.93	1.84	1.91	1.83
Low Deploy Mach	>	1.1	0.055	1.155	[ ]	1.66	1.52	1.62	1.50	1.58	1.47	1.53	1.42	1.48	1.39
High Deploy Dynamic Pressure	<	750	37.5	712.5	Pa	599.44	600.18	598.60	598.79	598.12	600.17	599.61	599.57	598.94	602.34
Low Deploy Dynamic Pressure	>	300	15	315	Pa	487.64	470.33	492.68	474.69	498.19	479.01	503.12	493.04	505.60	503.41
Total Angle of Attack	<	9.7	2.2	7.5	deg	2.73	2.50	2.68	2.58	2.66	2.62	2.62	2.77	2.66	3.10
Low Altitude at Parachute Deploy					m	9696.88	7662.07	9222.95	7269.55	8737.18	6930.76	7967.82	6279.90	7263.73	5826.14
High Altitude at Parachute Deploy					m	15439.87	14884.97	15322.23	14756.64	15156.14	14534.75	14739.48	14127.72	14197.40	13577.63
Heatshield Separation															
Attitude Rate Amplitude	<	100	15	85	deg/s	96.23	82.14	93.99	80.12	90.02	78.79	84.38	76.07	78.11	74.11
Leg Deploy															
Attitude Rate Amplitude	<	100	15	85	deg/s	77.91	67.65	75.17	67.11	74.44	65.30	69.25	63.44	64.53	62.35
MRD Init															
High Altitude	<	10051	820	9231	km	9643.17	10352.96	9633.14	10540.89	9828.72	10710.54	10222.99	11053.64	10468.32	11173.67
Low Altitude	>	2348	1640	3988	km	3808.54	3287.82	3566.86	3306.59	3485.03	3285.41	3446.33	3330.57	3467.67	3398.67
MRD Init Altitude Spread (99%-1%)						5834.6	7065.1	6066.3	7234.3	6343.7	7425.1	6776.7	7723.1	7000.7	7775.0
Lander Separation															
Attitude Rate Amplitude	<	60	5.7	54.3	deg/s	35.45	34.80	35.59	34.71	35.85	35.06	36.19	35.49	36.55	36.78

deploy trigger options, and (4) a final baseline which served as the EDL team's next baseline reference for the 2018 opportunity. Table 3 provides a summary of the "final baseline" performance for the open of the 2018 launch period (May 5, 2018), a nominal EFPA of -12.0º and the "background" (MKB), regional dust storm (MKR), decaying dust storm (MKD) and global dust storm (MKG) atmosphere models These results highlighted a few performance metrics which required close watching moving forward, including attitude rates at various events during EDL and the timing / altitude of the radar (coordinate system) initialization (MRD_Init).

C. ATLO and As-Built Simulation Campaigns

Once the new 2018 launch opportunity arrival conditions (including the desired EFPA) were established, the ATLO (Assembly, Test and Launch Operations) and As-Built simulation campaigns were used to benchmark the predicted EDL performance prior to launch using the most recent entry system mass property information. The ATLO simulation campaign provided EDL performance based on component and subsystem level mass properties prior to the full vehicle system assembly. At the time of the ATLO simulation campaign, the EDL team had also received an updated atmosphere model for the same four dust conditions expected at the time of the arrival in 2018. Also, due to the increased timeline margin provided in the 2018 opportunity, it was decided to allow the navigation team to target the nominal EFPA across a range between -11.85º and -12.15º in order to help optimize trajectory correction maneuver (TCM) design and minimize the landing footprint error associated with predicting the wrong atmospheric dust condition in the landing site targeting process.

Table 4 shows just one example of the scorecards from the ATLO simulation campaign performance, which included analyses across the nominal EFPA range, the beginning and close of the launch period and across all atmospheric dust conditions. In addition, verification cases using the high-fidelity radar model (indicated by "hi-fi radar") were also included.

The As-Built simulation campaign included the same set of analyses as the ATLO campaign, however, it utilized the measured mass properties of the full system following assembly, including information provided by the spin-

Table 3. Hiatus Simulation Campaign Final Baseline Scorecard (Launch Period Open, -12.0º EFPA)

EDL Metric	>,<,=	Requirement Value	Desired Margin	Target Value	Units	Type	MKB	MKR	MKD	MKG
Monte Carlo										
Number of Successful Cases	>	2001	1%	7920	[ ]	Size	7998	7996	7988	7984
Landing Accuracy										
99%-tile Landing Ellipse Major Axis	<	150	0	150	km	Nominal	109.92	111.59	116.91	116.22
99%-tile Landing Ellipse Minor Axis	<	35	0	35	km	Nominal	23.73	24.17	25.94	26.34
Touchdown Conditions										
High Vertical Velocity	<	3.4	0.1	3.3	m/s	99%-tile	2.63	2.65	2.64	2.64
Low Vertical Velocity	>	1.4	0.1	1.5	m/s	1%-tile	1.72	1.72	1.73	1.73
Horizontal Velocity	<	1.4	0.1	1.3	m/s	99%-tile	0.75	0.75	0.76	0.80
Attitude Rate (RSS pitch/yaw)	<	11.3	1.7	9.6	deg/s	99%-tile	7.70	7.39	7.86	7.70
Max Attitude Rate During EDL	<	200	40	160	deg/s	99%-tile	167.16	164.66	156.57	151.20
Overall Probability of Safe Landing						Mean	99.23	99.13	98.96	98.87
Propellant Consumption										
Propellent Used During Hypersonic	<	1.0	1.0	0.0	%	% of Cases	0.00	0.00	0.00	0.00
Usable Propellent Remaining @ TD	>	0	1.6	1.6	kg	1%-tile	10.71	10.12	10.72	10.91
Aeroheating										
Heat Rate Indicator	<	61.5	0	61.5	W/cm^2	99%-tile	47.12	46.99	46.22	44.34
Total Angle of Attack at Peak Heating	<	10	0	10	deg	99%-tile	2.02	2.00	2.03	2.00
Integrated Heat Load Indicator	<	3497	0	3497	J/cm^2	99%-tile	2812.88	2862.23	2908.07	2960.06
Loads										
Peak Deceleration	<	13	0.4	12.6	Earth g's	99%-tile	8.04	7.95	7.60	6.86
Parachute Inflation Load Indicator	<	15	0	15	1000 lbs	99%-tile	14.24	14.24	14.39	14.42
Parachute Deploy Conditions										
High Deploy Mach	<	2.3	0.115	2.185	[ ]	99%-tile	1.92	1.92	1.85	1.83
Low Deploy Mach	>	1.1	0.055	1.155	[ ]	1%-tile	1.51	1.50	1.43	1.39
High Deploy Dynamic Pressure	<	750	37.5	712.5	Pa	99%-tile	572.43	571.30	574.55	572.08
Low Deploy Dynamic Pressure	>	300	15	315	Pa	1%-tile	481.90	481.75	466.81	476.86
Total Angle of Attack	<	9.7	2.2	7.5	deg	99%-tile	2.67	2.66	2.63	3.12
Low Altitude at Parachute Deploy					m	1%-tile	7800.79	8218.74	6870.54	6214.09
High Altitude at Parachute Deploy					m	99%-tile	14656.27	15588.02	15116.37	14418.10
Number of cases with deploy on velocity						Size	893	667	274	257
Heatshield Separation										
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	83.35	82.91	76.89	75.44
Leg Deploy										
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	68.19	68.50	64.88	63.25
MRD Init										
High Altitude	<	10051	820	9231	m	99%-tile	8236.42	8891.73	8944.88	8696.42
Mean Altitude					m	mean	6057.75	6355.84	6250.99	6022.27
Low Altitude	>	2348	1640	3988	m	1%-tile	4015.93	3852.65	3623.03	3102.33
MRD Init Altitude Spread (99%-1%)					m		4220.49	5039.09	5321.85	5594.09
Number of cases with MRD init @ 35 sec						Size	13	2	1220	2701
Number of cases with MRD Init @ 85 sec						Size	954	1085	0	0
Lander Separation										
Attitude Rate Amplitude	<	60	5.7	54.3	deg/s	99%-tile	36.57	35.93	34.50	35.70

balancing of the full launch stack (entry vehicle plus cruise stage). Although the nominal mass properties did not change much, it was important to benchmark this point in the EDL system development in support of launch preparations and approval. In addition to changes in the mass properties, very minor flight software updates (concerned mainly with the parachute deploy trigger and landing radar activation timing) were also included here. As shown in Table 5, the performance of the As-Built simulation campaign was very similar to that of the ATLO campaign.

D. Robustness Simulation Campaign

Once the InSight EDL team had a baseline of the expected system performance, it was next necessary to explore the robustness of the system by examining several stressing scenarios. These scenarios expanded beyond the expected or considered flight condition envelope to provide an assessment for how quickly performance might degrade to the point of mission failure. The Robustness simulation campaign focused on the open of the launch period (since previous simulation campaigns provided sufficient information to understand the effects of launch date on the critical EDL metrics). However, in most cases, each scenario still needed to consider all four possible atmospheric dust conditions. Although results are not presented here, a list and description of the various scenarios considered for this simulation campaign is provided in Table 6.

E. Flight Reference Simulation Campaign

The InSight Flight Reference simulation campaign (Table 7) was the first to be executed after launch. Because of this timing, actual navigation and maneuver performance information was incorporated into the entry state dispersions. This provided an update to the As-Built simulation campaign baseline, repeating all analyses combinations, and was used to support flight, including day-of-landing, operations analyses. As updated information was made available to

Table 4. ATLO Simulation Campaign Scorecard (-12.0º EFPA)

							OPEN (2018-05-05)						CLOSE (2018-0608)			
EDL Metric		Requirement Value	Desired Margin	Target Value	Units	Type	MKB	MKB hi-fi radar	MKR	MKD	MKG	MKG hi-fi radar	MKB	MKR	MKD	MKG
Monte Carlo																
Number of Successful Cases	>	2001	1%	7920	[ ]	Size	8001	8001	8001	8001	8001	8000	8001	8001	8001	8001
Propellant Consumption																
Propellent Used During Hypersonic	<	1.0	1.0	0.0	%	% of Cases	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Usable Propellent Remaining @ TD	>	0	1.6	1.6	kg	1%-tile	11.30	10.60	10.91	10.56	10.68	9.91	11.36	10.93	10.55	10.75
Aeroheating																
... using Sutton-Graves																
Heat Rate Indicator	<	61.5	0	61.5	W/cm^2	99%-tile	48.37	48.37	47.35	47.16	45.32	45.32	50.80	49.68	49.54	47.59
Total AoA at Peak Heating	<	10	0	10	deg	99%-tile	2.03	2.03	2.00	2.09	2.06	2.06	2.00	1.96	2.02	2.05
Integrated Heat Load Indicator	<	3497	0	3497	J/cm^2	99%-tile	2831.77	2831.77	2878.10	2957.84	3007.14	3007.15	2956.30	3010.77	3086.58	3137.07
... using CFD fit																
Heat Rate Indicator	<	61.5	0	61.5	W/cm^2	99%-tile	50.86	50.86	49.77	49.36	47.83	47.83	53.95	52.84	52.51	50.79
Total AoA at Peak Heating	<	10	0	10	deg	99%-tile	2.00	2.00	2.01	2.06	2.03	2.03	2.00	2.02	2.06	2.08
Integrated Heat Load Indicator	<	3497	0	3497	J/cm^2	99%-tile	2828.30	2828.30	2873.75	2964.80	3009.81	3009.81	2980.25	3036.13	3125.09	3173.05
Loads																
Peak Deceleration	<	13	0.4	12.6	Earth g's	99%-tile	8.11	8.11	8.04	7.64	6.95	6.95	8.25	8.18	7.78	7.08
Parachute Inflation Load Indicator	<	15	0	15	1000 lbs	99%-tile	14.29	14.29	14.25	14.50	14.51	14.51	14.25	14.22	14.45	14.45
Parachute Inflation Load Indicator	<	15	0	15	1000 lbs	99%-tile	12.40	12.40	12.35	12.52	12.52	12.52	12.39	12.35	12.51	12.49
Parachute Deploy Conditions																
High Deploy Mach	<	2.3	0.115	2.185	[ ]	99%-tile	1.86	1.86	1.85	1.80	1.77	1.77	1.87	1.86	1.82	1.79
Low Deploy Mach	>	1.1	0.055	1.155	[ ]	1%-tile	1.51	1.51	1.50	1.48	1.46	1.46	1.52	1.51	1.49	1.48
High Deploy Dynamic Pressure	<	750	37.5	712.5	Pa	99%-tile	575.67	575.67	572.37	580.76	579.75	579.75	575.43	572.46	578.79	579.08
Low Deploy Dynamic Pressure	>	300	15	315	Pa	1%-tile	464.39	464.39	465.89	460.15	460.94	460.94	462.63	463.80	457.52	457.23
Total Angle of Attack	<	9.7	2.2	7.5	deg	99%-tile	6.06	6.06	5.77	2.48	2.56	2.56	6.03	5.33	2.42	2.45
Low Altitude at Parachute Deploy						1%-tile	8016.67	8016.67	8423.87	7181.58	6876.21	6876.18	8173.50	8599.48	7371.62	7108.66
High Altitude at Parachute Deploy						99%-tile	14380.8	14380.8	15330.7	14288.9	13833.0	13833.1	1444.0	15420.6	14599.5	14121.3
No. of cases with deploy on velocity						Size	772	772	619	829	646	646	883	640	1025	728
Heatshield Separation																
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	81.47	81.47	81.05	74.94	72.67	72.68	82.09	80.64	75.73	74.54
Leg Deploy																
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	68.30	68.30	67.26	62.74	61.25	61.25	67.46	67.77	63.46	62.79
MRD Init																
High Altitude	<	10051	820	9231	m	99%-tile	9033.71	9033.71	9292.11	8907.56	8862.54	8862.54	9136.21	9371.19	8956.76	8876.36
Mean Altitude						Mean	6378.08	6378.08	6347.14	6323.91	6225.62	6225.65	6399.60	6357.34	6373.90	6255.88
Low Altitude	>	2496.9	1640	4136.9	m	1%-tile	4181.80	4181.80	3689.94	3816.32	3651.69	3651.66	4152.63	3650.54	3818.74	3705.16
MRD Init Altitude Spread (99%-1%)	<	7554.1	2460	5094.1	m	Nominal	4851.91	4851.91	5602.17	5091.24	5210.84	5210.88	4983.58	5720.65	5138.02	5171.20
No. of cases w/ MRD Init @ 35 sec						Size	39	39	7	1459	1939	1939	49	3	1335	1629
Low Time Chute Deploy to MRD Init						1%-tile	36.39	36.39	43.79	35.09	35.09	35.09	38.79	45.19	35.09	35.09
High Time Chute Deploy to MRD Init						99%-tile	72.89	72.89	79.59	66.89	61.79	61.79	73.59	80.39	69.99	65.09
Lander Separation																
Attitude Rate Amplitude	<	60	5.7	54.3	deg/s	99%-tile	39.89	39.30	39.56	36.72	36.51	36.34	39.79	39.11	36.76	36.44
Landing Accuracy																
99%-tile Landing Ellipse Major Axis	<	150	0	150	km	Nominal	114.33	114.51	115.78	119.04	119.55	119.69	118.20	120.20	123.95	123.14
99%-tile Landing Ellipse Minor Axis	<	35	0	35	km	Nominal	24.92	24.95	25.35	24.87	25.40	25.42	25.24	25.86	26.07	26.38
Touchdown Conditions																
High Vertical Velocity	<	3.4	0.1	3.3	m/s	99%-tile	2.80	2.64	2.82	2.82	2.84	2.64	2.80	2.82	2.82	2.82
Low Vertical Velocity	>	1.4	0.1	1.5	m/s	1%-tile	1.95	1.73	1.93	1.94	1.95	1.71	1.94	1.95	1.94	1.92
Horizontal Velocity	<	1.4	0.1	1.3	m/s	99%-tile	0.62	0.77	0.63	0.79	0.83	0.86	0.62	0.66	0.73	0.75
Attitude Rate (RSS pitch/yaw)	<	11.3	1.7	9.6	deg/s	99%-tile	7.04	7.63	7.09	6.95	7.22	7.73	6.99	7.21	7.00	7.15
Overall Probability of Safe Landing					%	Mean	99.23	99.23	99.16	99.04	98.82	98.82	99.19	99.18	99.24	99.22

the EDL team during flight, this simulation campaign became the basis of comparison for evaluating unexpected changes in the mission or in observed system performance.

F. Survivability Simulation Campaign

The Survivability simulation campaign was an extension of a similar process developed for the Phoenix mission where a first order assessment on the likelihood of lander survivability could be made in the event that the operational analysis capability is lost. This could result from, for example, insufficient time available to complete the nominal analyses prior to a required decision point or lack of information on the state or condition of the vehicle (e.g. loss of communications and/or control authority). This simulation campaign used a series of Monte Carlo analyses to generate a database of EDL metric performance used by the InSight EDL Survivability Tool which would then estimate metric sensitivities and determine a probability of not meeting mission requirements and/or conducting a safe landing.

Physical survivability, or the ability to physically survive EDL, was assessed across the same EFPA range as in the Robustness simulation campaign, as well as across a range of EFPA delivery errors. In addition to the four atmospheric dust conditions typically considered, two additional atmospheric cases were also used; a clear atmosphere which assumed no dust in the atmosphere, and an extreme dust condition which assumed a greater amount of dust than even the global dust storm case. Figure 1 provides an example of the physical sensitivity of just one critical EDL metric, the peak heat rate indicator. Each of these curves is comprised of several Monte Carlo analyses across the range of interest, and provided the partials used within the EDL Survivability Tool itself.

Table 5. As-Built Simulation Campaign Final Baseline Scorecard (Launch Period Open, -12.0º EFPA)

EDL Metric		Requirement Value	Desired Margin	Target Value	Units	Type	MKB	MKR	MKD	MKG
Monte Carlo										
Number of Successful Cases	>=	8001	1%	7920	[ ]	Size	8001	8001	8001	8000
Propellant Consumption										
Propellent Used During Hypersonic	<	1.0	1.0	0.0	%	% of Cases	0.04	0.09	0.00	0.00
Usable Propellent Remaining @ TD	>	0	1.6	1.6	kg	1%-tile	8.90	7.83	8.18	8.02
Aeroheating (Sutton-Graves)										
Heat Rate Indicator	<	51.8	0	51.8	W/cm^2	99%-tile	48.32	48.99	45.25	45.25
Total Angle of Attack at Peak Heating	<	10	0	10	deg	99%-tile	2.03	2.03	2.09	2.07
Integrated Heat Load Indicator	<	3200	0	3200	J/cm^2	99%-tile	2813.38	2962.51	2893.72	2988.13
Loads										
Peak Deceleration	<	13	0.35	12.65	Earth g's	99%-tile	8.18	8.01	7.79	7.00
Parachute Inflation Load Indicator	<	15	0	15.0	1000 lbs	99%-tile	14.19	14.18	14.40	14.24
(Alt) Parachute Inflation Load Indicator	<	15	0	15.0	1000 lbs	99%-tile	12.39	12.27	12.41	12.28
Parachute Deploy Conditions										
High Deploy Mach	<	2.3	0.115	2.185	[ ]	99%-tile	1.93	1.82	1.77	1.71
Low Deploy Mach	>	1.1	0.055	1.155	[ ]	1%-tile	1.47	1.46	1.44	1.42
High Deploy Dynamic Pressure	<	750	37.5	712.5	Pa	99%-tile	573.16	569.66	574.45	568.61
Low Deploy Dynamic Pressure	>	300	15	315	Pa	1%-tile	479.56	442.52	439.56	443.91
Total Angle of Attack	<	9.7	2.2	7.5	deg	99%-tile	6.46	2.78	2.48	2.50
Low Altitude at Parachute Deploy						1%-tile	7620.07	7148.79	6736.60	6322.34
High Altitude at Parachute Deploy						99%-tile	14898.97	14616.59	13758.71	13242.06
Heatshield Separation										
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	91.74	74.63	73.54	72.28
Mach	<	0.8	0	0.8	[ ]	99%-tile	0.67	0.63	0.61	0.60
Leg Deploy										
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	73.69	63.37	62.05	60.88
MRD Init										
High Altitude	<	10051.0	631.5	9419.5	m	99%-tile	8931.20	9720.92	9326.18	8919.23
Mean Altitude						Mean	6236.60	6532.36	6408.74	6192.61
Low Altitude	>	2496.9	1263.0	3759.9	m	1%-tile	4015.13	3828.04	3584.17	3301.76
MRD Init Altitude Spread (99%-1%)	<	7554.1	1894.5	5659.6	m	Nominal	4916.07	5892.89	5742.01	5617.47
Number of cases with MRD Init @ 35 sec						Size	796	1276	1628	2389
Low Time from Chute Deploy to MRD Init						1%-tile	35.09	35.09	35.09	35.09
High Time from Chute Deploy to MRD Init						99%-tile	89.29	60.29	53.59	51.69
Lander Separation										
High Altitude						99%-tile	1419.13	1427.29	1426.98	1429.95
Low Altitude						1%-tile	937.05	935.88	935.33	934.98
Attitude Rate Amplitude	<	60	5.3	54.7	deg/s	99%-tile	41.41	37.80	39.95	37.52
Landing Accuracy										
99%-tile Landing Ellipse Major Axis	<	150	0	150	km	Nominal	110.94	118.50	118.50	119.54
99%-tile Landing Ellipse Minor Axis	<	35	0	35	km	Nominal	24.14	24.53	24.33	25.05
Touchdown Conditions										
High Vertical Velocity (wrt ellipsoid)	<	3.4	0.1	3.3	m/s	99%-tile	2.82	2.83	2.83	2.84
Low Vertical Velocity (wrt ellipsoid)	>	1.4	0.1	1.5	m/s	1%-tile	1.96	1.93	1.94	1.93
Horizontal Velocity (wrt ellipsoid)	<	1.4	0.08	1.32	m/s	99%-tile	0.60	0.82	0.75	0.82
Attitude Rate (RSS pitch/yaw)	<	11.3	1.64	9.66	deg/s	99%-tile	6.99	7.13	7.17	7.29
Overall Probability of Safe Landing					%	Mean	99.00	99.09	98.96	98.65

Knowledge survivability, or the ability to execute a successful landing given the accuracy of the onboard state knowledge, was assessed across a range of time, position and velocity errors in the onboard flight software entry state. Figure 2 shows the knowledge survivability summary for the same metric used in Figure 1 to demonstrate physical survivability, the peak heat rate indicator.

VI. Operational Analyses

The EDL analyses performed during flight operations followed a similar process as the simulation campaigns used during development. In place of the simulation campaign, the EDL team utilized EDL Parameter Update (EPU) opportunities. These fell in conjunction with planned TCMs during cruise and approach (with the exception of the last EPU) and were used to provide any necessary updates to the EDL flight software parameters onboard the spacecraft. They consisted of the same Monte Carlo analysis framework described earlier for the Flight Reference simulation campaign, but with a couple of notable differences.

As the InSight lander approached Mars, the atmospheric science team was provided periodic updates of atmospheric measurements from near and around the landing site from the Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (MCS) instrument. This information was then used to develop and provide a specific "day-of" atmosphere model which represented the best estimate for landing day conditions given the recent observations. Therefore, it was no longer necessary to run analyses covering the wide range of possible dust conditions as a single condition was then assumed for landing day.

Table 6. Robustness Simulation Campaign Stress Cases

ID	Stress Case Name	Description
1	Density	Considered a 10% increase or decrease in dispersed atmospheric density profiles.
2	Wind	Dispersed wind profiles across only the ≥90%-tile high wind velocity cases found in the nominal wind profiles
3	No Wind	Set winds in all directions to zero
4	Parachute Dynamics	Increased vehicle dynamics at parachute deploy by changing winds with step function of ±20 m/s or ±50 m/s
5	Integration Step Size	Quantified numerical differences to predicted performance with simulation integration step size halved or doubled
6	Radar/Heatshield Interaction	Defined heatshield radar cross section (constant, variable or zero) for a range of landing radar threshold settings and various terrain type background (high fidelity radar model only)
7	Flight Software Atmosphere	Tuned flight software for specific atmospheric dust conditions, but set actual atmosphere in simulation to another
8	DEM Variability	Defined stressing terrain across entire landing footprint, including cases where the hazard heights are artificially stretched by factors of 2 to 3
9	Aerodynamics / RCS interactions	Increased likelihood of reaction control system (RCS) firings during hypersonic flight by increasing dispersions on the aerodynamic pitching moment coefficient to 150% (3σ)
10	Entry Vehicle Center of Gravity	Increased lateral dispersions in expected entry vehicle configuration center-of-gravity to 125% and 150% (3σ)
11	Lander Center of Gravity	Increased dispersions in expected lander terminal descent configuration center-of-gravity to 125% and 150% (3σ)
12	Reduced Propellent Load	Fixed lowest propellent margin cruise usage and dispersed cruise propellent usage assuming 30 m/s and 40 m/s
13	TCM-5 Delivery Error	Delivery error in dispersed entry states assuming the final TCM cannot be performed
14	Parachute Off-Loading:	Utilized parachute off-loading model (at lander separation) developed for MSL
15	EFPA Sweep	Considered wider range of EFPA (-10º to -14º) compared to previous campaigns
16	Touchdown Vertical Velocity Bias	Changed flight software to target lower within the acceptable range of vertical velocity at touchdown
17	Torque vs. Inertia	Use minimum thruster force / maximum vehicle inertias and maximum thruster force / minimum vehicle inertias
18	Atmosphere Dispersions Only	Used only dispersed entry states and density profiles (all other inputs nominal)

Table 7. Flight Reference Simulation Campaign (Launch Period Open, -12.0º EFPA)

EDL Metric	>, <, =	Requirement Value	Desired Margin	Target Value	Units	Type	MKB	MKR	MKD	MKG
Monte Carlo										
Number of Successful Cases (out of 8001)	>=	8001	1%	7920	[ ]	Size	8001	8001	8001	8000
Propellant Consumption										
Propellent Used During Hypersonic	<	1.0	1.0	0.0	%	% of Cases	0.02	0.05	0.00	0.00
Usable Propellent Remaining @ TD	>	0	1.6	1.6	kg	1%-tile	15.74	14.41	15.05	14.85
Aeroheating (Sutton-Graves)										
Heat Rate Indicator	<	51.8	0	51.8	W/cm^2	99%-tile	48.24	48.88	45.14	45.22
Total Angle of Attack at Peak Heating	<	10	0	10	deg	99%-tile	1.97	1.98	2.02	2.00
Integrated Heat Load Indicator	<	3200	0	3200	J/cm^2	99%-tile	2803.62	2951.42	2889.52	2975.95
Heat Pulse Duration	<	232.24	3.64	228.6	sec	99%-tile	201.93	206.57	213.69	219.19
Loads										
Peak Deceleration	<	13	0.35	12.65	Earth g's	99%-tile	8.15	7.99	7.79	6.99
Parachute Inflation Load Indicator	<	15	0	15.0	1000 lbs	99%-tile	14.18	14.27	14.34	14.33
(Alternate) Parachute Inflation Load Indicator	<	15	0	15.0	1000 lbs	99%-tile	12.36	12.52	12.50	12.44
Parachute Deploy Conditions										
High Deploy Mach	<	2.3	0.115	2.185	[ ]	99%-tile	1.92	1.97	1.93	1.90
Low Deploy Mach	>	1.1	0.055	1.155	[ ]	1%-tile	1.49	1.48	1.46	1.44
High Deploy Dynamic Pressure	<	750	37.5	712.5	Pa	99%-tile	571.63	577.50	577.30	573.63
Low Deploy Dynamic Pressure	>	300	15	315	Pa	1%-tile	477.56	479.38	479.03	479.66
Total Angle of Attack	<	9.7	2.2	7.5	deg	99%-tile	6.41	2.73	2.62	2.62
Low Altitude at Parachute Deploy					m	1%-tile	7890.55	7424.77	6981.36	6656.45
High Altitude at Parachute Deploy					m	99%-tile	14914.40	16101.97	15310.48	15015.49
Heatshield Separation										
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	90.72	92.72	88.26	82.22
Mach	<	0.8	0	0.8	[ ]	99%-tile	0.67	0.69	0.67	0.66
Leg Deploy										
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	73.70	75.37	71.85	67.95
MRD Init										
High Altitude	<	10051.0	631.5	9419.5	m	99%-tile	8997.87	9328.86	9068.45	8755.45
Mean Altitude					m	Mean	6320.11	6267.06	6168.30	6141.64
Low Altitude	>	2496.9	1263.0	3759.9	m	1%-tile	4102.23	3743.45	3596.98	3476.59
MRD Init Altitude Spread (99%-1%)	<	7554.1	1894.5	5659.6	m	Nominal	4895.64	5585.41	5471.47	5278.86
Number of Cases with MRD Init @ 35 sec					[ ]	Size	660	841	1396	2029
Low Time from Parachute Deploy for MRD Init					sec	1%-tile	35.09	35.09	35.09	35.09
High Time from Parachute Deploy for MRD Init					sec	99%-tile	87.99	91.29	90.89	90.29
Lander Separation										
High Altitude					m	99%-tile	1412.86	1421.26	1418.53	1420.72
Low Altitude					m	1%-tile	935.52	935.80	935.32	935.27
Attitude Rate Amplitude	<	60	5.3	54.7	deg/s	99%-tile	40.66	38.40	40.50	38.41
Landing Accuracy										
99%-tile Landing Ellipse Major Axis	<	150	0	150	km	Nominal	111.64	119.19	117.68	116.40
99%-tile Landing Ellipse Minor Axis	<	35	0	35	km	Nominal	24.60	25.20	24.92	25.10
Touchdown Conditions										
High Vertical Velocity (wrt ellipsoid)	<	3.4	0.1	3.3	m/s	99%-tile	2.80	2.80	2.80	2.80
Low Vertical Velocity (wrt ellipsoid)	>	1.4	0.1	1.5	m/s	1%-tile	1.93	1.94	1.93	1.95
Horizontal Velocity (wrt ellipsoid)	<	1.4	0.08	1.32	m/s	99%-tile	0.59	0.78	0.71	0.71
Attitude Rate (RSS pitch/yaw)	<	11.3	1.64	9.66	deg/s	99%-tile	6.85	6.76	6.83	7.06
Overall Probability of Safe Landing	>	95	3.9	98.9	%	Mean	99.00	99.02	98.96	98.96
Number of Cases Off Hazard Map					[ ]	Size	1	0	0	0

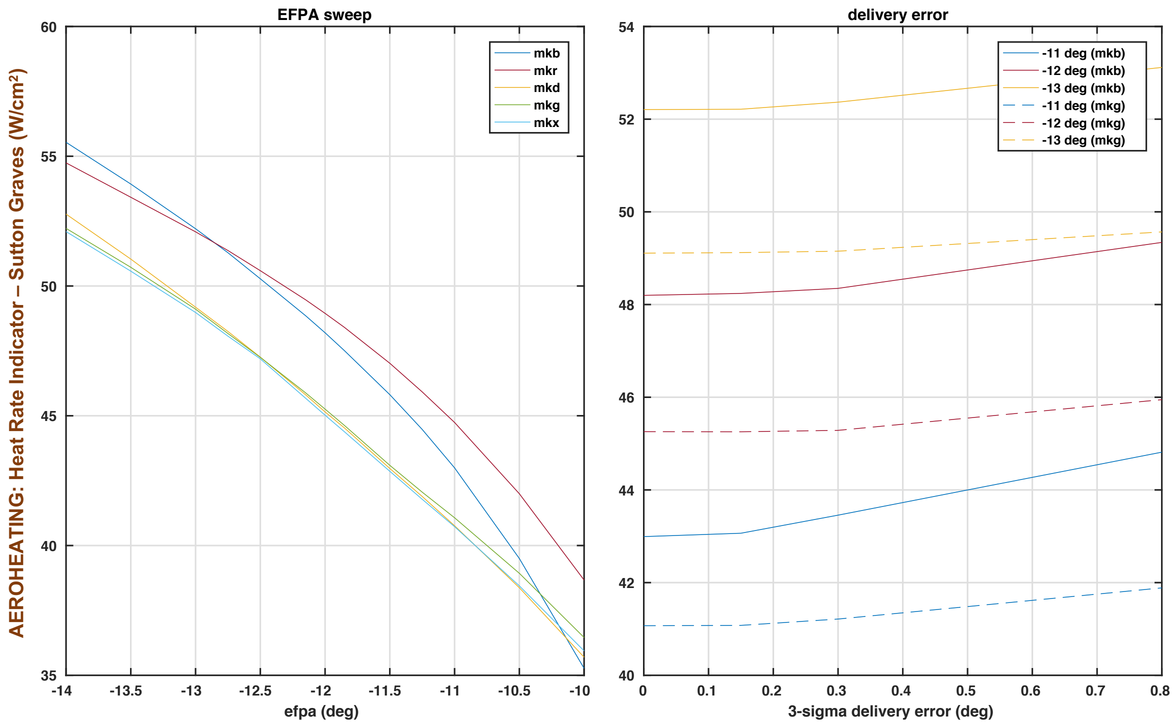

Figure 1. Example of Physical Survivability Summary

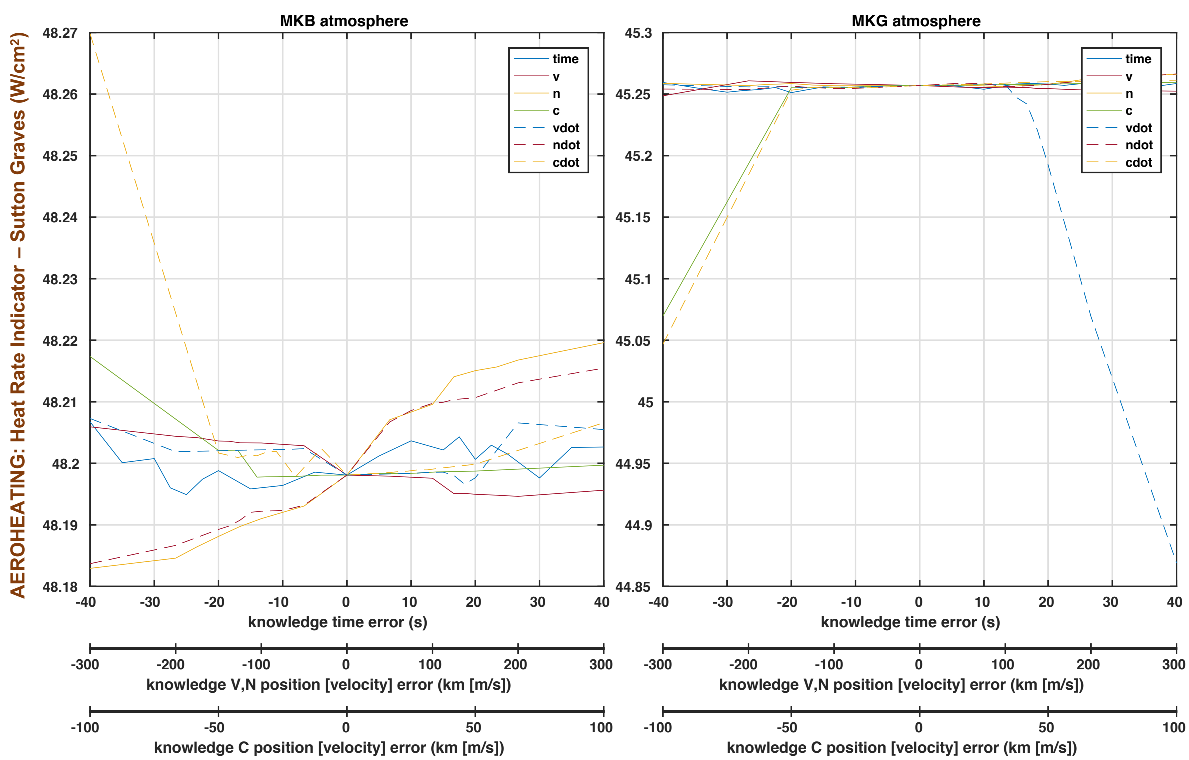

Figure 2. Example of Knowledge Survivability Summary

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 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). An example of the performance summary, provided in the same scorecard format as the simulation campaigns, is shown Table 8. This data provided the EDL team a way to assess these options in a very familiar way and provided an easy way to compare against the nearest (in terms of atmospheric conditions) Flight Reference baseline. In many cases, this set of analyses was performed multiple times during a single EPU cycle, using updated navigation data as it was made available.

These scorecards were then among the information used by the EDL team to inform the InSight project and operations teams of the likely outcomes when choosing whether or not to execute a TCM and/or updating the onboard EDL flight software parameters. Ultimately, the decision was left to the project since any change to the spacecraft state presented a risk to both the spacecraft and mission, this information was critical for the project to make an informed decision.

Table 8. Example of Flight Operations Scorecard (EPU-E/TCM-6)

EDL Metric	>, <, =	Requirement Value	Desired Margin	Target Value	Units	Type	Flight Reference (MKB)	Onboard NoBurn	Update NoBurn	Onboard Burn	Update Burn
Monte Carlo											
Number of Successful Cases (out of 8001)	>=	8001	1%	7920	[ ]	Size	8001	8001	8001	8001	8001
Propellant Consumption											
Propellent Used During Hypersonic	<	1.0	1.0	0.0	%	% of Cases	0.02	0.02	0.01	0.01	0.01
Usable Propellent Remaining @ TD	>	0	1.6	1.6	kg	1%-tile	15.74	15.50	15.77	15.69	15.62
Aeroheating (Sutton-Graves)											
Heat Rate Indicator	<	51.8	0	51.8	W/cm^2	99%-tile	48.24	47.68	47.68	48.19	48.19
Total Angle of Attack at Peak Heating	<	10	0	10	deg	99%-tile	1.97	2.00	1.99	1.98	1.98
Integrated Heat Load Indicator	<	3200	0	3200	J/cm^2	99%-tile	2803.62	2820.28	2820.37	2796.35	2796.37
Heat Pulse Duration	<	232.24	3.64	228.6	sec	99%-tile	201.93	204.32	204.37	201.50	201.52
Loads											
Peak Deceleration	<	13	0.35	12.65	Earth g's	99%-tile	8.15	7.89	7.89	8.10	8.10
Parachute Inflation Load Indicator	<	15	0	15.0	1000 lbs	99%-tile	14.18	14.06	14.16	14.06	14.13
(Alt) Parachute Inflation Load Indicator	<	15	0	15.0	1000 lbs	99%-tile	12.36	12.27	12.40	12.28	12.32
Parachute Deploy Conditions											
High Deploy Mach	<	2.3	0.115	2.185	[ ]	99%-tile	1.92	1.92	1.93	1.92	1.92
Low Deploy Mach	>	1.1	0.055	1.155	[ ]	1%-tile	1.49	1.48	1.50	1.48	1.48
High Deploy Dynamic Pressure	<	750	37.5	712.5	Pa	99%-tile	571.63	566.02	571.35	568.40	568.78
Low Deploy Dynamic Pressure	>	300	15	315	Pa	1%-tile	477.56	474.91	477.86	474.82	476.21
Total Angle of Attack	<	9.7	2.2	7.5	deg	99%-tile	6.41	6.37	5.90	6.53	6.29
Low Altitude at Parachute Deploy					m	1%-tile	7890.55	8051.14	8132.96	7972.83	7983.57
High Altitude at Parachute Deploy					m	99%-tile	14914.40	15064.43	15147.31	15014.23	15025.59
Heatshield Separation											
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	90.72	89.11	93.22	88.87	89.30
Mach	<	0.8	0	0.8	[ ]	99%-tile	0.67	0.67	0.67	0.66	0.66
Leg Deploy											
Attitude Rate Amplitude	<	100	15	85	deg/s	99%-tile	73.70	73.20	75.40	72.51	73.06
MRD Init											
High Altitude	<	10051.0	631.5	9419.5	m	99%-tile	8997.87	8886.12	9063.18	8975.42	9030.67
Mean Altitude					m	Mean	6320.11	6192.30	6358.26	6301.04	6365.37
Low Altitude	>	2496.9	1263.0	3759.9	m	1%-tile	4102.23	3975.79	4138.90	4080.67	4136.38
MRD Init Altitude Spread (99%-1%)	<	7554.1	1894.5	5659.6	m	Nominal	4895.64	4910.33	4924.29	4894.76	4894.28
Number of Cases with MRD Init @ 35 sec					[ ]	Size	660	401	462	624	642
Low Time from Chute Deploy to MRD Init					sec	1%-tile	35.09	35.09	35.09	35.09	35.09
High Time from Chute Deploy to MRD Init					sec	99%-tile	87.99	92.09	89.89	91.99	89.39
Lander Separation											
High Altitude					m	99%-tile	1412.86	1413.51	1412.96	1412.73	1414.22
Low Altitude					m	1%-tile	935.52	935.60	935.65	935.66	935.71
Attitude Rate Amplitude	<	60	5.3	54.7	deg/s	99%-tile	40.66	41.29	41.09	41.12	41.18
Landing Accuracy											
99%-tile Landing Ellipse Major Axis	<	150	0	150	km	Nominal	111.64	84.56	84.80	95.40	96.05
99%-tile Landing Ellipse Minor Axis	<	35	0	35	km	Nominal	24.60	24.11	24.17	24.16	24.34
Touchdown Conditions											
High Vertical Velocity (wrt ellipsoid)	<	3.4	0.1	3.3	m/s	99%-tile	2.80	2.70	2.80	2.78	2.80
Low Vertical Velocity (wrt ellipsoid)	>	1.4	0.1	1.5	m/s	1%-tile	1.93	1.84	1.95	1.94	1.94
Horizontal Velocity (wrt ellipsoid)	<	1.4	0.08	1.32	m/s	99%-tile	0.59	0.63	0.61	0.62	0.60
Attitude Rate (RSS pitch/yaw)	<	11.3	1.64	9.66	deg/s	99%-tile	6.85	6.83	6.80	6.69	7.01
Overall Probability of Safe Landing	>	95	3.9	98.9	%	Mean	99.00	98.84	98.87	98.98	99.03
Number of Cases Off Hazard Map					[ ]	Size	1	0	0	0	0

VII. Conclusions

The pre-flight EDL performance assessment for InSight consisted of several simulation campaigns, each of which consisted of multiple individual Monte Carlo analyses. With these, the EDL team was able to provide confidence that the EDL system would perform successfully, meeting all mission requirements, despite the level of uncertainty in the many areas considered. Possibly more important than any one analysis was the understanding of trends and sensitivities gained through close examination of each simulation campaign, both individually and when compared to other simulation campaigns. This process improved the project's general understanding of EDL performance and vehicle behavior and, in some cases, provided partials or "rules-of-thumb" that will feed forward to future missions.

Compared to Phoenix, the number of EDL simulation analyses completed for InSight was an order of magnitude or greater, with individual trajectory runs well into the millions. Much of this was made possible due to improvements in cluster computing capabilities and resource availability. As these capabilities continue to improve over time, future projects will have the ability to conduct even more analyses to understand behaviors at a much deeper level. Using the simulation campaign approach to organize the large number of analyses and provide a "quick reference" scorecard to aid in the understanding and performance assessment at a high level, proved to be a tremendous asset to the InSight EDL team. Developing similar approaches for future missions to assist in the organization and mining of the of EDL data available and in the understanding and assessment of the system's performance will be of great benefit as well.

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