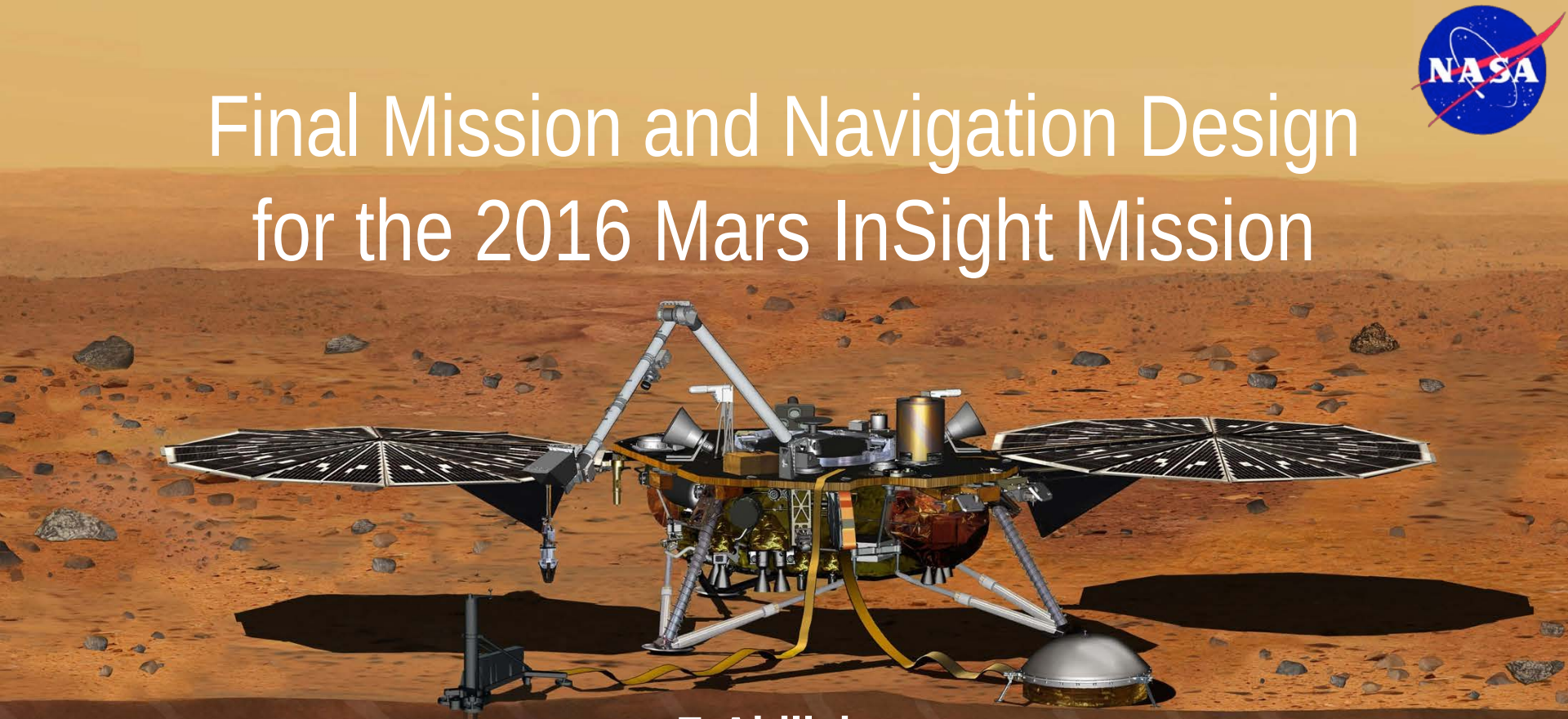
Final Mission and Navigation Design for the 2016 Mars InSight Mission



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Disclaimer

The InSight launch in 2016 was suspended due to critical issues with the Seismic Experiment for Interior Structure (SEIS) instrument that could not be fixed prior to the planned launch period. This presentation and its corresponding paper represent the state of the design for the 2016 mission. No attempt has been made to reflect the latest developments.

Preamble

- After thorough examination, NASA decided to **suspend** the planned March 2016 launch of the **IN**terior exploration using **S**eismic **I**nvestigations, **G**eodesy, and **H**eat **T**ransport (InSight) mission
- The decision follows unsuccessful attempts to repair a pressure leak in a section of the prime instrument in the science payload
- The instrument involved was the Seismic Experiment for Interior Structure (SEIS), a seismometer provided by France's Centre National d'Études Spatiales (CNES) designed to measure ground movements as small as the diameter of an atom. To achieve this accuracy, the instrument required a vacuum seal around its three sensors
- A decision on a path forward will be made in the coming months

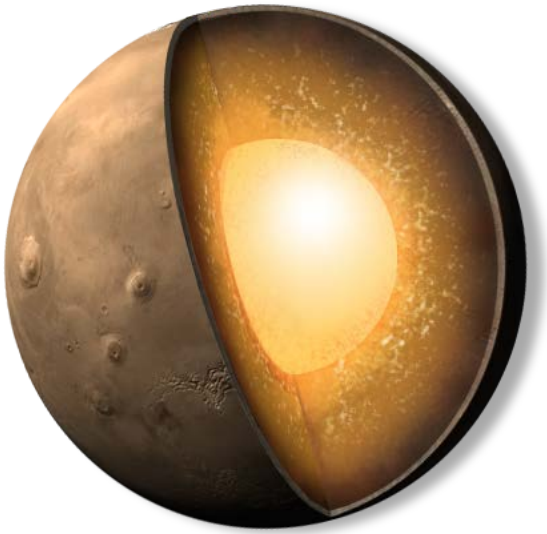
Sections of the launch vehicle fairing at Astrotech Space Operations processing facility at Vandenberg Air Force Base in California. Photo credit: NASA.

ULA's Atlas V first stage booster hoisted into vertical position. Photo credit: NASA.

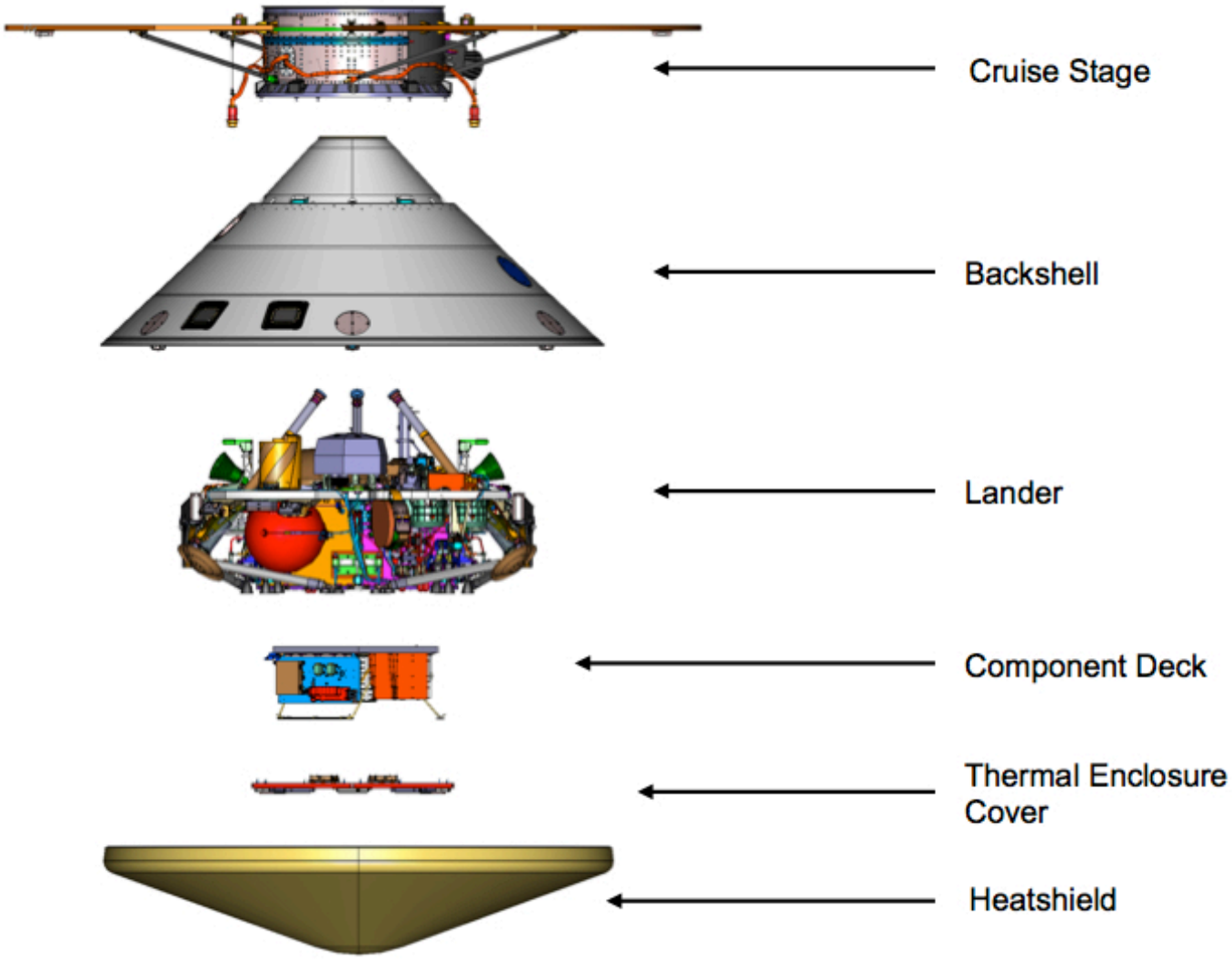
Lockheed Martin delivered the InSight Spacecraft to Vandenberg on 12/16. Photo credit: Lockheed Martin.

Project Overview

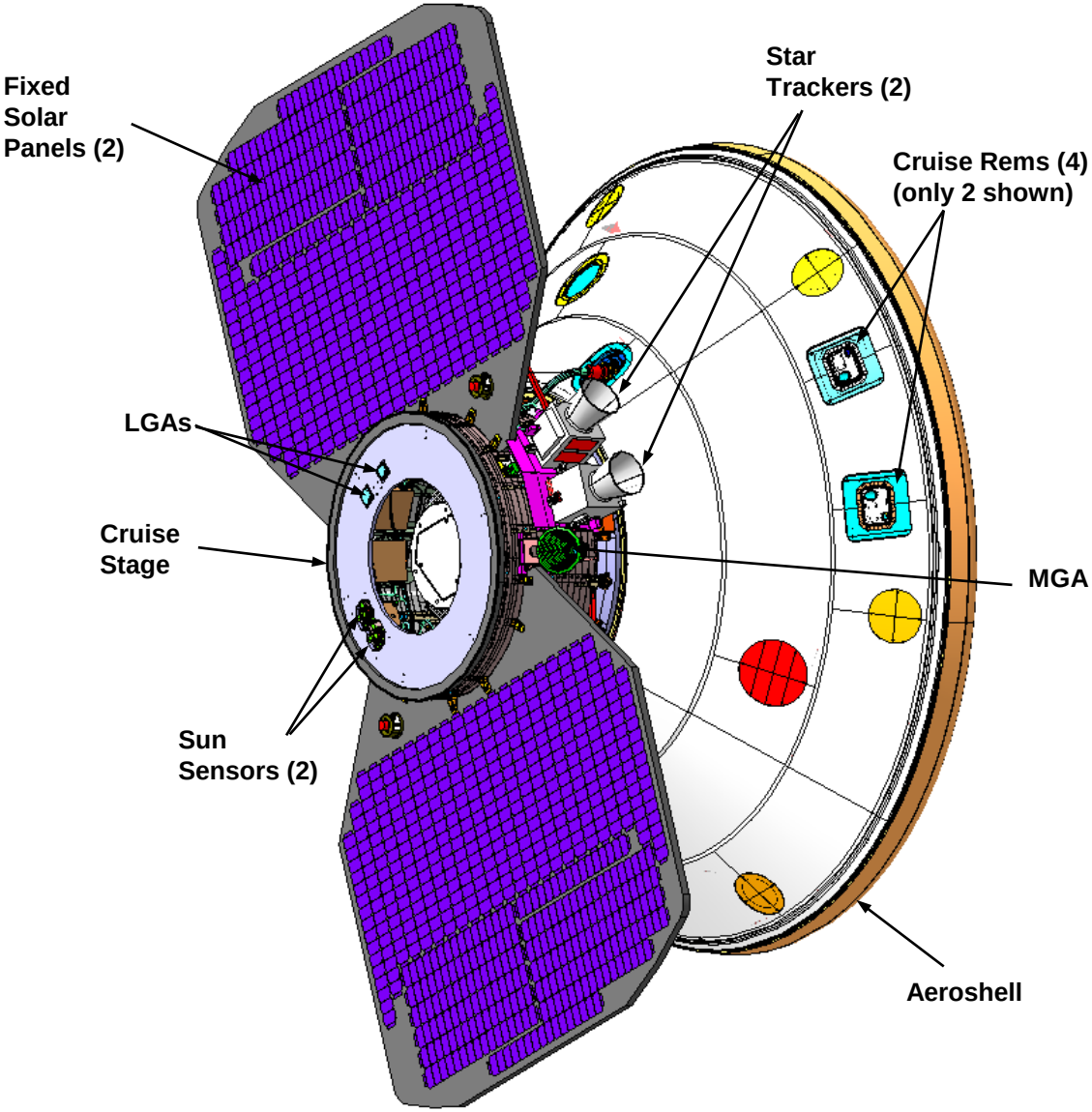
- NASA's 12th Discovery Program mission that will place a single geophysical lander on Mars to study its deep interior using seismic (tidal, marsquake, and impact), rotational, and thermal measurements
  - First mission to unveil the composition, structure and thermal state of martian crust, mantle and core
- Rebuild of the Phoenix flight system, upgraded with Juno/GRAIL avionics
  - Phoenix cruise stage: 3-axis stabilized, 3.2 m^2 UTJ solar array, X-band telecom
  - Phoenix aeroshell (heat shield, backshell, parachute)
  - Phoenix lander: radar, pulsed thrusters, legs, payload deck, 5.1 m^2 UTJ solar arrays, two redundant Li-ion batteries, UHF/X-band telecom
  - Dual string: Internally or functionally-redundant equipment
- Science Payload
  - SEIS (Seismic Experiment for Interior Structure) / CNES
    - Three-axis seismometry, to measure seismic waves traveling through the interior
  - HP3 (Heat Flow and Physical Properties Probe) / DLR
    - Subsurface heat probe, to measure the heat flux from the interior
  - RISE (Rotation and Interior Structure Experiment) / JPL
    - Radiometric geodesy, to determine precession & nutation of the planet's rotation axis

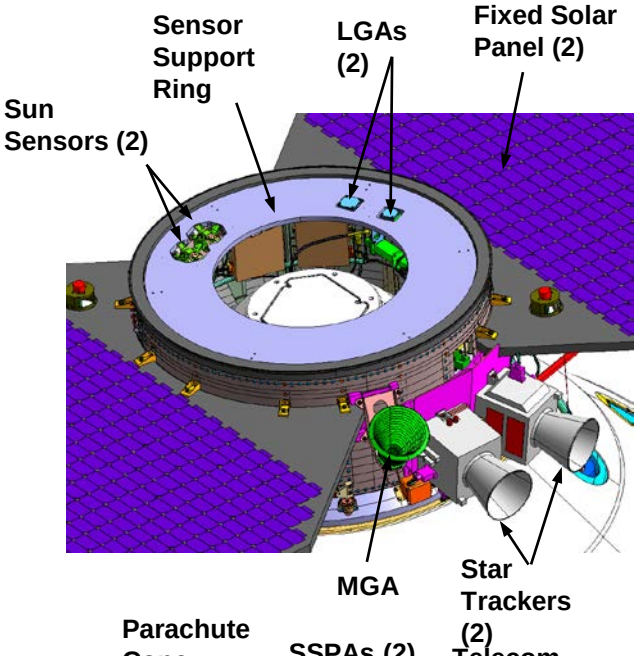


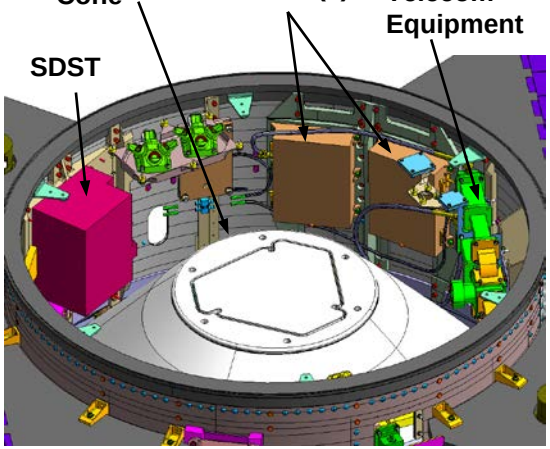
Flight System



Cruise Stage



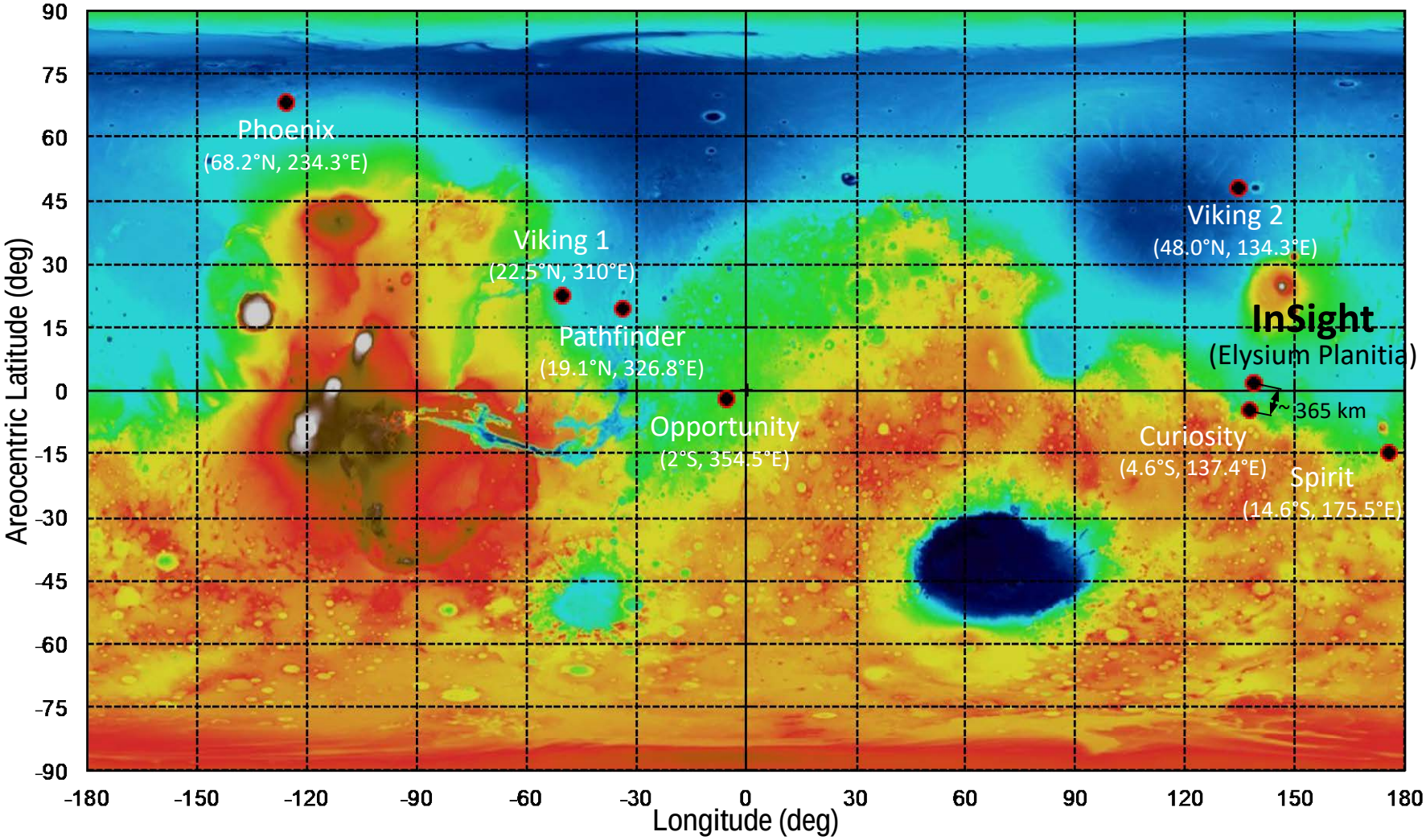




*Sensor Support Ring Omitted For Clarity

Landing Site: Elysium Planitia

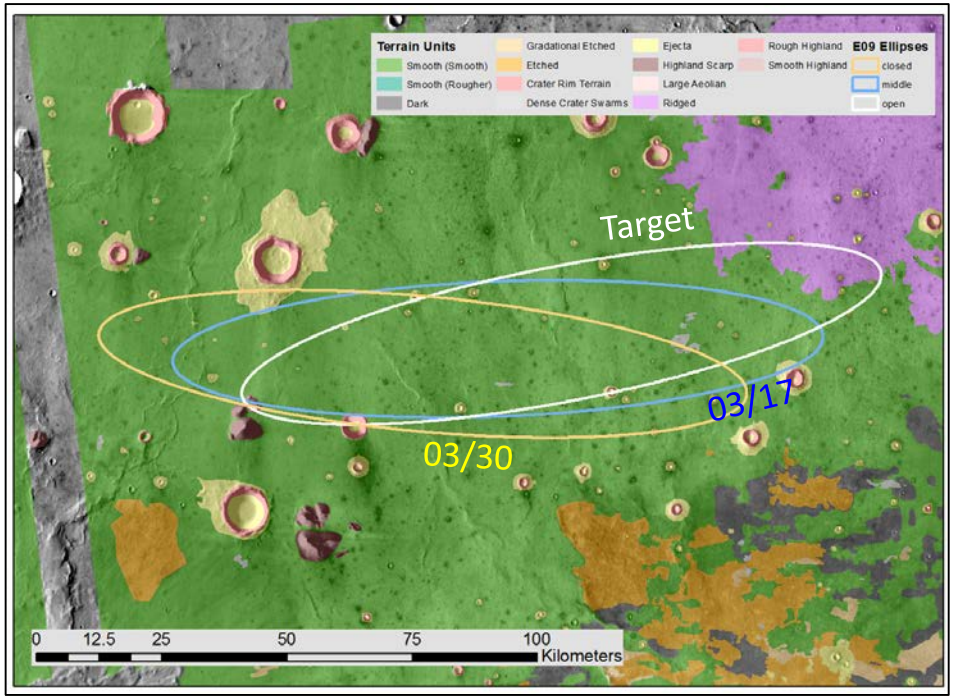
<u>InSight Landing Site constrained by</u>: Power (5°N to 2°N), elevation (<-2.5 km MOLA), ellipse size (130 km x 27 km), thermal inertia (<100-140 $Jm^{-2}K^{-1}s^{-1/2}$), rock abundance (<10%), slopes (<15°), and regolith (>5 m thick).



Landing Target

- All trajectories target the E09 reference site on launch day 1 at the launch window open
- Landing site latitude/longitude targets based on the 130 x 27 km rotated landing ellipse frozen on 09/16/14
- Additional updates to landing ellipse center will have negligible effects on launch targets or navigation performance

Landing Ellipse Azimuth Variation Across Launch Period



Landing Site	Latitude (deg)	Longitude (deg)	MOLA Elevation (km)
Latest Landing Site Working Group update (01/16/15)			
E09o (03/04)	4.427	135.841	-2.658
E09o (03/17)	4.376	135.626	-2.607
E09o (03/30)	4.326	135.373	-2.629
Used for Target Generation (based on 09/16/14 update)			
E09o (03/04)	4.460	135.970	-2.655

* o = Denotes launch window open

Mission Design and Navigation Overview

LAUNCH

March 2016

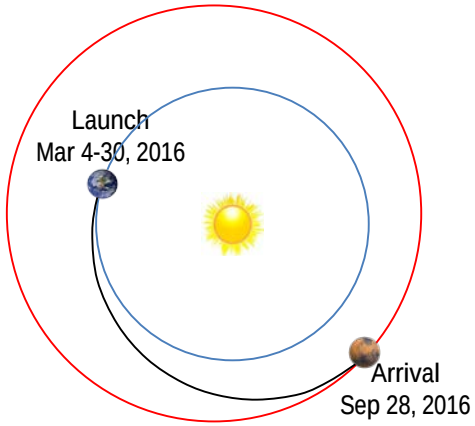
InSight Stowed in 4-m Payload Fairing

Vandenberg Air Force Base (Western Test Range)

Atlas V 401

INTERPLANETARY CRUISE

182 days to 208 days

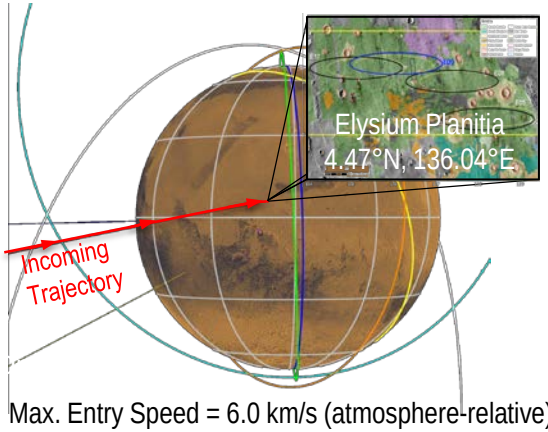


Type 1 Trajectory

Max C3 = 20.2 km^2/s^2, max DLA = -50.7 deg

APPROACH & EDL

Ballistic Entry



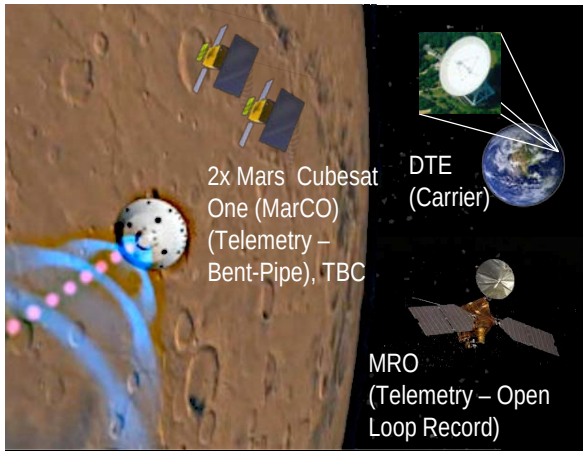
Max. Entry Speed = 6.0 km/s (atmosphere-relative)

Ls = 232 deg (dust storm season)

Landing LMST = ~1:44 PM – 1:57 PM

EDL COMMUNICATIONS

Ultra-High Frequency Link

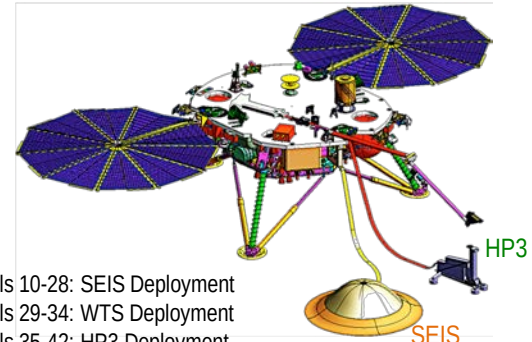


DEPLOYMENT

44 Sols

Sols 0-4: Lander Initialization

Sols 5-9: Instrument Placement Site Confirmation



Sols 10-28: SEIS Deployment

Sols 29-34: WTS Deployment

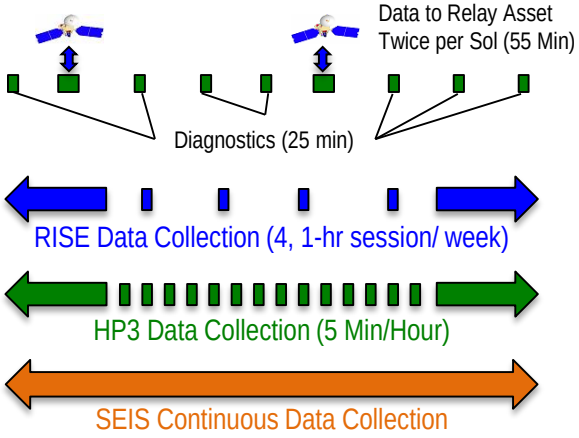
Sols 35-42: HP3 Deployment

Sols 43-86: HP3 Penetration

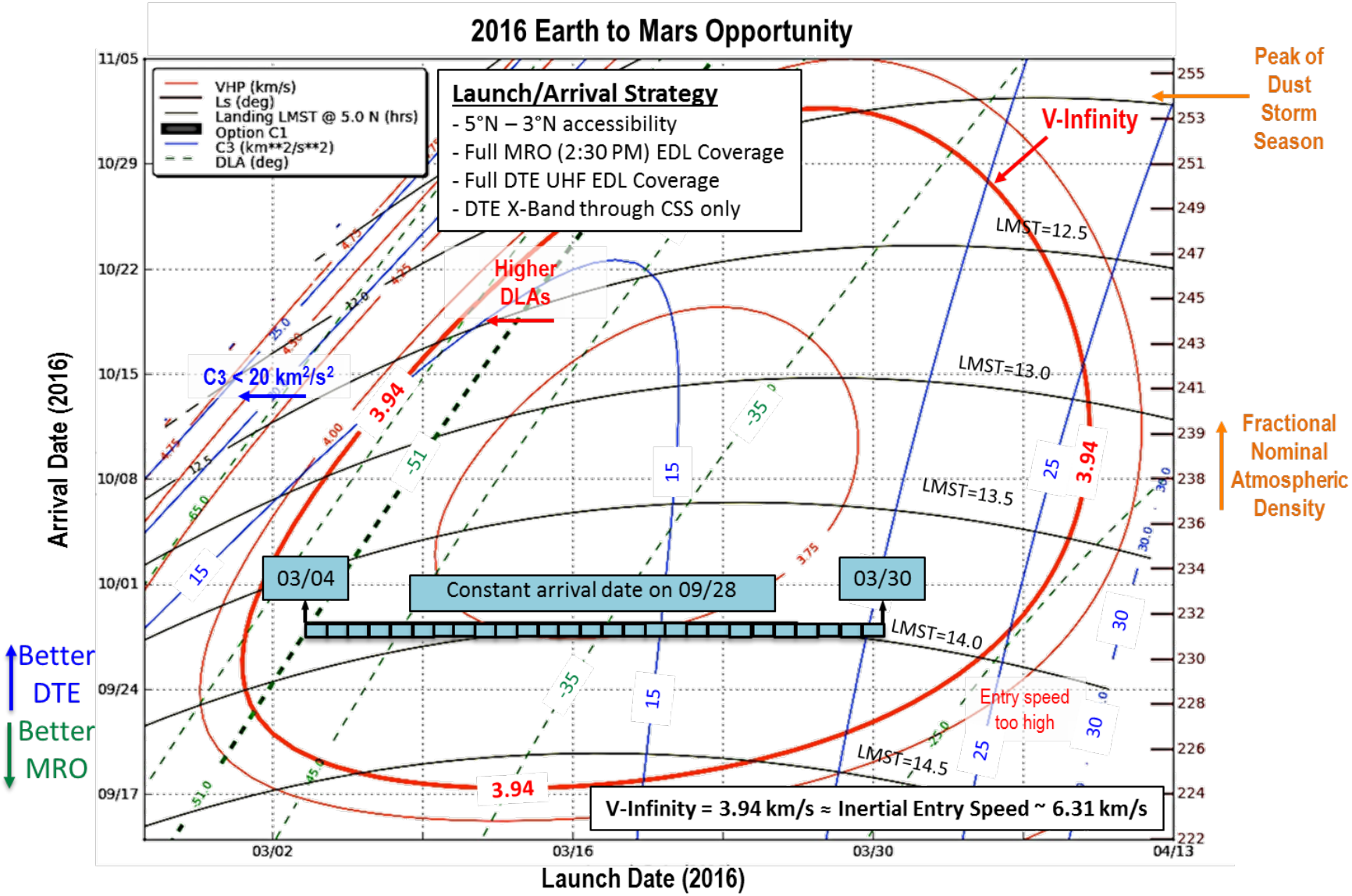
Sols 87-709: Science Monitoring

SCIENCE MONITORING

One Martian Year (sol 41 – sol 710)

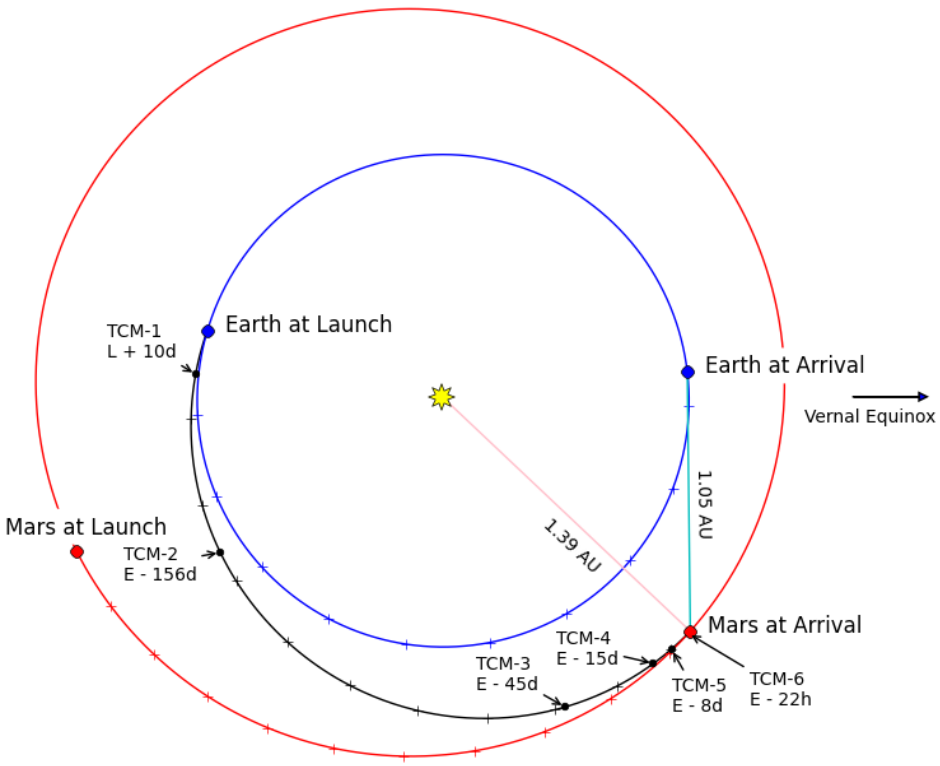


Launch/Arrival Strategy



Launch Targets and Cruise Trajectory

Launch Day	Launch Date (2016, UTC)	Launch Window Duration (min)	Earth Centered (EME2000)			IAU Mars Pole	
			C3 (km^2/s^2)	DLA (deg)	RLA (deg)	Arrival V-infinity (km/s)	Arrival Declination (deg)
1	03/04	120	11.980	-50.715	192.440	3.849	11.020
2	03/05	120	11.886	-49.280	193.120	3.828	10.222
3	03/06	120	11.841	-47.878	193.736	3.809	9.455
4	03/07	120	11.842	-46.512	194.301	3.793	8.717
5	03/08	120	11.887	-45.186	194.829	3.780	8.006
6	03/09	120	11.973	-43.903	195.330	3.768	7.320
7	03/10	115	12.098	-42.667	195.814	3.758	6.657
8	03/11	115	12.258	-41.482	196.284	3.750	6.015
9	03/12	110	12.452	-40.349	196.746	3.744	5.394
10	03/13	110	12.676	-39.271	197.199	3.739	4.792
11	03/14	105	12.927	-38.247	197.645	3.736	4.208
12	03/15	105	13.205	-37.275	198.082	3.734	3.640
13	03/16	105	13.508	-36.356	198.511	3.733	3.087
14	03/17	95	13.834	-35.487	198.931	3.733	2.549
15	03/18	95	14.184	-34.665	199.341	3.735	2.024
16	03/19	95	14.556	-33.891	199.744	3.737	1.513
17	03/20	90	14.950	-33.163	200.137	3.741	1.012
18	03/21	90	15.367	-32.482	200.522	3.745	0.523
19	03/22	90	15.806	-31.851	200.891	3.751	0.044
20	03/23	90	16.267	-31.273	201.228	3.758	-0.424
21	03/24	90	16.743	-30.714	201.492	3.765	-0.884
22	03/25	85	17.235	-30.087	201.734	3.773	-1.337
23	03/26	85	17.763	-29.463	202.071	3.783	-1.783
24	03/27	80	18.323	-28.905	202.442	3.793	-2.222
25	03/28	80	18.915	-28.405	202.821	3.804	-2.653
26	03/29	75	19.531	-27.933	203.178	3.816	-3.077
27	03/30	75	20.175	-27.489	203.528	3.829	-3.495



Tick marks every 20 days

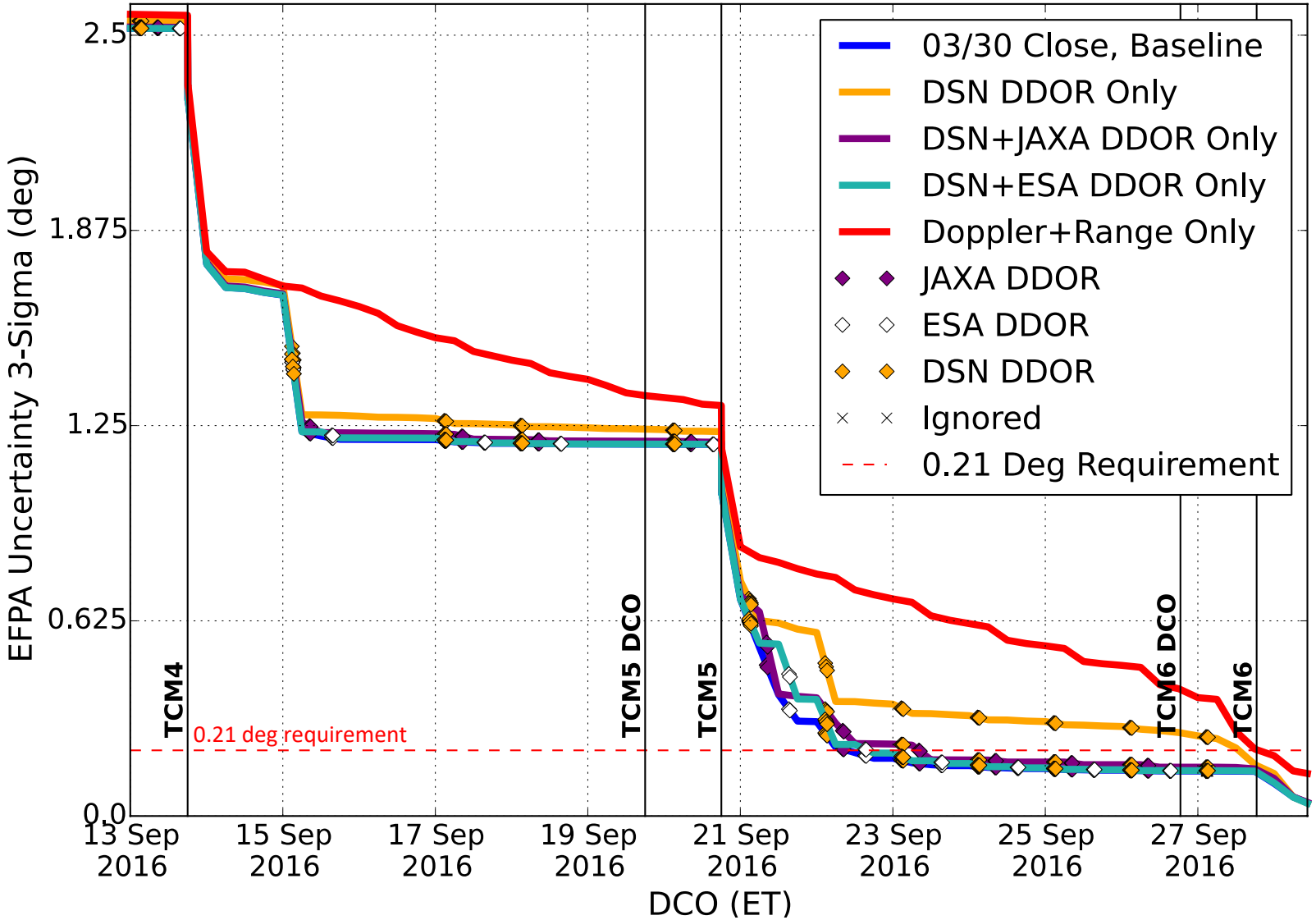
TCM-6 EFPA Delivery

- Small trend of increasing EFPA uncertainty for later launch dates
- Non-DSN DDOR required to meet the EFPA uncertainty requirement
- **EFPA uncertainty of less than ±0.21 is satisfied with ample margins**

Launch Date	Launch Window	EFPA 3-σ Uncertainty (deg) All Cases include Doppler and Range Data				
		No ΔDOR	DSN ΔDOR	DSN+ESA ΔDOR	DSN+ JAXA ΔDOR	DSN+ESA +JAXA ΔDOR
03/04/2016	Opt – 60m	0.3314	0.2584	0.1502	0.1633	0.1475
	Optimal	0.3315	0.2585	0.1502	0.1634	0.1475
	Opt + 60m	0.3316	0.2585	0.1501	0.1633	0.1474
03/17/2016	Opt – 60m	0.3568	0.2576	0.1488	0.1616	0.1458
	Optimal	0.3570	0.2577	0.1488	0.1616	0.1458
	Opt + 60m	0.3572	0.2578	0.1488	0.1616	0.1458
03/30/2016	Opt – 60m	0.4027	0.2648	0.1514	0.1639	0.1482
	Optimal	0.4027	0.2647	0.1512	0.1637	0.1479
	Opt + 60m	0.4030	0.2649	0.1514	0.1639	0.1482

Launch period close (03/30/2016 at opt+60 min) is the most stressing case.

EFPA Uncertainty Evolution—ΔDOR Sensitivity



TCM ΔV Statistics

- Each biased aimpoint produces the minimum deterministic ΔV required to target back to the desired final aimpoint in the Mars B-plane
- **Cumulative ΔV99 for all Trajectory Correction Maneuvers requirement of less than 30 m/s is satisfied with ample margins**

Event	TCM Schedule		TCM ΔV Statistics (m/s)					
	Relative Time	OD Data Cutoff	Deterministic ΔV	Mean ΔV	1σ ΔV	ΔV01	ΔV99	Cumulative ΔV_{99}
TCM-1	L+10d	TCM-5d	7.267	8.613	3.554	3.462	19.315	19.315
TCM-2	L+60d	TCM-5d	0	0.418	0.212	0.079	1.085	19.970
TCAL	E-127d	-	0.283	0.285	0.054	0.159	0.415	20.250
TCM-3	E-45d	TCM-5d	0	0.283	0.165	0.045	0.785	20.545
TCM-4	E-15d	TCM-1d	0	0.092	0.038	0.023	0.193	20.669
TCM-5	E-8d	TCM-1d	0	0.063	0.025	0.015	0.128	20.714
TCM-5×*	E-5d	TCM-1d						
TCM-6	E-22h	TCM-10h	0	0.243	0.103	0.053	0.528	20.929
TCM-6×*	E-8h	TCM-24h						
		Total ΔV:	7.550	9.996	3.619	4.640	20.929	-

* Contingency maneuvers

Launch day 16 (03/19/2016 at opt + 60m) has the highest ΔV99.

50-year Planetary Protection Requirement

- **Evaluated three different scenarios: Both MarCO spacecraft deploy, one MarCO spacecraft deploys, and no MarCO deployments**
- **Maximum impact probabilities across the three scenarios satisfy the 50-year Planetary Protection requirement of 1.0×10^{-4}**

Launch Date	Launch Window	99th Percentile Probability of Impact ($x10^{-4}$)		
		Both MarCO deploy	One MarCO deploys	No MarCO deployments
03/04/2016	Opt – 60m	0.69	0.68	0.69
	Optimal	0.69	0.69	0.69
	Opt + 60m	0.70	0.70	0.70
03/17/2016	Opt – 60m	0.69	0.69	0.69
	Optimal	0.69	0.69	0.69
	Opt + 60m	0.76	0.69	0.69
03/30/2016	Opt – 60m	0.69	0.69	0.69
	Optimal	0.69	0.69	0.69
	Opt + 60m	0.69	0.69	0.69

For details about the Planetary Protection methodology, refer to M. Wallace, "Massively Parallel Bayesian Approach to Planetary Protection Trajectory Analysis and Design", *2015 AAS/AIAA Astrodynamics Specialists Conference*, Vail, Colorado, August 9-13, 2015.

Non-Nominal Impact Probability

- **Cumulative impact probabilities for launch period open, middle, and close satisfy the non-nominal impact probability requirement of 1.0×10^{-2}**

Event	Location	03/04/2016			03/17/2016			03/30/2016		
		P(i)	Q(i+1)	P(i)*Q(i+1)	P(i)	Q(i+1)	P(i)*Q(i+1)	P(i)	Q(i+1)	P(i)*Q(i+1)
Launch		0	7.36E-06	0	0	4.38E-06	0	0	4.38E-06	0
Injection		1.00E-04	7.11E-04	7.11E-08	1.00E-04	7.15E-04	7.15E-08	1.00E-04	7.17E-04	7.17E-08
TCM-1	L+10d	0.279	2.94E-03	8.19E-04	0.284	2.03E-03	5.76E-04	0.283	1.12E-03	3.16E-04
TCM-2	E–156d	0.000	2.03E-03	1.17E-12	0.000	2.03E-03	6.06E-12	0.000	2.03E-03	4.78E-12
TCAL	E-127d	0.581	5.72E-03	3.32E-03	0.588	5.72E-03	3.36E-03	0.587	5.72E-03	3.35E-03
TCM-3	E–45d	0.979	2.10E-03	2.05E-03	0.981	2.10E-03	2.06E-03	0.980	2.10E-03	2.06E-03
TCM-4	E–15d	1.000	4.90E-04	4.90E-04	1.000	4.90E-04	4.90E-04	1.000	4.90E-04	4.90E-04
TCM-5	E–8d	1.000	4.91E-04	4.91E-04	1.000	4.91E-04	4.91E-04	1.000	4.91E-04	4.91E-04
TCM-6	E–22h	1.94E-05	6.42E-05	1.25E-09	1.51E-05	6.42E-05	9.71E-10	2.16E-05	6.42E-05	1.38E-09
			Cumulative Total:	7.18E-03		Total:	6.98E-03		Total:	6.71E-03

P(i) : probability of impact after maneuver i
= total impact probability (100 km atmosphere) for all maneuvers except TCM-6
= probability of impact for non-nominal entry flight path angles for TCM-6
Q(i+1) : probability of not being able to execute maneuver i+1 given that maneuver i has occurred.

Landing Ellipse Size

- **Two methods used to calculate 99% ellipse size**
  - Contouring method (contains 99% of the landing points) and a Gaussian (assumes Gaussian distribution along each axis)
  - Gaussian method is typically more conservative
- **Estimated landing footprint satisfies the landing ellipse size requirement of 150 x 35 km**

Launch Date	Azimuth (deg)	Contour Method		Gaussian Method	
		99% Along-track* (km)	99% Cross-track** (km)	99% Along-track* (km)	99% Cross-track** (km)
03/04/2016	79.8	121.7	26.4	130.3	28.3
03/17/2016	89.0	115.3	25.5	124.2	27.6
03/30/2016	95.5	117.9	26.1	124.8	27.7

Requirements vs. Performance Summary

Key Driving Requirement Description	Impact	Requirement	Performance
The launch/arrival strategy shall launch between the dates of March 4 and March 30, 2016 both inclusive.	Launch/arrival strategy	03/04-30/16	03/04-30/16
The launch/arrival strategy shall support a Mars arrival of September 28, 2016.	Launch/arrival strategy	09/28/16	09/28/16
The launch/arrival strategy shall approach EDL with a V-infinity upper limit of 3.941 km/s.	Launch/arrival strategy	< 3.941 km/s	3.849 km/s
The launch/arrival strategy shall land a region bounded by 5°N to 3°N.	Launch/arrival strategy	5°N to 3°N	5°N to 3°N
MDNAV shall design a spacecraft trajectory that provides line of sight to the Earth from entry through touchdown plus 60 s.	EDL Comm	Entry through landing plus 60 s	Entry through landing plus 6 min
MDNAV shall design a spacecraft trajectory that has the capability to support UHF-band telecommunications with Mars Reconnaissance Orbiter (MRO) from entry through touchdown plus 60 s.	EDL Comm	Entry through landing plus 60 s	Entry through landing plus 5 min
MDNAV shall assume that the cumulative ΔV99 for all Trajectory Correction Maneuvers (TCMs) targeted to the nominal landing site shall not exceed 30 m/s.	ΔV99	< 30 m/s	20.9 m/s
The InSight project injection aimpoint for launch shall be biased away from Mars such that the probability of the launch vehicle upper stage impacting Mars is less than 1.0×10^{-4} for fifty years after launch.	DV99	$< 1.0 \times 10^{-4}$	0.76×10^{-4}
Probability of non-nominal impact of Mars by the InSight project due to failure during the Cruise Phase shall not exceed 1.0×10^{-2}.	DV99	$< 1.0 \times 10^{-2}$	0.72×10^{-3}
The entry vehicle shall approach EDL with an Entry Flight Path Angle (EFPA) of -12.5 deg ± 0.21 deg, 3-sigma.	TCM strategy, tracking data	< ±0.21 deg	±0.16 deg
MDNAV shall design a trajectory that has the capability to land the spacecraft within a 150 km by 35 km ellipse with a probability greater than or equal to 99%	TCM strategy, tracking data	< 150 x 35 km	130 x 28 km

Summary

- InSight will be the first planetary mission to be launched from Vandenberg Air Force Base (VAFB)
- Design uses high heritage from the successful Mars Phoenix mission, thereby reducing technical and programmatic risk
- A 27-day launch/arrival strategy has been identified which meets all key and driving Mission Design and Navigation requirements with ample margins

* If launch is approved for the next Earth to Mars opportunity and it launches from VAFB.

Questions?

Backup

Radiometric Tracking Data Assumptions and Schedule (1 of 2)

- Tracking data types are 2-way coherent X-band Doppler, range and ΔDOR
- 8-hour tracks from Goldstone, Canberra, and Madrid (when available)
  - The InSight interplanetary cruise trajectories limit the Goldstone/Madrid tracking coverage due to southern declination
    - DSN DDOR limited to Goldstone-Canberra baseline
    - Non-DSN DDOR baseline (e.g., New Norcia-Madrid) needed to meet entry requirements
- Continuous tracking coverage around TCM execution (TCM ±2 days)

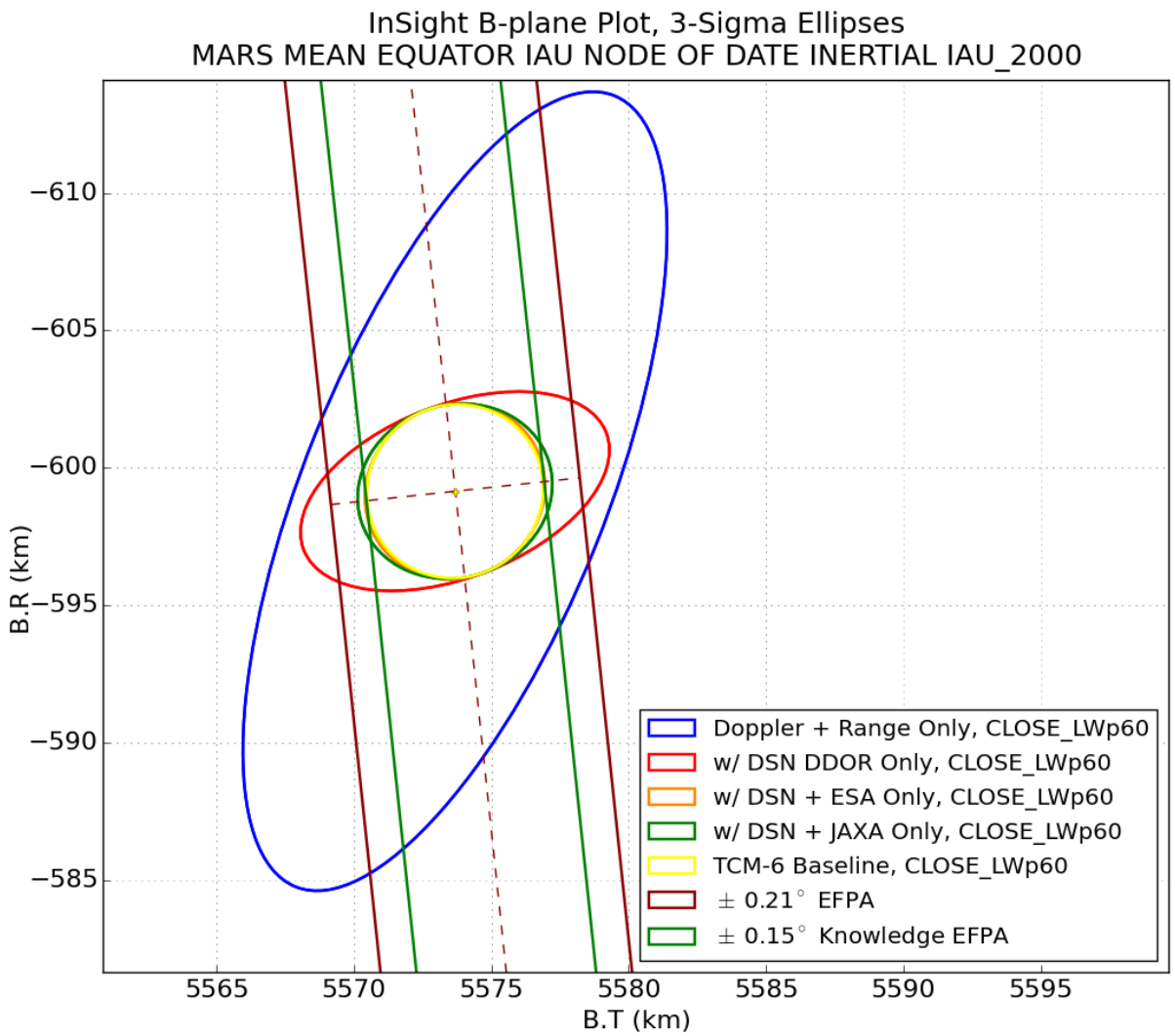
Phase	Relative Dates	Support
Cruise	Launch to L + 15 days	Continuous 34-m coverage
	L + 15 days to E - 60 days	Three 34-m 8-hour passes/week*
	L + 58 days to L + 74 days	One 34-m 8-hour pass/day**
	E - 64 days to E - 47 days	Two 34-m 8-hour pass/day
	E - 47 days to Entry	Continuous 34-m coverage
	*Additional 4 days continuous coverage for TCMs + Thruster Calibration. **TCM-2 DCO	

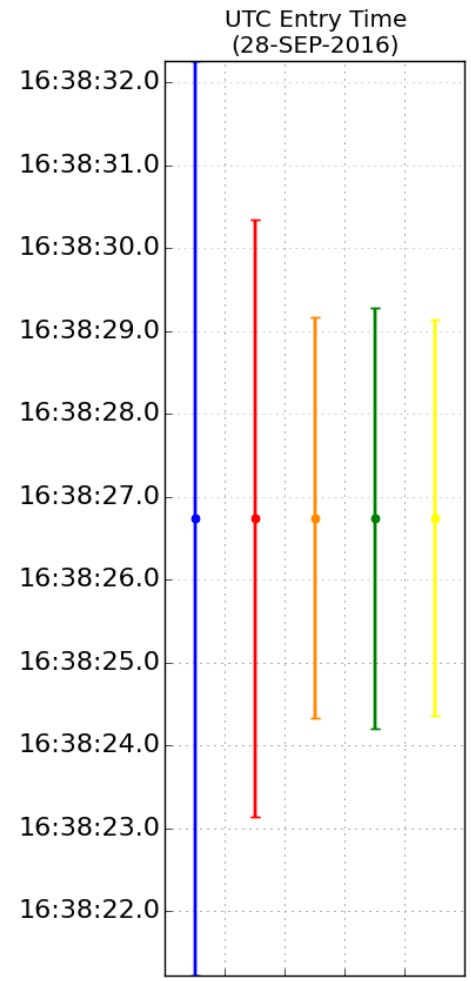
Radiometric Tracking Data Assumptions and Schedule (2 of 2)

- Metric data accuracy of ΔDOR observable
  - 60 ps for DSN and JAXA (1-σ), 120 ps for ESA (1-σ)
- Quasar angular positions are assigned an uncertainty of 1 nrad (1-σ)
- 2-hour latency for DSN-DSN baselines and 24-hour for ESA-ESA, DSN-ESA and DSN-JAXA baselines

Phase	Dates (UTC)	Stations	Number of ΔDOR	Duration (pre/post included)
Demonstration	06/23/2016 – 07/21/2016	NNO+CEB	3	2 hours
		GLD/CAN+MLG	3	
		CAN+USUDA	3	
Pre TCM-3	08/04/2016 – 08/08/2016	NNO+CEB	2	2 hours
		GLD/CAN+MLG	2	
		CAN+USUDA	2	
Pre TCM-4	08/17/2016 – 09/11/2016	NNO+CEB	6	2 hours
		GLD/CAN+MLG	6	
		CAN+USUDA	6	
Pre TCM-5	09/13/2016 – 09/18/2016	NNO+CEB	4	2 hours
		GLD/CAN+MLG	4	
		CAN+USUDA	4	
Approach	09/20/2016 – 09/27/2016	NNO+CEB	7	2 hours
		GLD/CAN+MLG	8	
		CAN+USUDA	7	
Total	**45 ESA ΔDOR Passes (including demo passes):** **- Malargüe: 23** **- Cebreros + New Norcia: 22** **22 JAXA ΔDOR Passes (including demo passes)** **NNO = New Norcia, CEB = Cebreros, GLD = Goldstone, CAN = Canberra, MLG= Malargüe**			

ΔDOR Sensitivity (B-Plane)





- Launch period close (p60) has worst EFPA uncertainty.