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Mars Reconnaissance Orbiter Navigation Strategy for Support of InSight Lander's Entry, Descent and Landing Sequence

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Mars Reconnaissance Orbiter Project

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Mars Reconnaissance Orbiter (Mission, Spacecraft and PSO)

MRO launched in August 2005 from Cape Canaveral Air Force Station arrived at Mars in March 2006 and started science operations in November 2006. It has completed 13 years since launch (58,450 orbits by January 14, 2018) and to date has returned over 350 Terabytes of data.

MRO Primary Science Orbit (PSO):

- **Sun-synchronous** orbit ascending node at 3:00 PM $\pm$ 15 minutes Local Mean Solar Time (LMST) (daylight equatorial crossing)
- Periapsis is **frozen** about the Mars South Pole
- **Near-repeat ground track walk (GTW)** every 17-day, 211 orbit (short-term repeat) MRO targeting cycle, exact repeat after 4602 orbits. The nominal GTW is 32.45811 km West each 211 orbit cycle (maintained within $\pm$60 km with periodic maneuvers)

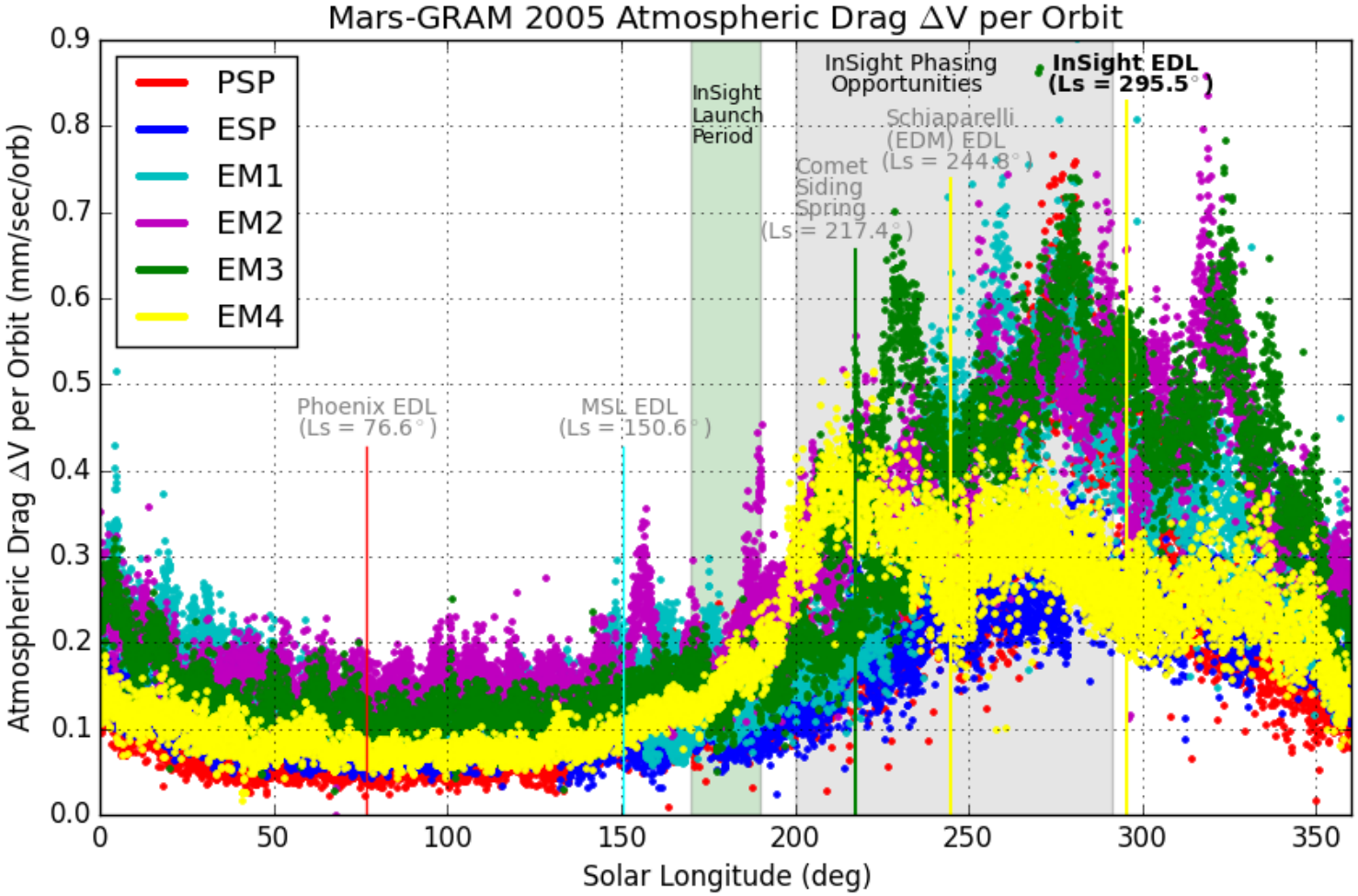
MRO Spacecraft:

- **Spacecraft Bus:** 3-axis stabilized ACS system; 3-meter diameter High Gain Antenna; hydrazine propulsion system
- **Instrument Suite:** HiRISE Camera, CRISM Imaging spectrometer, Mars Climate Sounder, Mars Color Imager, Context Camera, Shallow Subsurface Radar, Electra engineering payload (among other instrument payloads)

Navigation Plan

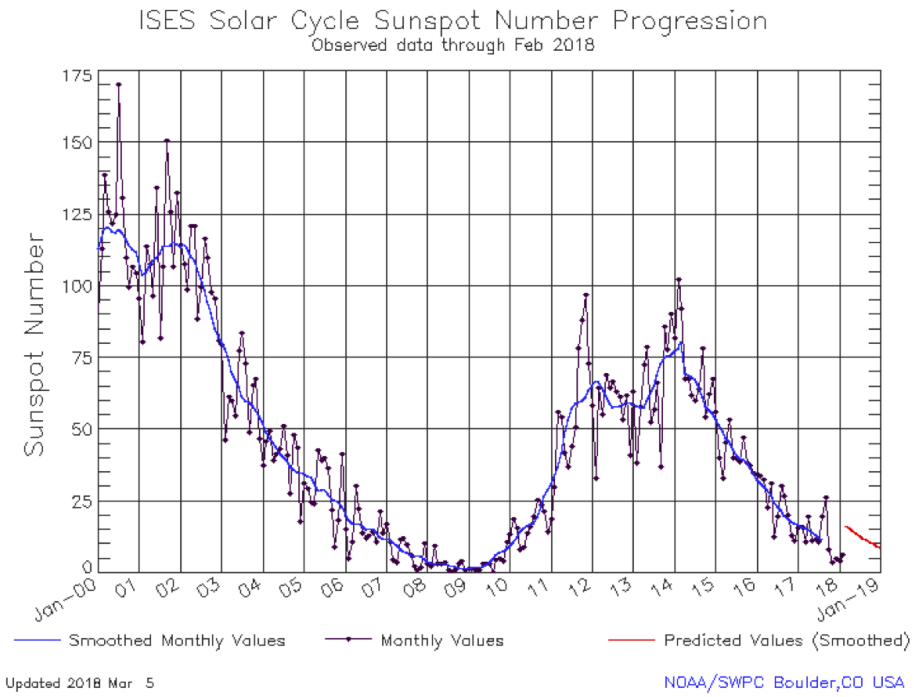
- MRO Navigation Team was tasked to develop the strategy to phase MRO to support InSight lander
  - EDL relay support
    - EDL relay support using UHF antenna
    - Maintain orbit for 7 sols of uninterrupted overflight support
    - Subsequent surface operations support
- Phasing Target
  - Per target given in EDL Relay Target File (ERTF)
    - Time to cross a set latitude
    - Optimized to support EDL
  - Navigation Requirement: ± 30 seconds
- Navigation Plan
  - Phasing offset at time of maneuver planning was 55 minutes (early)
    - About 1/2 of the orbit period ($\sim$112 minutes)
  - 2 pro-velocity maneuvers were planned and implemented
    - Phasing correction in accordance with Navigation uncertainty
    - To increase semi-major axis and the orbit period
    - Slow-down approach also aided GTW countering atmospheric drag

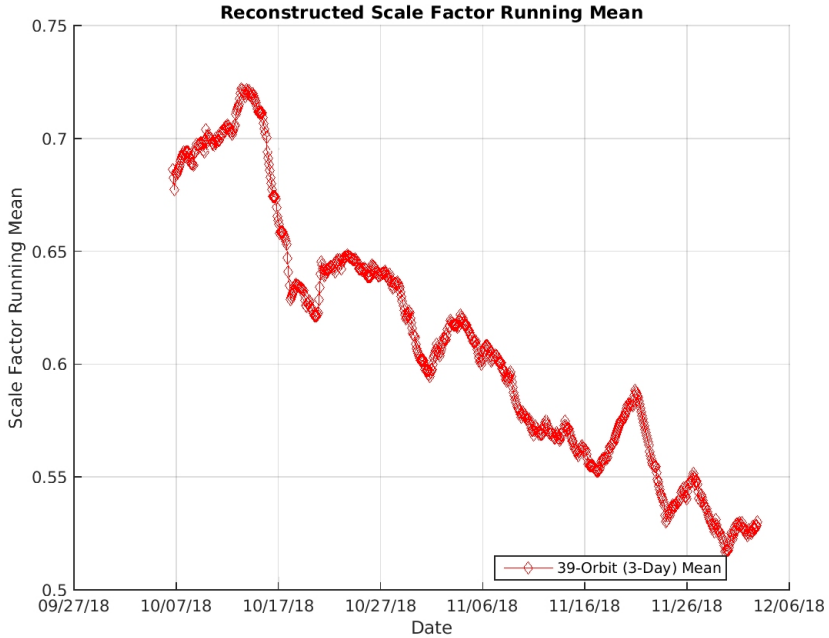
Mars Atmospheric Density Variation



- **Atmospheric density variation is a significant navigation error source**
- **Anticipated drag ΔV:** 0.35-0.45 mm/s/orbit at the time of maneuvers leading to InSight landing
- **Similar to EDM third overfight phasing support (10/2016) and larger than earlier phasing support:** Phoenix EDL (03/2008), MSL EDL (08/2012) & CSS Risk Mitigation (10/2014)

Solar Cycle and Reconstructed Density Scale Factor





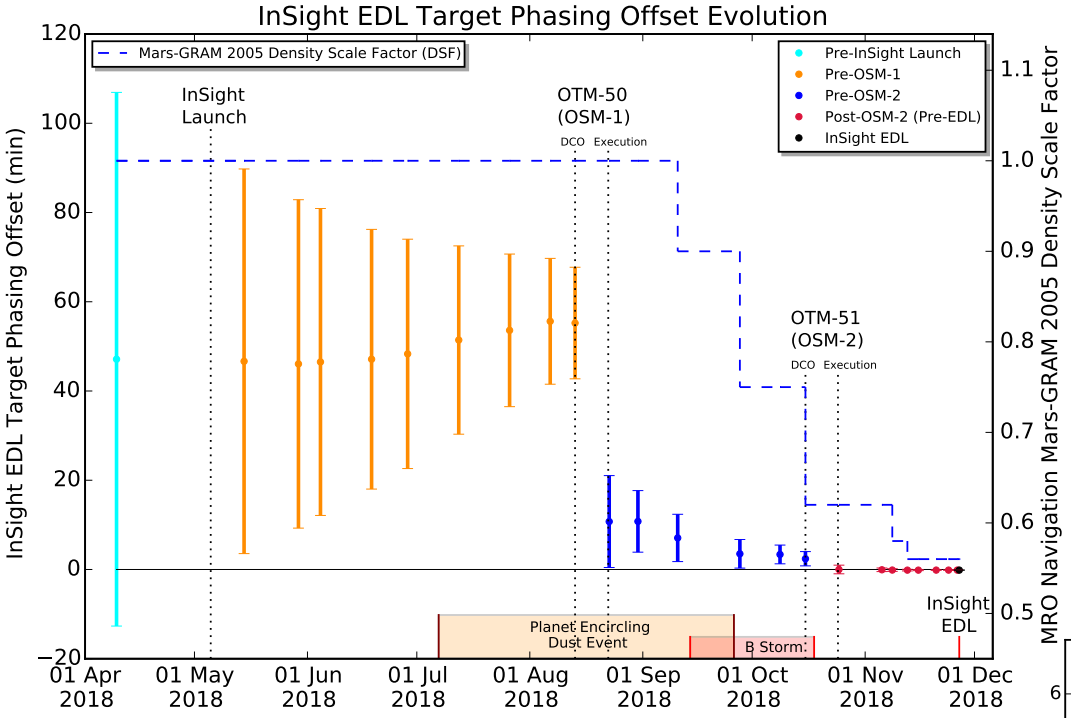
- **Solar Cycle:**
  - Approaching solar minimum
  - Low volatility in the atmospheric density variations
- **Reconstructed DSF:**
  - Considered DSF behavior from previous Mars year (MY 33)
  - Average DSF 0.62 was selected for the final maneuver

Maneuvers and Phasing Corrections

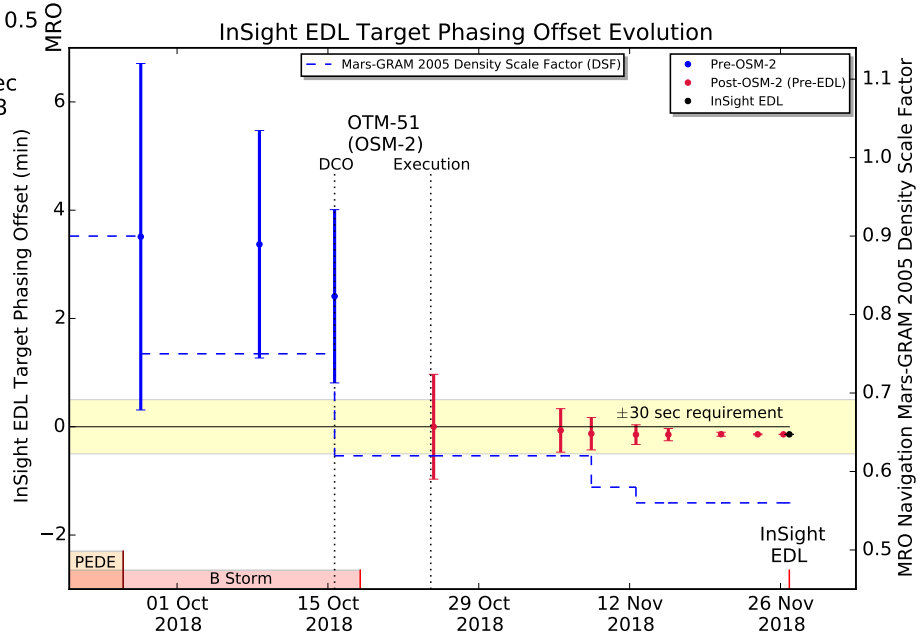
	OTM-50 (OSM-1)	OTM-51 (OSM-2)	OSM-3	InSight EDL Target
Event Date	8/22/2018	10/24/2018	11/14/2018	11/26/2018
OSM Execution Prior to InSight EDL	96 days	33 days	12 days	
OSM ΔV (Designed)	0.3384 m/s	0.0568 m/s	*cancelled*	
Target File	ERTF-10	ERTF-15		ERTF-15
InSight EDL Phasing Offset (Pre-OSM)	55.23 min early	2.41 min early		
InSight EDL Phasing Offset (Post-OSM)	10.74 min early	0.03 sec early		**8.41 sec late**
InSight EDL Phasing Correction via OSM	**44.5 min early**	**2.4 min early**		**(reconstructed)**
Down-Track Timing Uncertainty (3-σ)	12.5 min	1.6 min	18.0 sec	
OD DCO for OSM	8/13/2018	10/15/2018	11/8/2018	
DCO Prior to InSight EDL Target	105 days	42 days	18 days	

- **Phasing Maneuvers:** OTM-50 (8/22) and OTM-51 (10/24)
- **Post-OTM-51 phasing offset:**
  - Grew to 8.41 seconds (ERTF-15) at the time InSight landing
  - Actual offset was 15.68 seconds (ERTF-20 including InSight TCM-6)

Phasing Offset History

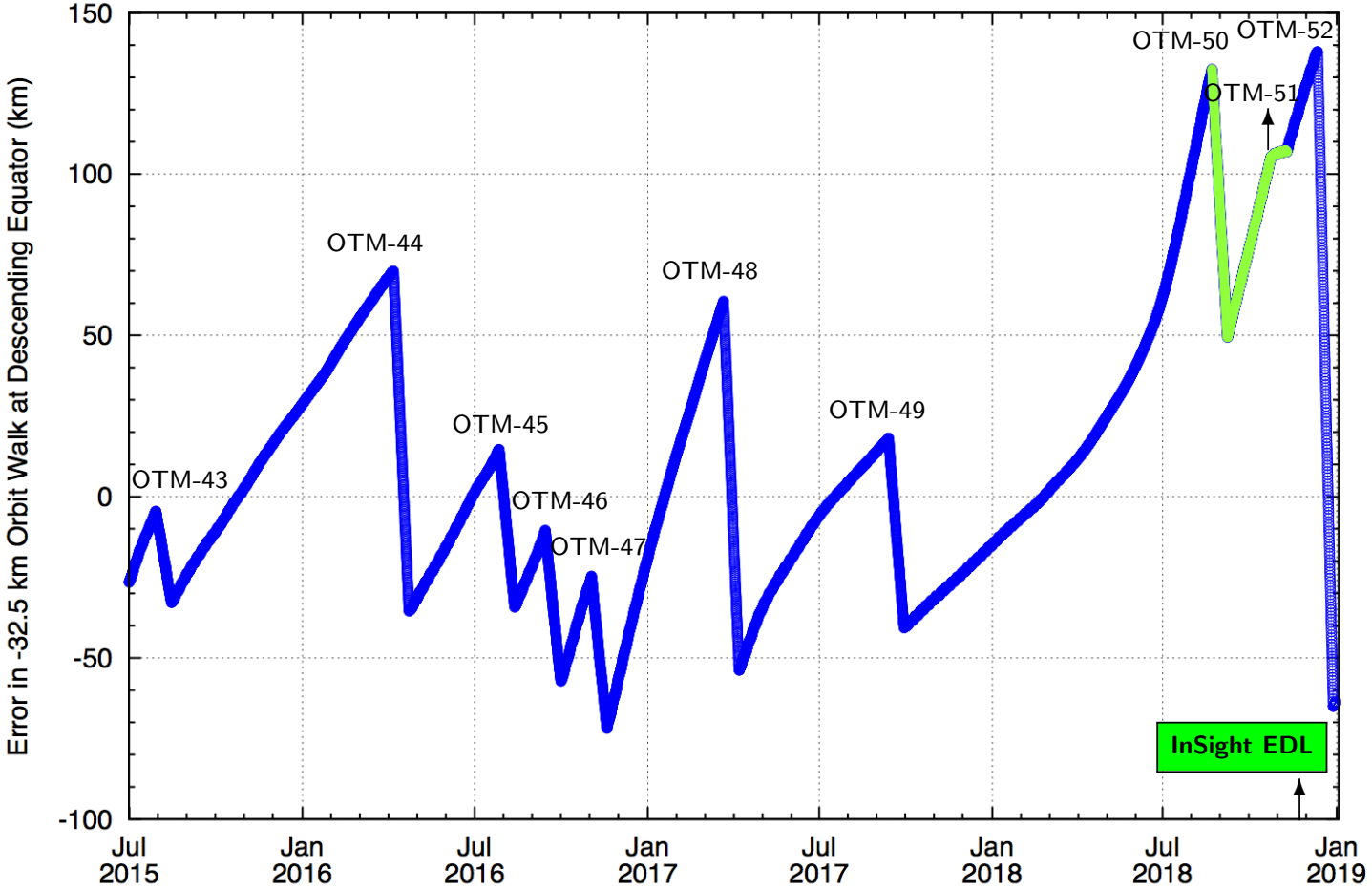


- **First Phasing Maneuver:** OTM-50 (OSM-1) on August 22, 2018
  - Designed to remove about 43 minutes of the predicted phasing offset
- **Second Phasing Maneuver:** OTM-51 (OSM-2) on October 24, 2018
  - Designed to remove remaining offset of about 2.41 minutes



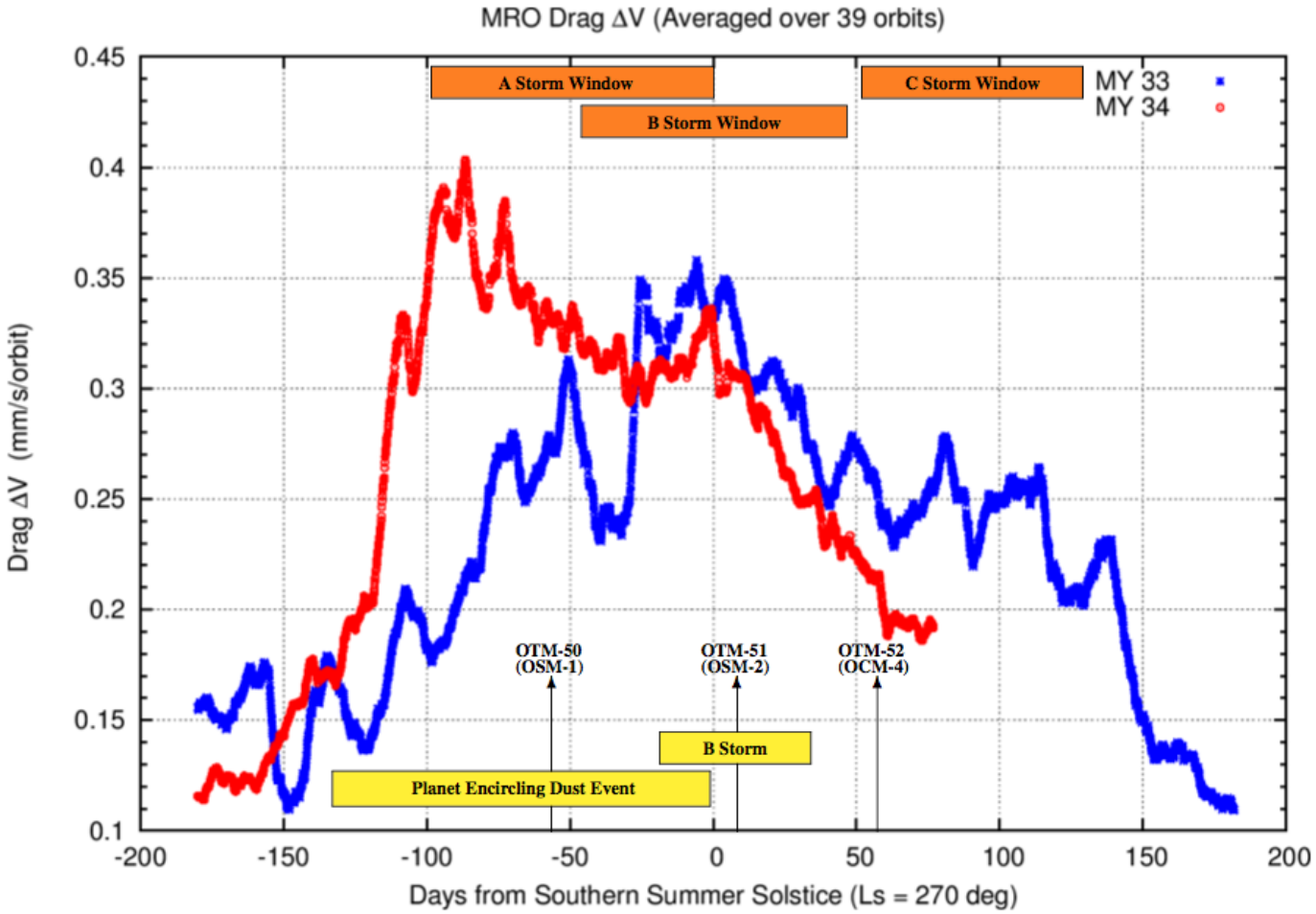
- **Phasing offset monitoring:** Started from 262 days prior to InSight landing
- **Navigation uncertainty:** 12.5 min (OTM-50), 2.5 min (OTM-51)
- **Final phasing offset:** 8.41 sec << 30 seconds requirement

Ground Track Walk Error at InSight EDL



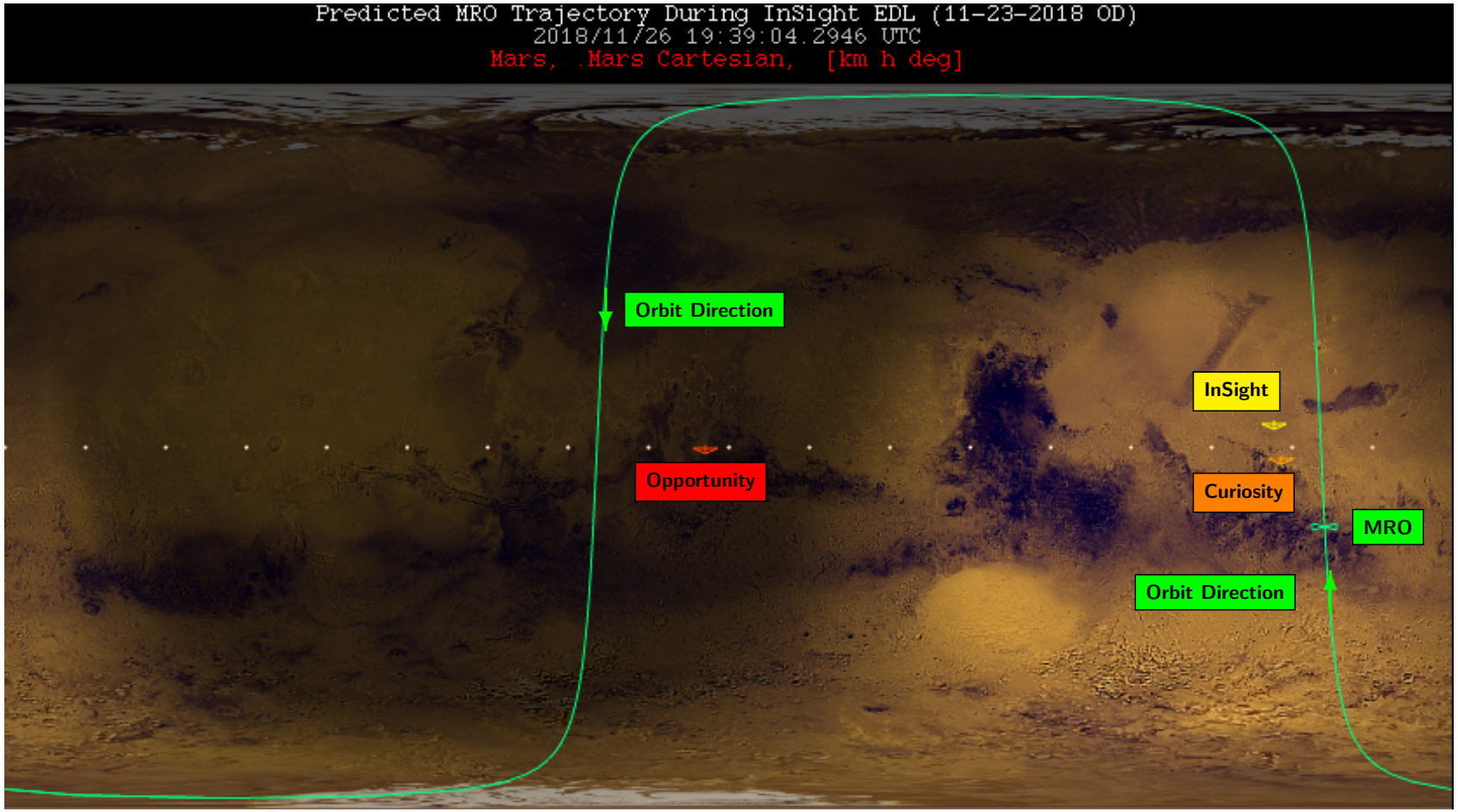
- Pro-velocity maneuvers (OTMs 50 & 51) to achieve InSight EDL target
  - GTW error grew to about 140 km
- Inclination-change maneuver (OTM-52) to achieve 3:15 PM LMST for Mars 2020 EDL and return to PSO

Atmospheric Drag ΔV



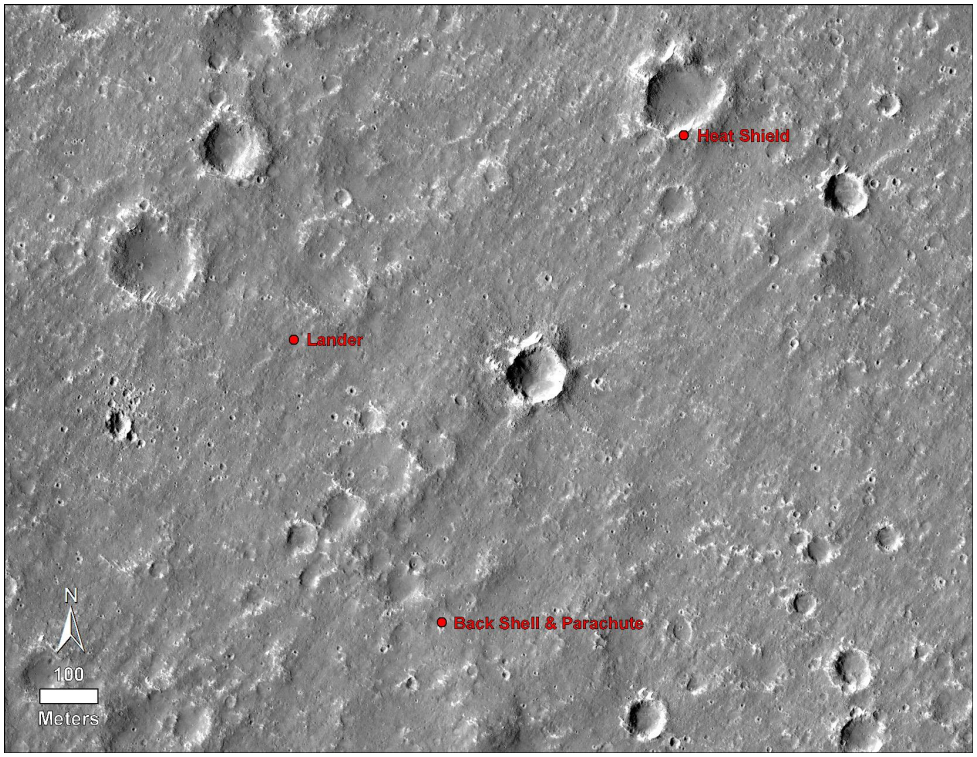
- **Maneuver ΔV:** Pro-velocity decreases effective drag on the S/C
- **Dust Activity:** Dust storm adds to the drag ΔV
- Overall drag effects comparable to previous Mars year

InSight Landing Site

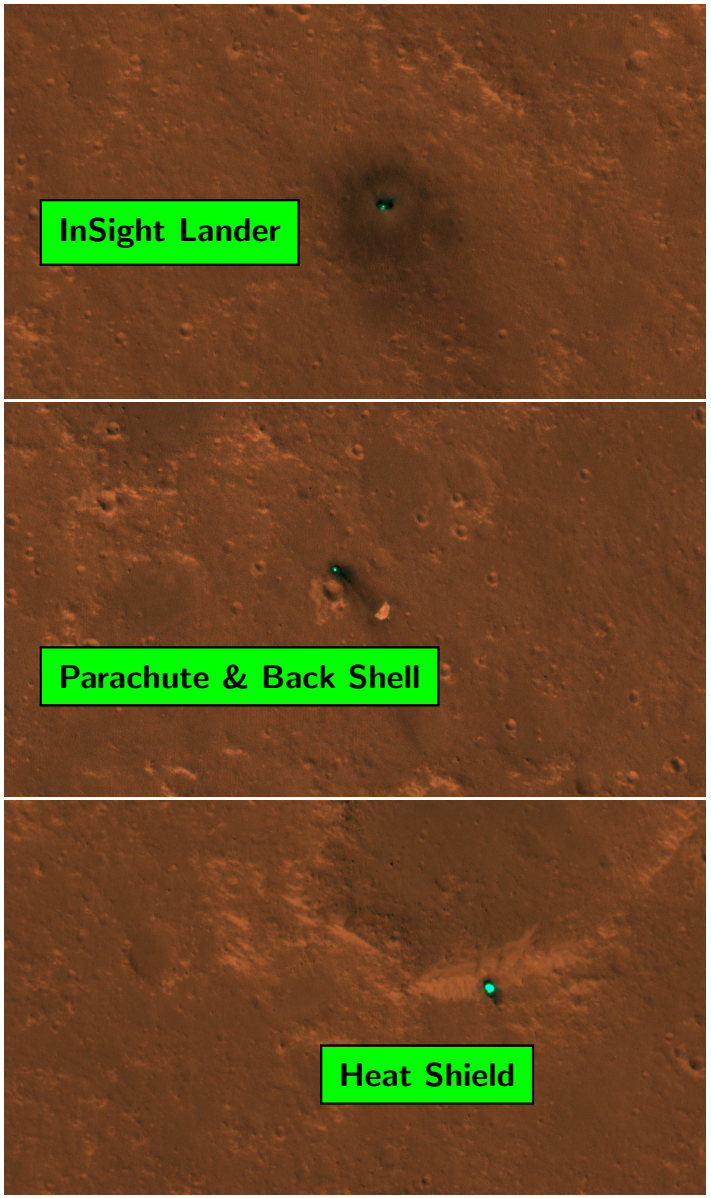


- InSight landing location: 4.50° N, 135.94° E in Elysium Planitia region, just north of Curiosity landing site (4.59° S, 137.44° E)
- MRO ground track for InSight EDL is shown in green

Impact Site Images Taken by MRO's HiRISE Camera



An annotated image of the surface of Mars, taken by HiRISE camera on May 30, 2014. The annotations – added after InSight landed on Nov. 26, 2018 – display the locations of NASA's InSight lander, its heat shield & parachute. Source: NASA/JPL-Caltech/University of Arizona.



Summary

- MRO was successfully phased to support InSight EDL
  - Final phasing offset was 8.41 seconds late (ERTF-15)
  - Actual phasing offset was 15.68 seconds late (ERTF-20 modeling InSight TCM-6)
  - Well within the ± 30 seconds timing requirement given in ERTF-15 (final target)
  - Accurate phasing led to good EDL relay support by ELECTRA
- Post-landing observations done by CTX and HiRISE cameras
  - InSight lander, parachute, back shell, & heat shield
- MRO back in nominal Primary Science Orbit (PSO)
  - OTM-52 performed on December 12, 2018 to return to PSO and set course for Mars 2020 EDL support in February 2021
  - Resumed MRO science operations and surface operations support to landers

Backup Slides

InSight ERTF-15 and ERTF-20

```
-----------------------------------------------------------------
EDL RELAY TARGETS FILE (ERTF)
-----------------------------------------------------------------
Data generated on Wed Oct 17 10:33:08 2018 PDT by M. Wallace,
NASA Jet Propulsion Laboratory

NSYT SPK File: nsyt_spk_cruise_od089_v1_approach2surface.bsp
MRO SPK File:
spk_psp_20181008-20181213_20181008_ERTF14_forInSight_traj_only.bsp

*************************************************************
*   MRO RELAY TARGETS (2000 IAU Mars Fixed)
*   Epoch               : 26-NOV-2018 19:40:13.4776 ET
*   LMST (Asc.Eq.Cross): 14:50:40
*   Latitude            : -19.5547 deg
*************************************************************

NSYT Data (2000 IAU Mars Fixed)
Entry Epoch                : 26-NOV-2018 19:40:13.4776 ET
     Entry Latitude        : 1.7152 deg
     Entry Longitude       : 124.5611 deg
Landing Epoch              : 26-NOV-2018 19:46:58.9678 ET
     Landing Latitude      : 4.5102 deg
     Landing Longitude     : 135.9910 deg
     Landing Radius        : 3393.0620 km

MRO Data - Keplerian Osculating Elements (2000 IAU Mars Pole)
Entry Epoch                : 26-NOV-2018 19:40:13.4776 ET
     Semimajor Axis        : 3663.6992 km
     Eccentricity          : 0.009595
     Inclination           : 92.5900 deg
     RAAN                  : -165.5901 deg
     Arg. of Periapsis     : 270.3522 deg
     Mean Anomaly          : 69.0412 deg
     True Anomaly          : 70.0723 deg

MRO Data - Spherical Coordinates (2000 IAU Mars Fixed)
Entry Epoch                : 26-NOV-2018 19:40:13.4776 ET
     Target Latitude       : -19.5547 deg
     Target Longitude      : 148.3097 deg
     LMST (Asc.Eq.Cross)   : 14:50:40
     LTST (Asc.Eq.Cross)   : 14:12:52
Landing Epoch              : 26-NOV-2018 19:46:58.9678 ET
     MRO Lat. at Landing   : 2.1775 deg
     MRO Lon. at Landing   : 145.6430 deg
```

(a) InSight ERTF-15 (Used for Final MRO Phasing Maneuver)

```
-----------------------------------------------------------------
EDL RELAY TARGETS FILE (ERTF)
-----------------------------------------------------------------
Data generated on Sun Nov 25 10:31:57 2018 PST by M. Wallace,
NASA Jet Propulsion Laboratory

NSYT SPK File: nsyt_spk_cruise_od115_v1_approach2surface.bsp
MRO SPK File:
spk_psp_20181120-20181213_20181120_forInSight_traj_only.bsp

*************************************************************
*   MRO RELAY TARGETS (2000 IAU Mars Fixed)
*   Epoch               : 26-NOV-2018 19:40:13.3470 ET
*   LMST (Asc.Eq.Cross): 14:50:40
*   Latitude            : -19.1708 deg
*************************************************************

NSYT Data (2000 IAU Mars Fixed)
Entry Epoch                : 26-NOV-2018 19:40:13.3470 ET
     Entry Latitude        : 1.7105 deg
     Entry Longitude       : 124.5549 deg
Landing Epoch              : 26-NOV-2018 19:46:40.5970 ET
     Landing Latitude      : 4.4959 deg
     Landing Longitude     : 135.9386 deg
     Landing Radius        : 3393.0998 km

MRO Data - Keplerian Osculating Elements (2000 IAU Mars Pole)
Entry Epoch                : 26-NOV-2018 19:40:13.3470 ET
     Semimajor Axis        : 3663.8102 km
     Eccentricity          : 0.009603
     Inclination           : 92.5899 deg
     RAAN                  : -165.5911 deg
     Arg. of Periapsis     : 270.4383 deg
     Mean Anomaly          : 69.3366 deg
     True Anomaly          : 70.3706 deg

MRO Data - Spherical Coordinates (2000 IAU Mars Fixed)
Entry Epoch                : 26-NOV-2018 19:40:13.3470 ET
     Target Latitude       : -19.1708 deg
     Target Longitude      : 148.2897 deg
     LMST (Asc.Eq.Cross)   : 14:50:40
     LTST (Asc.Eq.Cross)   : 14:12:52
Landing Epoch              : 26-NOV-2018 19:46:40.5970 ET
     MRO Lat. at Landing   : 1.5840 deg
     MRO Lon. at Landing   : 145.7436 deg
```

(b) InSight ERTF-20 (InSight TCM-6 Design Incorporated)

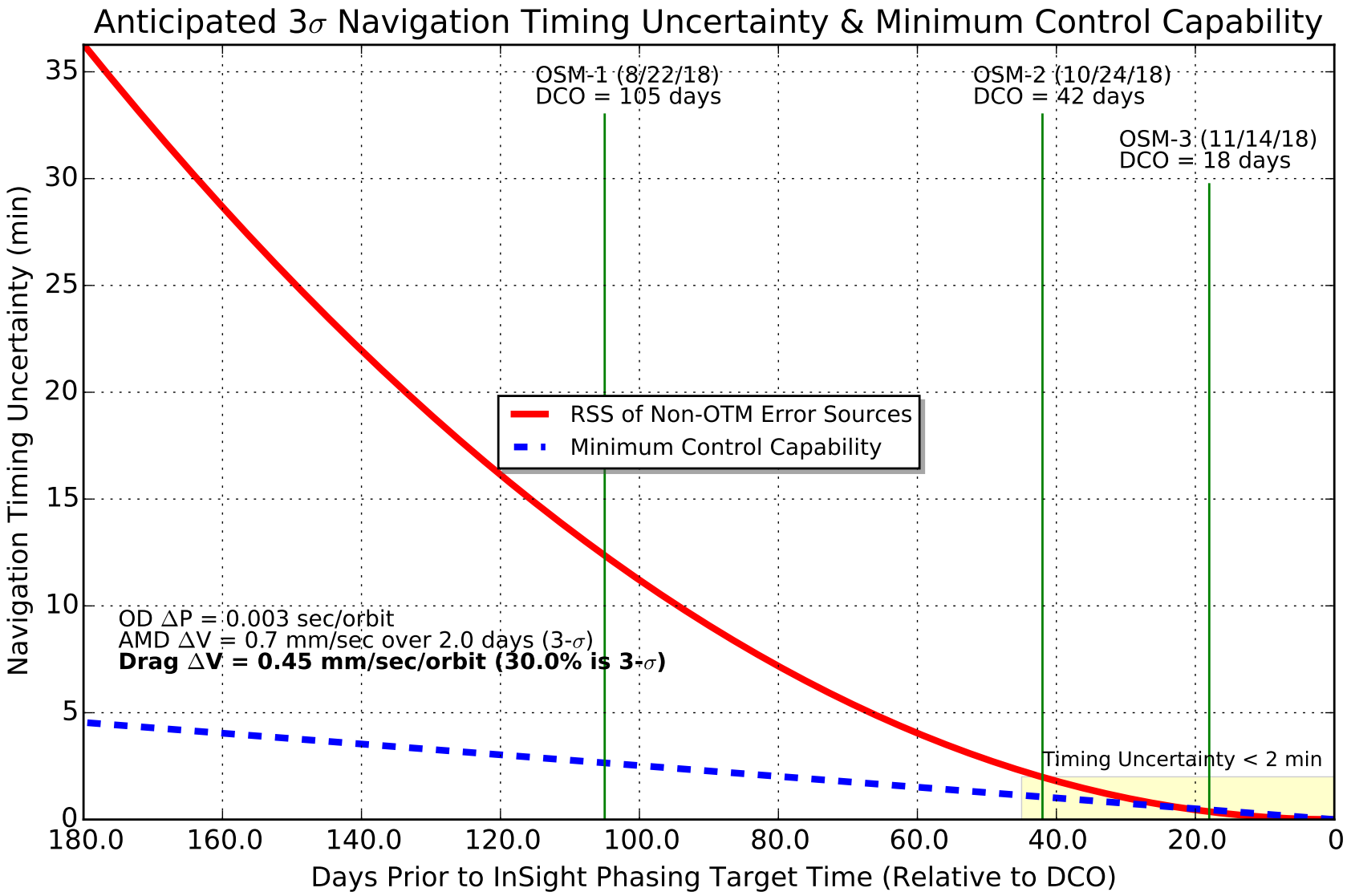
Maneuver ΔV and Direction

Maneuver	Maneuver Epoch (UTC SCET)	Orbital Apsis/ Node	Data Source	ΔV (mm/s)		Right Ascension (deg)		Declination (deg)		Duration (sec)	
				Value	|*err*|	Value	|*err*|	Value	|*err*|	*Dur*	|*err*|
OTM-48 (OCM-3)	22-Mar-2017 13:38:40	DEq	Recon	3203.3	6.6	191.02	0.36	13.11	0.62	45.1	0.7
			Design	3196.7		191.37		12.49		45.8	
OTM-49	13-Sep-2017 13:34:55	Apo	Recon	217.7	1.7	197.52	0.03	19.74	0.04	10.0	0.2
			Design	216.0		197.55		19.78		9.8	
OTM-50 (OSM-1)	22-Aug-2018 12:25:50	Peri	Recon	343.8	5.3	196.27	0.22	19.01	0.08	15.1	0.0
			Design	338.4		196.48		19.09		15.1	
OTM-51 (OSM-2)	24-Oct-2018 13:01:46	Peri	Recon	58.6	1.8	225.65	0.35	3.19	0.22	2.9	0.2
			Design	56.8		226.01		2.96		2.7	
OSM-3	14-Nov-2018	Peri	..... *Contingency maneuver if ±30 sec requirement not met*								
OSM-3C	19-Nov-2018	Peri	..... *Contingency maneuver if ±30 sec requirement not met*								
InSight EDL Target Time: 26-Nov-2018 19:40:13.4776 ET SCET											
OTM-52 (OCM-4)	12-Dec-2018 14:18:23	DEq	Recon	-	-	-	-	-	-	-	-
			Design	1403.0		1.23		−60.50		20.3	

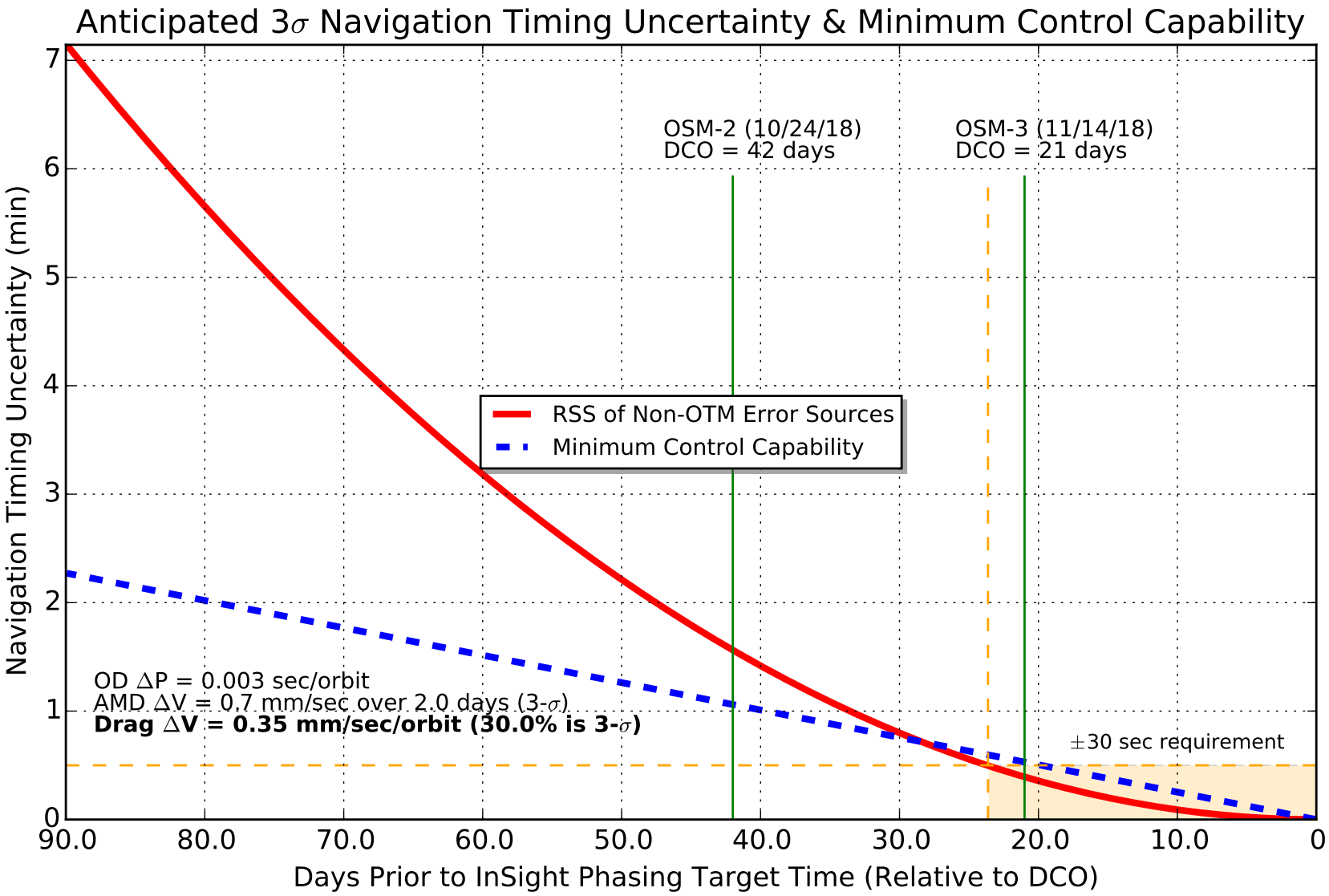
Evolution of Phasing Offset

ERTF for Phasing / Post-OSM Status *Post-ERTF-15 Tracking*	OD Data Cut-off (ET)	Days to EDL from DCO	Avg. DSF	3σ Nav. Timing Unc.	Phasing Offset from EDL Target + (early) − (late)	Post-ERTF-15 Phasing Offset Tracking + (early) − (late)
ERTF-01a	09-APR-2018 14:54:00	231.2	1.00	59.8 min	+47.12 min	
ERTF-02	14-MAY-2018 14:40:00	196.2	1.00	43.1 min	+46.66 min	
ERTF-03	29-MAY-2018 12:42:00	181.3	1.00	36.8 min	+46.07 min	
ERTF-04	04-JUN-2018 13:40:00	175.2	1.00	34.4 min	+46.51 min	
ERTF-05	18-JUN-2018 14:15:00	161.2	1.00	29.1 min	+47.12 min	
ERTF-06	28-JUN-2018 11:40:00	151.3	1.00	25.7 min	+48.32 min	
ERTF-07	12-JUL-2018 12:10:00	137.3	1.00	21.1 min	+51.42 min	
ERTF-08	26-JUL-2018 10:55:00	123.4	1.00	17.1 min	+53.59 min	
ERTF-09	06-AUG-2018 14:20:00	112.2	1.00	14.1 min	+55.62 min	
ERTF-10	13-AUG-2018 10:00:00	105.4	1.00	12.5 min	+55.23 min	
OSM-1/OTM-50 (22-AUG-2018 12:26:59 ET): designed to remove 42.73 min of offset (12.5 min remaining)						
Post-OSM-1 Status	22-AUG-2018 18:45:00	96.0	1.00	10.3 min	+10.74 min	
ERTF-11	30-AUG-2018 15:53:30	88.2	1.00	6.9 min	+10.78 min	
ERTF-12	10-SEP-2018 13:46:00	77.2	0.90	5.3 min	+7.07 min	
ERTF-13	27-SEP-2018 15:10:00	60.2	0.75	3.2 min	+3.51 min	
ERTF-14	08-OCT-2018 15:29:00	49.2	0.75	2.1 min	+3.37 min	
ERTF-15	15-OCT-2018 14:53:00	42.2	0.62	1.6 min	+2.41 min	
OSM-2/OTM-51 (24-OCT-2018 13:02:55 ET): designed to remove remaining offset						
Post-OSM-2 Status	24-OCT-2018 19:29:00	33.0	0.62	58.1 sec	+0.03 sec	
ERTF-15, *ERTF-16*	05-NOV-2018 14:23:00	21.2	0.62	24.1 sec	−4.05 sec	*−4.15 sec*
ERTF-15, *ERTF-17*	08-NOV-2018 10:42:00	18.4	0.58	18.0 sec	−7.65 sec	*−7.62 sec*
ERTF-15, *ERTF-17*	12-NOV-2018 14:05:00	14.2	0.56	10.9 sec	−8.72 sec	*−8.69 sec*
ERTF-15, *ERTF-18*	15-NOV-2018 14:15:00	11.2	0.56	6.8 sec	−8.71 sec	*−8.71 sec*
ERTF-15, *ERTF-19*	20-NOV-2018 11:45:00	6.3	0.56	2.2 sec	−8.28 sec	*−8.24 sec*
ERTF-15, *ERTF-19*	23-NOV-2018 21:15:00	2.9	0.56	0.51 sec	−8.40 sec	*−8.37 sec*
ERTF-15, *ERTF-20*	26-NOV-2018 06:30:00	0.5	0.56	0.03 sec	−8.41 sec	*−15.69 sec*
MRO Reconstruction at InSight EDL Target		0.0	0.56	0.0 sec	**−8.41 sec**	*−15.68 sec*

Nav. Timing Unc. (3-σ) for OSM-1 (Drag ΔV = 0.45 mm/s/orbit)



Nav. Timing Unc. (3-σ) for OSMs 2 & 3 (Drag ΔV = 0.35 mm/s/orbit)



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