Mars Reconnaissance Orbiter Navigation Strategy for Mars Science Laboratory Entry, Descent and Landing Telecommunication Relay Support

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Mars Reconnaissance Orbiter

Mission, Spacecraft and PSO

The Mars Reconnaissance Orbiter spacecraft launched in August 2005 from the Space Launch Complex 41 at Cape Canaveral Air Force Station and arrived at Mars in March 2006. MRO began science observations in November 2006.

MRO Spacecraft:

- **Spacecraft Bus:** 3-axis stabilized ACS system; 3-meter diameter High Gain Antenna; hydrazine propulsion system
- **Instrument Suite**: HiRise Camera, Electra engineering payload (among other instrument payloads)

MRO Primary Science Orbit (PSO):

- **Sun-synchronous** orbit ascending node at 3:00 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 ± 40 km)


MRO Launch. Image via NASA.

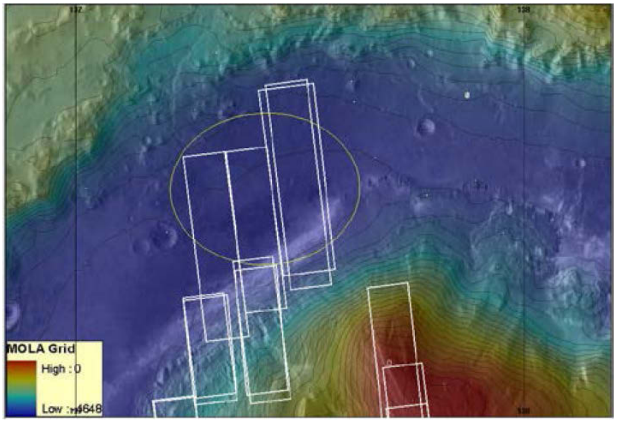

MRO at Mars. Image via NASA/JPL.

Support of Mars Program Office Assets

Past, Present and Future Support for MER, Phoenix and MSL

Mission and Navigation Design — *Mars Reconnaissance Orbiter*

Landing Site Characterization Observations (via MRO Instrument Suite)



(Gale Crater Imaging, via HiRise)

Relay Communication (via Electra Transceiver)

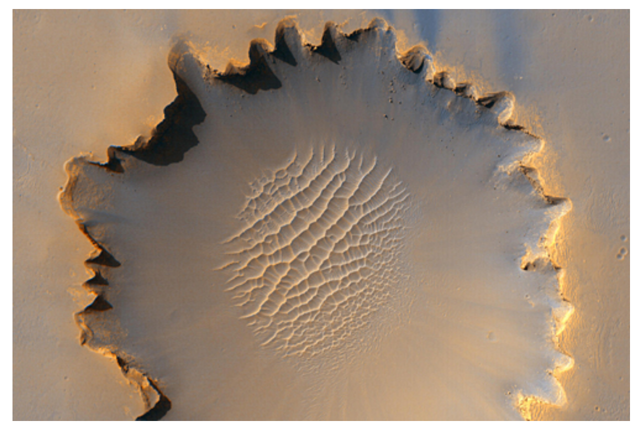
Mars Exploration Rover Relay Passes

MSL Relay Passes

Critical Event Support (Telecommunication and Imaging)

Entry, Descent and Landing (EDL) Imaging
(Mars Phoenix Lander at EDL, via HiRise)

Overflight Imaging (High-Resolution Imaging via HiRise Camera)



Mars Exploration Rover Imaging
(Opportunity at Victoria Crater, via HiRise)

MSL EDL Support Requirements

MRO will provide telecommunication (primary) and imaging (secondary) support to MSL during the MSL Entry, Descent and Landing sequence. The orbit requirements requested of MRO by MSL at the time of MSL EDL are:

- ***Local Mean Solar Time (LMST)*** at the orbit Ascending Node is to be no earlier than the specified target minus 10 minutes and no later than the specified target plus 30 seconds.
- ***Phasing control*** capability is to be within ± 30 seconds of the specified MSL Entry epoch. This may also be expressed as within ± 1.6 degrees of a requested latitude target specified at MSL Entry.

The MRO target conditions are specified to MRO Navigation by MSL Navigation in an ***EDL Relay Targets File (ERTF)***. Information about the ERTF is documented in an Operational Interface Agreement (OIA) between the two teams.

MRO Propulsive Maneuvers

If the requested target conditions cannot be naturally met by the PSO configuration within the required tolerances, MRO Navigation will perform propulsive maneuvers to achieve them.

MRO nominally implements a propulsive maneuver in one of two standard maneuver attitudes: **in-plane** (~ ± spacecraft velocity vector) or **out-of-plane** (~ ± spacecraft angular momentum vector). A “combination” maneuver, with maneuver components in both orientations, may also be used.

- Typical PSO maintenance maneuvers (Orbit Trim Maneuvers, or OTMs) are for apses height control; most have been performed at orbit periapsis to raise orbit apoapsis. These maneuvers are used to maintain the PSO GTW
- Only one combination maneuver has been performed for PSO LMST + GTW maintenance

The standard MRO maneuver attitudes are used to meet MSL requirements:

- Orbit phasing is achieved via an in-plane maneuver
  - Phasing control maneuvers are referred to as **Orbit Synchronization Maneuvers** (OSMs)
- Orbit LMST control is achieved via out-of-plane maneuver
  - LMST control maneuvers are referred to as **Orbit Change Maneuvers** (OCMs)
- A combination maneuver may be used to control both orbit phasing and orbit LMST

Propulsive Maneuver Strategy

LMST Control Maneuvers

Strategy: *Longer drift times between maneuvers decreases ΔV (propellant) consumption. Maneuvers should not be performed prior to MSL launch.*

Maneuver	Purpose	Relative Placement
OCM1	Trend LMST to MSL-requested condition	Post-MSL Launch
OCM2	*Trend LMST to PSO configuration*	*Post-MSL EDL*
OCM3	*Re-establish sun-synchronous condition*	*Post-OCM2*

Phasing Control Maneuvers

Strategy: *Orbit phasing performed well prior to EDL decreases ΔV (propellant) consumption; however, down-track timing uncertainty errors decrease over time. Maneuvers should not be performed prior to MSL launch.*

Maneuver	Purpose	Relative Placement
OSM1	Remove a large initial phasing bias	Post-MSL Launch
OSM2	Remove most of the remaining phasing bias	As needed
OSM3	Target to the requested phasing conditions	Prior to MSL EDL
OSMC	Contingency phasing maneuver	Post-OSM3

** Not discussed*

Propulsive Maneuver Strategy

LMST Control Maneuvers

***Strategy**: Longer drift times between maneuvers decreases ΔV (propellant) consumption. Maneuvers should not be performed prior to MSL launch.*

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OCM2	*Trend LMST to PSO configuration*	*Post-MSL EDL*
OCM3	*Re-establish sun-synchronous condition*	*Post-OCM2*

Phasing Control Maneuvers

***Strategy**: Orbit phasing performed well prior to EDL decreases ΔV (propellant) consumption; however, down-track timing uncertainty errors decrease over time. Maneuvers should not be performed prior to MSL launch.*

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OSM1	Remove a large initial phasing bias	Post-MSL Launch
OSM2	Remove most of the remaining phasing bias	As needed
OSM3	Target to the requested phasing conditions	Prior to MSL EDL
OSMC	Contingency phasing maneuver	Post-OSM3

Integrated Strategy

Maneuver	Purpose	Relative Placement
OCM1 / OSM1	Remove a large initial phasing bias and trend LMST to MSL-requested condition	Post-MSL Launch
OSM2	Remove most of the remaining phasing bias	As needed
OSM3	Target to the requested phasing conditions	Prior to MSL EDL
OSMC	Contingency phasing maneuver	Post-OSM3
OCM2 / OTM	*Trend LMST to PSO configuration and maintain orbit GTW*	*Post-MSL EDL*
OCM3 / OTM	*Re-establish sun-synchronous condition and maintain orbit GTW*	*Post-OCM2*

** Not discussed*

Maneuver Dates

MRO Navigation has negotiated a series of nominal maneuver dates for MSL EDL support OCM/OSM placement.

Days Prior to MSL Entry	Date
201 days	01/18/2012
187 days	02/01/2012
173 days	02/15/2012
159 days	02/29/2012
145 days	03/14/2012
131 days	03/28/2012

Days Prior to MSL Entry	Date
117 days	04/11/2012
103 days	04/25/2012
89 days	05/09/2012
75 days	05/23/2012
61 days	06/06/2012
54 days	06/13/2012

2x monthly opportunities up to EDL – 60 days

Days Prior to MSL Entry	Date
47 days	06/20/2012
40 days	06/27/2012
33 days	07/04/2012
26 days	07/11/2012
19 days	07/18/2012
12 days	07/25/2012
MSL EDL	*08/05/2012**

1x weekly opportunities up to EDL

** MSL EDL occurs on August 5, 2012 at ~ 10:12 PM PDT.*

Maneuver Dates

MRO Navigation has negotiated a series of nominal maneuver dates for MSL EDL support OCM/OSM placement. These maneuver opportunities are arranged for operational convenience (coincide with nominal OTM opportunities) and are de-conflicted with CRISM observation dates.

Days Prior to MSL Entry	Date
201 days	01/18/2012
187 days	02/01/2012
173 days	02/15/2012
159 days	02/29/2012
145 days	03/14/2012
131 days	03/28/2012

Days Prior to MSL Entry	Date
117 days	04/11/2012
103 days	04/25/2012
89 days	05/09/2012
75 days	05/23/2012
61 days	06/06/2012
54 days	06/13/2012

Days Prior to MSL Entry	Date
47 days	06/20/2012
40 days	06/27/2012
33 days	07/04/2012
26 days	07/11/2012
19 days	07/18/2012
12 days	07/25/2012
MSL EDL	*08/05/2012**

2x monthly opportunities up to EDL – 60 days

1x weekly opportunities up to EDL

Legend	
Yellow	Nominal OCM/OSM Date (as scheduled pre-MSL launch)
Aquamarine	Avoided to de-conflict CRISM observations
Cyan	Avoided due to holiday conflict

Highlighted rows: 187 days (02/01/2012), 47 days (06/20/2012), 19 days (07/18/2012) — yellow; 145 days (03/14/2012), 131 days (03/28/2012), 75 days (05/23/2012) — aquamarine; 33 days (07/04/2012) — cyan.

** MSL EDL occurs on August 5, 2012 at ~ 10:12 PM PDT.*

Timing Error Model

Model Values, Evaluation Method, and Parameter Updates

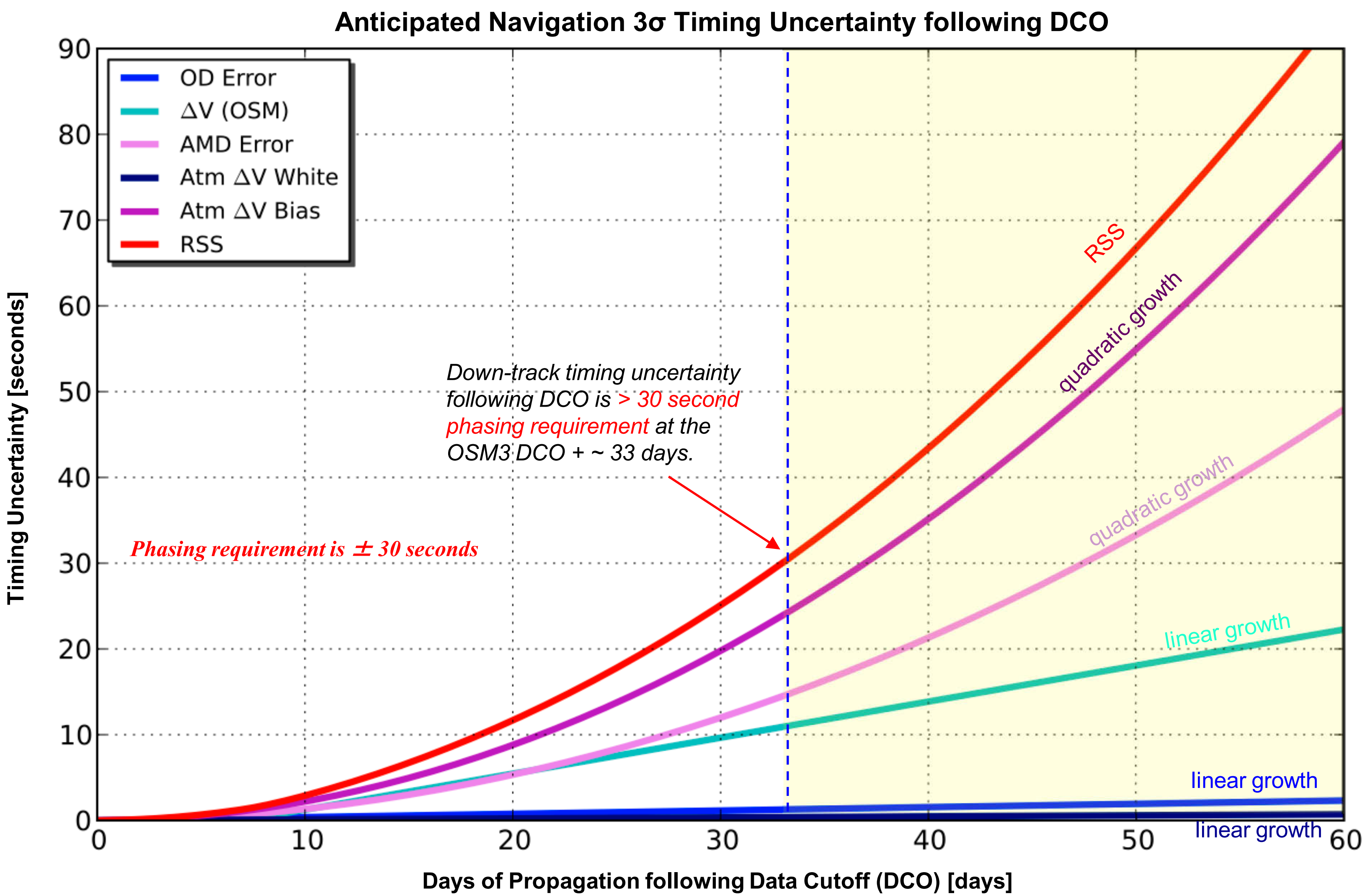
MRO models the trajectory down-track timing uncertainty via individual model components that are combined via root-sum-square. MRO flight data was used to validate/modify the model parameters chosen.

	Contribution / Frequency	Model Value	Re-Evaluation Method	Parameter Updates?
Atmospheric Drag Error: Bias	Quadratic contribution Events 1x/orbit	30%, 3σ	Evaluation of low-density season reconstructed atmospheric drag ΔV per orbit	Flight data, 3σ = 25% (10% 1σ uncertainty) The modeled value is appropriate
Angular Momentum Desaturation (AMD) Events	Quadratic contribution Events 1x / 2 days	0.7 mm/sec/event, 3σ	Evaluation of periapsis AMD events from March 2011 to May 2012	Flight data, 3σ = 0.6 mm/sec/event (30% 1σ uncertainty) The modeled value is appropriate
Maneuver Execution Error	Linear Contribution Singular event	2% Proportional, 5 mm/sec Fixed magnitude error, 3σ	Evaluation of maneuvers since OTM12 (start of ESP) and small maneuvers	The less conservative model is kept: 2% proportional and 5 mm/sec fixed magnitude error
Atmospheric Drag Error: White Noise	Linear Contribution Events 1x/orbit	105%, 3σ	Evaluation of low-density season reconstructed atmospheric drag ΔV per orbit	Flight data, 3σ = 25% (10% 1σ uncertainty) The modeled value is appropriate
Orbit Determination Error	Linear Contribution Singular event	3.00E-3 sec/orbit, 3σ	No re-evaluation	No re-evaluation

$$\Delta t = \sqrt{\Delta t^2_{atm,bias} + \Delta t^2_{atm,white} + \Delta t^2_{AMD} + \Delta t^2_{OSM} + \Delta t^2_{OD}}$$

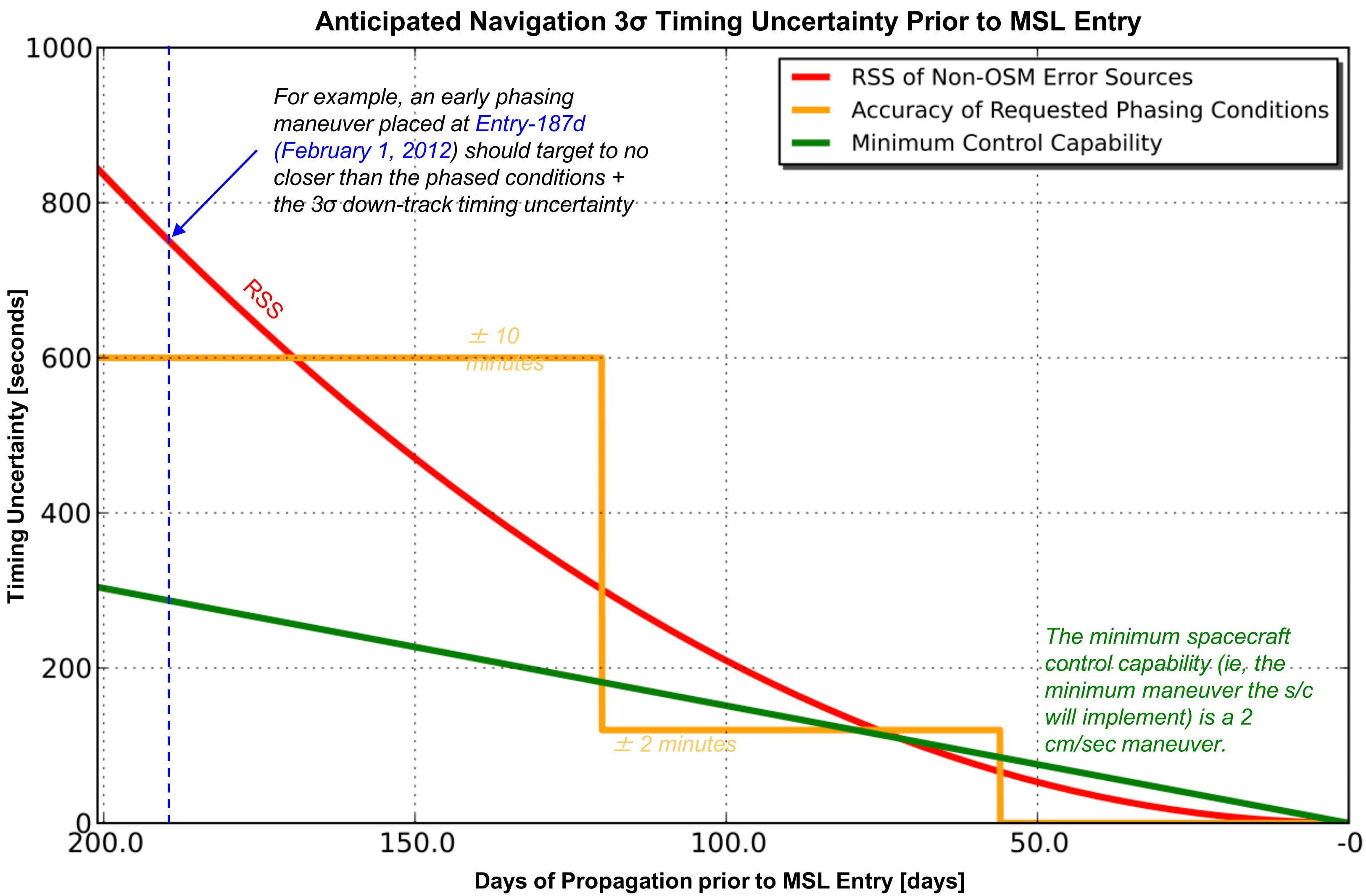
Timing Error Model

Short Term Error Growth following Data Cut-Off (DCO)



Timing Error Model

Long Term Error Convergence Approaching MSL Entry



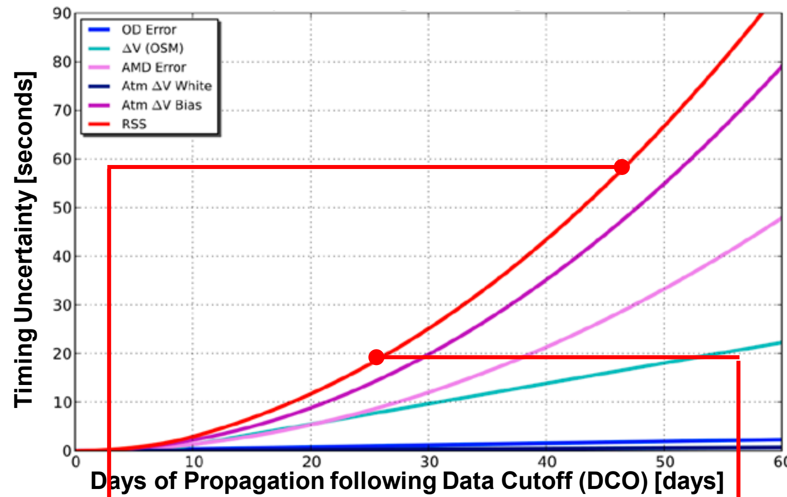
Satisfying the Phasing Requirement

"Odds of Success" Computed using Percentile Z-Score

Implementing the final OSM no earlier than 07/11/2012 will satisfy the ± 30 second timing requirement to greater than 3σ Navigation down-track timing uncertainty.

Navigation Timing Uncertainty Model Parameters	
Atmospheric Drag: White Noise	105% (3σ)
Atmospheric Drag: Bias	30% (3σ)
Atmospheric Drag ΔV per Orbit	0.15 mm/sec
AMD x-wheel ΔV (per event)	0.7 mm/sec
Maneuver Execution: Fixed Magnitude Error	2%
Maneuver Execution: Fixed Pointing Error	5 mm/sec

Anticipated Navigation 3σ Timing Uncertainty following DCO



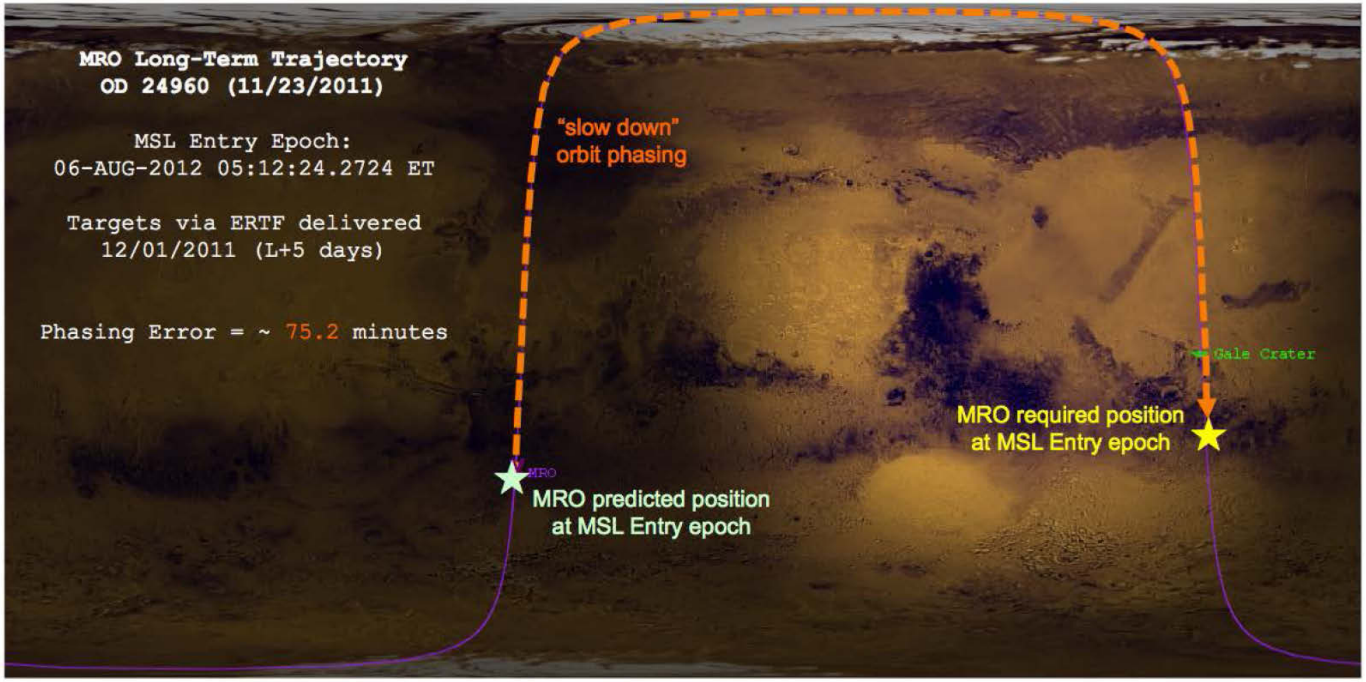
OSM3 Date :	6/20/2012	6/27/2012	7/4/2012	7/11/2012	7/18/2012
OSM Timing (prior to EDL)	46.6 days	39.6 days	32.6 days	25.6 days	18.6 days
DCO Timing (prior to EDL)	53.6 days	46.6 days	39.6 days	32.6 days	25.6 days
3σ Timing Errors mapped to EDL event	76.2 sec	58.1 sec	42.2 sec	29.2 sec	18.1 sec
What n*sigma is the 30s timing requirement?	1.18σ	1.55σ	2.13σ	3.08σ	4.97σ
% of cases that will be "in the box"?	76.2%	87.9%	96.7%	99.8%	100.0%

MSL Launch

MSL launched from the Space Launch Complex 41 at Cape Canaveral Air Force Station on November 26, 2011.

MRO Orbit at MSL Launch (ERTF #1)

Per ERTF #1, the MRO trajectory would arrive at the requested target conditions ~ 75.2 minutes “early” or 37.0 minutes “late”.



MRO Navigation elected to achieve the target conditions via orbit raise maneuvers, increasing the PSO orbit period and causing MRO to arrive at the target conditions “later” than originally predicted (“slow down” orbit phasing).

Maneuver Implementation

Phasing Control Maneuvers

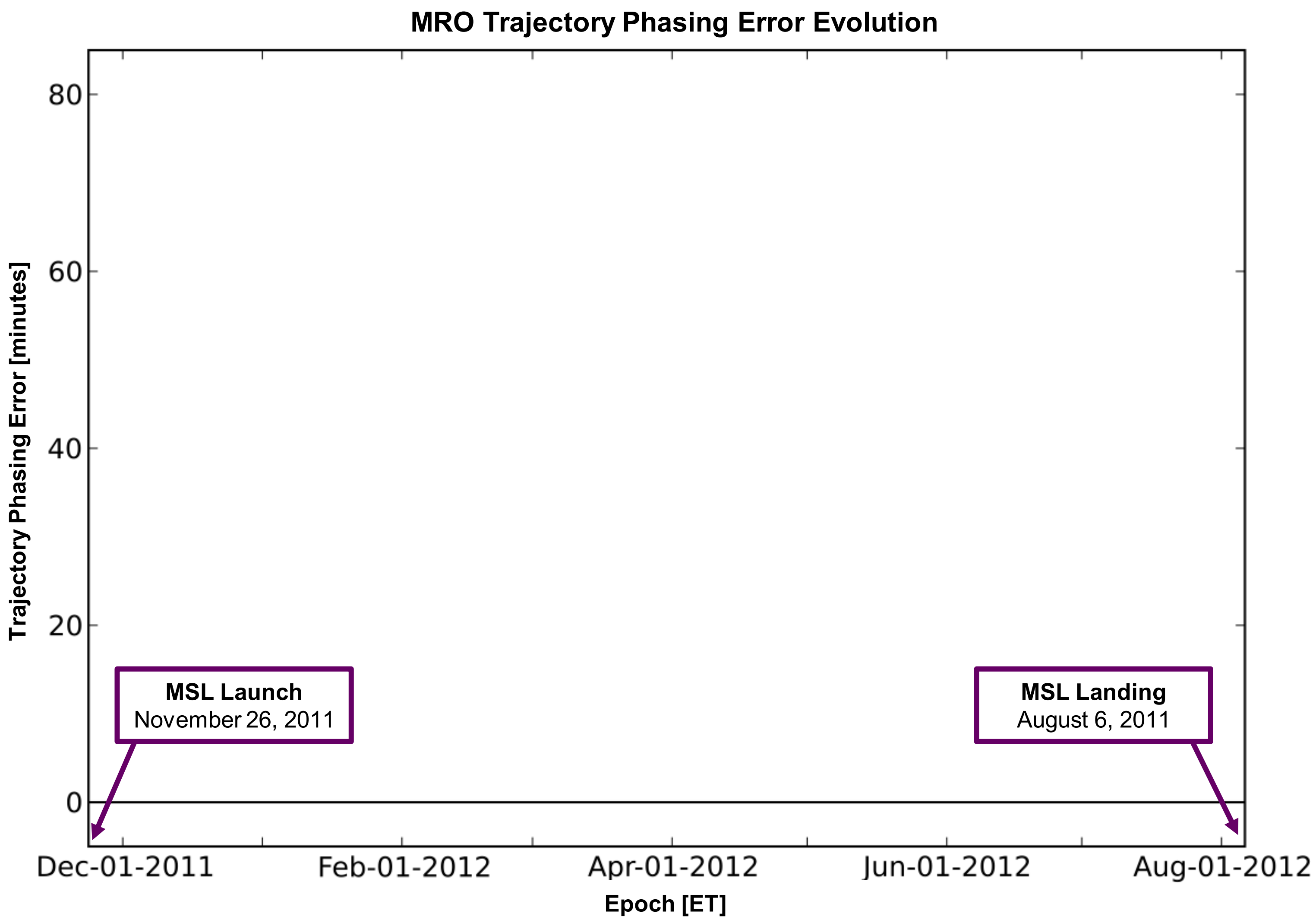
Maneuver	OSM1 (OTM-26)	OSM2	OSM3 (OTM-27)
Planned Epoch	**February 1, 2012** (MSL EDL-187 days)	**June 20, 2012** (MSL EDL-47 days)	**July 18, 2012** (MSL EDL-24 days)
Updated Epoch?	February 1, 2012 (no change)	June 20, 2012 (no change)	July 13, 2012 (to accommodate Mars Odyssey Maneuver and to "get in the box" slightly earlier)
Phasing Error Pre-Maneuver	48.9 minutes	251.9 seconds	225.0 seconds
Down-Track Timing Uncertainty	13.5 minutes	56.8 seconds	22.2 seconds
Maneuver Magnitude	0.1500 m/s	*OSM2 Cancelled (following May 2012 Navigation Advisory Group Review)*	0.1265 m/s
Maneuver Magnitude (Reconstructed)	0.1521 m/s (2.1 mm/sec error, 1.4%)		0.1305 m/s (4.0 mm/sec error, 3.1%, ≈ 7.8 seconds phasing error contribution)
Phasing Error Post-Maneuver	12.4 minutes		-11.3 seconds
MRO LMST at MSL Entry 1	02:57:50 PM	02:57:55 PM	02:57:55 PM

LMST Control Maneuvers

At MSL launch, the predicted MRO orbit LMST was within the tolerances specified in the OIA. No OCMs were needed for MSL EDL support.

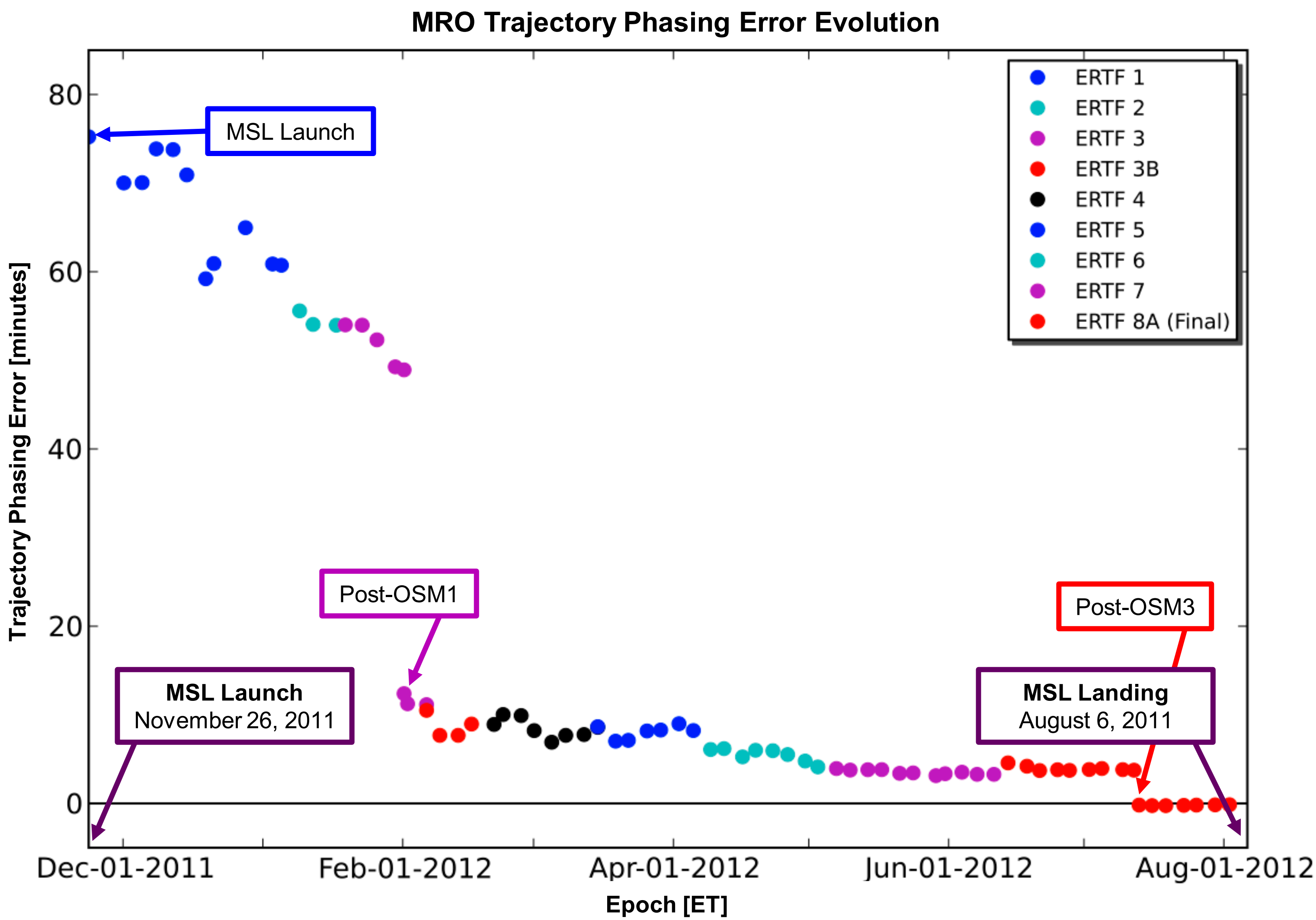
MRO Orbit Phasing

MSL Events



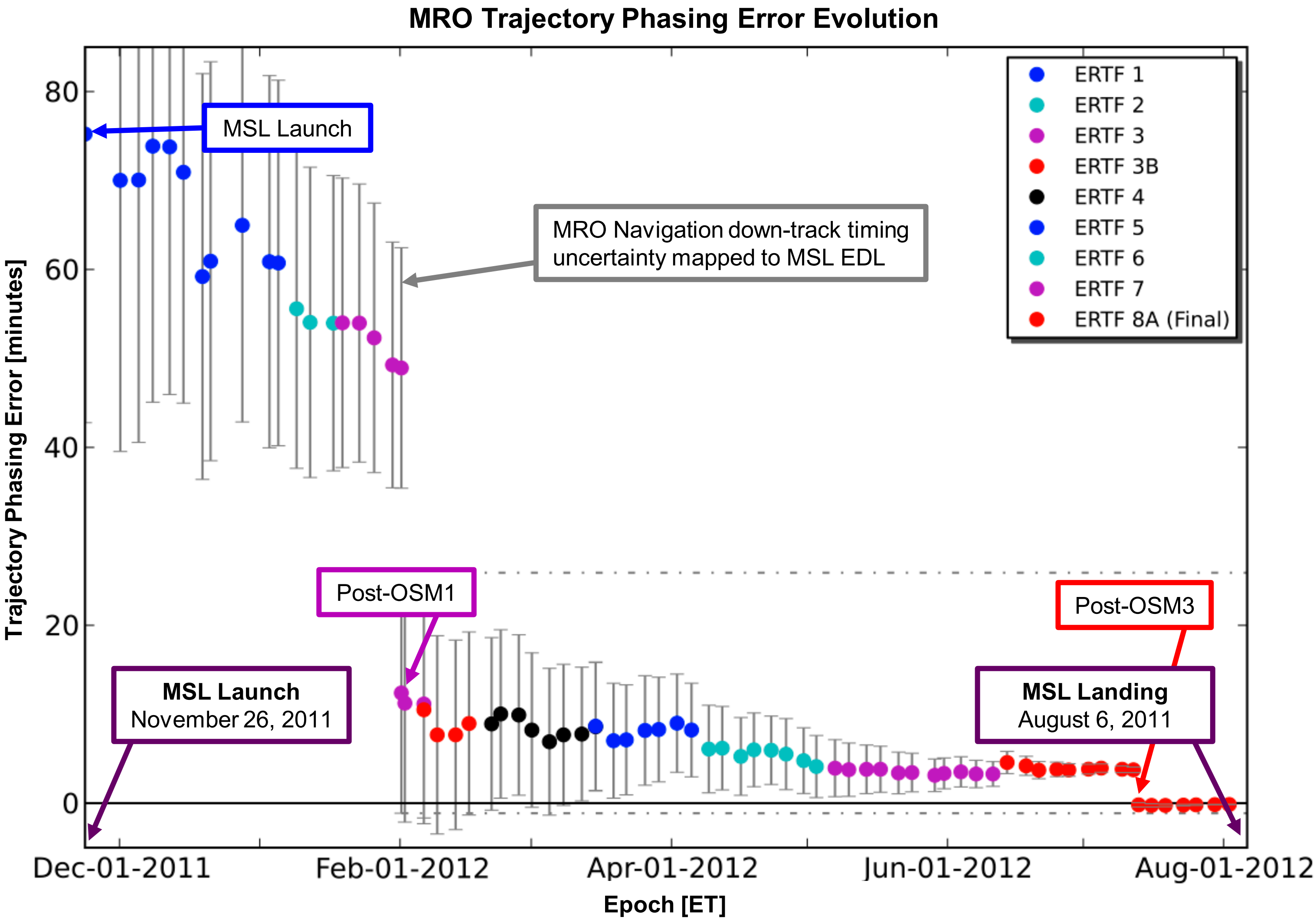
MRO Orbit Phasing

Phasing Error of Every MRO OD Solution Following MSL Launch



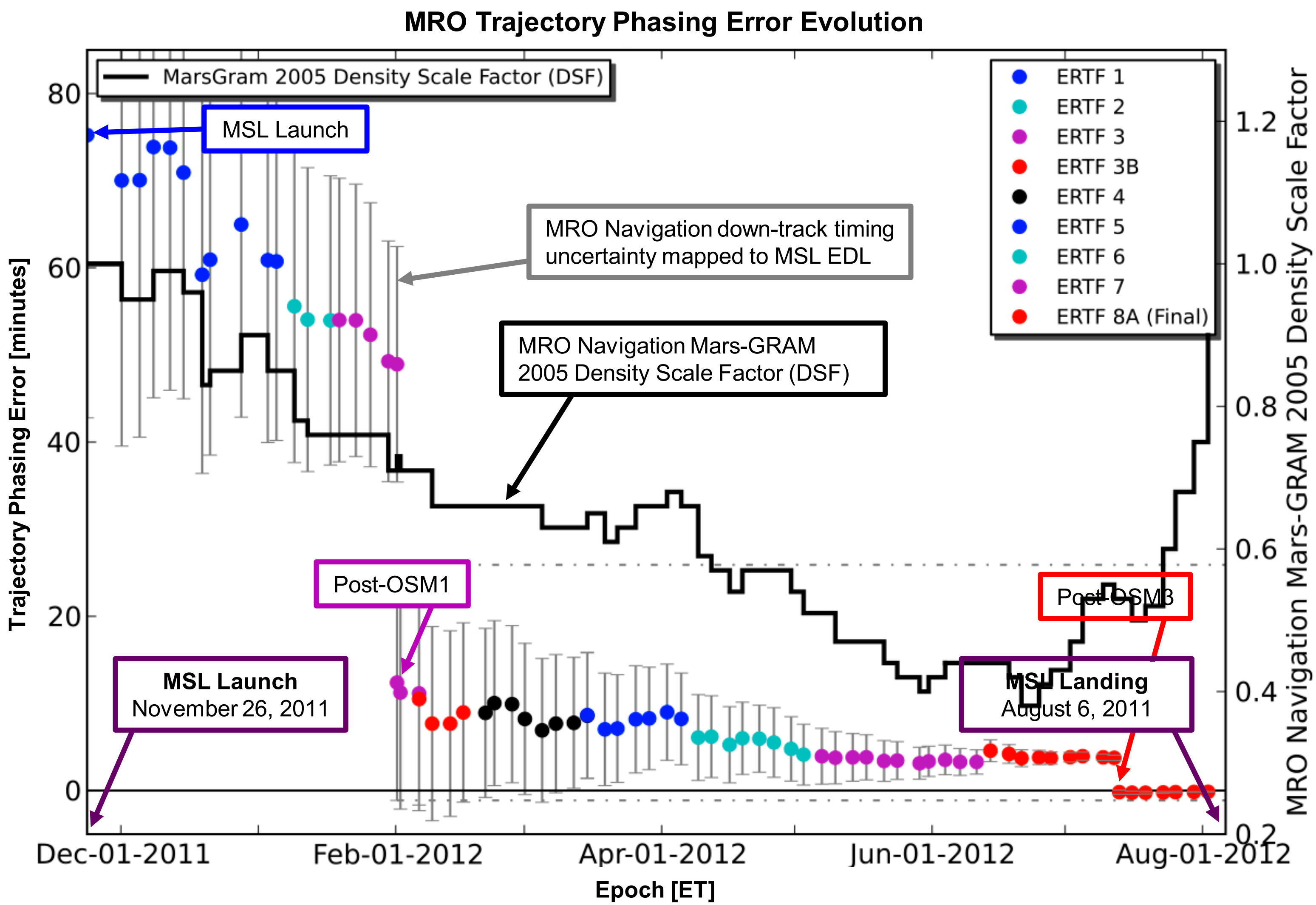
MRO Orbit Phasing

Down-Track Timing Uncertainty for Each OD Solution



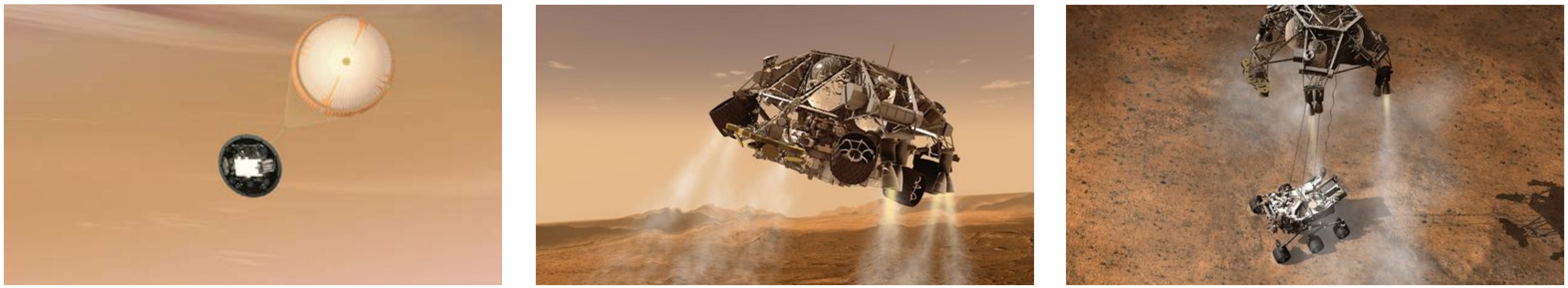
MRO Orbit Phasing

Mars-GRAM 2005 Density Scale Factor



MSL Entry, Descent and Landing Event

MSL EDL was successfully performed on August 6, 2012.



Artist's Concept Images, via Mars Science Laboratory

MRO Navigation achieved the requested target conditions to within the specified tolerances.

Phasing Requirement: Post MSL EDL, per the reconstructed trajectory, MRO Navigation satisfied orbit phasing to 9.0 seconds (late relative to targets) (ERTF #8A, final phasing target requirements). Phasing targets for the final ERTF delivery (#13) were satisfied to 18.9 seconds (late relative to targets).

– Allowable tolerance is ± 30 seconds orbit phasing

LMST Requirement: *Post MSL EDL, per the reconstructed trajectory, MRO Navigation achieved the requested LMST target to xx seconds (the target was 14:57:55 PM and the MRO trajectory was at 14:57:55 PM at the nearest ascending node crossing to the MSL Entry Epoch).*

– *Allowable tolerance is -10 minutes to + 30 seconds LMST*

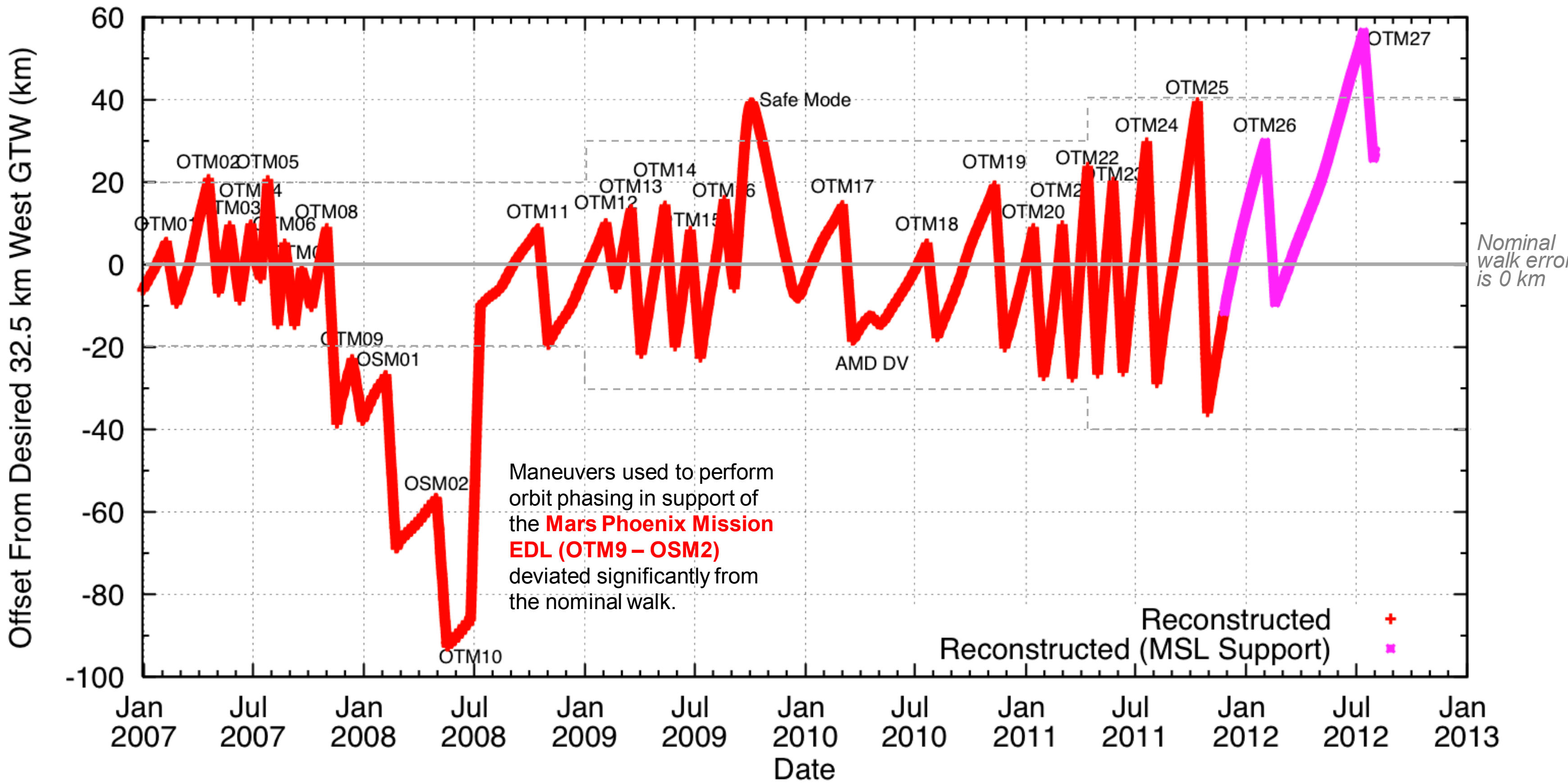
MRO PSO Assessment

Mission Ground Track Walk (Repeat Track)

Mission and Navigation Design — *Mars Reconnaissance Orbiter*

The mission GTW requirement has increased from ± 20 km (PSP) to ± 30 km (ESP) to ± 40 km (EM). During the period of MSL EDL support, the GTW briefly exceeded + 40 km near the time of MSL EDL and shortly afterwards.

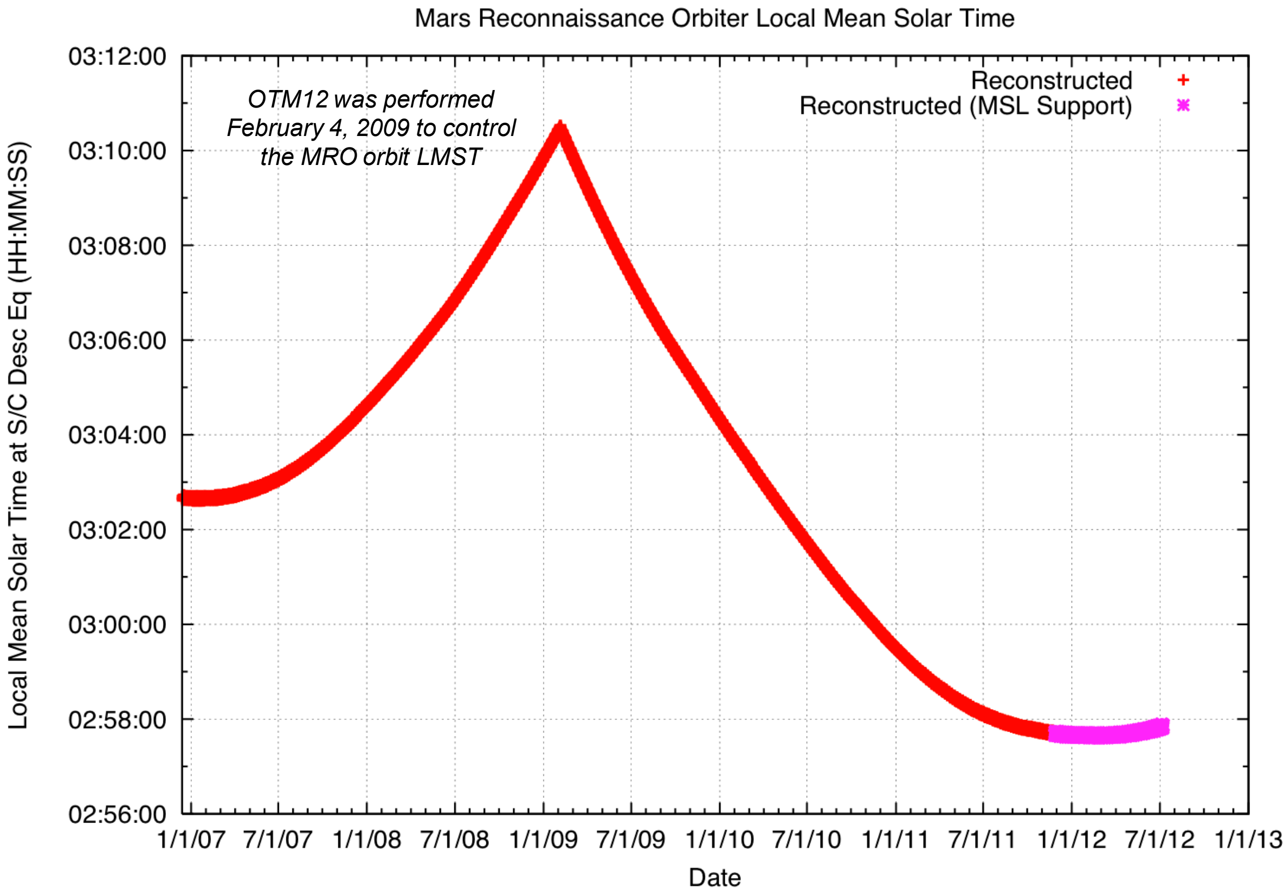
MRO 211-Orbit Ground Track Walk Repeat Error



MRO PSO Assessment

Mission LMST (Sun-Synchronous Orbit)

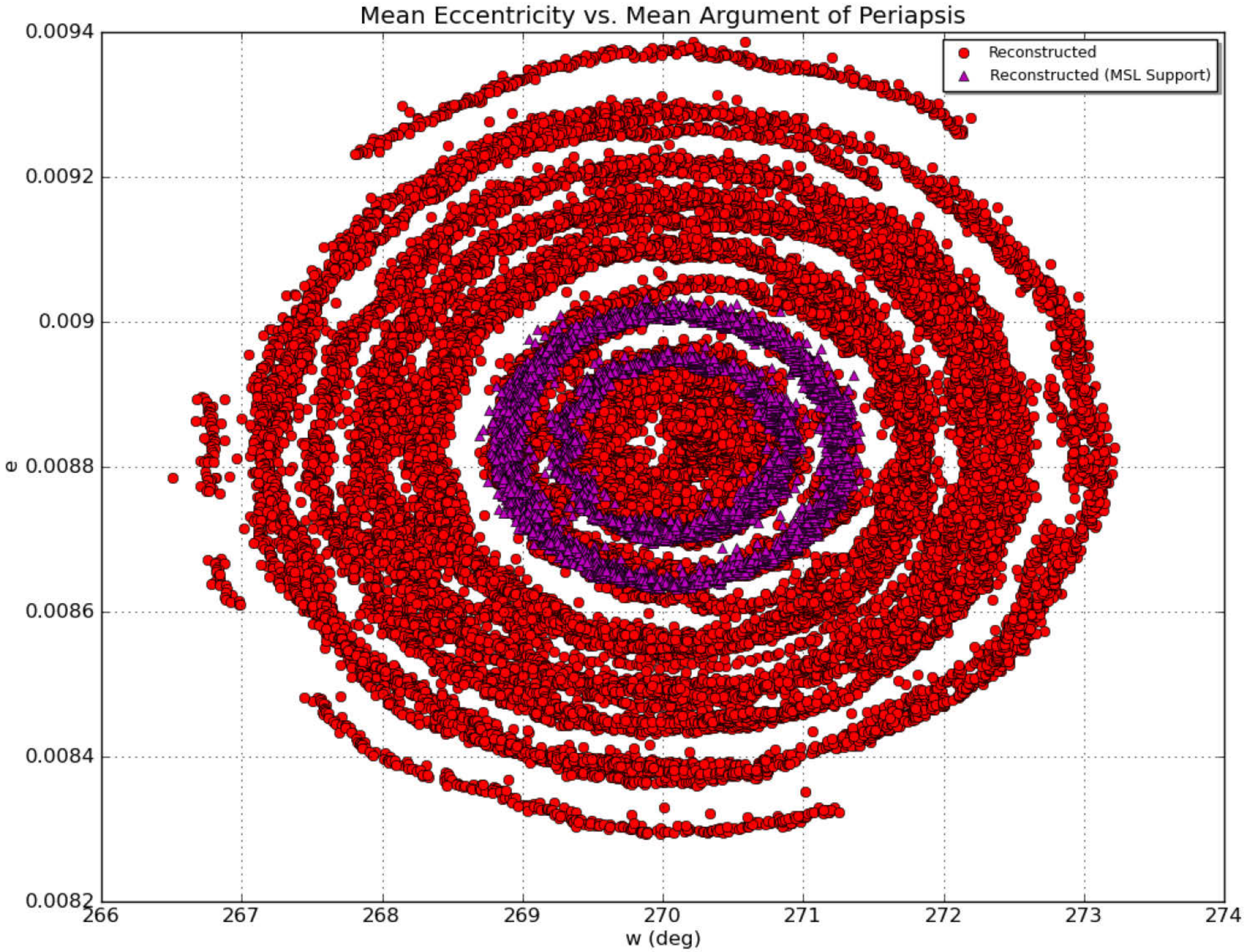
The orbit LMST was unchanged from the nominal PSO configuration for support of MSL EDL. The two phasing maneuvers (OTM26 and OTM27) slightly impacted the orbit Sun-Synchronous condition.



MRO PSO Assessment

Mission e-ω (Frozen Orbit)

The orbit frozen condition was mostly unaffected by the maneuvers used to support MSL EDL orbit phasing.



Conclusions

MRO Navigation developed a ***flexible maneuver strategy*** in order to satisfy MSL EDL telecommunication and imaging support requirements.

The MRO Navigation phasing maneuvers balanced a desire to "***get in the box***" as soon as possible (i.e., satisfy the ± 30 second phasing requirement) with management of ***large down-track trajectory timing uncertainties***. The maneuvers implemented were ***operationally feasible***.

MRO ***satisfied both the LMST requirement and the phasing requirement*** at the time of MSL Entry. The propulsive maneuvers performed to phase the MRO trajectory to the requested conditions at the time of MSL Entry had **minimal impact on the PSO**.

MRO will provide MSL with Relay Communication during the MSL Surface Mission. In the future, nominal orbit maintenance maneuvers (OTMs) will be performed to maintain the MRO PSO.

Questions

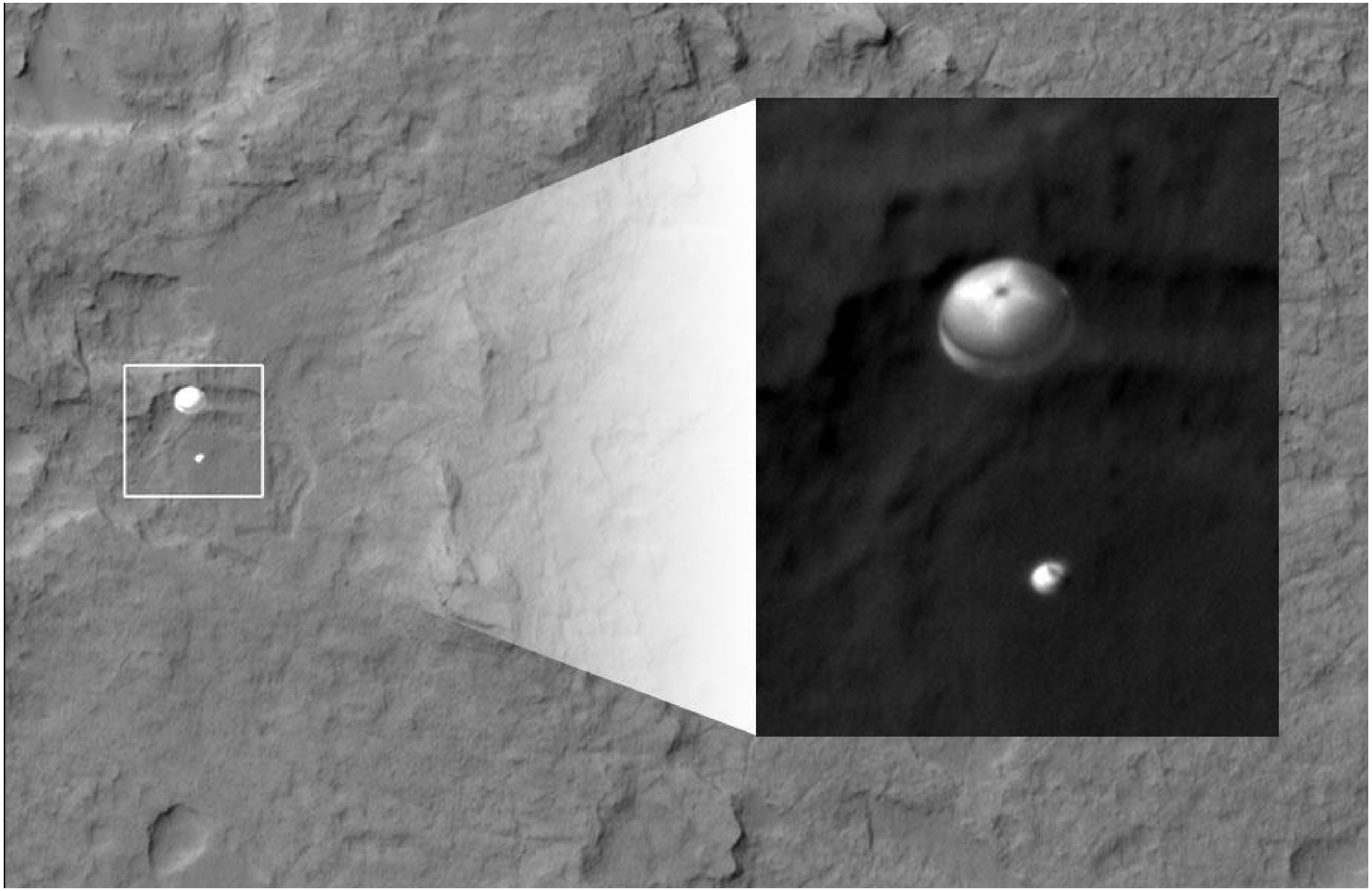


Image of MSL on parachute during descent via the MRO HiRise camera

Acknowledgements

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Roby Wilson (343)
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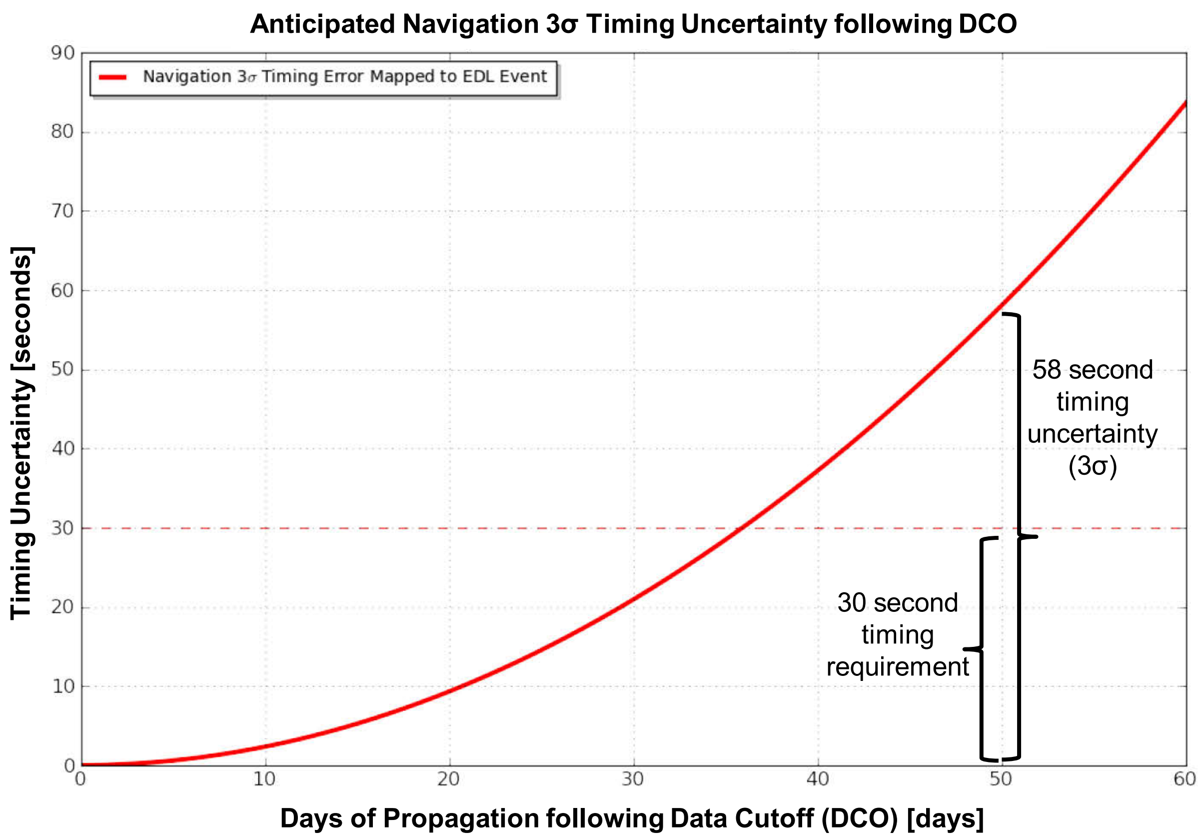
Backup

Orbit Phasing (± 30 Second) Requirement

“Odds of Success” via the Z-Score Computation

In order to compute the “odds” of “getting in the box” (i.e., satisfying the ± 30 second phasing requirement) via a final OSM performed a given number of day prior to the EDL event, the predicted Navigation 3σ timing uncertainty, mapped to the EDL event, is compared to the ± 30 second requirement (Z-score = 3) and converted to a percentile.



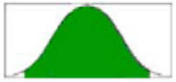
For an example OSM performed 43 days prior to EDL (DCO is at 50 days, shown):

$$\frac{58\,\text{sec}}{3\sigma} = \frac{30\,\text{sec}}{n\sigma}$$

n = 1.5517

Z-score to Percentile (2-sided distribution):

87.9 % of Normal Distribution is ≤ ± 30 seconds



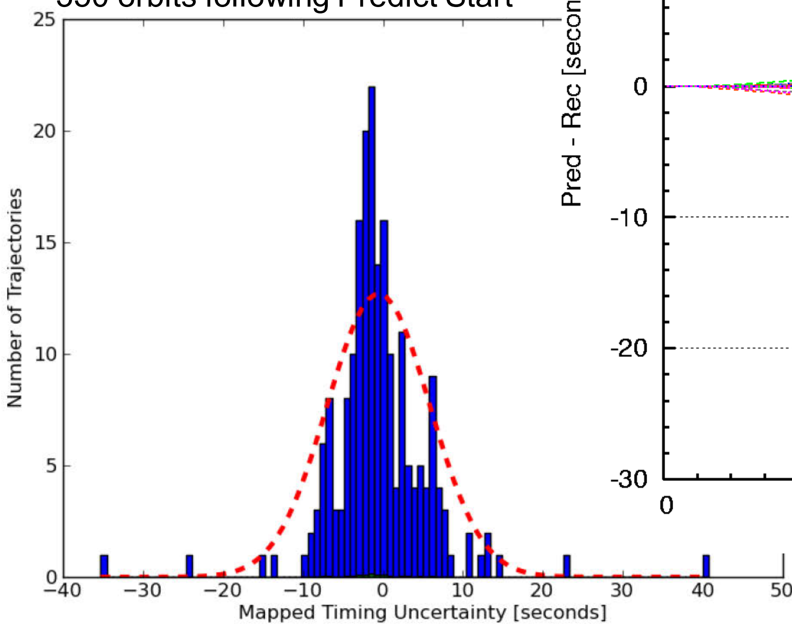
Timing Errors of MRO Predicted Trajectories

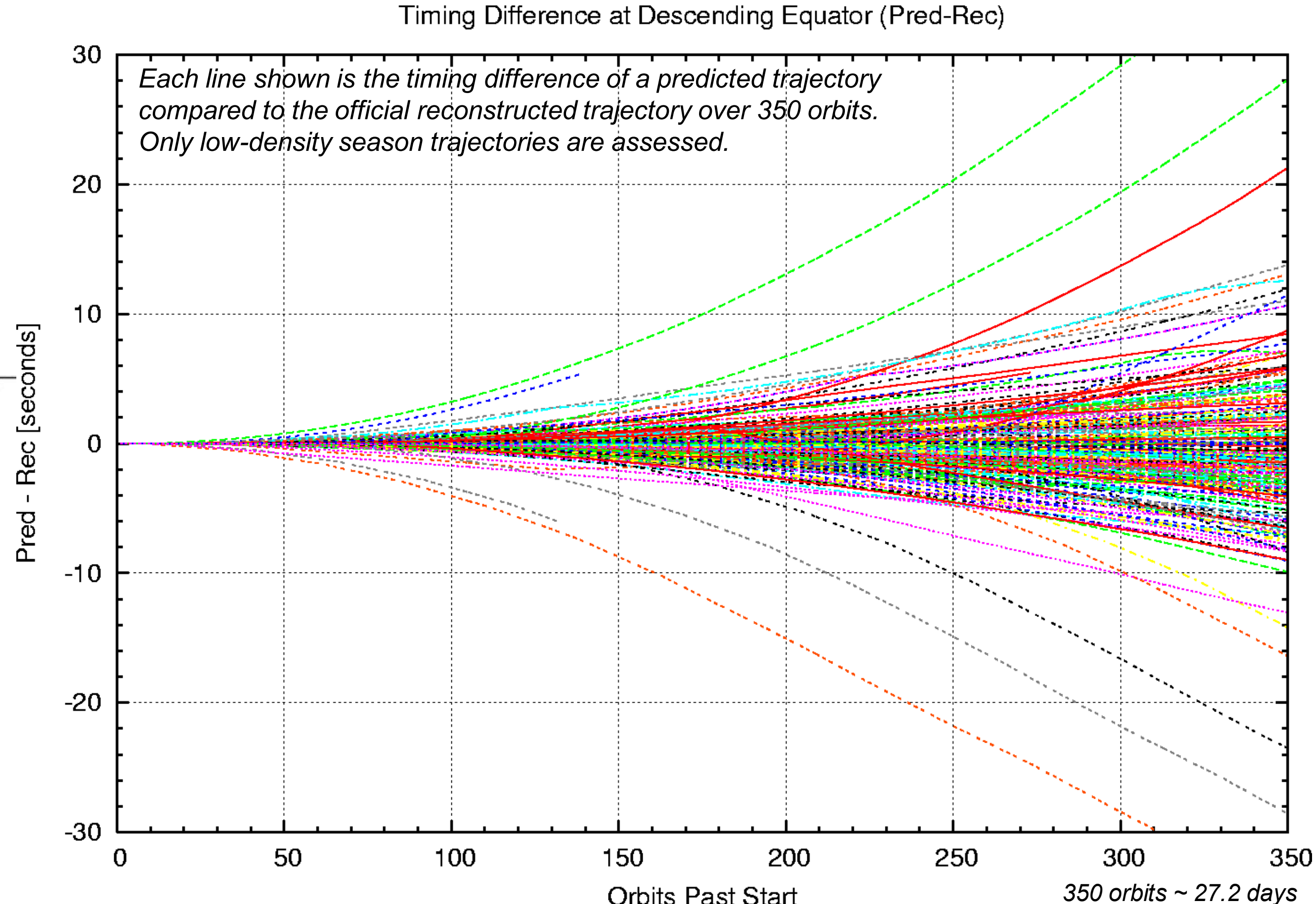
Distribution of Predicted vs Reconstructed Trajectory Timing Errors

The z-score / percentile analysis is valid for normal distributions. The distribution of observed trajectory timing errors during the low-density season is roughly normal (bell curve).

Histogram of Trajectory Timing Errors

350 orbits following Predict Start





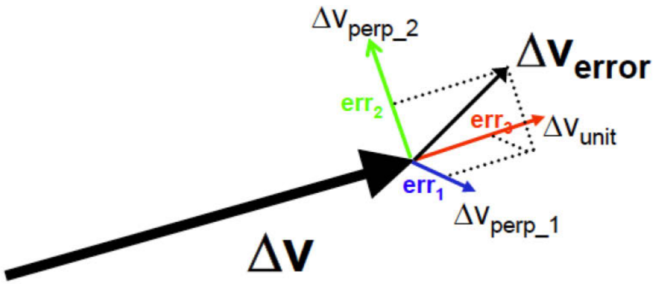
350 orbits ~ 27.2 days
206 trajectories shown
3σ Timing Uncertainty = 19.2 seconds

Maneuver Execution Error Model Evaluation

Navigation Model is 5 mm/sec Fixed, 2% Proportional Magnitude 3σ

All OTM's since INC Correction

OTM / magnitude	Magnitude Error [mm/sec]	Model Fixed Error [mm/sec]	Model Prop. Error [mm/sec] (2%)	Total Model Error, RSS [mm/sec]
13: 0.15 /s	4.0	5.0	3.1	5.9
14: 0.16 m/s	0.7	5.0	3.3	6.0
15: 0.16 m/s	0.9	5.0	3.2	5.9
16: 0.13 m/s	1.1	5.0	2.6	5.6
17: 0.12 m/s	1.0	5.0	2.5	5.6
18: 0.09 m/s	1.3	5.0	1.9	5.3
19: 0.15 m/s	3.4	5.0	3.1	5.9
20: 0.16 m/s	2.6	5.0	3.2	5.9
21: 0.22 m/s	4.4	5.0	4.3	6.6
22: 027 m/s	0.1	5.0	5.5	7.4
23: 0.23 m/s	4.0	5.0	4.7	6.9
24: 0.27 m/s	2.5	5.0	5.3	7.3
25: 0.29 m/s	1.5	5.0	5.8	7.7
26: 0.15 m/s	2.1	5.0	3.0	5.9
Average	2.1 mm/sec			
3sigma	4.3 mm/sec			



For orbit phasing, Navigation is concerned about magnitude error (down-track timing error contribution).

OTM's < 0.12 m/s

OTM / magnitude	Magnitude Error [mm/sec]	Model Fixed Error [mm/sec]	Model Prop. Error [mm/sec] (2%)	Total Model Error, RSS [mm/sec]
1: 0.07 m/s	1.9	5.0	1.4	5.2
3: 0.11 m/s	3.2	5.0	2.3	5.5
4: 0.12 m/s	1.0	5.0	2.5	5.6
7: 0.08 m/s	1.4	5.0	1.6	5.3
9: 0.08 m/s	0.6	5.0	1.5	5.2
OSM2: 0.12 m/s	1.6	5.0	2.4	5.6
11: 0.11 m/s	0.8	5.0	2.2	5.4
17: 0.12 m/s	1.0	5.0	2.5	5.6
18: 0.09 m/s	1.3	5.0	1.9	5.3
Average	1.4 mm/sec			
3sigma	2.3 mm/sec			

There are few OTMs (flight data) to compare to. For small maneuvers, fixed 5 mm/sec fixed error (dominant) and 2% proportional error encompass execution performance shown in data sets.