Mars Science Laboratory Orbit Determination

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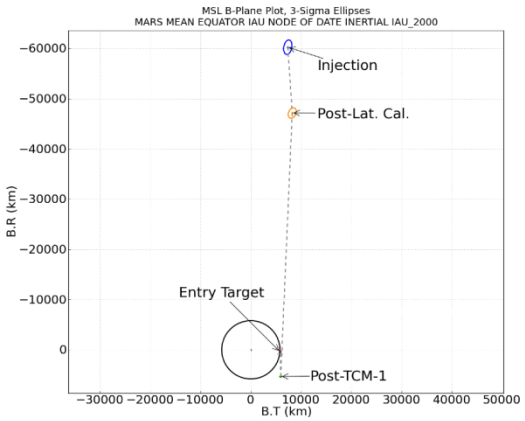
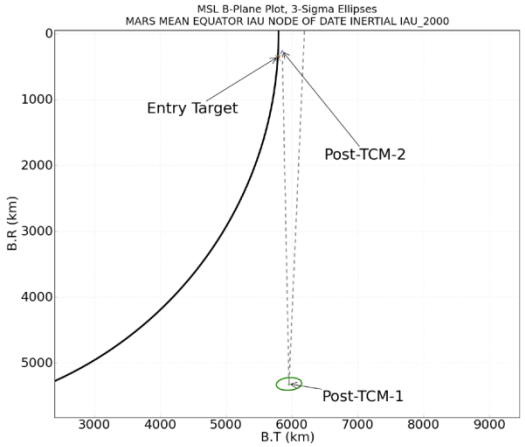
MSL Mission Overview

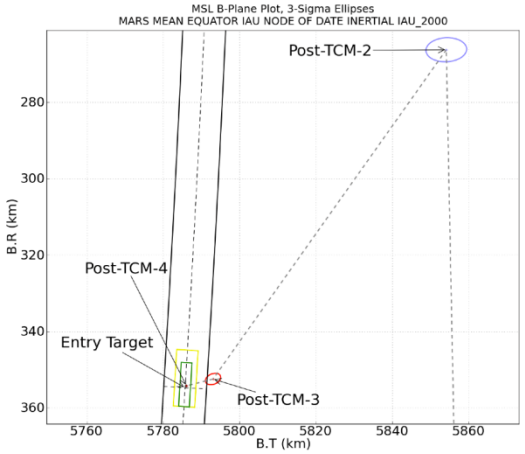
- MSL was launched on 26 November 2011 in a type I trajectory to Mars
- Atmospheric Entry at Mars occurred on 6 August 2012
- Four Trajectory Correction Maneuvers (TCM) were executed
- TCM-5 and TCM-6 were waived because the post TCM-4 orbit determination solutions were inside the TCM-5 decision B-plane criteria (green box)
- Target flight path angle of -15.5º with requirement corridor of +/- 0.2º in black
- Orbit determination results will be discussed per cruise phase as defined in table



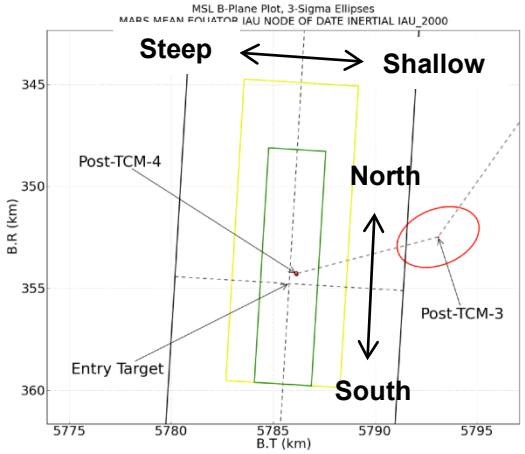
(a) Injection to TCM-1



(b) TCM-1 to TCM-2



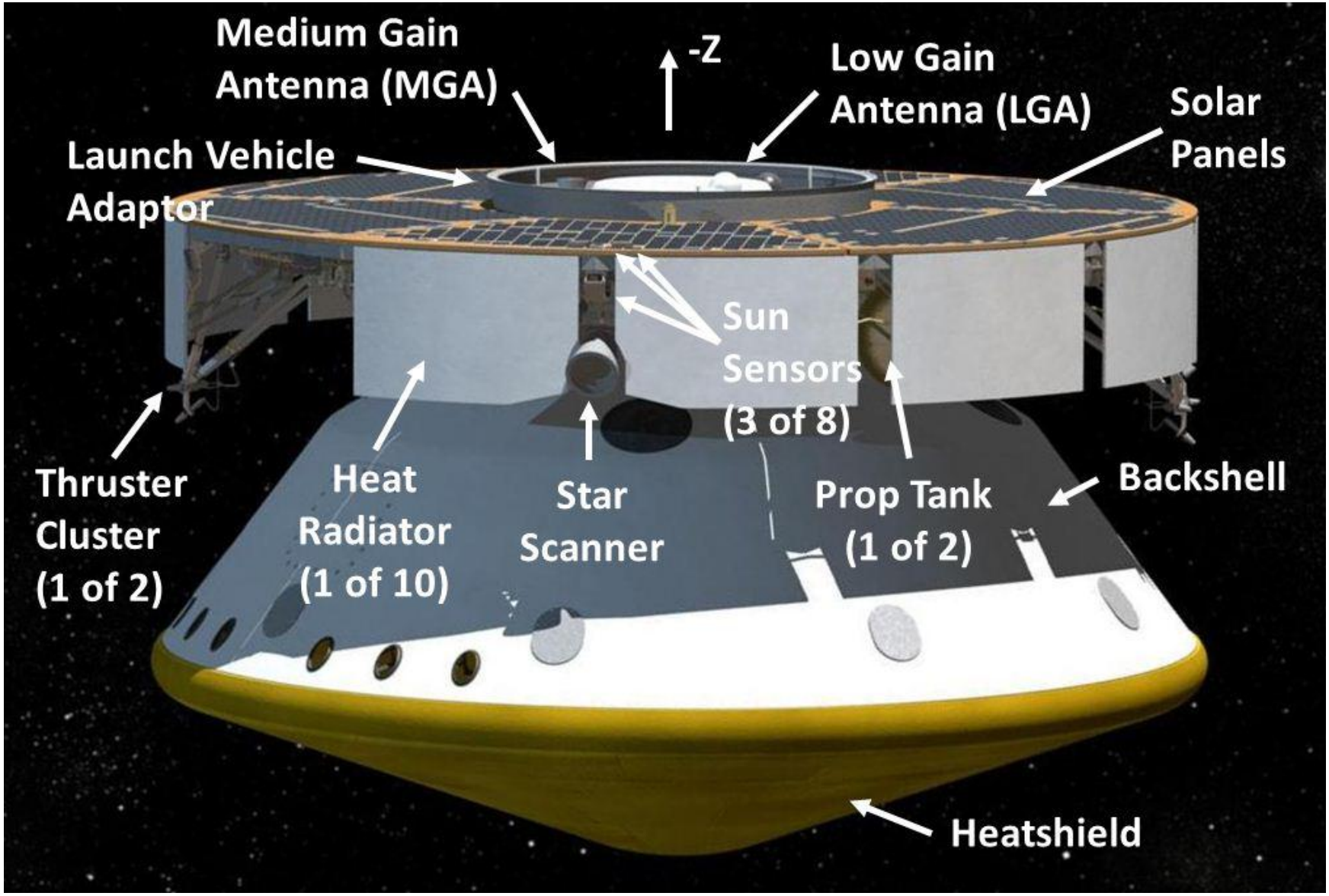
(c) TCM-2 to TCM-3



(d) TCM-3 to Entry

Phase	Start Date	End Date	Comment
Launch	26-Nov-2011	26-Nov-2011	First tracking pass
Early Cruise	26-Nov-2011	11-Jan-2012	Launch to TCM-1
Mid-Cruise	11-Jan-2012	05-Mar-2012	Starts at TCM-1
Late Cruise	05-Mar-2012	29-Jul-2012	Ends at TCM-4
Final Approach	29-Jul-2012	06-Aug-2012	TCM-4 to Entry

MSL Spacecraft



Selected MSL Orbit Determination Requirements

- Provide three updates of spacecraft ephemeris within the first 24 hours after launch
- Provide updates of spacecraft ephemeris at a minimum of every 14 days during cruise and approach
- Support development of Trajectory Correction Maneuvers (TCM) from 8 days to 12 hours prior to execution
- Support calibration of spacecraft attitude turn ΔV
- Support Entry Descent Landing (EDL) parameter updates (includes the entry state) as late as Entry – 2 hours
- Entry flight path shall be -15.5º +/- 0.2º
- Entry state knowledge shall be better than 2.8 km in position and 2.0 m/sec in velocity in a 3-σ sense

DSN Tracking Data and Spin Signature Removal

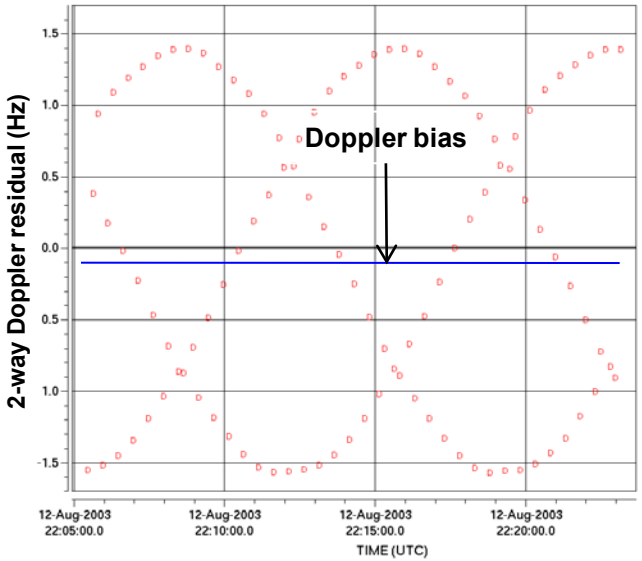
Relative Time (days)		Doppler and Range Coverage
Start	End	NAV request
Launch	L + 30 days	Continuous
L + 30 days	E – 45 days	5 8-hr passes per week*
E – 45 days	Entry	Continuous

*Additional continuous coverage from two days before to two days after TCM-2 and TCM-3

Relative Time (days)		ΔDOR Coverage
Start	End	NAV request
Launch	L + 30 days	None
L + 30 days	E – 67 days	1 per week
E - 67 days	E – 28 days	2 per week**
E – 28 days	Entry	2 per day**

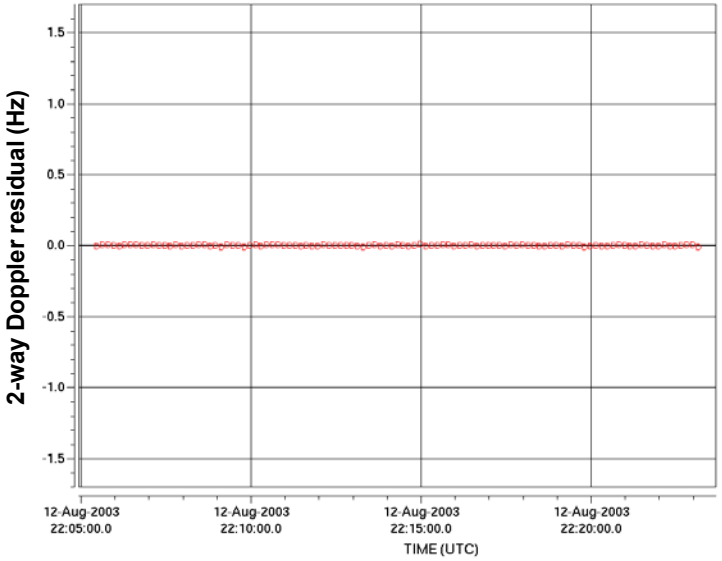
**Includes weekly ΔDOR planned between MSL and Mars orbiters MRO & ODY during approach

Standard deviation = 1.05112 Hz



Residual With Spin signature

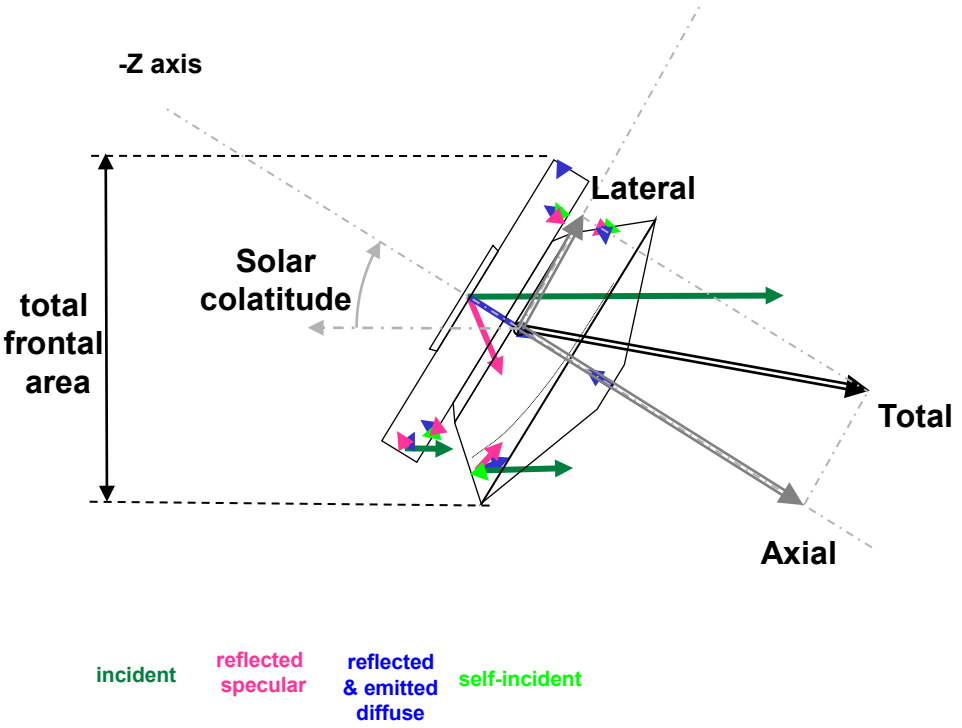
Standard deviation = 0.004308 Hz



Residual after spin signature and Doppler bias removal (same scale)

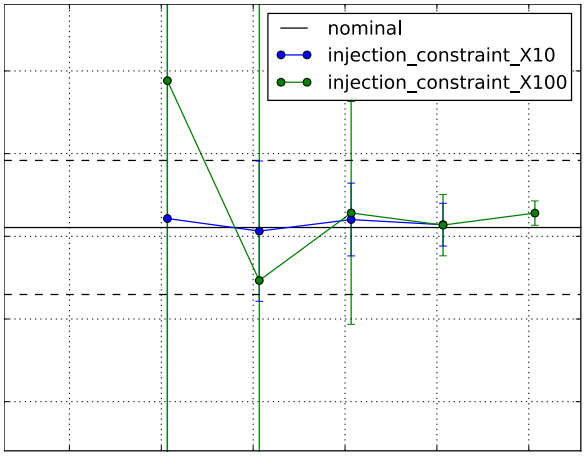
MSL Solar Radiation Pressure (SRP) Dynamic Model

- **MSL SRP net force modeled as a Fourier expansion with solar colatitude angle as independent variable, multiplied by appropriate scale factor to account for S/C mass, solar distance and solar flux.**
- **Fourier coefficients represent effective surface areas**
- **Nominal MSL SRP model consisted of Fourier coefficients up to degree 2 for a total of 18 coefficients. 6 coefficients per axis**
- **Pre-flight Fourier coefficients based on fit of MSL cylinder, flat plate, dish SRP model**
- **Estimated MSL SRP coefficients up to late cruise phase:**
  - X cosine[0,1,2] sine[1,2]
  - Y cosine[0] sine[1]
  - Z cosine[0,1,2] sine[1,2]
- **Estimated MSL SRP coefficients late cruise and approach phase:**
  - X sine[1], Y sine[1], Z sine [1]
  - Added stochastic acceleration in the Z-axis to model thermal radiation acceleration from RTG

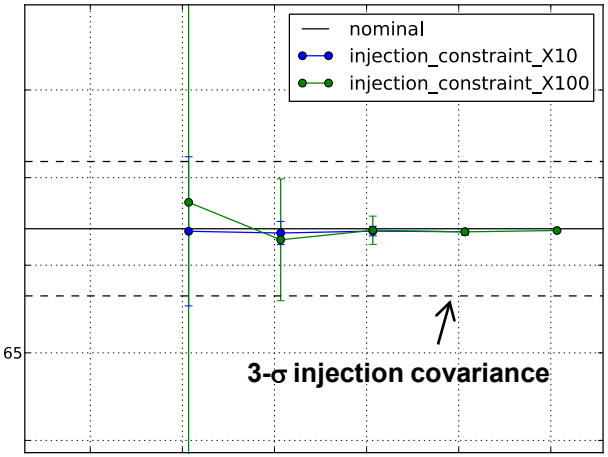


Launch Orbit Determination

- DSN acquisition occurred over Canberra at 15:52:09 UTC
- Estimated Parameters
  - State
  - Range Bias
  - Doppler Bias (constrained after polarization confirmed)
- Initial state constrained with launch vehicle injection covariance multiplied by a factor 10 and 100
- Spin signature and Doppler bias removed from Doppler data. Spin signature removed from Ranging data as well
- Doppler noise larger then expected due use of cross-polarization to attenuate the signal
- No inter-complex 3-way or 1-way differenced Doppler available during launch
- Initial estimated state for different constrained solutions converged after two hours
- Accurate launch injection at the 0.5 σ level



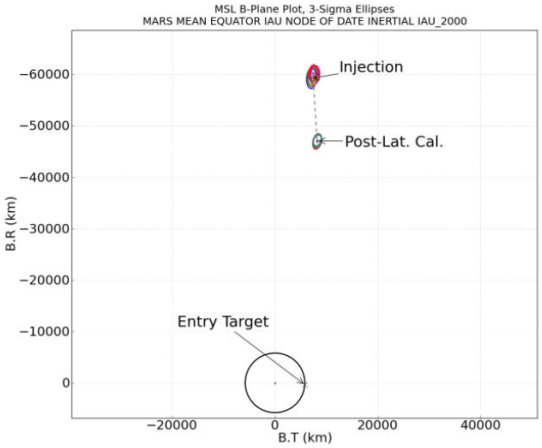
Right Ascension of out bound asymptote solution history as a function of Data Cut Off (DCO)



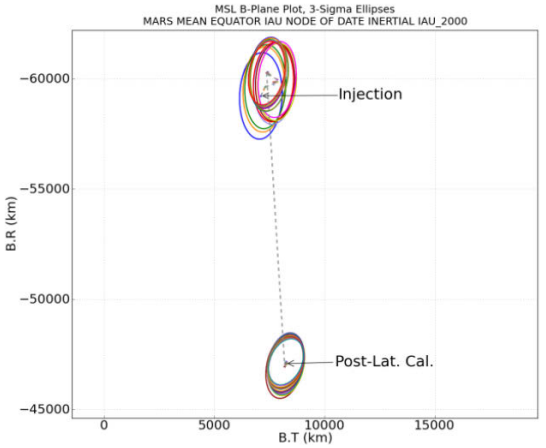
Energy (C3) solution history as a function of Data Cut Off (DCO)

Early Cruise Orbit Determination

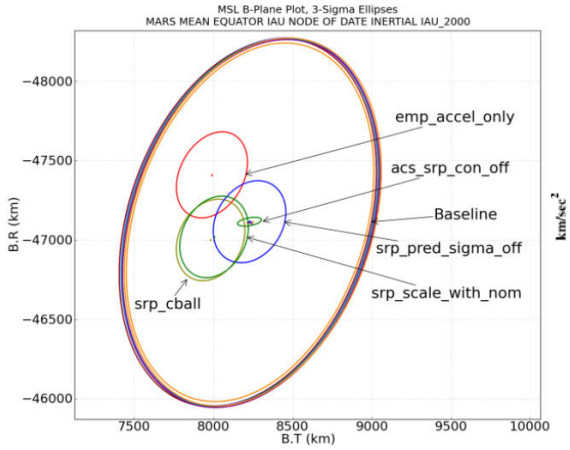
- OD focus on calibration of pre-flight dynamic models
- Limited ability to estimate dynamic model parameters due to:
  - Short orbit arcs
  - Spacecraft outgassing
- 12 Fourier SRP Coefficients estimated
  - Degree 0 coefficients stochastic
  - Conservative uncertainties set at DCO and mapped to Mars for degree 0 coefficients
- Stochastic Exponential decaying accelerations estimated to model outgassing
- ACS turn ΔV estimated for orbit arc and considered for future ACS turns
- Lateral Calibration reconstruction
  - Magnitude error = 1.9 %
  - Pointing error = 0.4º
- OD solutions become more stable and statistically consistent after outgassing subsides (~ 2 weeks after launch)



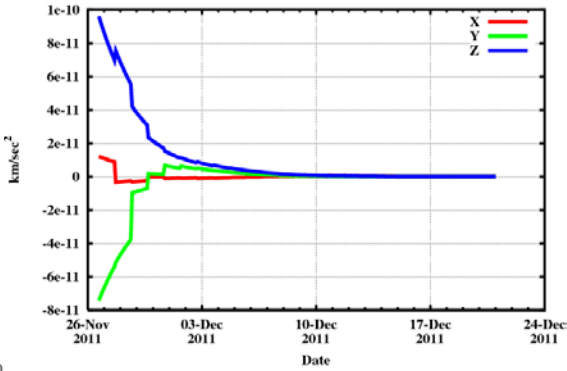
Official Trajectories in B-plane during early cruise



Official Trajectories in B-plane during early cruise (zoom in)



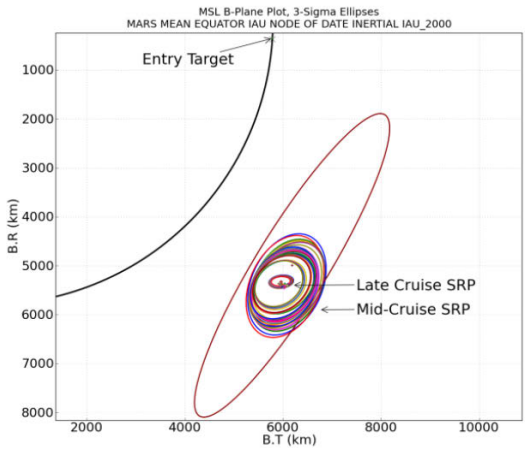
Filter strategy variations Focused on SRP



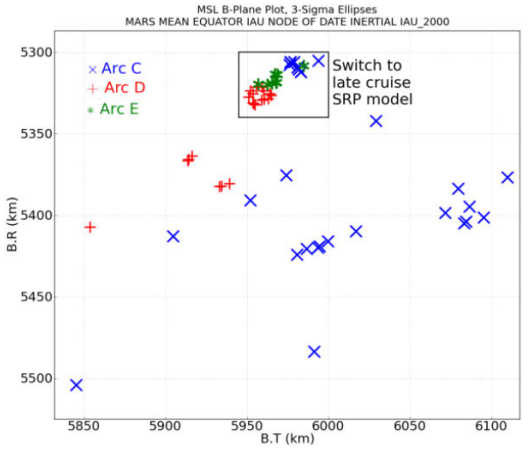
Estimated outgassing acceleration per spacecraft axis (final trajectory reconstruction)

Mid Cruise Orbit Determination

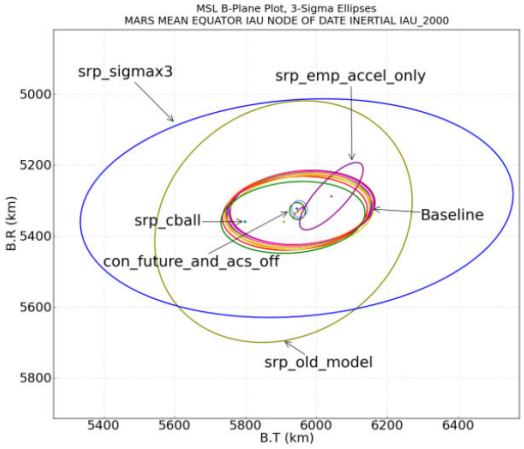
- OD focus on TCM-1 reconstruction, tracking data processing and dynamic modeling improvement
- Outgassing subsided leading to removal of stochastic exponential accelerations from OD filter
- Transition to late cruise SRP model with only 3 Fourier coefficients
  - Estimated uncertainty mapped to Mars
  - Addition to OD filter of stochastic acceleration (spacecraft Z-axis) to model thermal acceleration due to RTG
- ACS turn ΔV calibration performed with small estimates for turn ΔV
- TCM-1 reconstruction
  - Magnitude error = 2.3 %
  - Pointing error = 0.6º
- OD solutions are statistically consistent with significant reduced associated uncertainty ellipses after SRP model update
- OD solutions for different arc lengths are statistically consistent but systematic differences exist



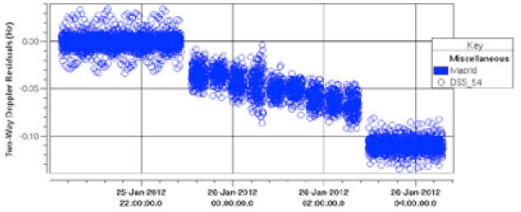
Official Trajectories in B-plane during mid cruise



Trajectories in B-plane for different orbit arc lengths during mid cruise



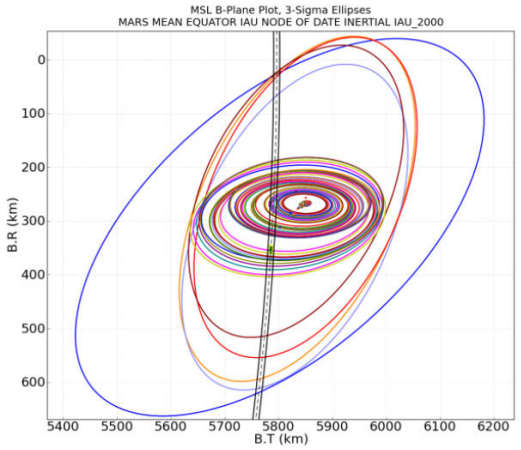
Filter Strategy Variations Focused On SRP



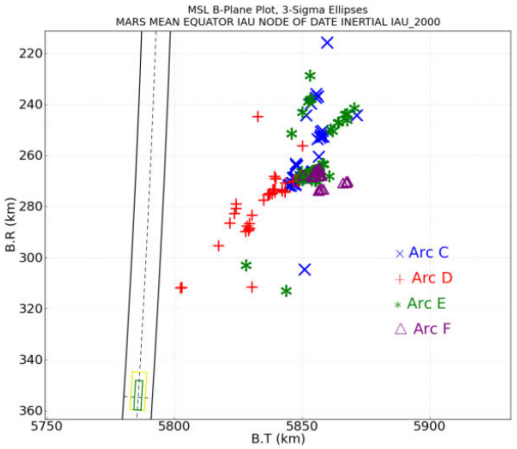
Two-way Doppler residuals during ACS turn ΔV calibration maneuvers

Late Cruise Orbit Determination (1/2)

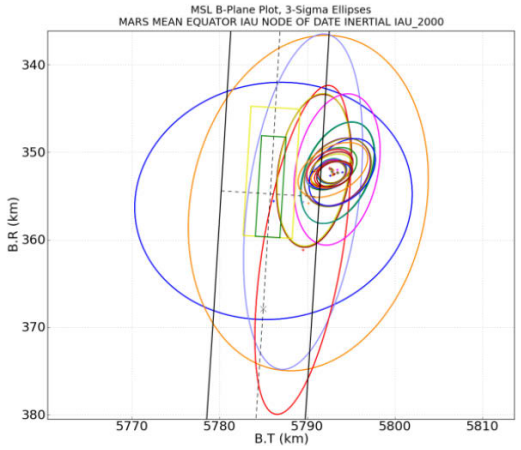
- OD focus on TCM-2 & TCM-3 reconstruction and dynamic modeling improvement
- Addition of following consider parameters to OD filter
  - Earth Pole and Length of Day
  - Tropospheric and ionospheric media calibrations
  - Mars and Earth Ephemerides
  - Mars GM
- TCM-2 reconstruction
  - Magnitude error = 0.04 %
  - Pointing error = 0.4º
- TCM-3 reconstruction
  - Magnitude error = 1.0 %
  - Pointing error = 2.5º
- OD solutions are statistically consistent
- OD solutions for different arc lengths are statistically consistent but systematic differences exist



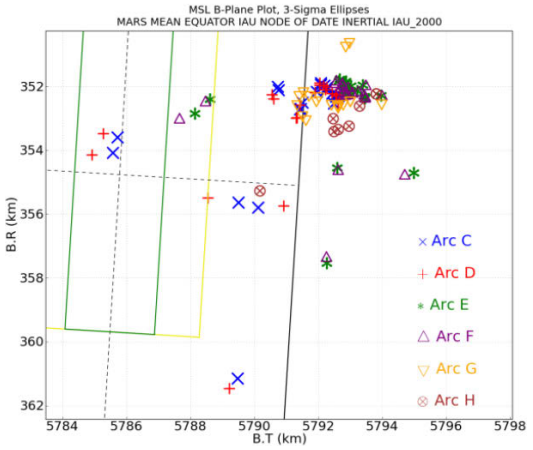
Official Trajectories in B-plane during late cruise prior to TCM-3



Trajectories in B-plane for different orbit arc lengths during mid cruise prior to TCM-3



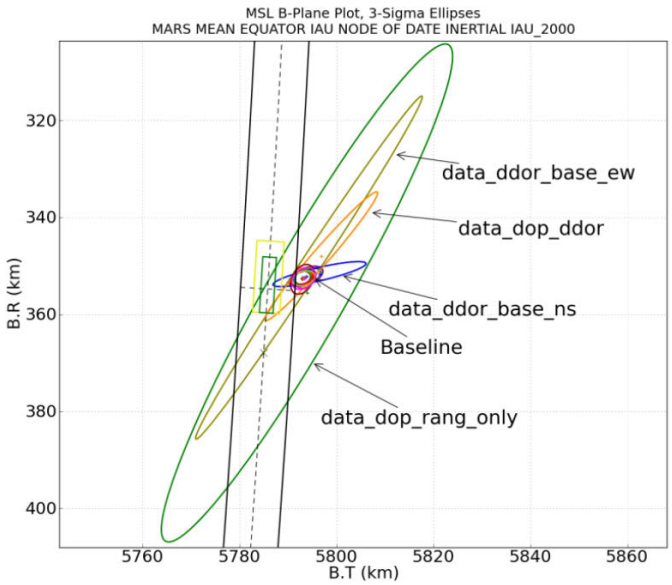
Official Trajectories in B-plane during late cruise prior to TCM-4



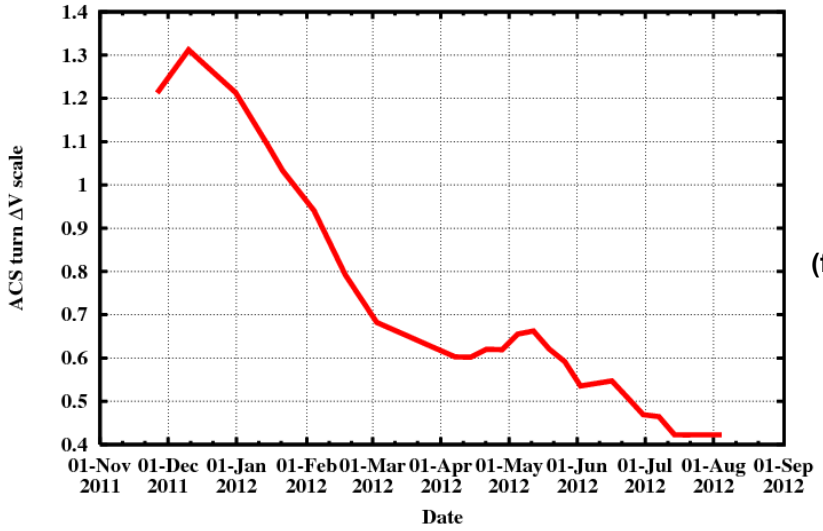
Trajectories in B-plane for different orbit arc lengths during mid cruise prior to TCM-4

Late Cruise Orbit Determination (2/2)

- During late cruise only tracking data variations show significant sensitivity in the uncertainty ellipses. Illustrates importance of combining range, Doppler and ΔDOR for precise OD
- ACS turn ΔV magnitude decreasing during flight. Stochastic scale factor added to OD filter
- Latest DCO ACS turn ΔV scale factor estimate was used for predicting future ACS turn ΔV



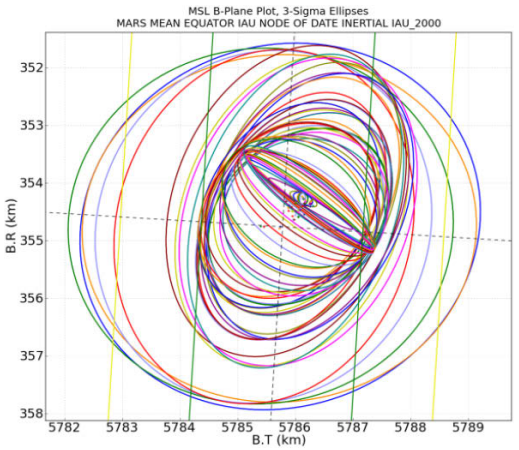
Filter strategy variations. Focused on tracking data variations



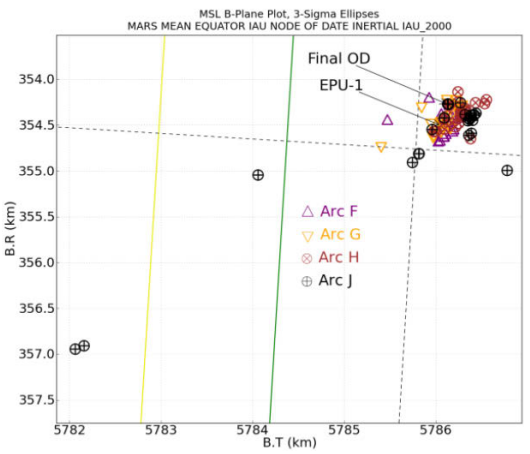
ACS turn ΔV scale factor estimate (final trajectory reconstruction)

Final Approach Orbit Determination

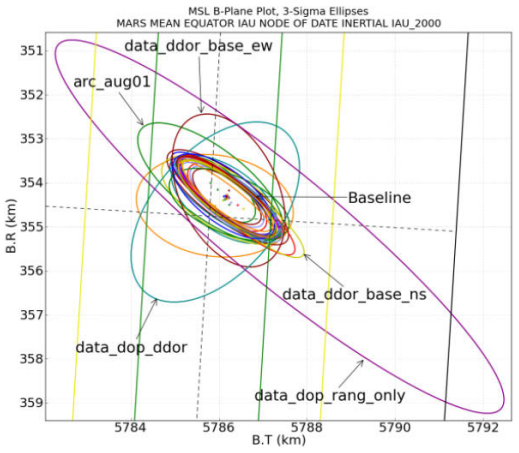
- Tuning of SRP Fourier coefficient uncertainties
- OD solutions are statistically consistent and stable
- OD solutions for different arc lengths are statistically consistent but systematic differences exist
- TCM-4 reconstruction
  - Magnitude error = 5.7 %
  - Pointing error = 1.8º
- TCM-5/6 waived
- Entry Parameter Update EPU-1 based on DCO of Entry – 6.5 days. EPU-2/3/4 waived due to stable OD.
- Tracking data variations show significant sensitivity in the uncertainty ellipses.
- Estimating or considering media calibrations affects uncertainty and trajectory
- Final OD about 200 m (cross track) separated from EPU-1 in B-plane.
- Position error at entry = 0.2 km
- Velocity error at entry = 0.11 m/s



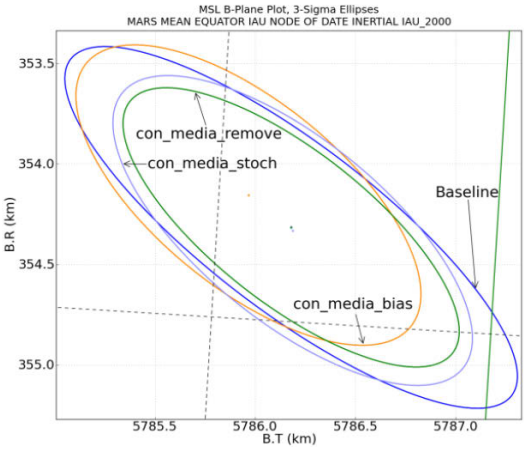
Official Trajectories in B-plane during approach



Trajectories in B-plane for different orbit arc lengths during approach



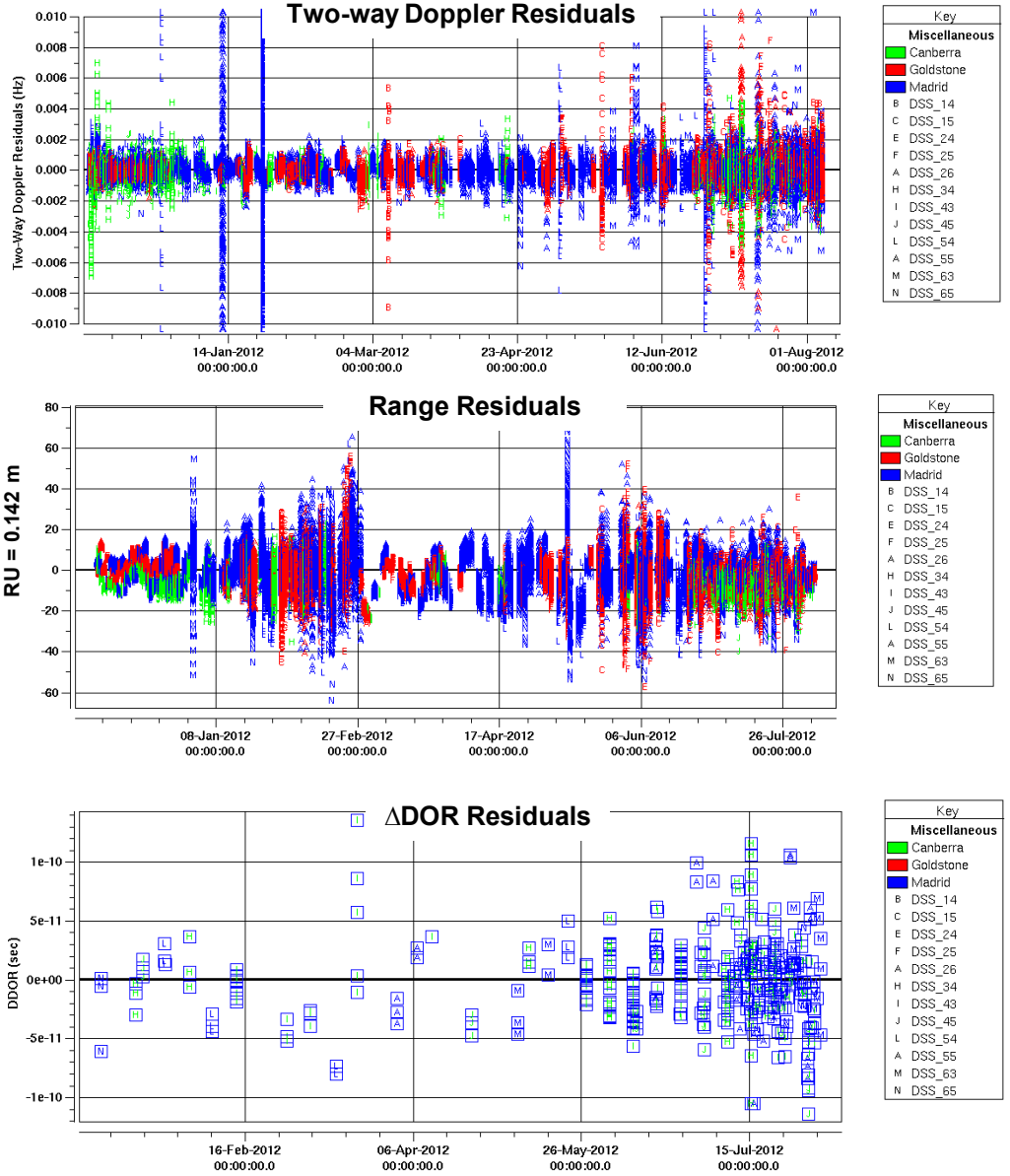
Filter Strategy Variations Focused on tracking data variations



Filter Strategy Variations Focused on media calibration treatment in filter

Final Trajectory reconstruction

- Final trajectory construction from launch to entry in one OD arc
- Doppler Data near TCMs used 10 second compression time resulting in higher noise.
- Excellent DSN data quality though out cruise:
  - Range biases at meter level
  - Range noise level at 1.1 m
  - Range noise improved after switch to MWA (early March 2012)
  - Doppler noise for 300 second compression time and after spin signature removal = 1.1 mHz
  - ∆DOR noise at 36 pico sec
- Coronal Mass Ejections caused solar plasma density variation clearly visible in Doppler residuals in early March 2012.
- Doppler residuals do not contain daily charged particle delay bias estimates in residual plot



Summary

- MSL Orbit Determination met all requirements with considerable margin
- MSL OD team developed spin signature removal tool and successfully used the tool during cruise
- A novel approach was used for the MSL solar radiation pressure model and resulted in a very accurate model during the approach phase
- The ΔV for ACS turns was successfully calibrated and with appropriate scale factor resulted in improved ΔV prediction for future turns
- All TCMs were successfully reconstructed and execution errors were well below the assumed pre-fight execution errors
- The official OD solutions were statistically consistent throughout cruise and for OD solutions with different arc lengths as well
- Only EPU-1 was sent to MSL. All other EPU updates were waived
- EPU-1 solution was only 200 m separated from final trajectory reconstruction in the B-plane