# Mars Reconnaissance Orbiter Interplanetary Navigation

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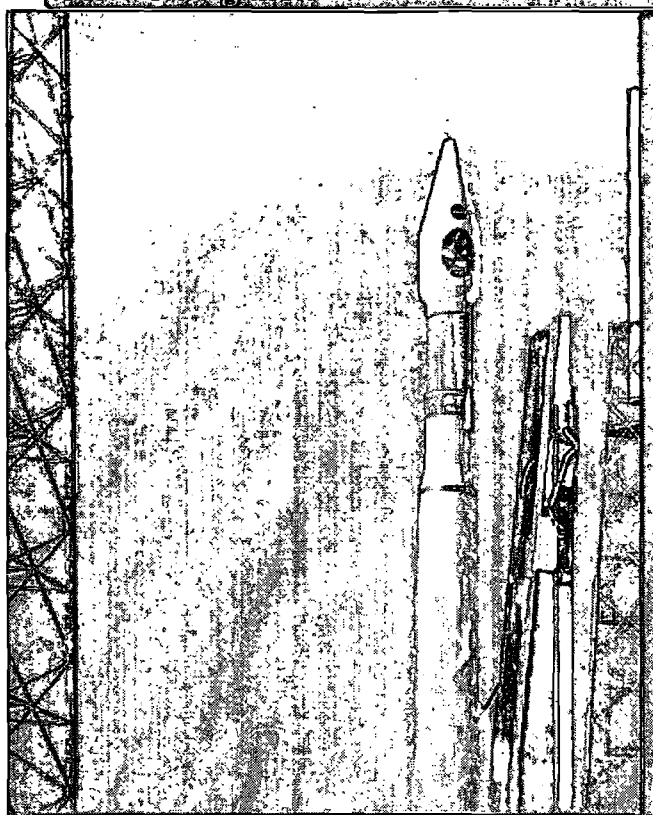
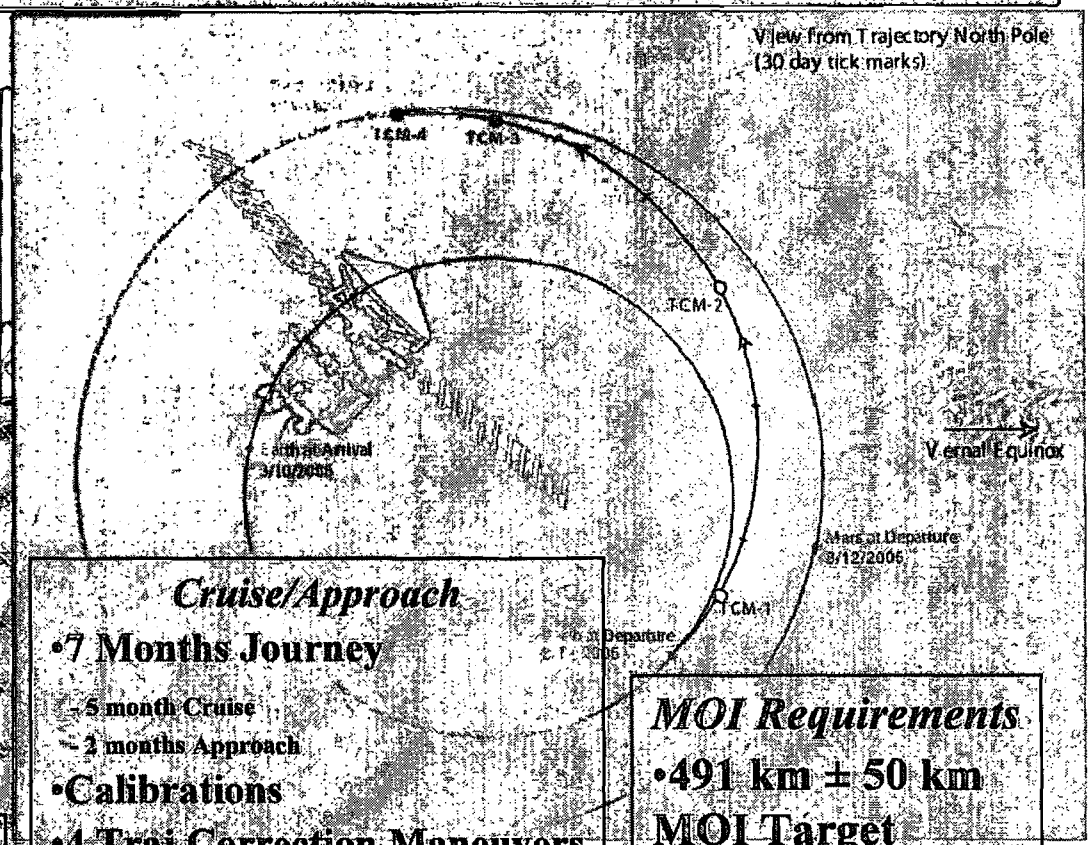
# Interplanetary Overview








## Launch

- 21-day Launch Period
- Daily Launch Window
- Discrete Launch Azimuths
- Centaur Optimization

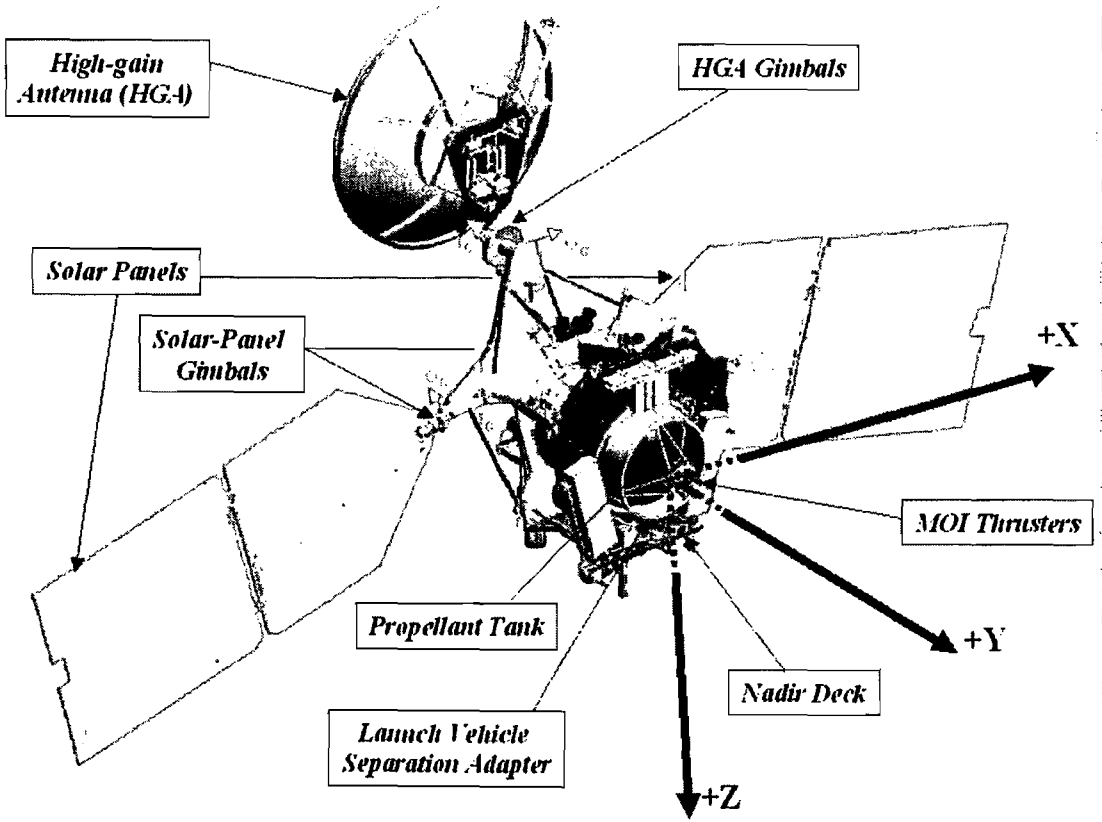
## Cruise/Approach

- 7 Months Journey
  - 5 month Cruise
  - 2 months Approach
- Calibrations
- 4 Traj Correction Maneuvers
- 2 Contingency Maneuvers
- 1000-m/s MOI Burn
  - 491-km Target Altitude
  - 35-hr Capture Orbit

## MOI Requirements

- 491 km ± 50 km MOI Target Altitude
- P1-8 within 300-500 km

# Spacecraft System




***Bus System***

- **Science Instruments**
- **Engineer Subsystems**
  - **GN&C, Telecom, Propulsion, Com & Data Handling, Thermal, Electrical**

***Gimbal Mechanism System***

- **Solar Arrays**
- **High Gain Antenna**

***Coordinate System***

# Key Non-gravitational Dynamic Models



***Solar Radiation Pressure***

- **Spacecraft Attitude**
- **Gimbal Motions**
- **Irregular-shaped Bus**

***Thruster Activities***

- **Angular Momentum Desaturation, ACS Events, Safe-hold,**

***Outgassing***

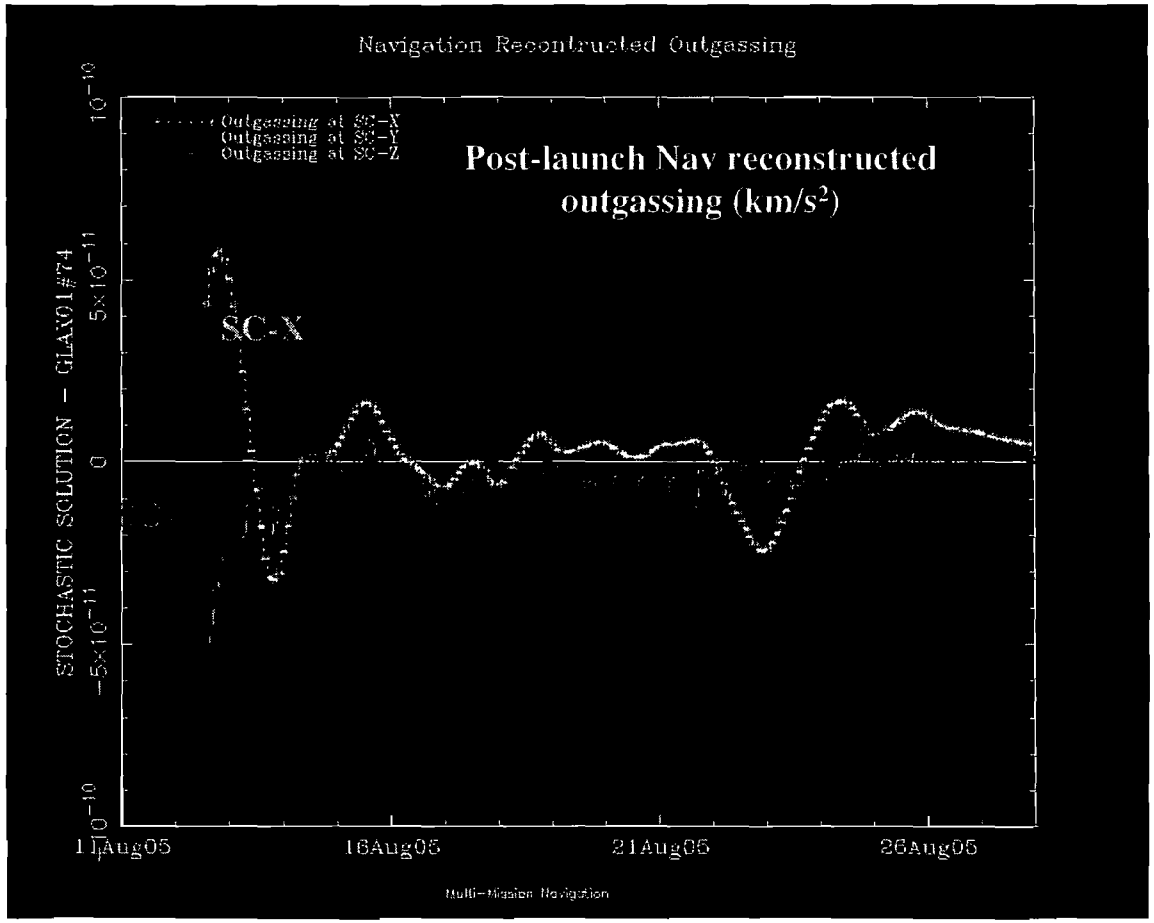
***Propulsive Finite Burns***

- **Trajectory Correction Maneuvers**

# Dynamic Model: Outgassing

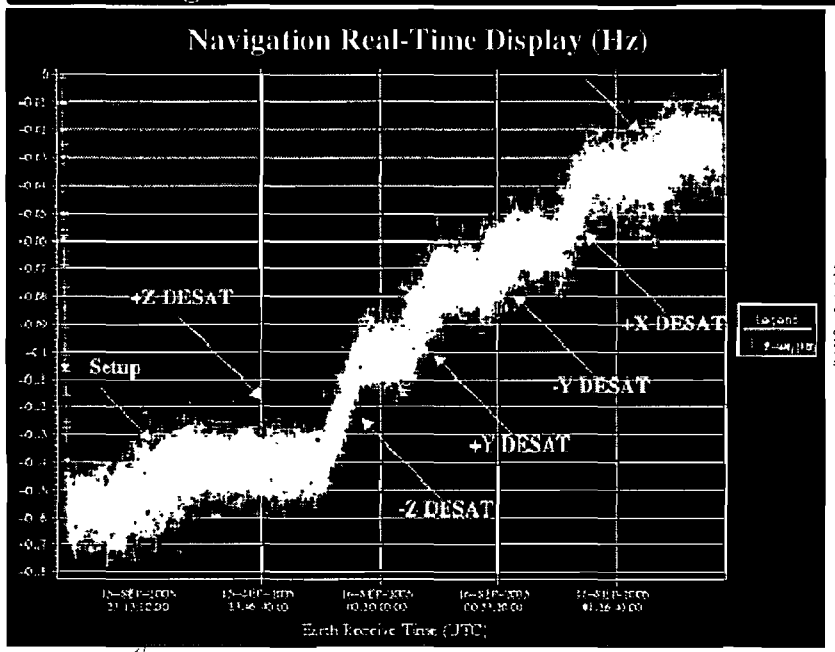


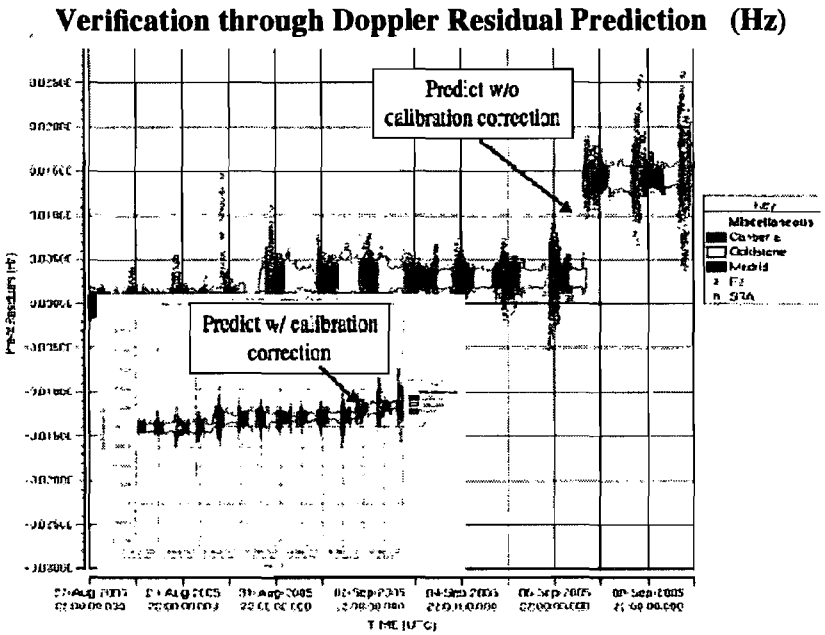
- Outgassing accelerations are at least an order of magnitude smaller than pre-launch expectation
- The outgassing, in cruise attitude, has decayed quickly to $10^{-12}$ km/s$^2$ level
- Significant outgassing, at level of $10^{-9}$ km/s$^2$, has been observed in non-cruise attitudes (due to tests or calibrations)
  - Does not have a long-term impact due to short durations
- No deterministic outgassing accelerations are included in the long-term model

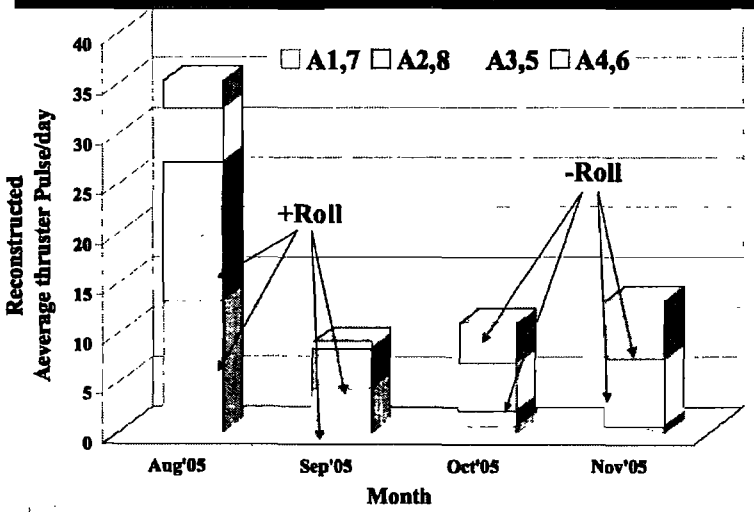


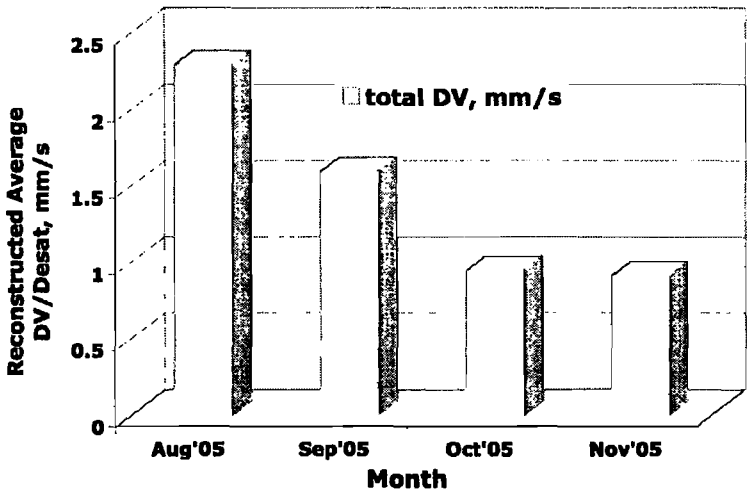
# Dynamic Model: Small Force Calibration and Trending

*MRO Navigation* — *Mars Reconnaissance Orbiter*



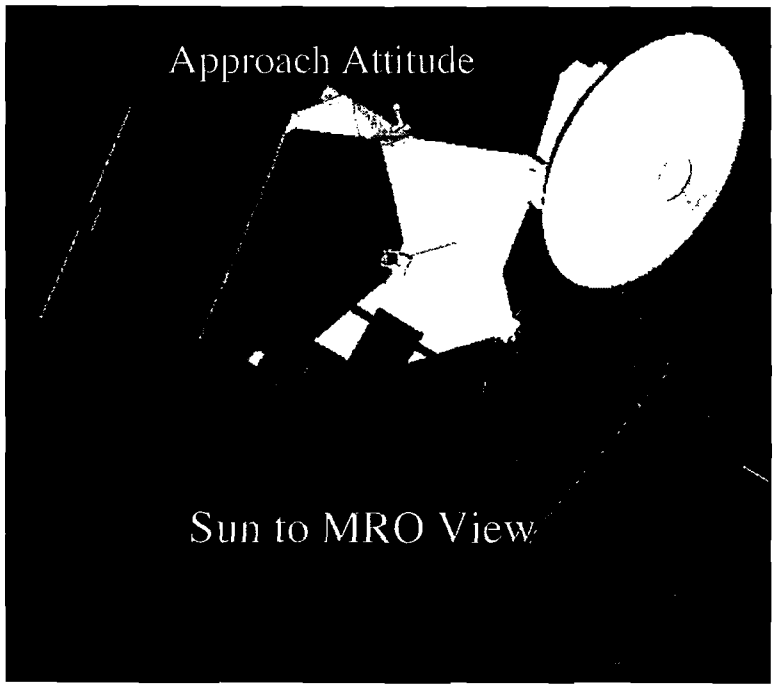



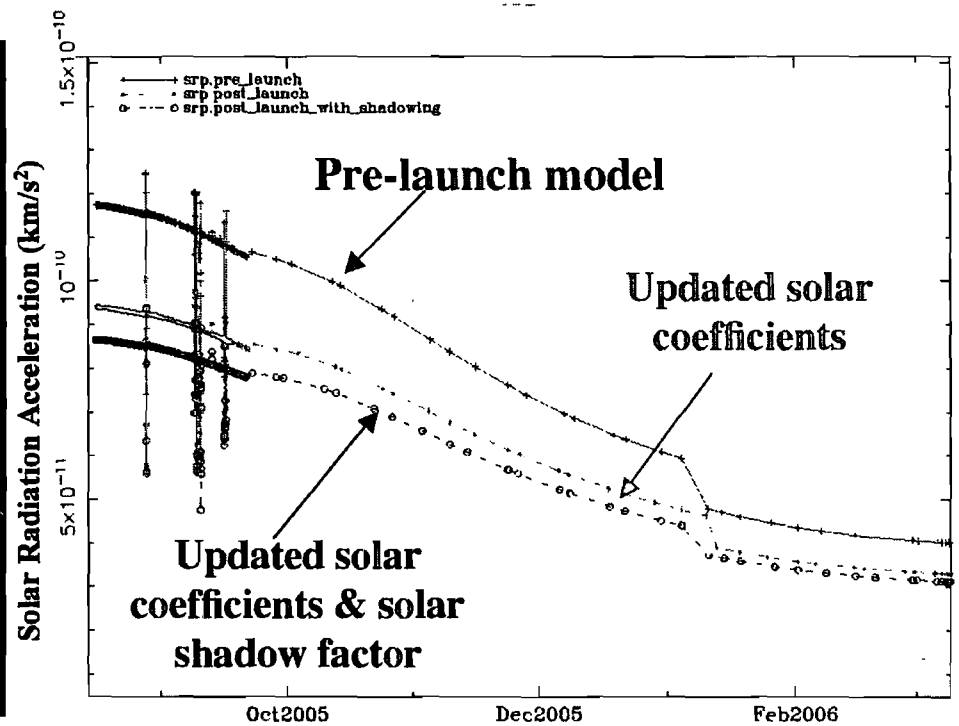



# Dynamic Model: Solar Radiation Pressure





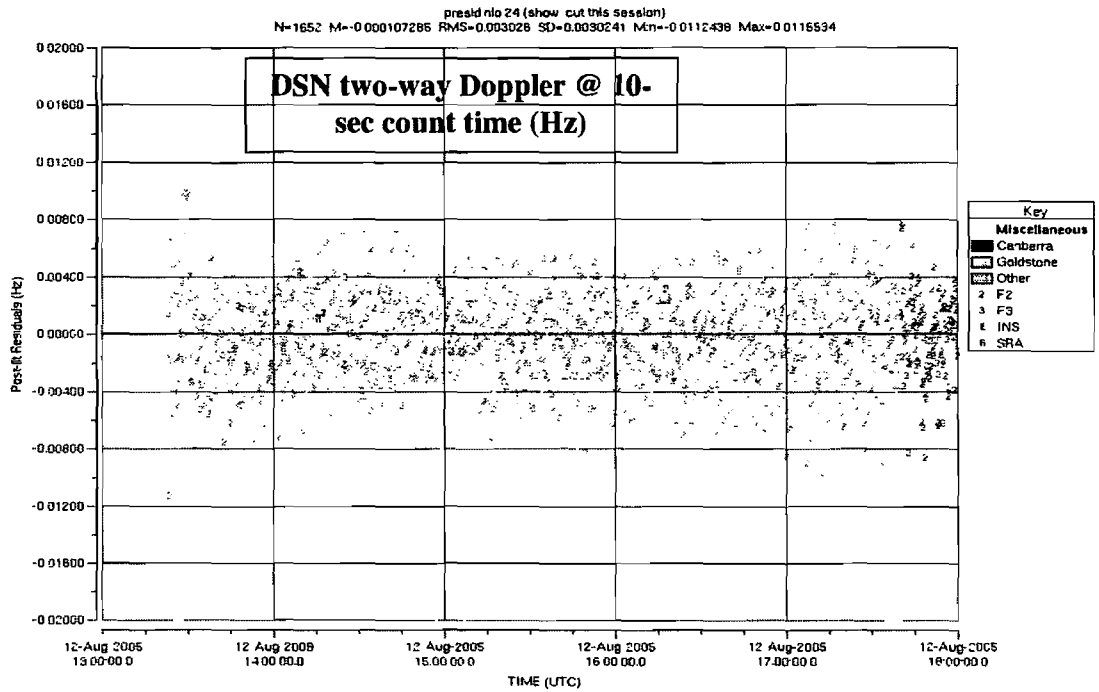

Multi-Mission Navigation

- **Post-Launch updates of solar pressure model**
  - Updated Solar-array reflectivity coefficients due to thermal imbalance
  - Implemented solar area scale factor to account for the component self-shadowing effect
  - Added a small plate to refine the component model
- **Un-modeled constant acceleration reduced significantly**
  - Estimated bias is less then 1.0E-12 km/s$^2$

# Flight Result: Injection Performance



- **Tracking Data**
  - **Good performance from both DSN and JAXA**
- **Orbit Determination**
  - **Continuous Support from L-6hrs to L+14hrs**
  - **Nav Delivered at L+3hrs, L+7hrs, L+13hrs, & L+24hrs**
- **The mapped point on the B-plane at Mars is within 1-sigma of requirement**
  - **Used Nav L+13hrs solution**

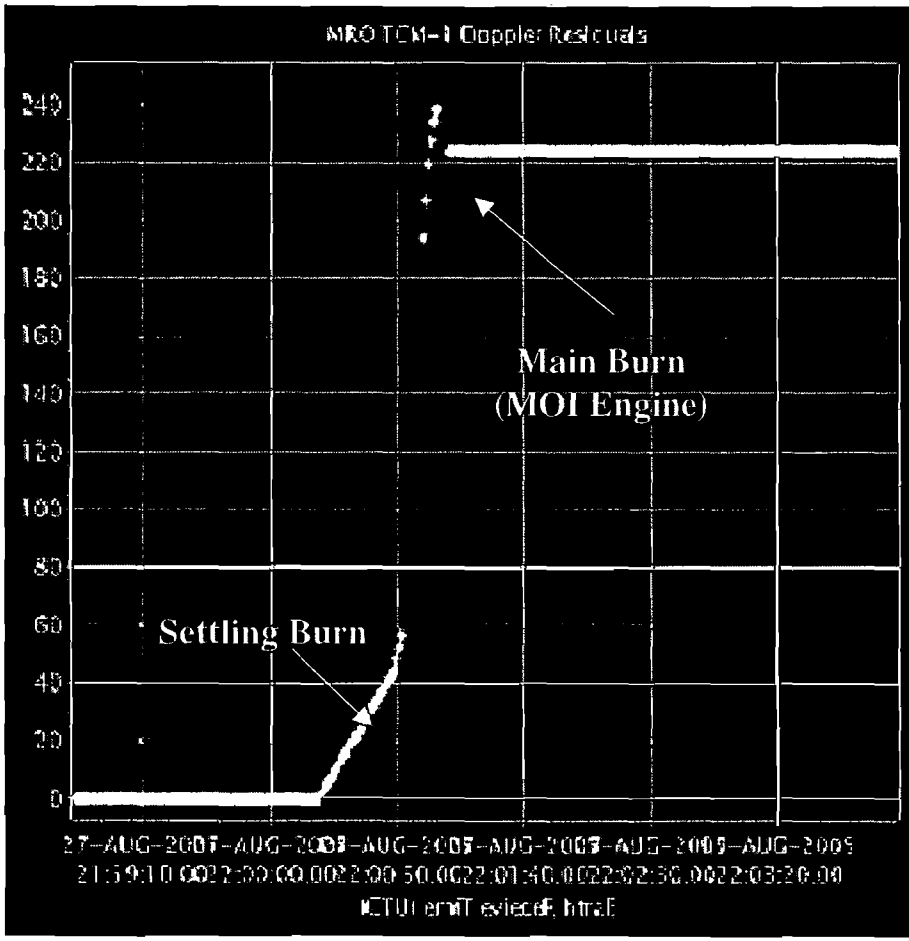



| Injection Solution Mapped to Mars | Error (ó) |
|---|---|
| B.R (km) | 0.5 |
| B.T (km) | 0.5 |
| TCA | 0.5 |

| Injection Parameter | Error in σ | 1σ OD Uncertainty |
|---|---|---|
| $C_3$ ($km^2/s^2$) | -0.8 | 2E-07 |
| DLA (deg) | -0.9 | 6E-06 |
| RA (deg) | 0.3 | 6E-06 |

# Flight Result: TCM1 Performance





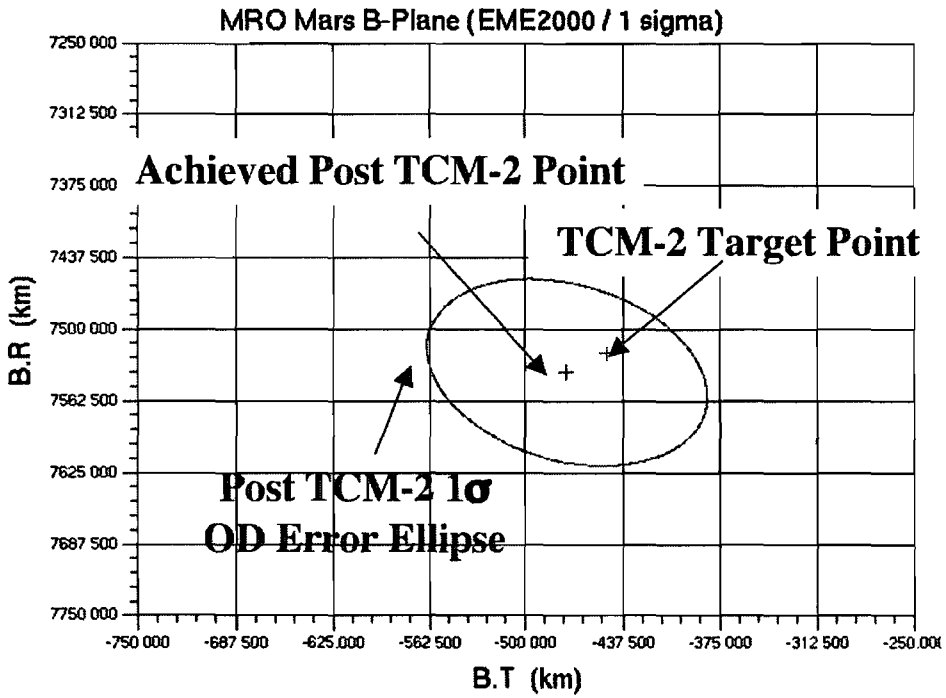

**TCM1: Navigation Real-Time Display (Hz)**

- Final OD solution performed at L+6 days
- TCM1 scheduled at L + 15 days
  - Epoch: 27 August 2005 22:00 UTC
  - Removed injection errors and correct injection bias
- To test the MOI execution mode, TCM-1 was implemented in a different mode than other TCMs

| Parameter | Design | Actual | Relative Error (ó) |
|---|---|---|---|
| ΔV (m/s) | 7.79 | 7.80 | 0.16 |
| Right Ascension (deg, EME2000) | 128.10 | 130.31 | 0.83 |
| Declination (deg, EME2000) | 65.20 | 65.43 | 0.21 |
| MOI Target Altitude (km) | 395 | 3800 | 0.85 |

# Flight Result: TCM2 Performance



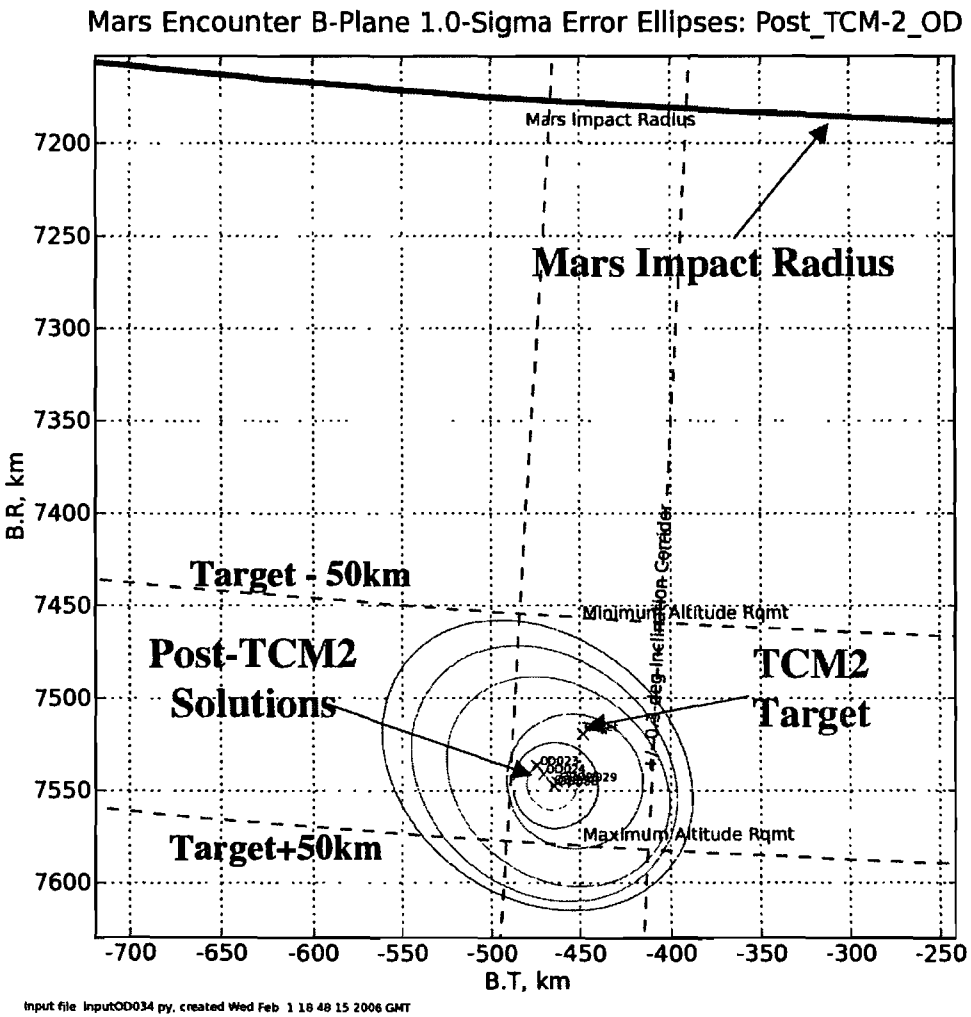



| Parameter | Design | Actual | Error in σ |
|---|---|---|---|
| ΔV (m/s) | 0.751 | 0.754 | 0.14 |
| Right Ascension (deg, EME2000) | 37.0 | 37.1 | 0.14 |
| Declination (deg, EME2000) | 12.3 | 12.1 | 0.23 |
| MOI Target Altitude (km) | 491 | 507 | 0.27 |

- **Final OD solution performed at L+92 days**
  - Used improved dynamic models
  - Hundreds solutions were produced based on various data arcs and filter variations
  - Final solution was used a 2-month data arc
  - Included two-way Doppler , range, ΔDOR from three DSN sites
- **TCM2 scheduled at L + 99 days**
  - Epoch: 18 November 2005 22:00 UTC
  - A single maneuver was designed to clean up the TCM1 execution error, orbit prediction error, and target to the updated final MOI aimpoint (491km)
- **TCM2 performance was well within one-sigma of delivery error**

# Flight Result: TCM3/TCM4 Cancellations





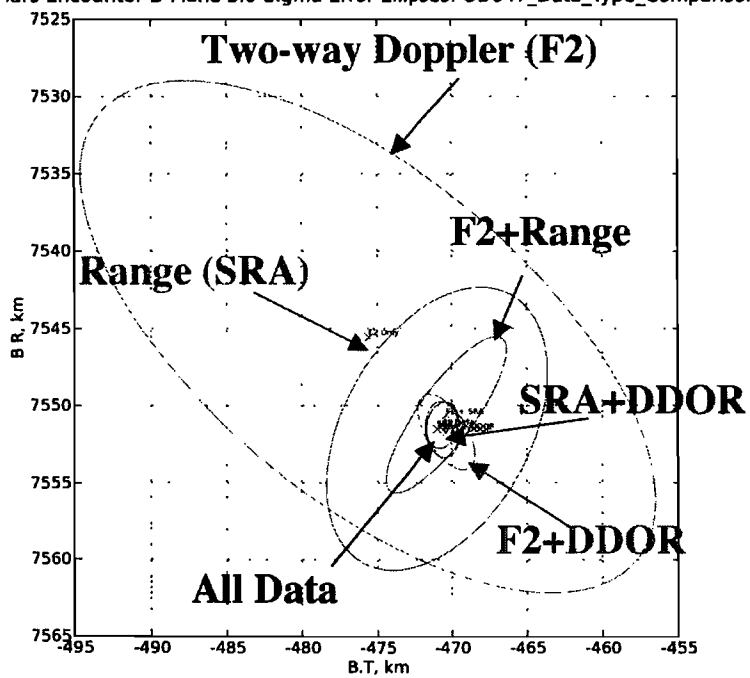

- **Post-TCM2 Solutions were very consistent**
  - Several hundred of solutions were performed using the "*filter loop*" strategy
  - Dynamic models well established
- **TCM3 and TCM4 were cancelled due to**
  - Solutions were within one-sigma of the error ellipses

# Flight Result: TCM5 Solution Assessments

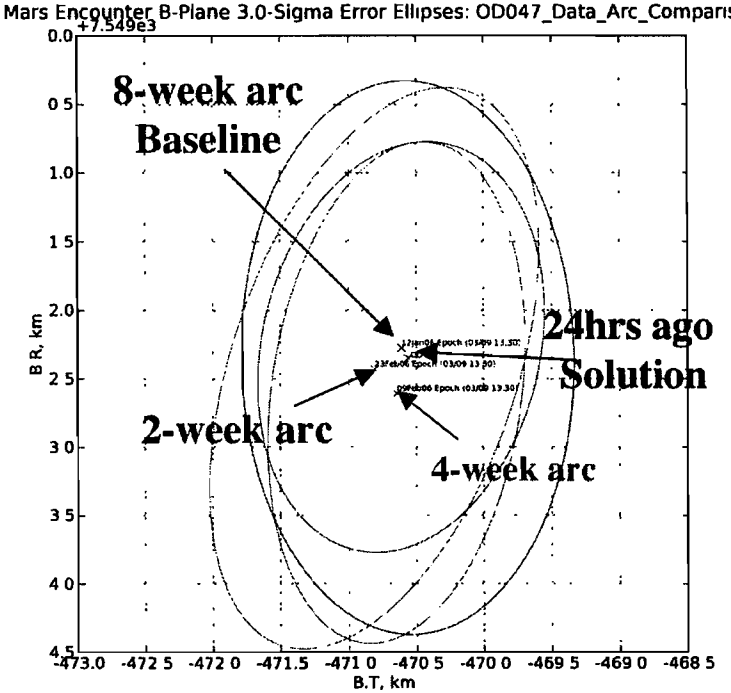
*MRO Navigation* — *Mars Reconnaissance Orbiter*

| Solution | BR (km) | BT (km) | TCA: March 10, 2006 utc | MOI Target Altitude |
|---|---|---|---|---|
| MOI Target | 7519.3 | -448.4 | 21:29:31.0 | 491 km |
| Post-TCM2 | 7536.5 ± 78.6 | -474.5 ± 86.6 | 21:29:14.2 ± 44.8 sec | 507 km |
| Final TCM3 | 7547.2 ± 23.3 | -464.0 ± 24.0 | 21:29:22.3 ± 9.1 sec | 514 ± 19 km |
| Final TCM4 | 7550.7 ± 5.3 | -470.8 ± 4.9 | 21:29:24.9 ± 1.8 sec | 518 ± 4.3 km |
| Final TCM5a | 7551.3 ± 0.5 | -470.6 ± 0.4 | 21:29:24.8 ± 0.1 sec | 518 ± 0.4 km |
| Final TCM5b | 7551.0 ± 0.4 | -470.7 ± 0.3 | 21:29:24.8 ± 0.1 sec | 518 ± 0.4 km |

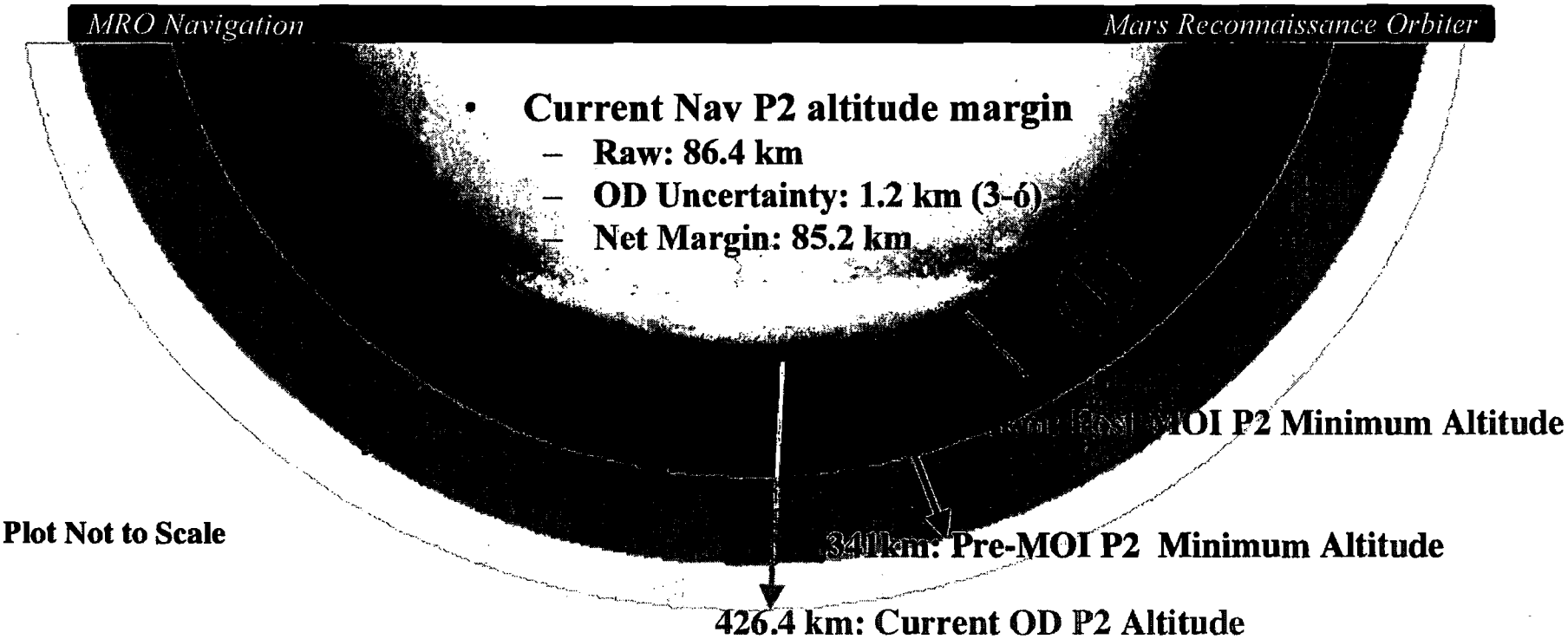
Mars Encounter B-Plane 3.0-Sigma Error Ellipses: OD047_Data_Type_Comparison




Mars Encounter B-Plane 3.0-Sigma Error Ellipses: OD047_Data_Arc_Comparison



# Flight Result: Contingency Maneuver Go/No Go

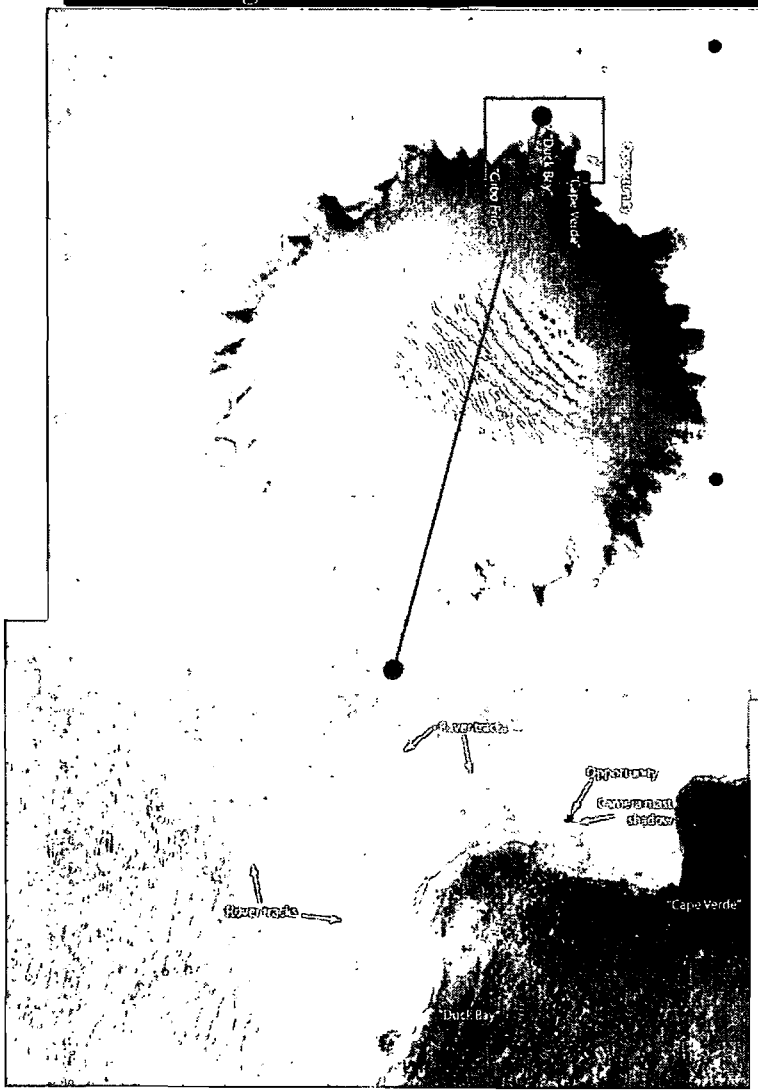



## TCM5a/b Were Not Needed

**Post-MOI Minimum Periapsis Altitude: 200km**
**3-sigma Fault Protection Scenario: 78km**
**Cutoff at Timer2 & 3-sigma Overburn: 63km**
**Minimum P2 altitude needed prior to MOI: 341km**

# Conclusions






- **MRO achieved a 426 km post-MOI periapsis altitude**
  - Only 10 km was attributable to navigation prediction error
  - With the last interplanetary maneuver performed 4 months before MOI, this was a significant accomplishment
- **Since MOI, MRO had successfully implemented the aerobraking operation and established the primary science orbit**
  - As of today, > 22 Terabits of science data returned

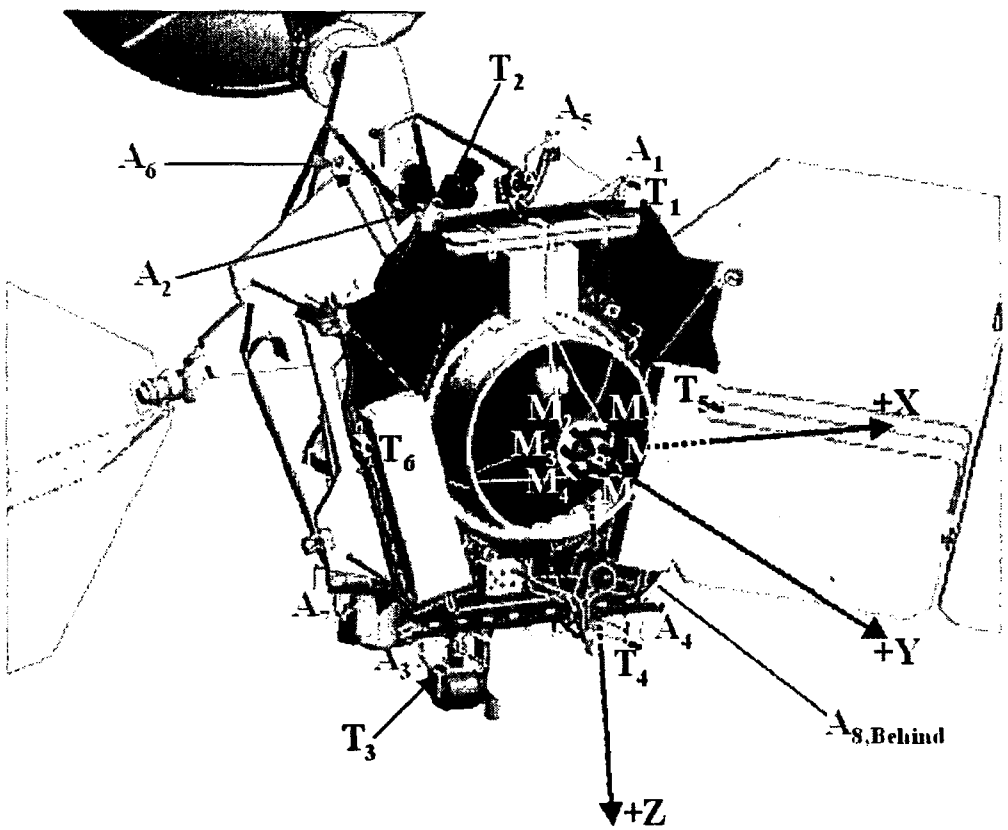
**Textbook Interplanetary performance**

- Paves the way for a successful MRO mission
- Extends its experience to future interplanetary missions

# Backup

# Thruster Configuration and TCM Strategy





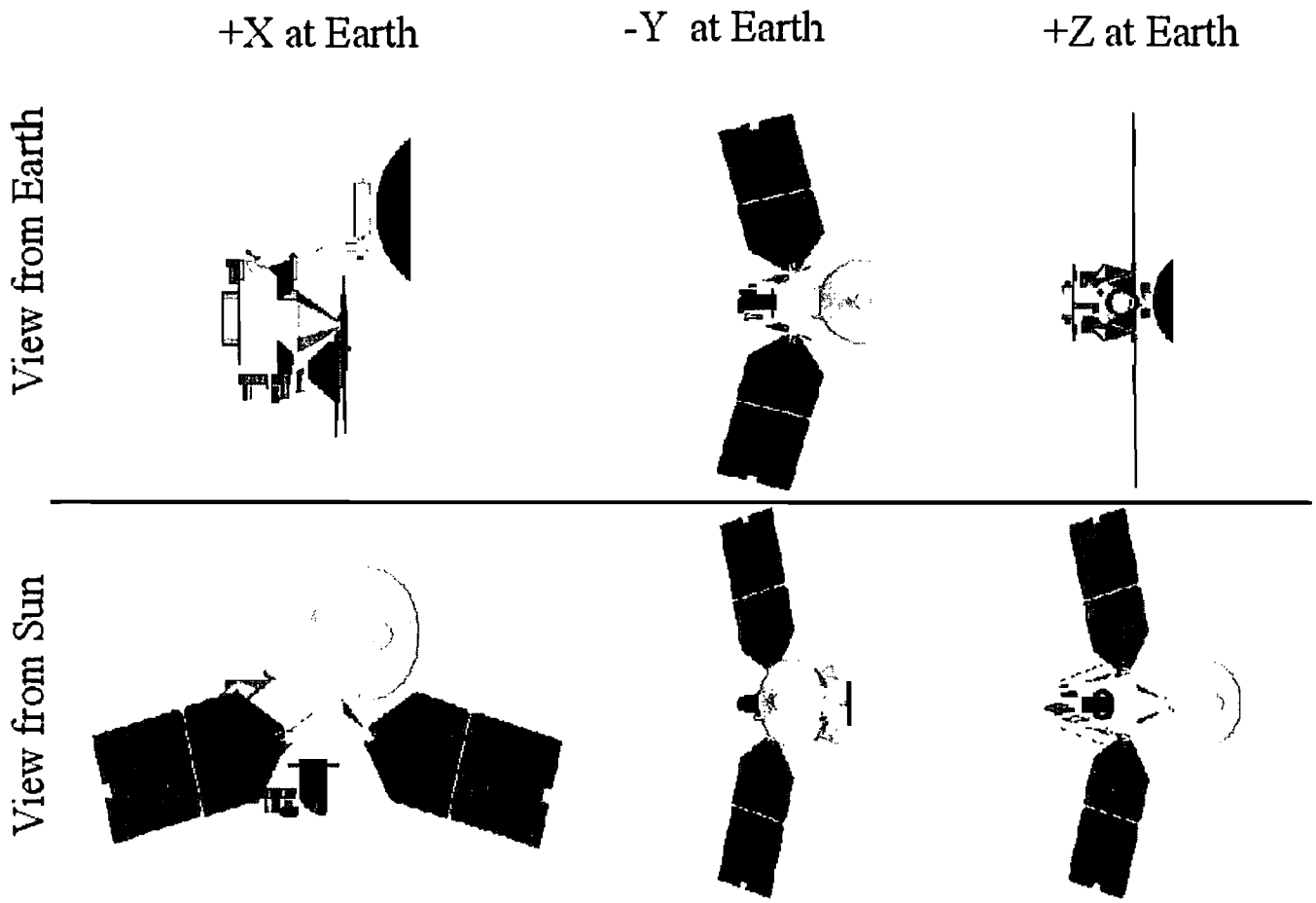

| Specification | Thrust (Newton) | No. Thrusters |
|---|---|---|
| MR-107N | 170 | 6 |
| MR-106E | 22 | 6 |
| MR-103D | 0.9 | 8 |

| Maneuver | Epoch |
|---|---|
| TCM 1 | Launch + 15 days |
| TCM 2 | Launch + 99 days |
| TCM 3 | MOI - 40 days |
| TCM 4 | MOI - 10 days |
| TCM 5 | A: MOI – 24hrs |
| | B: MOI-6hrs |

***ACS Thruster Events***
**•Modeled as Small Forces**

# Thruster Calibration Attitudes





# Tracking Schedule and Statistic



| Mission Phase | Key Events | Begin | End | Doppler Range | ΔDOR | Remark |
|---|---|---|---|---|---|---|
| **Launch** | | L+000d | L+030d | Continuous | | |
| | TCM1 | L+015d | | Continuous | | Dual Track |
| **Cruise** | | L+030d | M-060d | 1pass/day | L+040d to M-060d: 1/wk | 8 hrs/pass |
| | TCM2 | L+099d | | Continuous | | ±3days, Dual Track |
| **Approach & MOI** | | M-060d | M+007d | Continuous, X | M-060d to M-40d: 1-2/wk | |
| | | | | | M-040d to M-005d: 3/wk | |
| | TCM3 | M-040d | | Continuous, X | | Dual Track |
| | TCM4 | M-010d | | Continuous, X | | Dual Track |
| | TCM5ab | M-001d | M-006h | Continuous, X | | Dual Track |
| | MOI | M+000d | | Continuous, X | | Dual Track |

| Data Type | Accuracy (1σ) | Weight (1σ) | Remark |
|---|---|---|---|
| **Two-way Doppler** | 0.02 mm/s | 0.10 mm/s | 60 second compression |
| **Two-way range** | 0.16 m | 2.00 m | 1.00 m = 7.04 RU |
| **ΔDOR** | 1.17 nrad | 3.37 nrad | 37.45 nrad = 1.00 ns |

# Filter Loop Strategy



| Data Type Series (E-W: East-West Baseline, N-S: North-South Baseline) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Series100** | **Serie200** | **Series300** | **Series400** | **Series500** | **Series600** | **Series700** | **Series800** |
| **Doppler** | √ | √ | √ | √ | √ | √ | √ | X |
| **Range** | √ | √ | X | X | √ | √ | X | √ |
| **ΔDOR** | √ | X | √ | X | √ (E-W) | √ (N-S) | √ | X |

| Data Weight and Editing Variations for Series100 to Series800 (ns: nano-sec) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Data Weight Variations** | | | | **Data Editing Variations** | | | | | |
| | **Standard** | **Tight** | **Loose** | **Open** | **Case-1** | **Case-2** | **Case-3** | **Case-4** | **Case-5** | **Case-6** |
| **Doppler** | 5.63 mHz | 2.81 | 56.3 | 563 | Minimum 20deg elevation | Ignore data after a specified epoch | Remove Goldstone two-way data | Remove Canberra two-way data | Remove Madrid two-way data | 20m/pass *apriori* uncertainty for range data |
| **Range** | 2.0 m | 1.0 | 20.0 | 200 | | | | | | |
| **ΔDOR** | 0.09 ns | 0.065 | 0.03 | 1 | | | | | | |

| Dynamic Parameter Filtering Variations | | | | | |
|---|---|---|---|---|---|
| **Case-1** | **Case-2** | **Case-3** | **Case-4** | **Case-5** | **Case-6** |
| Add SC Y-axis acceleration to the baseline | Loose acceleration *apriori* Uncertainties (x5) | Tight Acceleration *apriori* uncertainties (/5) | No stochastic solar coefficient estimated | 150% uncertainty on the AMD scale factors | 300% uncertainty on the AMD scale factor |

# Filter Configurations

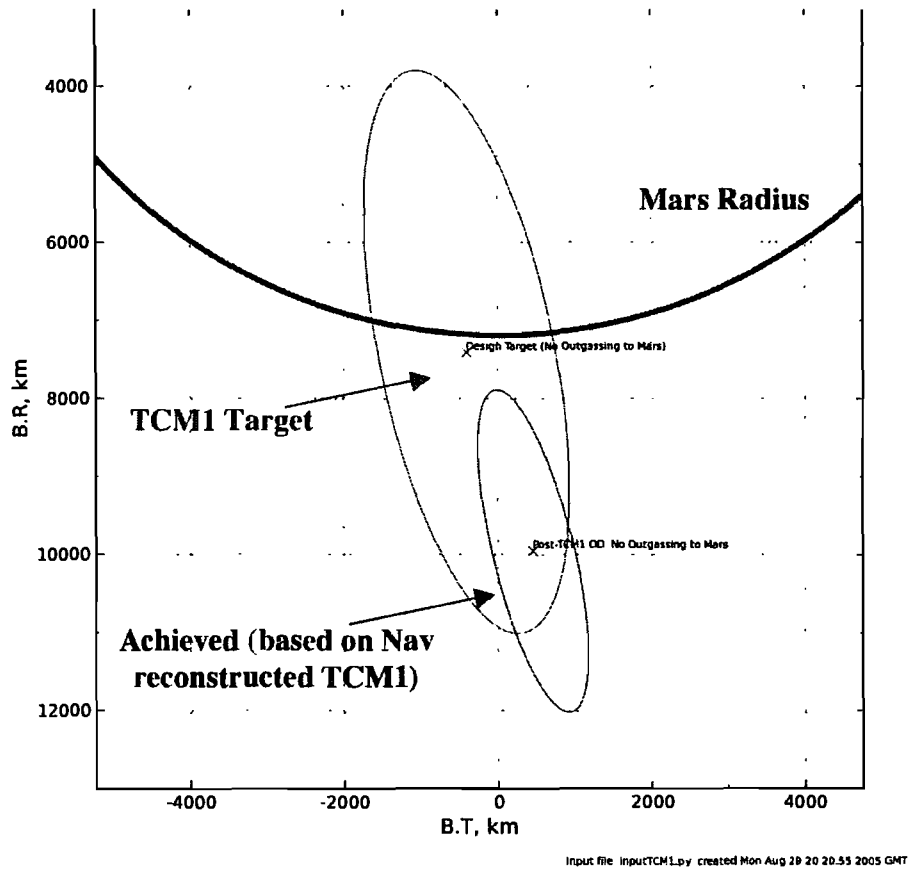
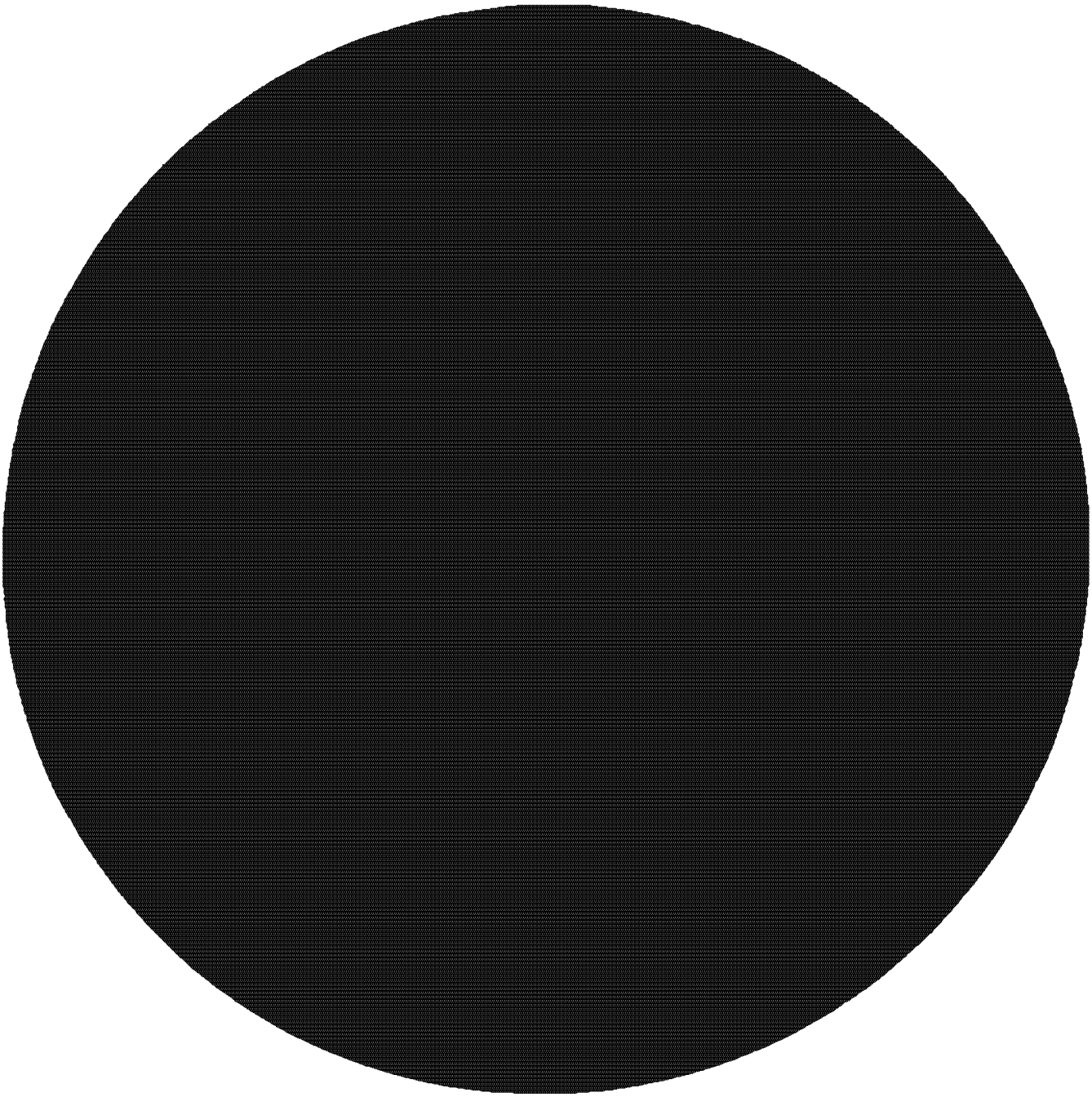


| Parameter | Estimate Type | *A priori* uncertainty (1σ) | Remark |
|---|---|---|---|
| **Epoch State Position** | - | 100,000 km | |
| **Epoch State Velocity** | - | 10 km/s | |
| **AMD Events** | Constant Bias | 30% | Per axis ΔV scale factor |
| **Solar Radiation Pressure** | Constant Bias | 10% | Overall scale factor |
| | Stochastic | 3% | Uncorrelated 2 day batches |
| **Thermal Reradiation** | Constant Bias | $3.0 \times 10^{-12}$ km/s$^2$ | **Along X and Z axes** |
| **Outgassing Events** | Constant Bias | $3.0 \times 10^{-6}$ km/s | **Estimation type and *a priori* would vary with the instrument calibration** |
| | Stochastic | $3.0 \times 10^{-11}$ km/s$^2$ | |
| **Range Bias** | Stochastic | 2.0 m | **Uncorrelated per pass** |
| **Earth, Moon & Mars GM** | Consider | 0.05 / 0.001 /0.05 km$^3$/s$^2$ | |
| **Station Locations** | Consider | Full Covariance | |
| **Quasar Locations** | Consider | 2 nrad | |
| **Earth Pole X, Y and UT1** | Consider | 2 cm / 2 cm / 3 cm | |
| **Ionosphere (day/night)** | Consider | 55 cm / 15 cm | S-band units |
| **Troposphere (dry/wet)** | Consider | 1 cm / 1 cm | |

# Flight Result: TCM1 Performance



**Mars Encounter B-Plane Error Ellipses (1 ó): Design vs. Achieved**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