A JOURNEY WITH MOM

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Abstract: *In late 2013, the Indian Space Research Organization (ISRO) launched its "Mars Orbiter Mission" (MOM). ISRO engaged NASA's Jet Propulsion Laboratory (JPL) for navigation services to support ISRO's objectives of MOM achieving and maintaining Mars orbit. The navigation support included planning, documentation, testing, orbit determination, maneuver design/analysis, and tracking data analysis. Several of MOM's attributes had an impact on navigation processes, e.g., S-band telecommunications, Earth Orbit Phase maneuvers, and frequent angular momentum desaturations (AMDs). The primary source of tracking data was NASA/JPL's Deep Space Network (DSN); JPL also conducted a performance assessment of Indian Deep Space Network (IDSN) tracking data. Planning for the Mars Orbit Insertion (MOI) was complicated by a pressure regulator failure that created uncertainty regarding MOM's main engine and raised potential planetary protection issues. A successful main engine test late on approach resolved these issues; it was quickly followed by a successful MOI on 24-September-2014 at 02:00 UTC. Less than a month later, Comet Siding Spring's Mars flyby necessitated plans to minimize potential spacecraft damage. At the time of this writing, MOM's orbital operations continue, and plans to extend JPL's support are in progress. This paper covers the JPL's support of MOM through the Comet Siding Spring event.*

Keywords: *ISRO, JPL, Mars orbiter, orbit determination, maneuver design/execution, international collaboration.*

1. Introduction

The Indian Space Research Organization (ISRO) was founded in the 1960's, and has grown in size and complexity ever since. There are over 20 facilities throughout India, an active commercial launch program, a new navigation satellite system, and significant activities in space research. In late 2013, ISRO launched its most ambitious mission to date - the "Mars Orbiter Mission", affectionately known as "MOM". MOM's "primary driving technological objective" was to "design and realize a spacecraft with a capability to perform in Earth Bound Manoeuvre (EBM), Martian Transfer Trajectory (MTT) and Mars Orbit Insertion (MOI) phases, supplemented by the science objective" [1]. The supplementary science objective was to deploy a suite of five "scientific instruments for exploration of Mars surface features, morphology, topography, mineralogy, and Martian atmosphere" [1], including a plan to sniff the Martian atmosphere for the biomarker methane.

As part of its operations plan, in spring 2012 ISRO began discussions with NASA and the Jet Propulsion Laboratory (JPL) Mission Design and Navigation Section (MDNAV) to engage JPL's services for consultation, verification, and validation of MOM navigation operations. The navigation support effort built on the successful lunar mission collaboration between ISRO and NASA/JPL MDNAV on ISRO's Chandrayaan-1 mission in 2008-2009 [2, 3]. JPL MDNAV was to validate ISRO's mission design and support the MOM mission in its objectives of achieving and maintaining Mars orbit. MOM successfully achieved the main mission objectives, a fact of major significance given that India was the first Asian nation to achieve the goal of placing a spacecraft into orbit around Mars, and the first nation to do it on the first attempt, despite a very cost effective mission. These were some of the main reasons that *TIME Magazine* rated MOM one of the Top 25 Inventions of 2014 [4, 5]. MOM's success was an incredible achievement given the many significant challenges.

2. The Team

MOM's primary flight dynamics team consisted of a large contingent of personnel from ISTRAC (ISRO Satellite Tracking Center) and ISAC (ISRO Satellite Center) in India; ISRO had primary flight dynamics responsibility for the mission. JPL MDNAV's role/responsibility was to provide navigation support in development, design, and operations for MOM and participate in JPL-ISRO Technical Interchange Meetings (TIM) to support development and operations activities, develop and implement a JPL MOM navigation strategy, and validate radiometric data from ISRO’s 32-meter tracking station for use in deep space navigation. The JPL MOM navigation team consisted of a number of members of JPL's MDNAV Section (orbit determination groups, flight path control group, system administrators), and the Deep Space Network (Delta-DOR, radiometric data conditioning, network operations engineering, scheduling, media calibration). During three critical mission events, one member of the JPL navigation team was deployed as an on-site liaison at the ISTRAC operations center in Bangalore to provide navigation support, monitor critical events via real-time display, and support real-time US-India communication for MOM problem solving.

3. MOM Preliminaries

One of the first things that had to be accomplished by JPL's Interplanetary Network Directorate was to establish a Technical Assistance Agreement (TAA) specifying the work with ISRO and get it approved by several US government agencies (NASA, the US State Department, and the US Department of Defense). Serious technical interchange could not start until such a document had been negotiated and approved by all parties. Because a previous JPL/ISRO TAA was Chandrayaan-1 specific, and had expired, it was necessary to create a new TAA for MOM. Starting in October 2012, a new generic tracking and navigation TAA document was expeditiously drafted. The TAA was signed and approved in early February 2013 [6], relatively rapidly for such documents. An agreement for the reimbursable NASA/ISRO contract followed shortly in April 2013.

In preparation for one of the first planning teleconferences in October 2012, a list of questions was prepared by JPL MDNAV that covered overall mission design (e.g., planned mission duration at Mars, science objectives, schedule margins), tracking plans (e.g., which ISTRAC stations would be used, what was the plan for validating their collected data, amount of Deep Space Network (DSN) tracking required, uplink/downlink bands, Delta-DOR plans), and orbit determination software development status. There were also many detailed questions regarding the spacecraft and its mission (e.g., ΔV_{99}, commanded ΔV accuracy, orientation constraints, main engine tests and results, planetary protection, mission disposal), and expectations with respect to JPL's roles and responsibilities.

4. Interfaces and Models

The NASA/JPL navigation support for the ISRO MOM mission necessitated the exchange of many navigation data products in order to keep the efforts of the ISRO and JPL teams synchronized. Consequently, much of the early technical work required agreements between the two teams as to the interfaces and models that would be utilized to conduct the work. The data exchange was accomplished via interface servers that were established both at JPL and at ISRO (see Fig. 1). Files were exchanged both from JPL to ISRO and from ISRO to JPL. For security reasons, neither team wrote files to the server maintained by the other institution; thus ISRO deposited files on their server that were fetched by the JPL contingent, and JPL deposited files on their server (oscarx) that were fetched by the ISRO contingent. ISRO provided maneuver designs, CCSDS (Consultative Committee for Space Data Systems) Tracking Data Messages (TDM) [7], and small forces data (angular momentum desaturations (AMDs)) to JPL. JPL provided navigation solutions, maneuver designs, CCSDS TDMs, and a large variety of ancillary files to ISRO.

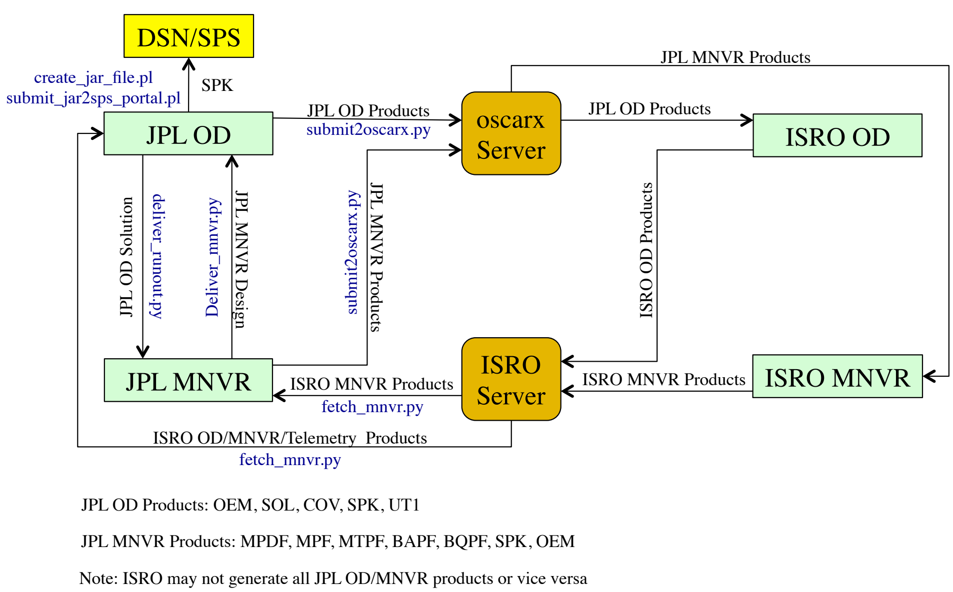

Figure 1. Navigation Data Exchange Configuration

One of the first orders of business was to develop a Navigation Interface Control Document (ICD) signed by both parties. The baseline for this document was the JPL/ISRO Navigation ICD for Chandrayaan-1 support from 2008-2009, modified to bring it up to date. Contents of this document included: Injection State Vector Interface, CCSDS Orbit Ephemeris Message (OEM) [8] Data Interface, STRATCOM (US Strategic Command) State Interface, SPICE[1] Spacecraft and Planet Kernel (SPK) Ephemeris Data Interface [9], Orbit Determination Solution File (SOL) Interface, Covariance (COV) File Interface, Maneuver Profile File (MPF) Interface, Burn Attitude Profile File (BAPF) Interface, Maneuver Target Profile File (MTPF) Interface, Maneuver Performance Data File (MPDF) Interface, Burn Quaternion Profile File (BQPF) Interface, Burn Performance History File (BPHF) Interface, Solar Panel Off-Sun Profile File (SPOSPF) Interface, Past Star Sensor Attitude File (SSAF) Interface, On-Board Reconstructed Small Forces (SMF) Interface, Accelerometer Profile File (APF) Interface, CCSDS TDM Interface [7], UT1-UTC Table, Post-Fit Residual Plots, Burn Reconstruction, Post-Burn Uncertainty Plots, and Tracking Data Real Time Interface.

The Navigation ICD also included descriptions of the respective server setups, the spacecraft frames, the dynamic models to be used, thruster information, thruster configuration, and much detail regarding the structure/content of the many navigation interfaces listed above, including samples.

Models used for MOM included:

Table 1. Models for MOM

Planetary Ephemeris	DE-424
Satellite Ephemeris	MAR063
Gravity Model (Earth)	GGM02C (100x100)
Gravity Model (Moon)	GRAIL360b6a (20x20)
Gravity Model (Mars)	MRO95A (95x95)
Earth Atmosphere	ISRO: DTM 2012 JPL : DTM 2010
Mars Atmosphere	MarsGram 2005
DSN Station Plate Motion	ITRF1993 frame, plate motion epoch 01-Jan-2003 00:00 UTC

5. Navigation Plan

JPL MDNAV's navigation plan for MOM involved the areas of schedule planning, ICD development, spacecraft dynamic model generation, mission profile validations, navigation system analyses, training, and testing across all of these areas. After launch, the major navigation activities included orbit determination and flight path control (maneuver). Output products from JPL MDNAV orbit determination and flight path control were all made available to the ISRO flight dynamics team on the JPL server (note: henceforth, this is called "delivery"). Once the navigation plan was completed, the JPL MDNAV task involved execution of that plan, encompassing all areas of navigation flight operations.

[1] SPICE is well known and widely used software in space applications. "SPICE" is the acronym of its principal data types: "Spacecraft, Planetary, Instrument, 'C-Matrix', Events".

6. Orbit Determination (OD)

JPL MDNAV's primary support for MOM was to provide orbit determination solutions using standard DSN S-band 2-way Doppler, 2-way ranging, and Delta-DOR data. JPL MDNAV also provided ISRO the DSN tracking data with media calibrations already applied for use in their analysis. Reconstruction and dynamic trending of thruster events was a major activity.

JPL MDNAV performed the cruise orbit determination using a variety of radiometric tracking data time spans or "arcs", shown in Table 2. The various tracking data arcs were differentiated with simple alphabetical labels: A, B, C, etc. In general, the shorter the arc, the greater the uncertainty in the Mars B-plane (arrival target plane) when compared with longer arcs; as the span of the arcs increases, the offsets between tracking arcs and their error ellipses will tend to shrink.

Table 2. JPL MDNAV Orbit Determination Data Arcs

Data Arc	Epoch	Rationale
A	30-Nov-2013 20:00 UTC	After TMI (Trans-Mars Injection)
B	02-Dec-2013 10:20 UTC	After TMI (for comparison with arc A)
C	05-Dec-2013 10:10 UTC	After TMI (for comparison with arcs A and B)
D	11-Dec-2013 01:34 UTC	After Trajectory Correction Maneuver 1 (TCM-1) (first pass was Doppler only)
E	11-Dec-2013 09:55 UTC	After TCM-1 (first pass with Doppler & range)
F	19-Feb-2014 04:00 UTC	After attitude calibration
G	15-Mar-2014 10:00 UTC	After solar array change
H	15-Apr-2014 02:00 UTC	After the change to HGA attitude
I	11-Jun-2014 22:00 UTC	After TCM-2
J	26-Jul-2014 22:30 UTC	Desire for a relatively short (approximately30 days) arc solution to compare against other long arcs since the shorter arc would not be too impacted by the buildup of dynamic model errors (mainly AMDs, but some SRP).
K	26-Aug-2014 20:45 UTC	Similar to rationale for J arc

Generally only 2 or 3 of the most current arcs at any given time were run and compared for any given OD solution. Some arcs were used for longer times than others (e.g., at the time the G-arc was retired, the team continued to run the F-arc because the two were very similar in the estimated SRP and the B-plane results, so the longer arc was retained). In total, 226 orbit determination solutions were generated by JPL MDNAV from launch through the MOI; 238 were generated from launch through the Comet Siding Spring event.

7. Flight Path Control / Maneuver Design

JPL MDNAV's basic maneuver responsibility was to provide independent confirmation of ISRO-designed maneuvers for the Earth orbit phase, cruise, and MOI, with an emphasis on confirming the Mars targeting. This effort involved maneuver targeting, design, analysis, comparisons with ISRO designs; real time monitoring of maneuvers; post-maneuver reconstruction; and mission total ΔV tracking and prediction.

The agreed maneuver design process involved both an ISRO design and a JPL design based on the JPL orbit determination solution. ISRO would prepare the relevant interface files describing their maneuver design (MPDF, MTPF) and an MPF for validation. JPL then compared both designs with respect to several attributes (burn start time, burn duration, delta-mass, ΔV, right ascension, declination). The projected effects on the Mars target orbit were also compared (e.g., B-plane coordinates, MOI epoch). An additional analysis involved a propagation using the ISRO design with the JPL models, and comparing this result with the propagated JPL design. For the later scheduled TCMs (TCM-3 and TCM-4), the next scheduled TCM was recomputed following each orbit determination and propagated forward to the MOI. The trend in design parameters for the upcoming TCM and the effects on B-plane targeting were analyzed and discussed during weekly team teleconferences. In general, the differences between the two designs were very small. ISRO would ultimately make the decision as to which maneuver design would be implemented. Post-maneuver reconstructions were performed by both ISRO and JPL.

8. MOM Trajectory

An informal "Pre-TAA" analysis performed by JPL mission designers using early trajectory information provided by ISRO on a MOM "Fact Sheet" was used to verify the feasibility of ISRO's MOM trajectory design; no formal report of optimality was published given the lack of a TAA. However, this pre-TAA analysis confirmed that the ISRO trajectory design was feasible. Given that MOM conducted its Trans-Mars Injection (TMI) twelve days after MAVEN launched (see section 13), the trajectory was almost identical to that of MAVEN. The target orbit at Mars was elliptical 372 km periapsis altitude x 80,000 km apoapsis altitude.

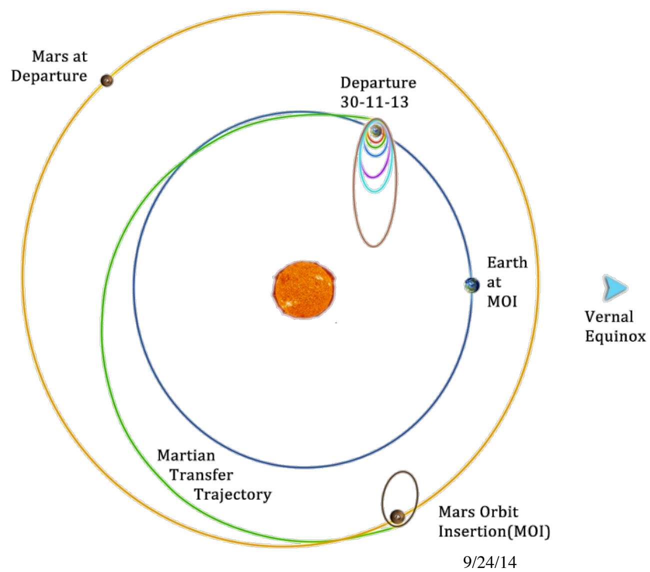

Figure 2. MOM Trajectory

9. Significant MOM Mission Attributes

A few significant attributes of the MOM mission had an impact on navigation processes: the use of S-band for telecommunications (see section 10), the use of an Earth orbit phase (see section 12), the use of unbalanced thrusters (see section 14.2), and intra-team communication between navigators that were geographically separated by 12.5 hours (see section 20.1).

10. S-Band Telecommunications

Whereas most current missions to Mars use X-band for telecommunications (7.145-7.190 GHz uplink, 8.400-8.450 GHz downlink), MOM utilized S-band (2.110-2.120 GHz uplink, 2.290-2.300 GHz downlink). As a result, the data noise was greater for both Doppler and Delta-DORs and the radio signal was more sensitive to charged-particle perturbations from Earth's ionosphere and interplanetary plasma. As an example, see Fig. 3 below for a plot showing the differences between S-band and X-band on Doppler Measurement Error for different compression times T.

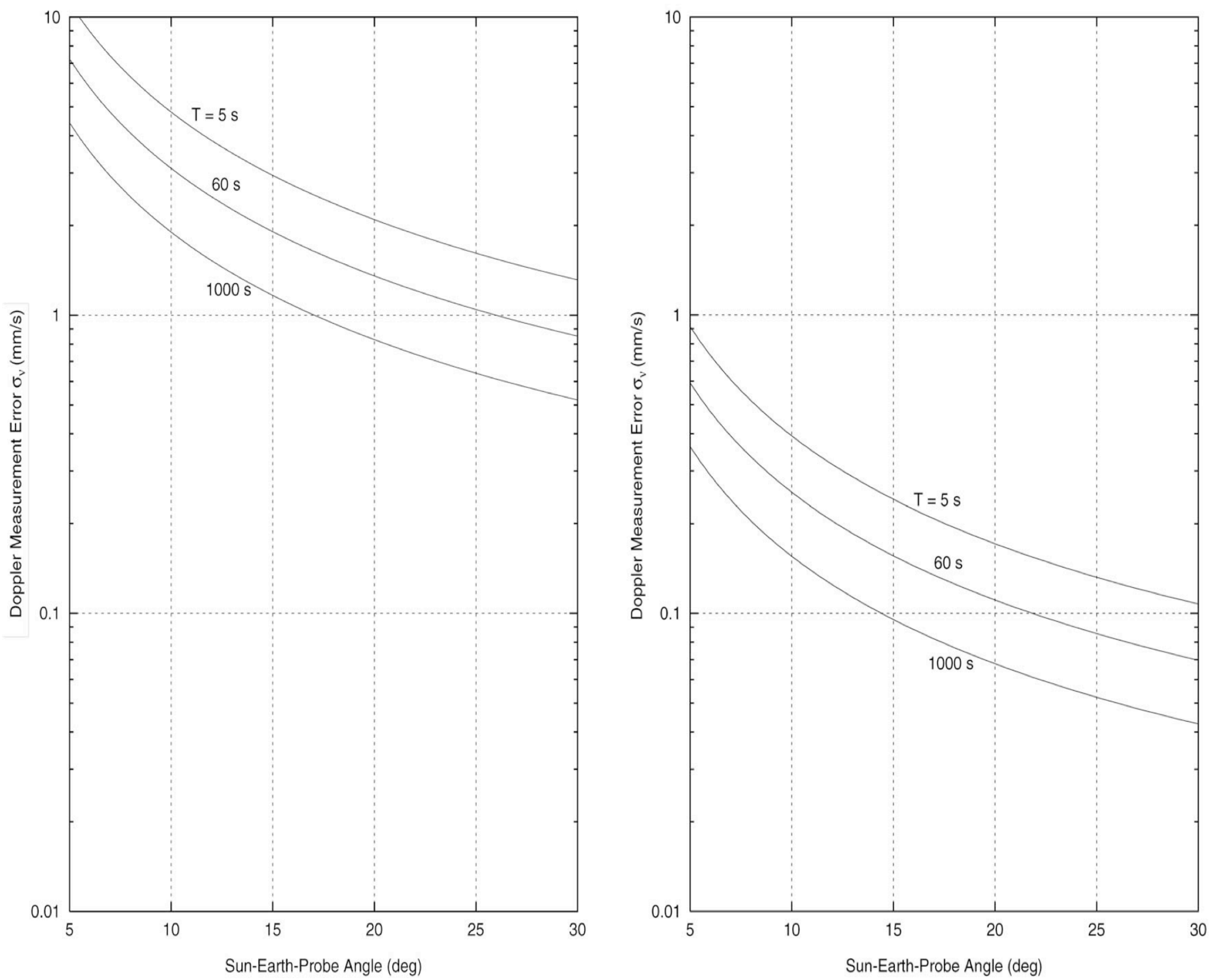

Figure 3. Doppler Measurement Error (mm/s): S-up/down (left), X-up/down (right) [10]

Another consequence of MOM's use of S-band telecommunications was that the DSN's Madrid complex could not be used for 2-way communications. Deep Space S-band uplink is not available at Madrid tracking stations (per agreement between NASA and the Secretaria de Estado de Telecomunicaciones para la Sociedad de la Informacion (SETSI)) due to a conflict with IMT-2000 mobile telecommunications users [11]. MOM's Doppler tracking from Madrid was thus necessarily downlink only, so not useful for navigation purposes.

11. MOM Launch

MOM was launched 05-Nov-2013 09:08:26 UTC from the Satish Dhawan Space Centre in Sriharikota, India on an ISRO Polar Satellite Launch Vehicle (PSLV) C-25, one of most reliable launchers in the world [12]. Because the planned launch date changed late in the process, the actual launch day trajectory was received only one week in advance. Arrangements had been made for several facilities to track MOM after launch, including antennas at Cuiaba (Brazil), Alcantara (Brazil), on the island of Mauritius, Bangalore, and the DSN's Madrid and Goldstone facilities. As a contingency, arrangements had also been made with USSTRATCOM to track the launch. The PSLV injection state accuracy was extremely good; MOM's achieved Earth orbit injection was 248.4 km perigee and 23,550 km apogee at an inclination of 19.27 degrees versus a planned orbit of 250 km x 23,500 km at 19.2 degrees [13].

12. Earth Orbit Phase

Unlike many other Mars missions, which generally launch on a direct interplanetary trajectory, MOM had an Earth Orbit Phase consisting of 6 apogee-raising maneuvers to pump up the energy, which included one partial burn and a make-up burn, concluding with the TMI. These phasing maneuvers performed at perigee did provide opportunities to rehearse critical maneuvers that were planned for later on in the mission. All of these Earth centered maneuvers utilized only MOM's main 440 Newton Liquid Apogee Motor (LAM); the eight 22 Newton attitude control system (ACS) thrusters were not used.

The Earth Burn Maneuvers (EBN) numbers 1, 2, and 3 were successfully executed on successive days 06-Nov-2013, 07-Nov-2013, and 08-Nov-2013. EBN-4 was scheduled to be performed on 10-Nov-2013; however, MOM's main engine did not function properly. Because the main engine had fired for only 0.7 seconds, in fault recovery the ACS thrusters fired for approximately 250 seconds, delivering 35 m/s ΔV compared to a planned main engine burn of 318.8 seconds with 130 m/s ΔV. The ISRO and JPL teams conferred in real time and confirmed the partial burn. At this time, both the DSN and MDNAV were seeing a very unstable lock, with residuals around 25 kHz. JPL MDNAV used the obtained information to quickly build a guess-estimated trajectory with a 35 m/s burn in place of the planned 130 m/s burn and uploaded it to the DSN. JPL MDNAV also informed the DSN Operations Chief to generate antenna predicts based on the revised ephemeris. In the mean time, the spacecraft was in and out of lock, and eventually, the DSN completely lost lock with MOM. When the DSN Operations Chief switched to the newly generated JPL MDNAV trajectory, the DSN regained lock with a residual near 8 Hz. With the revised predicts set, the DSN remained in lock until the end of the track. The following day 11-Nov-2013 a make up burn EBN-4B was performed.

Post-anomaly analysis revealed that the primary coil of the solenoid flow control valve was used successfully for the first three orbit-raising operations. However, during EBN-4, the redundancies built-in for the propulsion system were exercised, namely, (a) energizing both the primary and redundant coils of the solenoid flow control valve of the LAM and (b) logic for thrust augmentation by the ACS thrusters, when needed. It turned out, however, that when both primary and redundant coils of the LAM were energized together, the propellant flow to the LAM stopped. The thrust level augmentation logic, as expected, came in and the operation continued using the ACS thrusters.

After the EBN-4/EBN-4B pair of maneuvers, EBN-5 was successfully executed on 15-Nov-2013. Figure 4 below shows detail of the 5 planned EBN maneuvers (white) and the EBN-4B make-up maneuver (yellow).

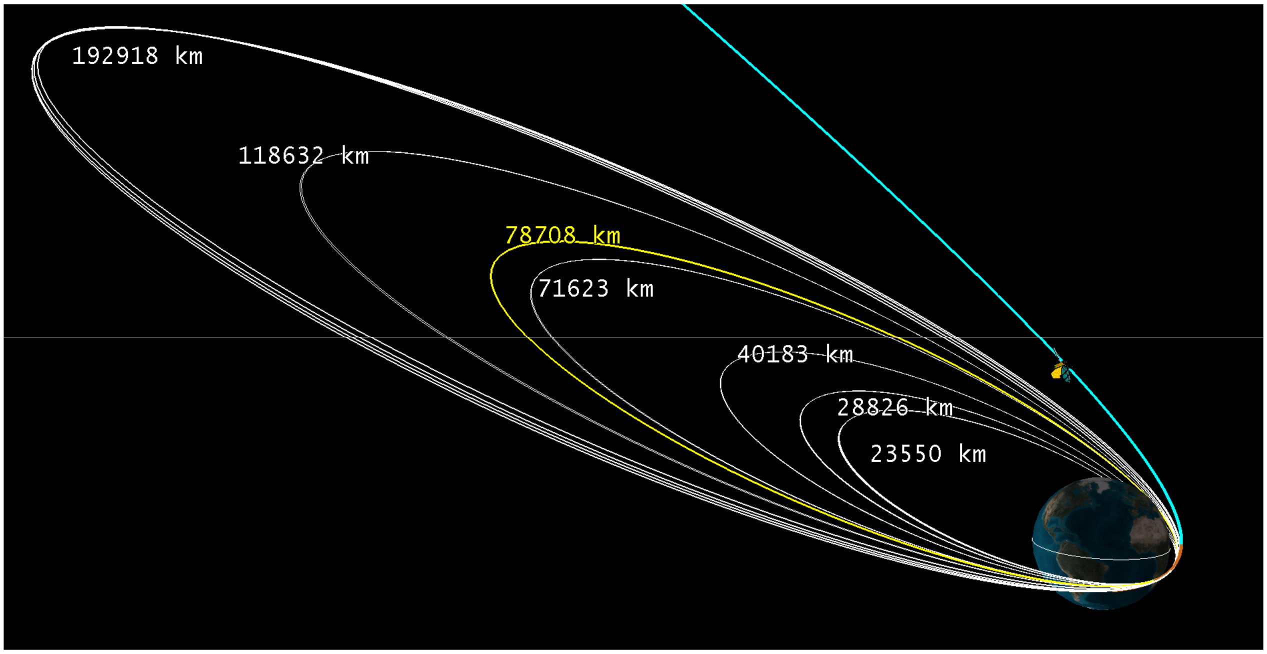

Figure 4. Earth Orbit Phase Maneuvers

13. Trans-Mars Injection

On Saturday 30-Nov-2013 19:19 UTC, MOM's Trans-Mars Injection (TMI) maneuver was performed (shown in blue in Fig. 4 above). This 23-minute burn completed the series of main engine burns and imparted the necessary ΔV for the spacecraft to leave Earth orbit and begin the interplanetary cruise to Mars. Remaining TCMs were planned to use only the ACS thrusters to setup the critical main engine MOI burn on 24-Sep-2014; this plan changed late in the cruise during the final approach to MOI (see section 14.4.2).

Preliminary indications were that the TMI burn appeared to have performed close to nominal. The first post-burn tracking data from Canberra looked good with residuals around 30 Hz, indicating a good burn. The JPL MDNAV liaison at ISRO also reported that the full ΔV was achieved. Reconstruction of the maneuver showed a very small overburn of 0.042% (648.14 m/s as opposed to a nominal 647.87 m/s). The MOM spacecraft crossed the lunar orbit distance around 00:00 UTC, 02-Dec-2013, and left Earth's sphere of influence on 04-Dec-2013.

14. Cruise

During MOM's 298 day cruise, major work included the planning, execution, and analysis of TCMs (see section 14.1 and section 14.4); "dealing with desats" (see section 14.2); and Indian Deep Space Network (IDSN) tracking data validation (see section 14.3).

14.1 Trajectory Correction Maneuvers (TCMs), Part I

As a general rule, a small number of TCMs are planned for Mars missions. Approximately four TCMs are usually scheduled, with 2 contingency maneuvers scheduled late on approach (which are cancelled if conditions are nominal). The MOM mission was planned according to this "standard" schedule, with four TCMs planned during cruise and two contingency TCMs late on approach. This section discusses the early TCMs (TCM-1 and TCM-2).

14.1.1 TCM-1

MOM's first TCM (TCM-1) was successful on 11-Dec-2013 01:00 UTC, with a burn of 44 seconds and a ΔV of 7.74 m/s. The TCM-1 performance was very accurate. Just prior to TCM-1, the real time Doppler residuals were showing near 0 values. Then there was a loss of lock after the turn-to-burn maneuver. When the spacecraft was locked up again, residuals were near 0 as before (see Fig. 5 below). Reconstruction showed a 0.65% overburn.

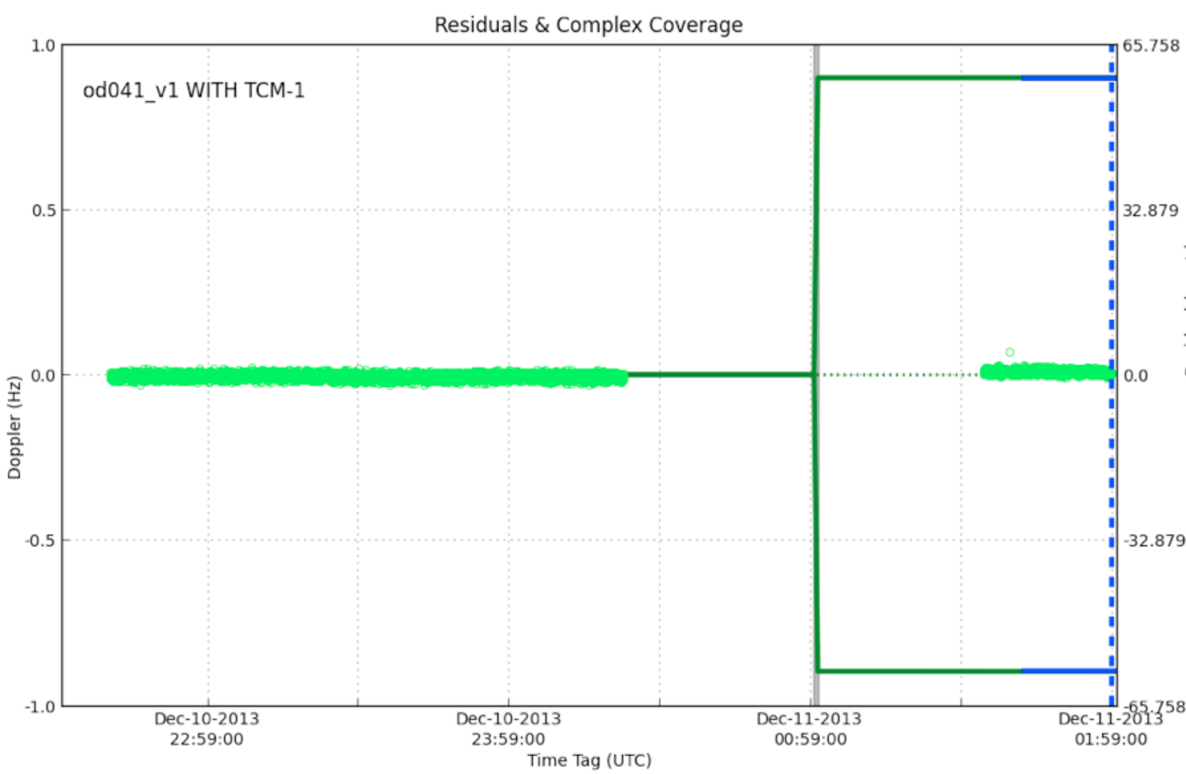

Figure 5. TCM-1 Real-time Residuals with TCM-1 Modeled

14.1.2 TCM-2

On 11-Jun-2014, MOM completed TCM-2. The MOM project reported a successful burn and telemetry showed nominal performance. Real-time residuals confirmed a burn very close to the nominal plan. OD estimates showed a 15.936 second burn resulting in a ΔV of about 1.590 m/s versus a planned 1.577 m/s, a 0.77% overburn.

14.2 Angular Momentum Desaturations (AMDs)

The MOM spacecraft had an unbalanced thruster alignment, which during cruise resulted in very frequent AMDs. Prior to 02-Jun-2014, there were generally 6 to 10 per day, each taking approximately 89 seconds to execute; on 02-Jun-2014 there was a solar array attitude change that caused the frequency of AMDs to increase even more, from 7 to 11 per day. A great deal of effort was expended accounting for all the AMDs; the uncertainties associated with the AMDs were a major source of the uncertainty in MOM's B-plane error ellipse. Fortunately for the navigation team, the largest component of these AMDs was in the Y-axis (spacecraft Roll), which was observable in the line-of-sight Doppler. An example plot of the number of AMD events per day and the spacecraft reference frame are shown in Fig. 6 and Fig. 7 below:

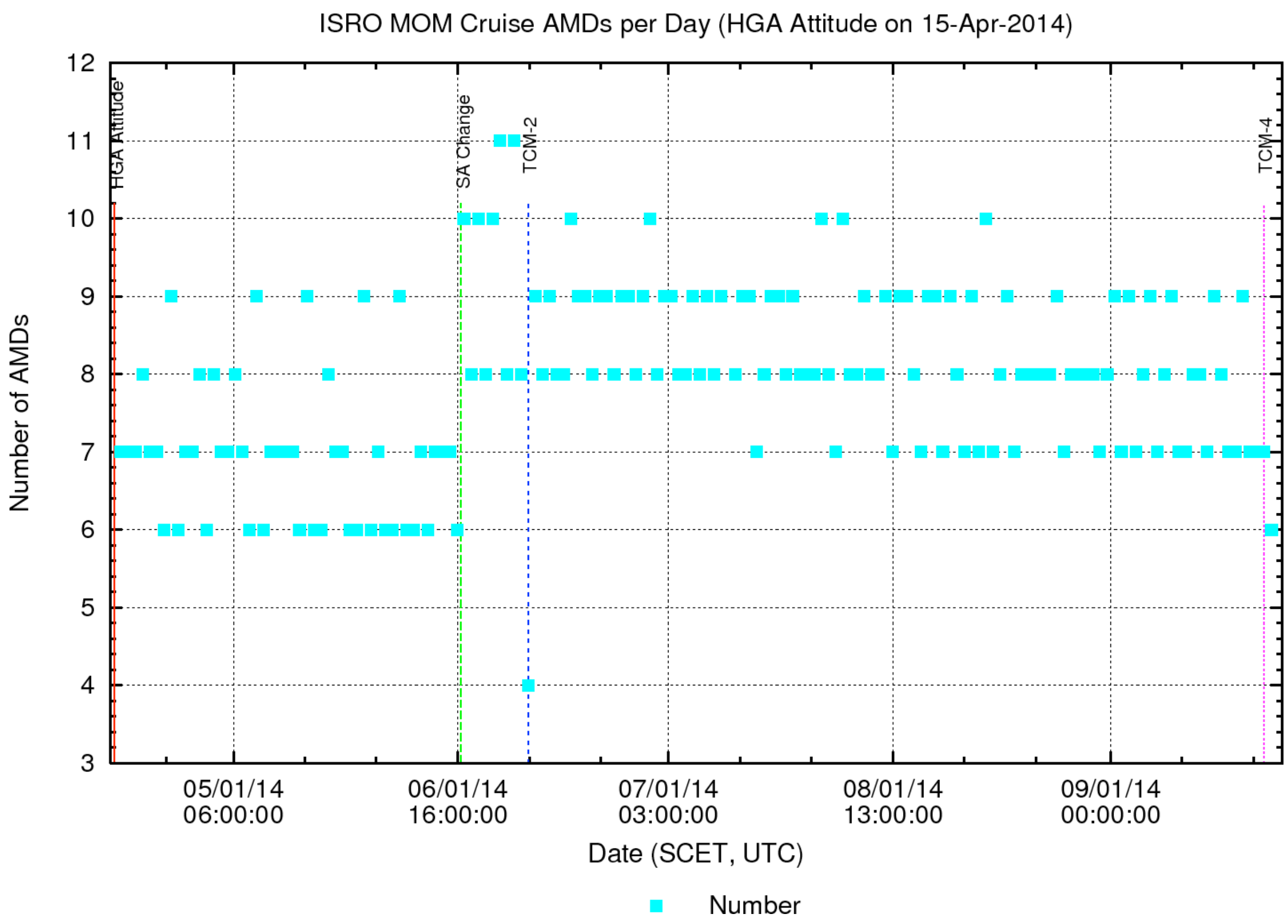

Figure 6. MOM AMDs per Day

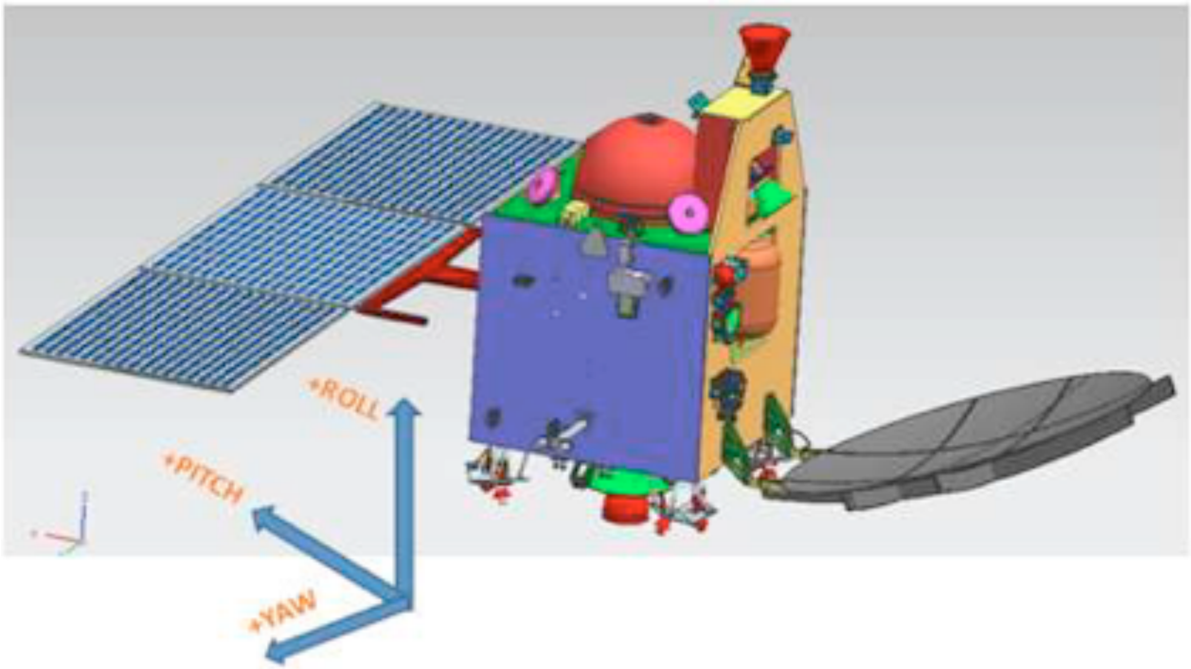

Figure 7. MOM "On Orbit Configuration"

S/C Body X == Yaw, S/C Body Y == Roll, S/C Body Z == Pitch

An example of the ΔV magnitude of the AMDs by component is shown in Fig. 8 below (ΔVy=dVy=1.3mm/s=spacecraft Roll, visible in line-of-sight Doppler):

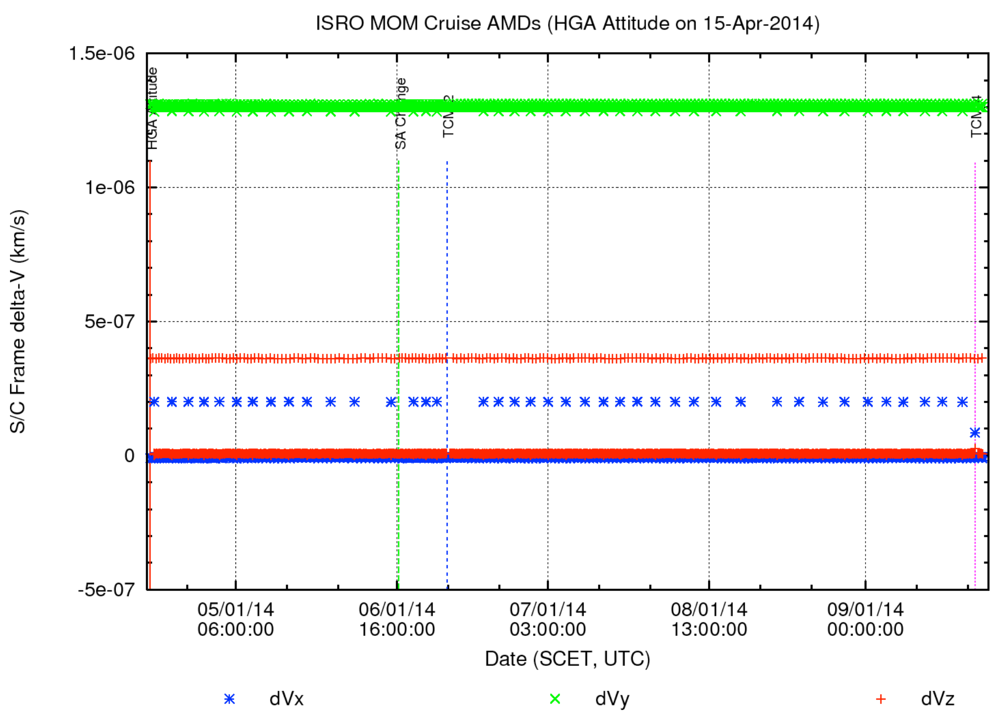

Figure 8. MOM AMD Component-wise ΔV

Table 3 below shows the final counts of MOM AMD activity during cruise after a solar array orientation change on 02-Jun-2014 01:10 UTC, as well their frequency and component-wise average magnitude. Reconstructed AMDs up to 24-Sep-2014 00:00 UTC included:

Table 3. Reconstructed AMDs

Axis/Type	Count	Frequency (Hours)	ΔVx S/C Frame (km/s)	ΔVy S/C Frame (km/s)	ΔVz S/C Frame (km/s)
Z/Pitch AMDs	28	95.12	0.20060e-06	1.28396e-06	0.00201e-06
Y/Roll AMDs	759	3.60	-0.00492e-06	1.29991e-06	0.00720e-06
X/Yaw AMDs	153	17.95	-0.00987e-06	1.31184e-06	0.36275e-06

14.3 MOM Tracking Data

The primary source of tracking data for the MOM mission was NASA/JPL's Deep Space Network (DSN); DSN tracking data included 2-way Doppler, 2-way range, and Delta-DOR. No special processing for DSN Doppler and range were required for MOM; however, the Delta-DOR tracking data received a great deal of attention due to its special contribution to interplanetary orbit determination solutions.

14.3.1 DSN Delta-DOR Sessions

Delta-DOR has proven to be an essential tracking data type for interplanetary missions. Doppler and range are primarily 1-D measurements (radial) and the Delta-DORs are needed to resolve the other dimensions in the plane of sky. Accordingly, Delta-DOR was an important part of the MOM tracking plan. A total of 44 DSN Delta-DOR sessions were conducted for MOM, starting in late June 2014 and extending until 22-Sep-2014 just prior to the MOI. Of the tracking sessions, 23 were on the Goldstone-Madrid baseline, and 21 were on the Goldstone-Canberra baseline.

For each data delivery, the DSN Delta-DOR team provided a recommended data weight based on the expected random error of each point for use in the orbit determination process. The expected error is substantially larger for MOM than for most other spacecraft due primarily to the elevated effects of Earth's ionosphere on S-band tracking data. The error estimate included effects due to thermal noise, station instrumentation, fluctuating troposphere, fluctuating ionosphere, and solar plasma. Systematic errors in UT1, polar motion, troposphere, ionosphere, station location, and quasar coordinates are modeled separately in the OD software.

On the Goldstone-Canberra baseline, the data weight was always in the range of 0.4 ns to 0.6 ns. However, primarily due to lower elevation tracks on the Goldstone-Madrid baseline and the resultant greater ionosphere effects, it was necessary to carefully evaluate the data weights on a per-pass basis (the ionosphere is hard to model when looking toward the equator at low elevation). The angular separation between spacecraft and selected quasar was also a factor in the recommended data weight. Per-pass data weights on the Goldstone-Madrid baseline generally varied from 0.4 ns to 1.5 ns, increasing as the mission progressed and the declination of the trajectory was increasingly southward. A maximum data weight of 4.7 ns was recommended for one track that showed a large ionosphere perturbation in the data.

B-plane mappings are typically used by navigators to show how TCMs, dynamic model errors, perturbative effects of AMDs, different data type mixes, etc. affect the spacecraft trajectory with respect to arrival at the target body [14]. The power of the Delta-DOR data type is shown in the B-plane plot Fig. 9 below; the three error ellipses using Doppler (F2) and range (SRA) only are significantly larger reflecting larger uncertainty, and they are oriented differently than the one that includes the Delta-DOR data. Similarly, as seen in the right hand portion of Fig. 9, the Mars arrival time was less uncertain when the Delta-DOR data was included in the solution.

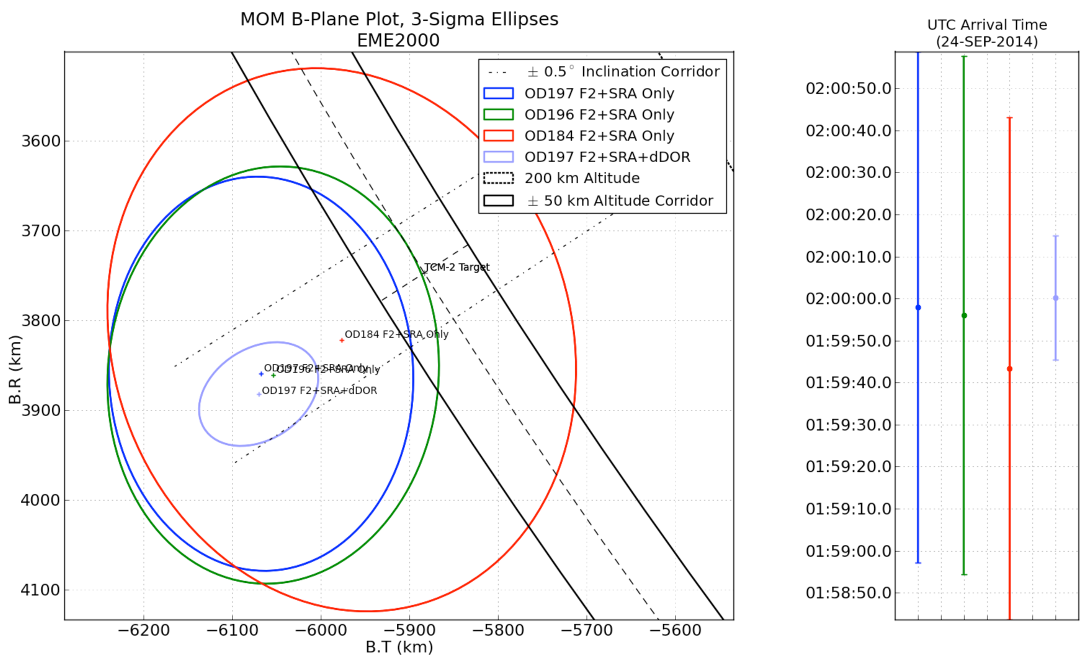

Figure 9. Influence of Delta-DOR on the B-Plane vs. Doppler and Range Only

Starting in late November 2014, the process of using mixed agency NASA/ISRO baselines commenced (i.e., a baseline consisting of one DSN antenna and the IDSN 32-meter antenna). Since the MOI, all of MOM's Delta-DOR tracks have been on the Madrid-Bangalore or Canberra-Bangalore baseline. These mixed baseline Delta-DORs have been for capability testing and/or IDSN station validation purposes only; they have not been used in the JPL orbit solutions.

14.3.2 ISRO Tracking Data

As part of the navigation responsibility, JPL MDNAV was also tasked with assisting ISRO in an assessment of Doppler and range tracking data collected via the IDSN, in particular the 32-meter station located near Bangalore known as DSS-95 in the DSN numbering. This was one of the major activities during cruise. In the original proposal [1], it was planned that DSS-95 would be the prime station for mission operations, with substantial backup support from the DSN, including times when the spacecraft was not in view from DSS-95. In practice, most of the tracking data used in JPL MDNAV solutions was DSN data. DSS-95 Doppler and range data was routinely sent to JPL for analysis of the quality of IDSN data compared to DSN data. Data analyses progressed from pass-throughs at the beginning of the analysis process to full orbit determination fits in combination with DSN data towards the end. A final analysis report from JPL MDNAV to ISRO Flight Dynamics documented what was observed when fitting IDSN and DSN tracking data and predicting the B-plane conditions and uncertainties at encounter for a data arc ending 3 days before MOI.

The assessment of IDSN tracking data occurred throughout MOM's cruise phase, and continued to a limited degree in the orbit phase as well. Data received during cruise is best suited for analysis due to the simpler dynamic models involved. In the orbit phase, gravity field model errors, for example, can significantly impact the ability to correctly analyze the data. Although the tracking data were analyzed on an ongoing basis throughout cruise, the focus of the final analysis was limited to the data acquired beginning on 26-Jul-2014 and ending 3 days before MOI. The ongoing partial analyses were performed with the latest OD solution; the final report was based upon JPL OD221_v1.

The IDSN tracking data analysis basically consisted of verifying that the two-way Doppler and range data scatter levels from the ISTRAC station were well-understood and consistent with forecasted performance. For MOM, there remained some questions as to the accuracy of the ISTRAC station location (for DSS-95) and time-tag stability. An estimate of a revised station location determined by the orbit determination was provided in JPL MDNAV's final report; there was an estimated change of approximately 0.5 meter in station radius from the spin axis and longitude. The difference in station location estimate led to B-plane differences of approximately 1 km.

Analysis showed that IDSN Doppler was compatible with the DSN Doppler to the level of several limiting factors. The most noticeable characteristic of the IDSN range was higher noise (3.8 m for ISRO compared to 0.6 m for the DSN). Limiting factors included the increased sensitivity of S-band signals to media perturbations, uncertainty as to the DSS-95 station location, the DSS-95 proximity to the geomagnetic equator, and the frequent AMDs that limited both higher precision trajectory determination and the accuracy to which solar radiation pressure could be modeled. There were also some mechanical changes to the DSS-95 antenna during the data collection period that improved the data quality. As issues were resolved with the IDSN station operation, and media calibrations became available for both the neutral and charged particles, the pass-through residuals showed increasing agreement with their DSN counterparts.

Figure 10 below shows post-fit Doppler residuals from a fit of DSN and IDSN Doppler, range, and Delta-DOR data collected 10-Sep-2014 through 17-Sep-2014 (60 second count time, scale is +/- 2 mm/s). The IDSN DSS-95 residuals are shown in green; other colors are associated with DSN antennas. As can be seen, results are generally congruent with DSN Doppler; the combined Doppler residuals show a small bias of 0.0011 Hz (0.07 mm/s) and a standard deviation of 0.0074 Hz (0.49 mm/s).

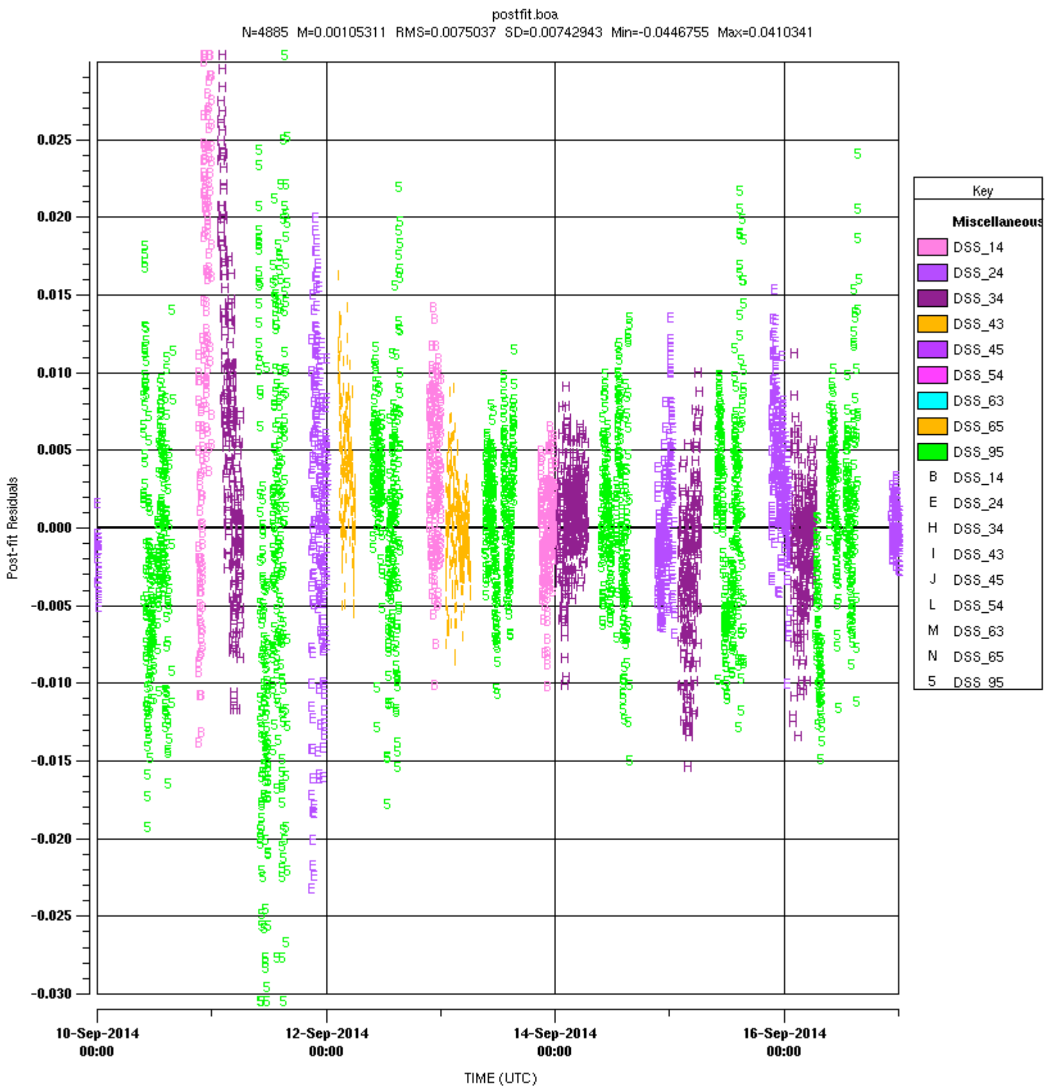

Figure 10. DSN/IDSN Doppler Residual Comparison (Hz) (IDSN=DSS-95, Green)

Figure 11 below shows post-fit range residuals from a fit of DSN and IDSN Doppler, range, and Delta-DOR data collected 10-Sep-2014 through 17-Sep-2014 (units = DSN Range Units (RU), 1 m ~ 7 RU, spacecraft transponder delay removed). ISDN data residuals are again shown in green. There is a small bias of around -0.06 meter and a standard deviation of about 1.2 meters. This data, taken close to the MOI, reflects several IDSN system changes implemented during the course of the MOM mission that improved the accuracy of the IDSN range data.

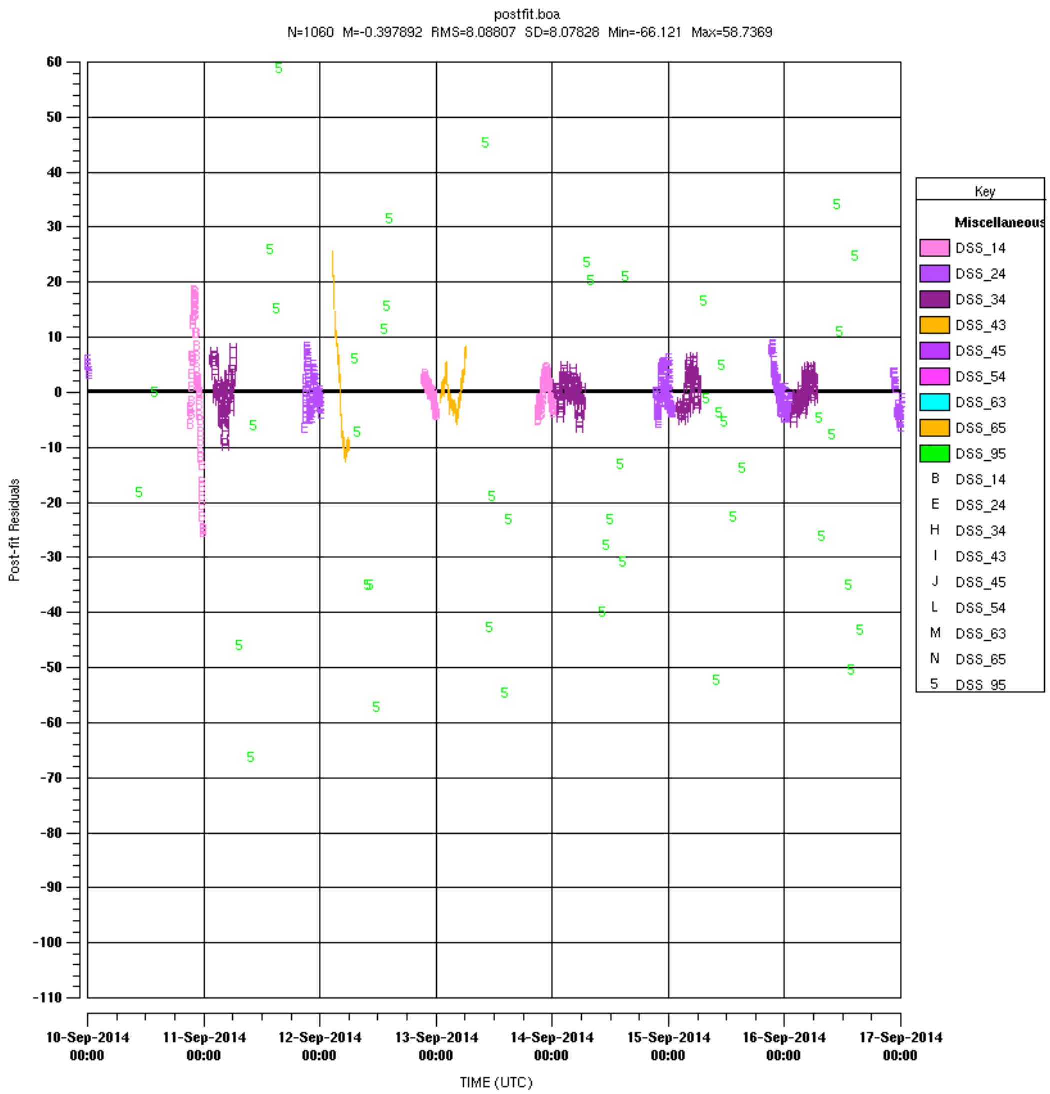

Figure 11. DSN/IDSN Range Residual Comparison (Range Units) (IDSN=DSS-95, Green)

14.4 Trajectory Correction Maneuvers (TCMs), Part II

Whereas MOM's early TCMs were executed more or less according to plan, the later scheduled TCMs illustrated well the old adage that "the only constant is change". This section discusses the later TCMs (TCM-3, TCM-4, TCM-5A, and TCM-5B).

14.4.1 TCM-3

Between late May and mid-August 2014, MOM's TCM-3 schedule changed several times: it was first scheduled for August 14, then August 21, then August 19, then preliminarily cancelled, then reinstated for August 30, and ultimately cancelled as ISRO determined it to be unnecessary.

14.4.2 TCM-4

As with TCM-3, the TCM-4 schedule changed frequently, and very close to the mission critical MOI. TCM-4 was originally scheduled for September 14 (MOI-10 days), then MOI-15 hours, then MOI-41 hours, then MOI-24 hours, and finally MOI-41 hours (again). The frequent changes in the schedule for the last two TCMs greatly increased the difficulty of scheduling DSN resources to provide the necessary tracking, given that DSN tracking time is generally very close to completely subscribed at all times. Complicating the tracking network scheduling for TCM-4 was NASA's MAVEN spacecraft also entering Mars orbit on 22-Sep-2014, just two days prior to MOM's MOI. This greatly limited the antenna resources available to MOM, particularly on short notice. The negotiation process required of the DSN scheduling team and the flight project schedulers was very challenging and the potential for risks to multiple flight projects (including MOM) was non-trivial.

However, changes for TCM-4 were not limited to schedule changes only. The original TCM-4 was a small maneuver using the 8 ACS thrusters at MOI-10 days, intended to lower periapsis altitude by approximately 200 km. Approximately a month prior to MOI, the original TCM-4 design was replaced by a 4 second test firing of MOM's main engine (the LAM) in order to gain confidence that the MOI would be successful. Due to a failed pressure regulator, there was uncertainty as to the viability of the main engine in blowdown mode for the MOI[2]. This uncertainty raised potential planetary protection issues that were ultimately resolved after the successful TCM-4/LAM Test conducted only 41 hours prior to the MOI. The TCM-4/LAM Test was designed based on OD210_v1 (same OD as used for the MOI design). ACS thrusters were planned to maintain attitude (no turn/burn for the LAM test). The scheduled firing was later refined to 3.968 seconds based on revised thrust and mass flow rates provided by ISRO; the TCM was redesigned using OD217_v1, with the final design using OD220_v1. In the trend analysis prior to TCM-4, the periapsis altitude had grown a few kilometers with each OD to around 725 km, causing some concerns; the TCM-4/LAM Test was targeted to lower the periapsis altitude into the acceptable range slightly greater than 500 km though the new target did lie slightly outside the originally planned inclination corridor, a consequence of not changing the spacecraft attitude for this burn. Thankfully, the TCM-4/LAM Test was a success; it was triumphantly announced by Indian broadcast news almost immediately upon test completion. The TCM-4/LAM Test had a 1.01 % overburn due to pre-LAM thruster activity (see Fig. 12 below).

[2] As early as October 2012 (pre-launch), *The Times of India* was already citing re-start of the LAM as a critical challenge in the mission [15]: "An ISRO official said the real challenge in the mission is that the engine has to restart after 300 days when the orbiter enters the Martian orbit.")

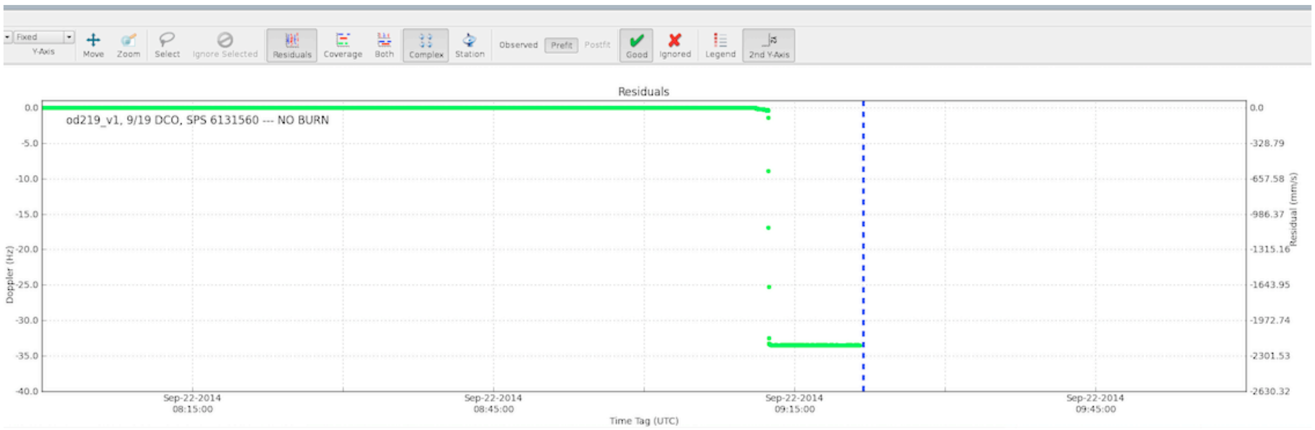

Figure 12. TCM-4/LAM Test Real Time Doppler Residuals (Burn Not Modeled)

Because there had been some uncertainty as to whether or not the LAM would restart successfully in the blowdown mode, a contingency maneuver TCM-4B had also been designed using only the 8 ACS 22N thrusters. TCM-4B was scheduled to be executed 2.5 hours after the TCM-4/LAM Test if it was not successful. The TCM-4B contingency maneuver design was not necessary given the successful TCM-4/LAM Test.

TCM-4B also set up an "MOI Plan B" contingency maneuver involving a 94-minute burn using only the 8 ACS thrusters. The achieved periapsis altitude from MOI-B would only have been 150 km versus the planned 500 km for a nominal MOI burn. The orbit eccentricity was close to 1, and the orbital period 49.2 days. Both JPL and ISRO orbit propagations showed that if MOI-B were executed, the spacecraft would impact the Mars surface in less than 6 months when coming near periapsis. It was also not entirely clear that MOI-B would not use all of MOM's available propellant. Analysis showed a high probability of a requirement to perform a periapsis raise maneuver at every apoapsis for MOM's continued survival, which was not consistent with the low remaining propellant budget projected after MOI-B. The MOI-B plan thus would not last 50 years and would not have met the COSPAR (Committee on Space Research) planetary protection requirements (probability of impact requirement no greater than 0.01 for 20 years after launch and no greater than 0.05 for the period 20-50 years post-launch) [16]. Again, due to the success of the TCM-4/LAM Test, activation of the MOI-B plan was not necessary.

14.4.3 TCM-5A and TCM-5B

Two contingency TCMs had also been planned (fairly standard for Mars missions), but had not been pre-designed. TCM-5A was scheduled 24 hours prior to MOI, and TCM-5B was scheduled 6 hours prior to MOI. Both were cancelled as unnecessary given the successful TCM-4/LAM Test. Had they not been cancelled, they would have had to be designed on a very tight schedule given that they were not pre-designed maneuvers.

As of the morning prior to the MOI, the contingency maneuver TCM-5B had not yet been cancelled, though doing a TCM seemed unlikely given post-TCM-4 stability as determined from the accelerometer telemetry data and the OD. At the mission meeting on 23-Sep-2014 that commenced at 09:30 UTC the TCM-5B was cancelled (as was expected). All looked good and stable, and there were no unexpected accelerations per the ISRO flight dynamics team chief.

15. Mars Approach and the B-Plane

Figure 13 below shows how MOM's B-plane error ellipses evolved over the course of the orbit determination. The uncertainties are the formal 1-sigma numbers. B-plane error ellipse values are labeled as "SMAA" for semi-major axis, "SMIA" for semi-minor axis, and "Theta" for the ellipse orientation. There was a great deal of interest from ISRO in understanding the evolution of MOM's B-plane error ellipses, particularly when the orientation of the error ellipses changed and the size of the error ellipses changed slowly. Understanding this behavior was a frequent topic on the weekly telecons, and during discussion at TIM #4 resulted in ISRO requesting daily OD deliveries in order to monitor the shrinkage of the B-plane error ellipses. As noted in section 14.3.1, the data types and volumes included in the OD solution had influence on the orientation of the error ellipses, and the large number of AMDs contributed to the relatively slow shrinkage of the axes.

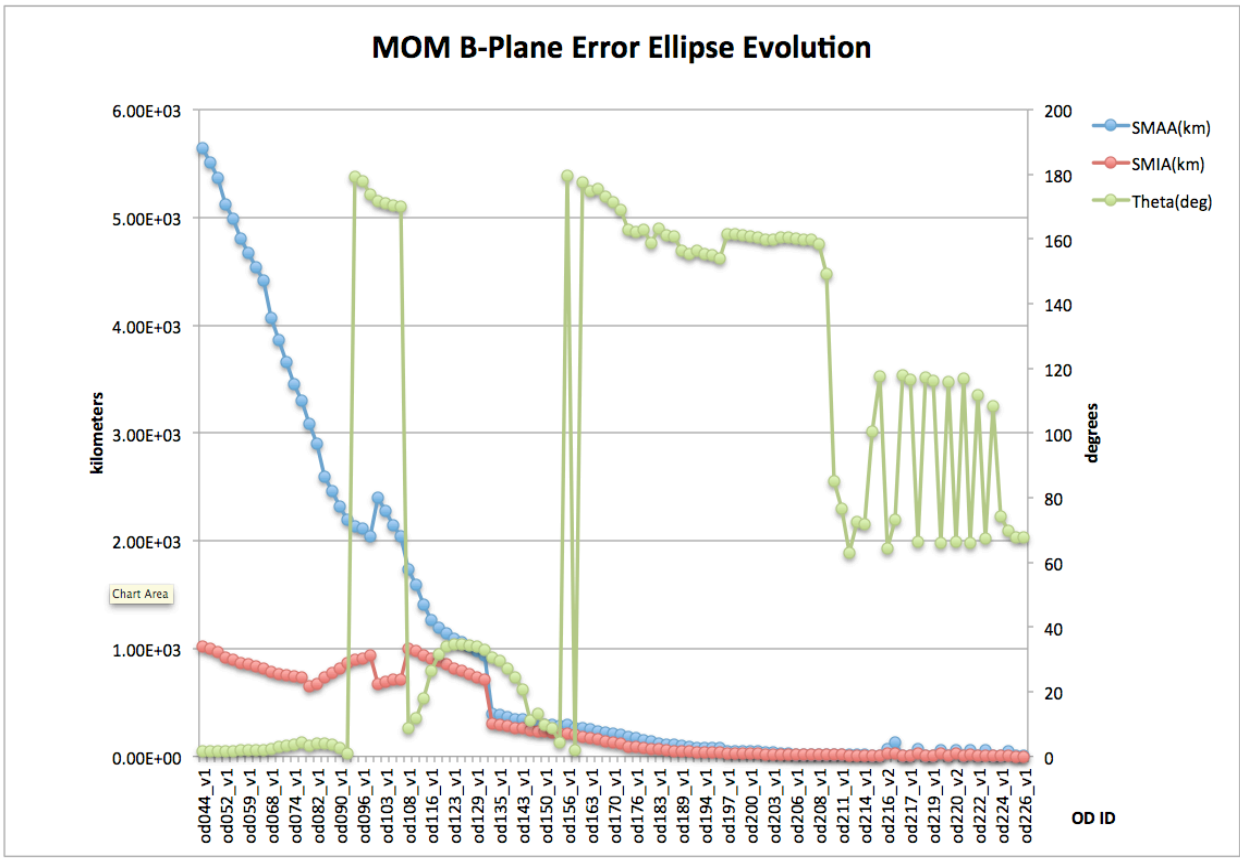

Figure 13. MOM B-Plane Error Ellipse Evolution

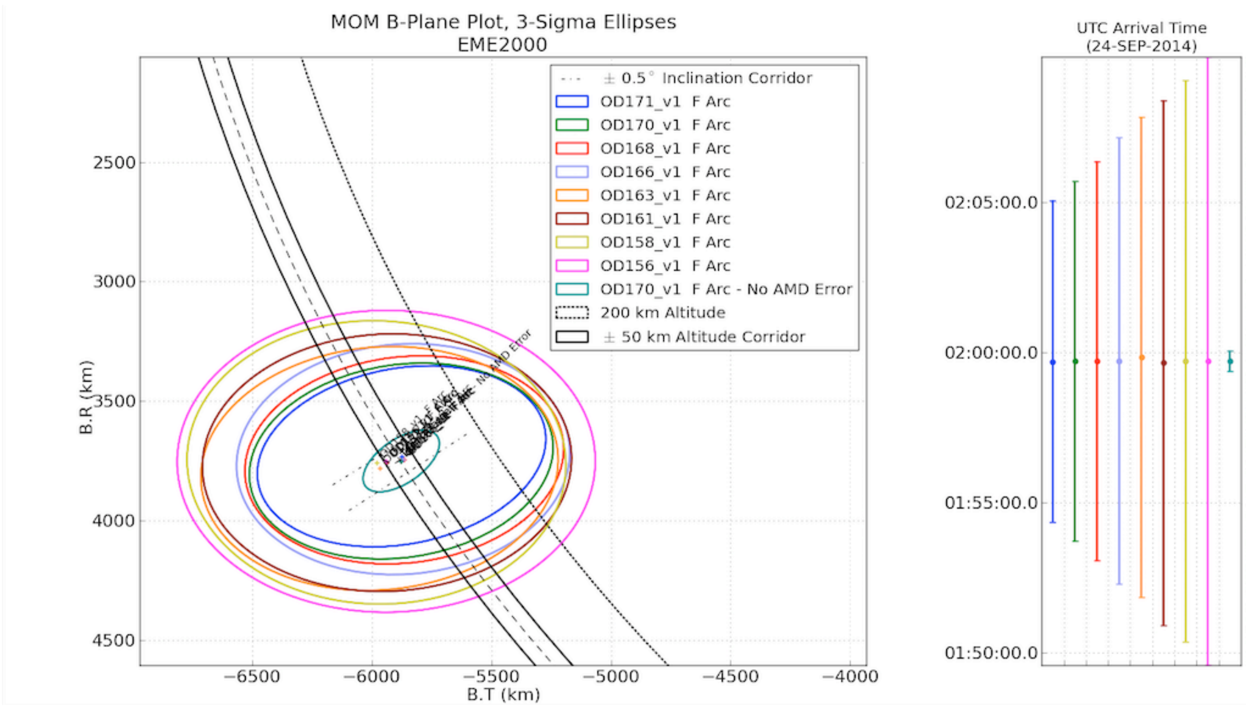

Figure 14. Effect of AMDs on B-Plane Uncertainty

Figure 14 above illustrates the relative sizes of the formal OD solution error that included future AMD uncertainties and the residual OD solution error without those future AMD uncertainties. It also shows that the B-plane changes from solution to solution were smaller than this residual uncertainty. The small central ellipse illustrates the effect of assuming no AMD uncertainties.

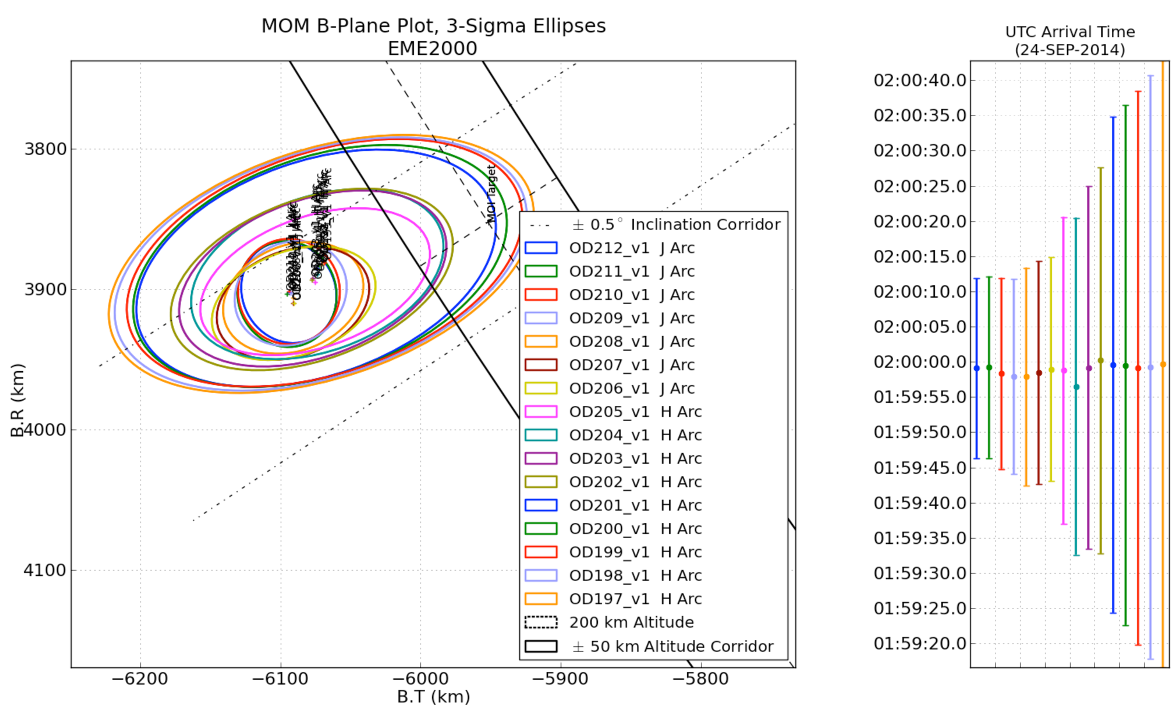

Figure 15. B-Plane 2 Weeks Prior to MOI

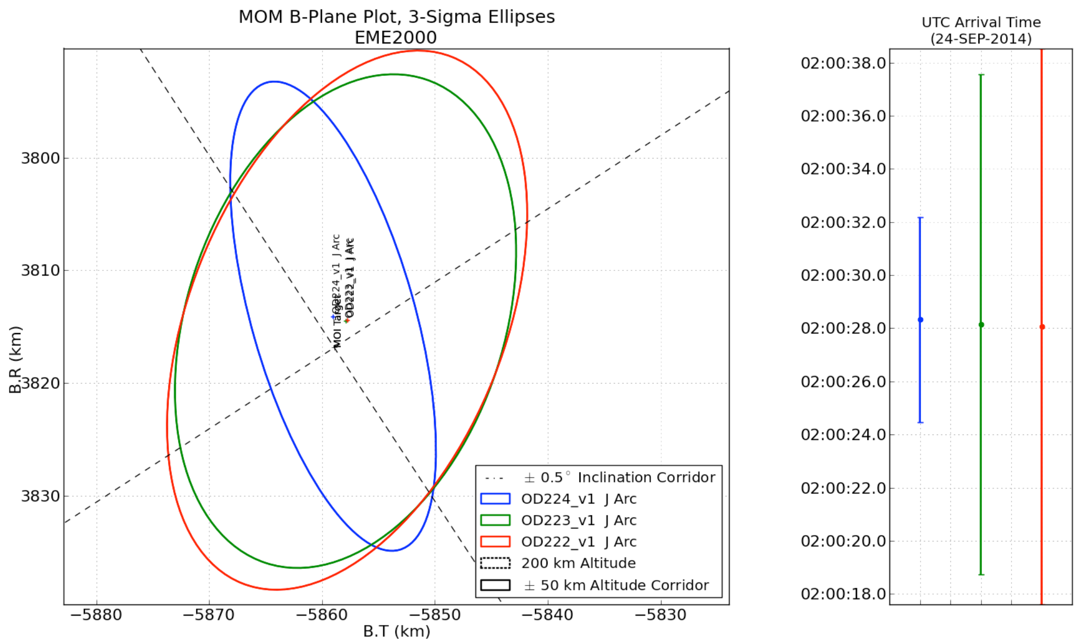

Figure 16. B-Plane 20 Hours Prior to MOI

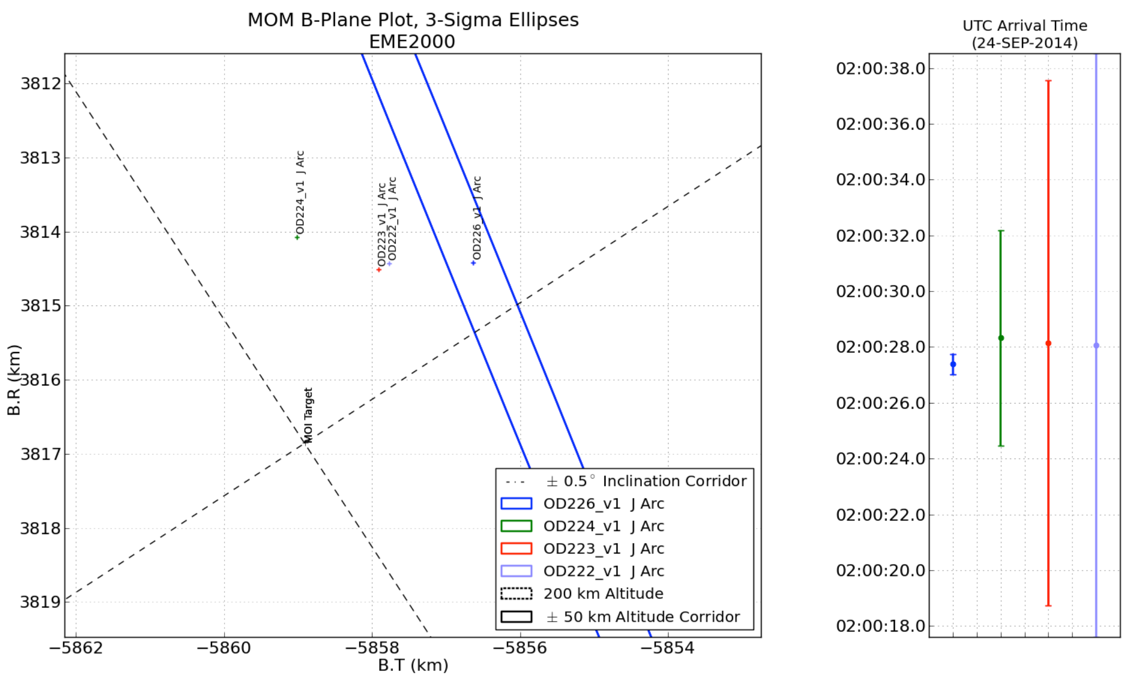

Figure 17. B-Plane Just 2 Hours Prior to MOI

Figure 15 above shows the MOM B-plane 2 weeks prior to MOI and before the TCM-4/LAM Test maneuver. The intersection of the dashed lines shows the target point framed by the nearly square "acceptable" target region of +/- 50 km radius and +/- 0.5° inclination in the B-plane.

Figures 16 and 17 above are zoomed in B-plane plots showing a very slight drift in the trajectory just before Mars arrival.

16. The Mars Orbit Insertion (MOI)

The overall ISRO MOI plan included a complex combination of main engine and ACS thruster firings, operating in eclipse, a communications/tracking blackout caused by occultation, several quick post-occultation telemetry data rate changes, and several transmitter on/off periods with changes made to the downlink frequency. From a JPL perspective, the overall telecom strategy planned during a critical event was extremely complicated.

The MOI maneuver was based on OD210_v1 and was designed/analyzed in the same way the TCMs had been; both ISRO and JPL designed maneuvers, the designs were compared and analyzed (see Table 4 below), and ISRO made the decision as to the desired design for implementation. For the MOI, the ISRO maneuver design was used for the implementation. By 20-Sep-2014, MOI design parameters (maneuver attitude profile and ΔV values) based on OD210_v1 had already been uplinked to the spacecraft, however, the expected thrust and mass flow rate values were slightly changed based on OD217_v1. The modified thrust and mass flow rates were used in the searched maneuver files for both the TCM-4/LAM Test and MOI.

Table 4. MOI Final Design Comparison

Maneuver Parameters	ISRO	JPL	(ISRO-JPL)
Burn Start Time (UTC)	24-SEP-2014 01:47:32.1130	24-SEP-2014 01:47:33.0975	-0.9845 sec
Burn End Time (UTC)	24-SEP-2014 02:11:45.9740	24-SEP-2014 02:11:45.1821	0.7919 sec
Burn Duration (sec)	1453.8610	1452.0846	1.7764 sec
Prop. Mass Spent (kg)	249.4824	249.2327	0.2497
ΔV (m/s)	1098.6610	1097.2300	1.4310
Yaw Bias (deg)	0.0	0.0	0.0
Pitch Bias (deg)	0.0	0.0	0.0

The first step in the MOI sequence was to re-orient the spacecraft to align the thrust vector before firing the engines to reduce the velocity and enable MOM to be captured by Mars. Because of the Mars-Sun-Earth geometry, the orbit insertion necessarily occurred while MOM was in eclipse; MOM entered eclipse 5 minutes before the MOI burn started. The MOI maneuver commenced when the LAM and the 8 ACS thrusters were fired to impart a planned braking velocity of 1098.66 m/s. Four minutes after the burn started, the radio link between MOM and the Earth ground stations was occulted by Mars as planned; MOM continued to execute all operations autonomously. The MOI maneuver was terminated based on accelerometer measurements when the required braking velocity was achieved, thus putting MOM into Mars orbit. Once the burn was complete, the spacecraft was re-oriented to point the antenna to Earth to resume communications.

It was anticipated that during the period immediately following the completion of the MOI burn navigators would be trying to figure out when a signal should and should not be expected from the spacecraft given the complicated sequence of nominal transmitter on/off times and data rate changes that were planned. The on/off times were non-deterministic because they were scheduled relative to the time of the end of the MOI burn, which was determined by the accelerometer measurement. However, knowing roughly when they were supposed to occur was helpful.

Six minutes after the MOI burn ended, the DSN locked up to MOM's signal, and the success of the MOI was confirmed! The Indian Prime Minister Sri Narendra Modi was present at the ISTRAC facility to congratulate ISRO on its success. He addressed the control room immediately upon reception of the signal confirming that MOM was in orbit, congratulating the ISRO team members and “all my fellow Indians on this historic occasion.” [17]

17. MOM Mars Orbit Insertion Results

Preliminary navigation results almost immediately after the MOI showed the burn to be very close to nominal. This was consistent with the ISRO telemetry. ISRO reported 1099.08 m/s from accelerometer data compared to the desired ΔV of 1098.66 m/s. A screen shot of the Doppler residuals is shown in Fig. 18 below, showing how well the actual residuals (light green) trace the predicted residuals (dark green). Real time Doppler residuals were also displayed in the JPL Network Operations Control Center, aka "the Darkroom" and by the JPL MDNAV liaison at ISTRAC. The early estimate of the orbit period was 3.04 days, where the targeted period was about 3.06 days (about 0.65% under plan).

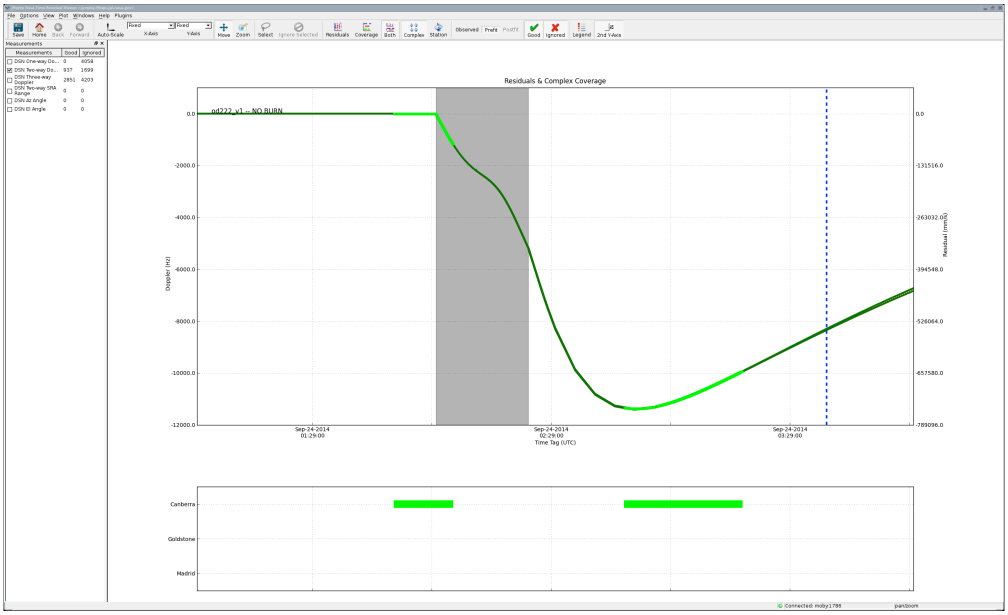

Figure 18. MOI Residuals (Planned vs. Actual)

18. Post-MOI, Plus Comet Siding Spring

A study of MOM's orbit variation about Mars was conducted the day after the MOI. A plot from that study (Fig. 19 below) shows that the periapsis would be fairly stable through early 2019, but would become very low in 2019-2020. Immediate planetary protection issues had been addressed with the MOI but there was something that would need to be done in order to keep MOM from impacting Mars in 2020.

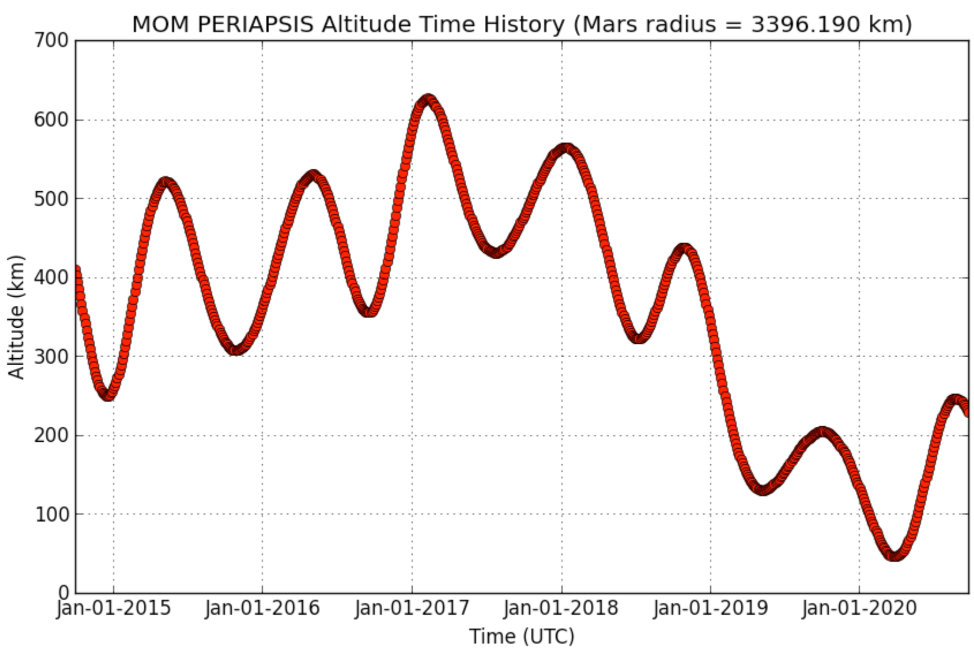

Figure 19. MOM Post-MOI Periapsis Altitude Forecast

A few days post-MOI, both the JPL MDNAV and DSN began plans for on-orbit operations, including planning for mixed baseline Delta-DOR validation, Comet Siding Spring preparations, and the requisite tracking schedule requirements.

Comet Siding Spring's (CSS) scheduled arrival at Mars less than a month after MOM's successful MOI added a new dimension to MOM mission planning. Prior to MOI, there was little attention paid to planning for what MOM would do with respect to the comet. That changed rapidly once the MOI was successful, and by 25-Sep-2014 the flight dynamics teams turned their attention in earnest to analyzing the spacecraft trajectory in conjunction with the comet trajectory.

The MOM navigation team prudently made plans both to minimize potential spacecraft damage due to cometary dust fluence and to make science observations. Similar planning was already being conducted by the teams of the other orbiters at Mars (NASA's Mars Odyssey, Mars Reconnaissance Orbiter, and MAVEN; and the European Space Agency's Mars Express). Per the usual practice, both the ISRO team and the JPL team designed phasing maneuvers to set up for the CSS avoidance. At the teleconference on Friday 03-Oct-2014, the ISRO team selected the JPL design for the CSS maneuver (35.8 second burn using the 8 x 22N ACS thrusters imparting 7.9 m/s ΔV). The JPL design placed MOM in occultation during the time of maximum fluence, whereas the ISRO design did not. As a nice side benefit, this same maneuver helped address the future 2020 planetary protection issue as well. A long-term propagation of the post-maneuver state showed that MOM's periapsis would not go below 100 km altitude through 2064; the minimum altitude reached would be 112.9 km on 08-Jul-2029.

MOM's phasing maneuver executed on 06-Oct-2014 04:43 UTC to place MOM behind Mars at the predicted time of maximum particle fluence 19-Oct-2014 20:07 UTC. Figure 20 below shows that the phasing maneuver went well. The real time residual plots were based on an OD solution which was a week old, which explains why the "with-burn" residual is around 6 Hz instead of closer to zero (Fig. 20, top) and why the "no-burn" case is several Hz away from the corridor (Fig. 20 bottom). The corridors represent maneuver execution errors on top of perfect OD. The "stale" OD was used for these plots because that was the solution that had been used in the maneuver design. Initial ISRO telemetry indicated a fraction of a percent overburn.

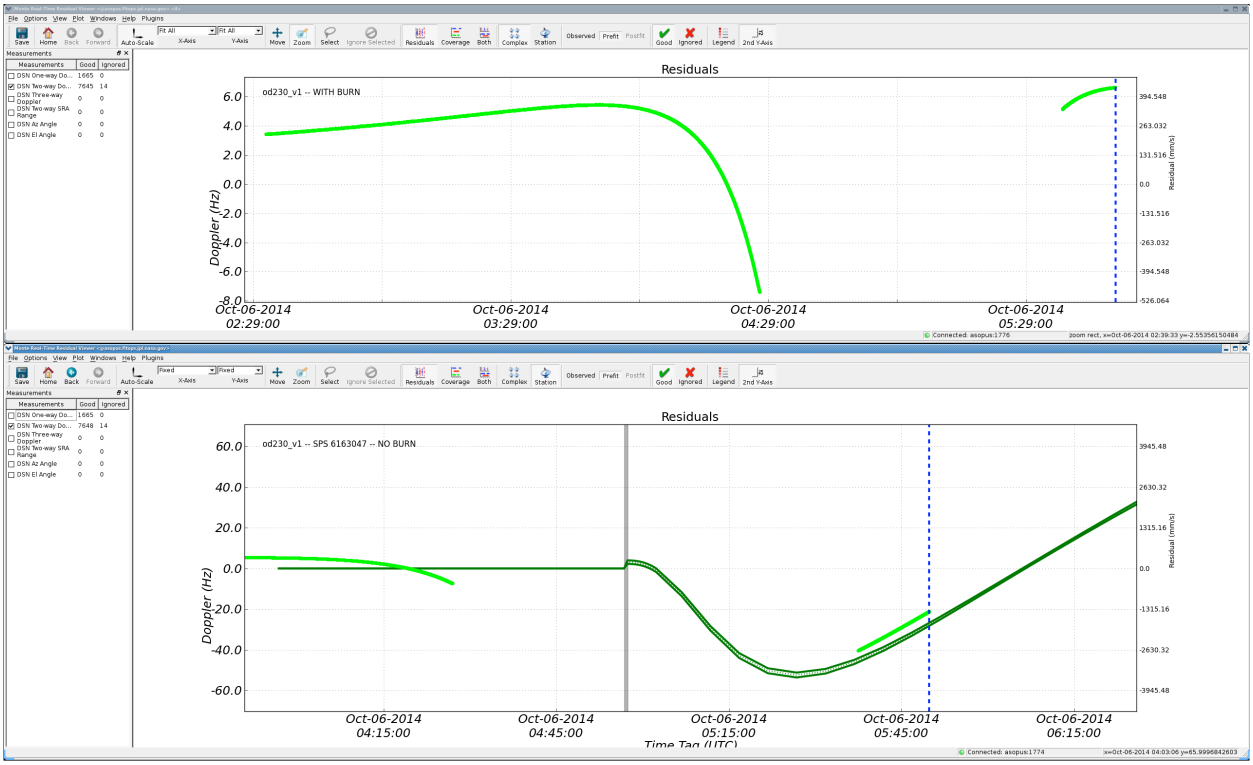

Figure 20. Real Time Residuals from Comet Siding Springs Maneuver

Figure 21 below shows the MOM periapsis projection immediately after the CSS phasing maneuver. As can be seen, the periapsis comes close to 100 km, but not below.

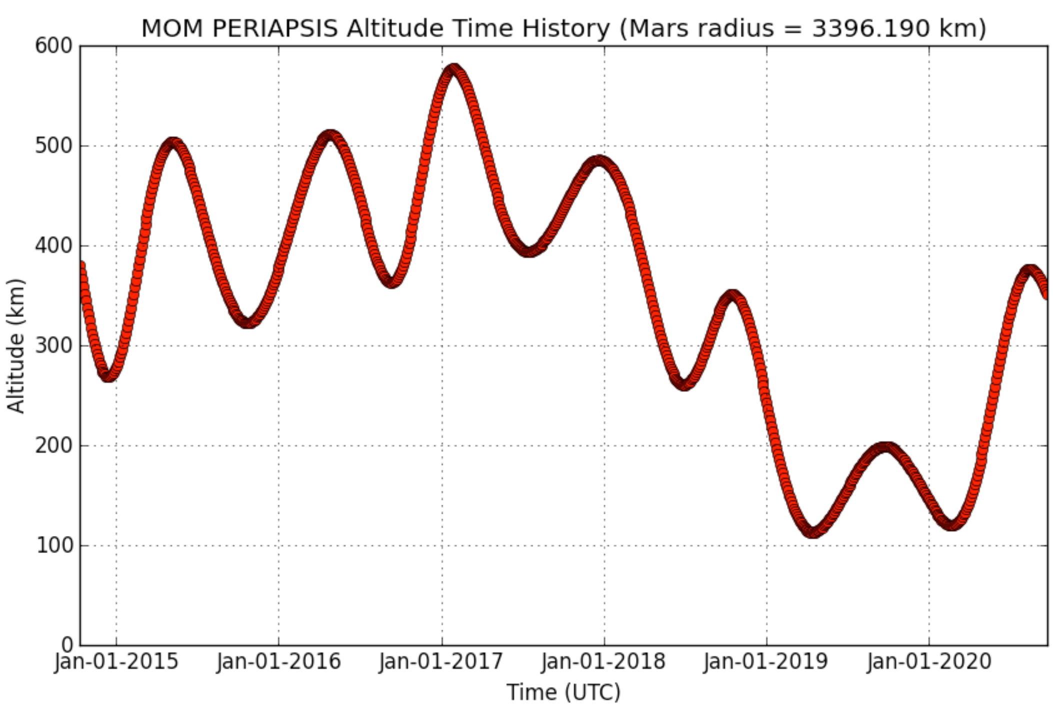

Figure 21. MOM Post-CSS Periapsis Altitude Forecast

19. Mars Orbital Environment Conjunction Assessment

Having joined "The Mars Club", MOM was also added to the routine Martian conjunction assessment processes performed by JPL MDNAV. In this conjunction assessment process, a software system known as MADCAP (Multimission Automated Deepspace Conjunction Assessment Process) analyzes current trajectories for spacecraft at Mars autonomously obtained from the DSN's Service Preparation Subsystem (SPS) [18]. These ephemeris files are the same ones used by the DSN for tracking the spacecraft. The conjunction assessment process involves pairwise comparisons over the span of the ephemerides to check for orbit crossing distances, orbit timing differences, and close approach distances below mission-established thresholds. To date no conjunctions involving MOM have been predicted, but the apparatus is there to detect something should the Mars orbital environment change.

20. Lessons Learned

The experience of working with ISRO resulted in several "Lessons Learned" for the JPL MDNAV team. For example, while having a tested schedule in place is very important, having a good planning process in place facilitates the ability to accommodate rapid plan changes. Most crucially, intra-project communications were exceptionally important to making MOM a success.

20.1 Intra-Project Communications

As might be expected, technical communications between two teams separated by half a world represented special challenges (some generic telecon technical issues, some cultural, some "time of day" related, and some US ITAR related). Communication among geographically separated teams was very important, especially given that things were often changing rapidly.

Weekly telecons commenced in May 2013 and were important to making MOM a success; they continued well past the Mars Orbit Insertion. While these helped work through issues, it was often very difficult for both teams to communicate technical details over the phone. Telecons were generally held in the late afternoon in Pasadena, which corresponded to early morning the following day in Bangalore due to the 12.5 hour time difference.

For the critical events of launch, TMI, and MOI, JPL MDNAV also had a liaison on site in Bangalore. The function of the liaison role was primarily to facilitate timely inter-team communication and the sharing of real time Doppler residual displays that were used to monitor the critical events. The JPL MDNAV team greatly benefited from having a liaison at ISRO. It may be prudent to increase the number/frequency of liaisons for future missions to facilitate communications even during non-critical mission events.

While weekly telecons and critical event liaisons were valuable, probably the greatest contributor to the intra-team communications crucial to MOM's success were the Technical Interchange Meetings (TIM) given the many challenges of navigating to Mars for the first time. At the beginning of the JPL MDNAV involvement with MOM, it was correctly foreseen that a broad set of detailed TIMs would be imperative. A total of four, week-long face-to-face TIMs were conducted in Bangalore (April 2013, July 2013, March 2014, and August 2014). Navigation is a very interdisciplinary function. There are contributions from the flight system (propulsion, telecom), mission system (trajectory design, maneuver planning/sequencing), tracking system, and flight dynamics (orbit determination, navigation software). On-site TIMs allowed for detailed interactions with project representatives from all these areas that were much less constrained by the clock than were the telecons. ISRO explained their navigation software methodology, their maneuver design capabilities, their navigation operations paradigms, orbit determination experience, etc. The amount of information exchanged was much greater than could be accomplished in a series of telecons. During these TIMs the JPL MDNAV team often learned of new aspects of the ISRO plans (e.g., changes in launch date, TCM schedule changes, tracking coverage changes, MOI implementation plans, attitude changes, small forces data).

During the first TIM in Bangalore in April 2013, the topics that received the most attention included validation of the trajectory design, navigation performance given the MOM spacecraft capabilities, planning for delta-DOR processing, planning for MOM/MAVEN coordination at Mars arrival, discussions of navigation interfaces, and prioritizing tasks.

Two of the main topics for TIM#2 in July 2013 were planning orbit determination for the complex, month-long Earth-orbiting phase into which MOM was launching, and planning for the six deterministic maneuvers during that period. The planning for this phase was very detailed and lengthy given the need to assure that MOM had sufficient commanding and tracking opportunities through both ISRO and DSN tracking stations to meet (among other things) navigation requirements. This TIM also introduced planning for validation of the radiometric data from ISRO stations, a key step towards alleviating potential tracking congestion issues later on in the mission.

A great deal of new information was learned at TIM#3 in March 2014. ISRO expressed a desire for thruster calibrations (to be accomplished with planned AMD analysis) and reported that the number of AMDs would greatly increase during the second half of cruise due to a solar array attitude change that was necessary to maintain adequate power levels (shown in annotation of Fig. 6 and Fig. 8). Due to issues with pressure regulators, the MOI would be in blowdown mode augmented by the 22N thrusters; one pressure regulator had already failed, and the backup was not trusted for a pressurized MOI. There were also changes/improvements in some of the models that greatly reduced trajectory differences between the ISRO and JPL team products. There was also a plan to perform two MOI rehearsals (mid-July 2014, late August 2014). The validation of the IDSN 32-meter station performance was a major topic in preparation for ISRO tracking of MOM on Mars approach and in the orbit phase.

The purpose of TIM#4 in August 2014 was to discuss operational planning for TCM-4, MOI Rehearsal, MOI, Operations Readiness Tests (ORT), and contingency plans; this was the last TIM prior to the MOI. At this last TIM, several changes to prior plans were discussed that had not been brought up on the weekly telecons. Discussions also included the ISRO tracking data assessment and validation of the IDSN data. The MOI planning was of principal interest given that it was less than 2 months away at the time of the TIM and many of the potential pitfalls that required extensive planning had not yet been fully addressed. There was also extensive discussion and planning of the DSN tracking plans for TCM-4 and the MOI, including the spacecraft configurations, detailed time sequences, required DSN configurations, DSN support levels, and other matters necessary to acquire the necessary tracking and telemetry data during these critical events. New items learned at TIM#4 included an assertion that there was a high probability TCM-3 would be reinstated, but on a date different than was in the previous plan; that ISRO had performed a successful ground test of the propulsion system which allowed a decision to implement the LAM+8 ACS thruster configuration for MOI (this was the configuration that JPL had been assuming in most of the MOI studies, but the decision allowed elimination of the work required to consider the LAM alone and LAM+4 possibilities); that the solar array pointing had an uncertainty of 2 or 3 degrees; and that ISRO wanted to include off-the-shelf possibilities for the contingency TCM-5 at MOI-24 and MOI-6 hours (although these were never designed) in addition to a full design possibility at any time after TCM-4 (a reversal with respect to previous TCM-5 planning). Due to ISRO's change of plans in late August, many of the plans discussed at TIM#4 regarding TCM-4 and MOI were never realized.

The four TIMs were an extremely valuable investment and were necessary to achieve successful international collaboration.

20.2 Agile, Flexible Mission Design/Operations

One learning experience for JPL navigators resulted from ISRO's method of agile, flexible mission design and operations planning. ISRO simply did things that JPL missions would probably consider outside JPL best practices. For example, once established, TCM schedules for JPL missions are usually quite fixed. As noted earlier, the schedules for TCM-3 and TCM-4 changed frequently, and the nature of TCM-4 changed completely very late in the mission. While the JPL MDNAV team successfully adapted, and responded quickly and effectively out of necessity, ISRO's deviations from carefully planned and tested schedules did add stress and increase risk.

20.3 Spacecraft Hardware

MOM reinforced two lessons learned in previous Mars missions. First, an X-band transponder would have improved the radiometric data quality. Second, having balanced thrusters would have greatly reduced the number of AMDs and the B-plane uncertainties they produced. Thus, X-band telecommunications and balanced thrusters would be helpful to future missions.

21. Conclusion

MOM's success strengthens India's experience and reputation in space research and space operations by adding an interplanetary dimension. MOM was declared one of the "25 Best Inventions of 2014" by *TIME Magazine* [4, 5], which noted that India was the first country to succeed with a Mars mission on the first attempt, was the first Asian nation to succeed at achieving Mars orbit, and MOM's low cost ($74 million, less than the budget for the movie "Gravity").

The ISRO/NASA collaboration on MOM was mutually beneficial and a learning experience for both organizations. It is a collaboration that we hope will continue in future deep space missions. It is anticipated that the success of the MOM mission could lead to future international collaboration on space missions between NASA and ISRO. JPL has continued to provide navigation support for one year after MOM entered its science orbit, and negotiations are currently in process to extend that support for one additional year.

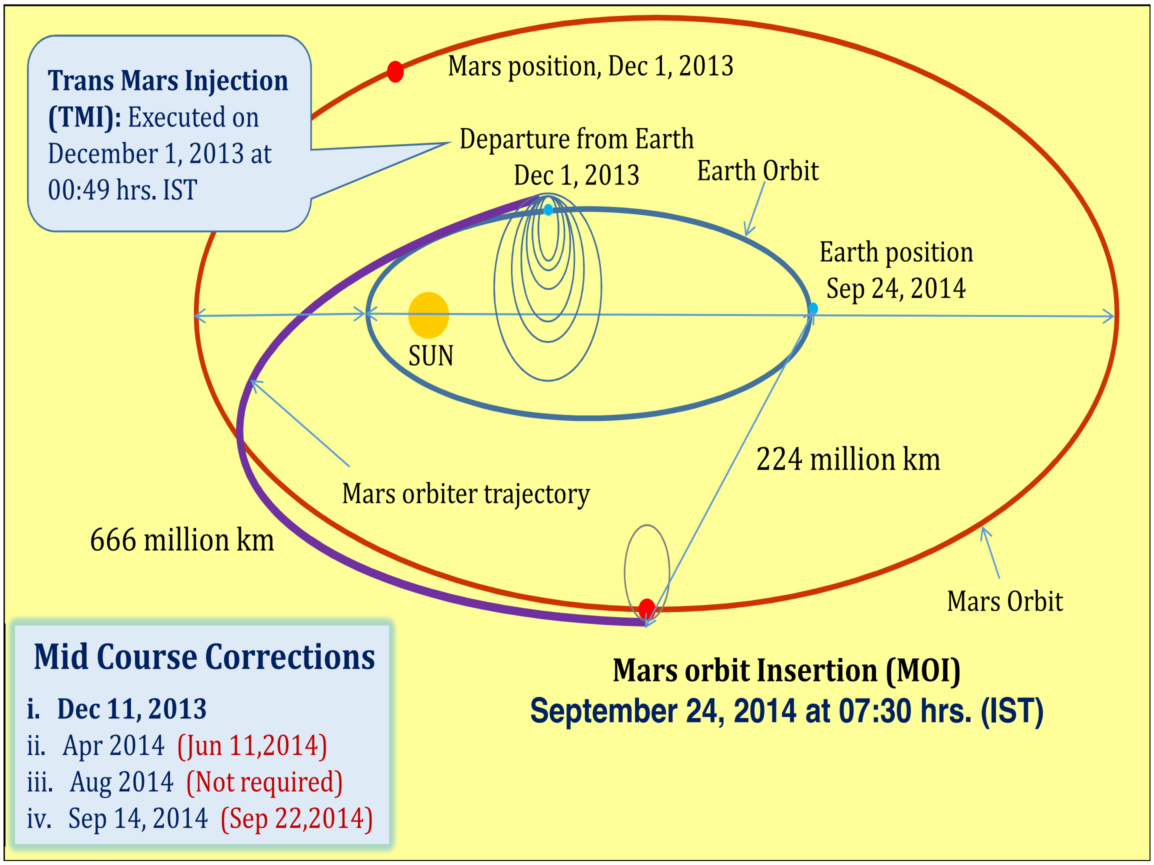

Figure 22. Concise MOM History from Launch to MOI (not to scale)

22. Acknowledgments

MOM's delivery to Mars is a direct result of the contributions of many people. The authors would like to express their appreciation and deep respect for the members of the ISRO navigation team. Special thanks are due to Susan Kurtik, the JPL Project Manager for MOM, who worked tirelessly on behalf of MOM and offered many helpful suggestions for this paper.

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Figure 23: A MOM Portrait of Mars