A JOURNEY WITH MOM

Cliff Helfrich[1], David S. Berry[2], Ramachandra Bhat[3], James Border[3], Eric Graat[3], Allen Halsell[3], Gerhard Kruizinga[3], Susan Kurtik[3], Eunice Lau[3], Neil Mottinger[3], Brian Rush[3], Roby Wilson[3], Tung-Han You[3]

[1] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, 818-354-1446, clifford.e.helfrich@jpl.nasa.gov*
[2] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, 818-354-0764, david.s.berry@jpl.nasa.gov*
[3] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109*

In late 2013, the Indian Space Research Organization (ISRO) launched its most ambitious mission to date - the "Mars Orbiter Mission", affectionately known as "MOM". As part of its operations plan, ISRO engaged the services of the Jet Propulsion Laboratory (JPL) Mission Design and Navigation Section (MDNAV) for consultation, verification, and validation of its navigation operations. This arrangement built on the successful Chandrayaan-1 lunar mission collaboration between ISRO/NASA-JPL MDNAV in 2008-2009. This paper will describe in detail the "shadow navigation" effort performed by JPL MDNAV in support of MOM to ensure that ISRO fulfilled its objectives of achieving and maintaining Mars orbit. Primary ISSFD areas of interest addressed will be flight dynamics operations; tracking and orbit determination; maneuver design; and space environment, orbital debris, collision risk mitigation.

JPL MDNAV's navigation plan for MOM covered schedule planning, software/hardware updates, interface control document development, spacecraft dynamic model generation, mission profile validations, navigation system analyses, training, and testing across all of these areas. After launch, the major shadow operations included orbit determination and flight path control (maneuver). Orbit determination included applying media calibrations to DSN tracking data; generation of the predicted and reconstructed spacecraft ephemeris; and reconstruction and dynamic trending of thruster events. Flight path control involved maneuver targeting, design, analysis, and validations/verifications; real time monitoring of maneuvers; post-maneuver reconstruction; and mission delta-V tracking and prediction. Output products from orbit determination and flight path control were all delivered to the ISRO flight dynamics team.

A few significant attributes of the MOM mission impacted navigation. Specifically, whereas most current missions to Mars use X-band for telecommunications, MOM utilized S-band; hence, 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. Unlike other Mars missions, MOM had an Earth Orbit Phase consisting of 7 apogee-raising maneuvers, which included one partial burn, a make-up burn, and the Trans-Mars Injection (TMI). The MOM spacecraft had an unbalanced thruster alignment, which resulted in frequent angular momentum desats (from 6 to 10 per day). A great deal of effort was expended accounting for all the desats; the uncertainties associated with the desats were a major source of uncertainty in MOM's B-plane error ellipse.

The primary source of tracking data for the MOM mission was NASA/JPL's Deep Space Network (DSN); however, JPL MDNAV also assisted ISRO in assessment of tracking data collected via the Indian Deep Space Network (IDSN). The 32-meter antenna near Bangalore, India was used by ISRO to track MOM, and the data was sent to JPL for analysis of the quality of IDSN Doppler, range, and VLBI data. Data analyses progressed from pass-throughs at the beginning to orbit determination fits in combination with DSN data towards the end.

As might be expected, technical communications between two teams separated by half a world represented special challenges (some telecon technical, some cultural, some "time of day" related, and some US ITAR related). In addition to weekly telecons, a total of four, week-long face-to-face Technical Interchange Meetings (TIM) were conducted in Bangalore. During these TIMs the JPL MDNAV team often learned of new aspects of the ISRO plan (e.g., changes in launch date, TCM changes, tracking coverage changes, Mars Orbit Insertion (MOI) implementation plans). For the critical events of launch, TMI, and MOI, JPL MDNAV also had liaisons on site in Bangalore to facilitate timely inter-team communication and the sharing of real time Doppler residual displays.

The ISRO plan included a complex MOI that involved a combination of main engine and RCS thruster firings, operating in eclipse, a communications/tracking blackout caused by occultation, and several quick post-occultation telemetry data rate changes. A failed pressure regulator created uncertainty as to the viability of the main engine for MOI. Late in cruise, this uncertainty raised significant planetary protection issues that were ultimately resolved after a successful main engine test conducted only 41 hours prior to the MOI.

MOM's successful MOI occurred less than a month prior to the arrival of Comet Siding Spring at Mars, adding a new dimension to the planning process. The MOM navigation team, as had the teams of other NASA and ESA orbiters at Mars, prudently made plans both to minimize potential spacecraft damage due to cometary dust fluence and to make science observations. MOM was also added to the routine Martian conjunction assessment processes performed by JPL MDNAV.

MOM's success strengthens the viability of India's participation in interplanetary space research and space operations. MOM was declared one of the "25 Best Inventions of 2014" by TIME Magazine, which cited its low cost ($74 million), the fact that India was the first country to succeed with a Mars mission on the first attempt, and the first Asian nation to succeed at achieving Mars orbit. The ISRO/NASA collaboration on MOM was a learning experience for both organizations, a collaboration that we hope will continue in future endeavors.

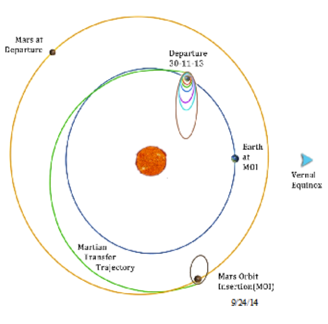

Figure 1: MOM Trajectory


Figure 2: MOM's First Picture of Mars