MARS EXPRESS INTERPLANETARY NAVIGATION FROM LAUNCH TO MARS ORBIT INSERTION: THE JPL EXPERIENCE

"18TH INTERNATIONAL SYMPOSIUM ON SPACE FLIGHT DYNAMICS"

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ABSTRACT

The National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) played a significant role in supporting the safe arrival of the European Space Agency (ESA) Mars Express (MEX) orbiter to Mars on 25 December 2003. MEX mission is an international collaboration between member nations of the ESA and NASA, where NASA is supporting partner. JPL's involvement included providing commanding and tracking service with JPL's Deep Space Network (DSN), in addition to navigation assurance. The collaborative navigation effort between European Space Operations Centre (ESOC) and JPL is the first since ESA's last deep space mission, Giotto, and began many years before the MEX launch. This paper discusses the navigational experience during the cruise and final approach phase of the mission from JPL's perspective. Topics include technical challenges such as orbit determination using non-DSN tracking data and media calibrations, and modelling of spacecraft physical properties for accurate representation of non-gravitational dynamics. Also mentioned in this paper is preparation and usage of DSN Delta Differential One-way Range (ΔDOR) measurements, a key element to the accuracy of the orbit determination.

1. INTRODUCTION

Mars Express was the first Mars interplanetary mission for the ESA, as well as its first deep space mission since Giotto, a mission to Comet Halley in the mid-1980s [1]. At that time, ESA established a relationship with the NASA JPL to assist with the deep space navigation. The success of the cooperation with Giotto led to the establishment of a similar relationship for tracking and navigation services for the Earth-to-Mars phase of MEX.

1.1 Mars Express Orbit Determination

MEX launched 3 June 2003 from the Baikonur Cosmodrome in Kazakhstan. Trajectory correction maneuvers were made along the way to precisely target the release location of the Beagle 2 lander on 19 December 2003. The following day, MEX performed a maneuver to divert from the impact trajectory necessary for Beagle 2 to a path that allowed the spacecraft to enter orbit around the Red Planet. It arrived at Mars on 25 December 2003, performing a flawless capture maneuver [2].

A critical aspect of such interplanetary navigation is the orbit determination (OD). The OD evaluates radiometric and interferometric tracking data to estimate the spacecraft position and velocity, along with other dynamic modelling quantities like solar radiation pressure. These parameters are then used to predict the trajectory and design maneuvers to keep the spacecraft on its intended path.

JPL heritage on deep space missions stretches back for 40 years, highlighted by flight-tested capabilities for trajectory modelling and orbit determination. The ESOC Flight Dynamics Division (FDD) developed new navigation software that required validation. The primary goal of the relationship between ESOC FDD and JPL Navigation was to produce comparisons of the output from their respective navigation tools, both before and after launch, to seek agreement in their basic capabilities.

1.2 JPL Navigation Responsibilities

The specific responsibilities of NASA regarding the MEX mission are set forth in a Memorandum of Understanding (MOU) between ESA and NASA [3]. The MOU requires NASA to provide the following navigation related items:

- Delta Differential One-way Ranging (DDOR);
- Approach navigation support;
- NASA-derived tracking data types for ESA validation of its navigation performance;
- Pre- and post-launch navigation support in consultancy, independent cross-verification of navigation, consultancy on interplanetary operational issues and necessary tracking data produced from the NASA DSN to ESA;
- All relevant review information as required supporting the above items.

1.3 JPL Role in Operations

Much of the cross-verification of navigation software and validation of tracking data types occurred prior to the MEX launch, making use of tracking data from the Ulysses spacecraft [4]. The focus of this paper, however, is the role that JPL Navigation played in MEX flight operations during Earth-to-Mars cruise.

Activities performed included a final software cross-verification test during an intensive two-week tracking campaign two months after launch; implementation and testing of DDOR measurements to greatly improve the accuracy of the orbit determination; and approach navigation support in the form of daily solution exchanges during the last several weeks before reaching Mars. Products provided in addition to those required by the MOU included estimates of the Beagle 2 atmospheric entry interface point and landing ellipse. The following sections provide details of each of these activities to summarize the JPL experience regarding MEX Earth-to-Mars navigation.

2. DYNAMIC MODELLING

Of the elements required to deliver a spacecraft successfully to Mars, proper dynamic modelling of the spacecraft is of prime importance. The gravitational influences upon the spacecraft are well understood and modelled in high fidelity. The forces that become less trivial to model are those due to non-gravitational sources. These forces can be understood as those due to solar radiation pressure, trajectory correction maneuvers (TCM), momentum wheel off-loadings (WOLs), and possible outgassing events. Residual acceleration models may also be required due to inexact or approximate modelling of the dynamics impressed upon the spacecraft.

2.1 ESOC Inputs

JPL Navigation relied upon ESOC Flight Dynamics to provide appropriate information concerning spacecraft dynamics. As part of the JPL Navigation/ESOC FDD agreement [5], a set of interface files was defined to provide this information. The files contained information related to the spacecraft attitude and planned thrusting events. Other relevant files provided as a means of dynamic model verification were an inertial accelerations file and a solar radiation pressure acceleration file.

Various scripts were employed to ingest these interface files and produce the appropriate inputs for the JPL navigation software. On a routine basis, the inputs used for orbit determination and trajectory modelling included the following:

- Maneuver summary, which included previously performed TCMs and WOLs reconstructed from spacecraft telemetry.
- Predicted maneuvers, which included the preliminary values for future TCMs and WOLs.
- Spacecraft attitude quaternions.
- Solar panel orientation (gimbal angles).

Each input provided key dynamic modelling information that allowed for more accurate estimation of thrusting events, solar radiation pressure, and trajectory prediction. As an example, without accounting for the commanded attitude and solar panel orientations, a noticeable dynamic mismodelling signature is introduced in the tracking data residuals. This, in turn, can be aliased into the spacecraft state estimation, producing a less accurate estimate of its true orbit.

2.2 JPL Models

The remainder of the dynamic modelling, including gravitational perturbations, solar radiation pressure, and spacecraft physical modelling, was performed with the capabilities of the JPL Navigation software. The physical model of MEX has a direct impact on the accuracy of the SRP computation. In order to properly model the SRP, JPL implemented a 6-component model. This model consisted of three flat plates to represent the spacecraft bus (taking into account the Beagle 2 lander attached to the spacecraft +Z face), two flat plates to represent the solar arrays, and a self-shadowing parabolic dish to represent the High-Gain Antenna (HGA). The HGA was modelled as having a 5° offset in the spacecraft X-Z plane rotated about the Y-axis by −5°. The solar power arrays were nominally pointed at the Sun. The spacecraft bus components were oriented along the spacecraft bus-fixed axes.

The spacecraft areas and optical properties were obtained primarily from the MEX Flight Dynamics Data Base (FDDB). These optical properties were then converted to the appropriate navigation software inputs. Interestingly, a consistent 14% bias in solar radiation pressure acceleration was estimated by both JPL and ESOC. Because other dynamic mismodelling effects such as outgassing are usually on the same order as the solar radiation pressure acceleration, it is difficult to separate or differentiate the source of dynamic mismodelling.

Therefore, in order to refine the solar pressure model, a quiescent time during cruise needed to be found so as to allow for the estimation of solar pressure areas and reflectivities without the possible aliasing effects from other sources (i.e. thrusting events, attitude changes, solar panel orientation changes, etc.). The quietest arc found (and used) was between August 6 and August 14, 2003. During this arc, there were only two momentum

WOLs. The refined areas and reflectivities produced a solar pressure scale factor estimate near the desired value of 1.0, versus the previous value of 1.14, which reflected the 14% bias.

3. TRACKING DATA

The primary ground station for MEX was the new ESA 35 meter deep space antenna located at New Norcia in southwestern Australia. The NASA Deep Space Network (DSN) provided additional coverage mainly from its ground station in Madrid, Spain, but occasionally from Goldstone, California, and Canberra, Australia. Tracking data used during the MEX interplanetary phase included radiometric and interferometric types.

3.1 Radiometric

The bulk of the MEX tracking data consisted of radiometric observations, primarily 2-way Doppler and ranging. The 2-way Doppler measures the Doppler shift in the frequency of a radio signal transmitted from the ground to the spacecraft, which then coherently retransmits the signal back to the ground. It is a direct measurement of the velocity of the spacecraft along the line of sight from the ground station. By modulating a known code onto the same carrier signal, the ground station also measures the range to the spacecraft by comparing the time of transmission to the time of reception of the code sequence. Assuming the signal travels at the speed of light, this is a measure of twice the distance to the spacecraft (up, then back).

JPL Navigation has had many years of experience processing the Doppler and range measurements from the DSN, which provided about half the radiometric tracking data for MEX. However, processing the measurements from the ESA ground station at New Norcia (NNO) was new to JPL. Fundamentally the same measurements, the NNO tracking data takes on a different format, referred to as Intermediate Frequency and Modem Systems (IFMS). The IFMS data had to be converted to an input format compatible with the JPL software, including transforming the range measurement from a different coding scheme to the equivalent DSN measurement. Also, without a direct link between NNO and JPL, the tracking data files had to be routed through ESOC Flight Dynamics, where they were pre-processed and then transferred to a server at JPL.

Since accurate computation of the Doppler and range requires adjusting for media effects, ionosphere and troposphere calibrations for New Norcia were also required. Ionosphere calibration files were generated by JPL using data from the Global Positioning System (GPS) Receiver at NNO. The GPS receiver is part of the International Global Network (IGS) of receivers used by JPL to produce global ionosphere maps. The troposphere calibration, however, required local weather measurements that are part of the IFMS delivery with the tracking data. Part of the pre-processing of the IFMS data performed by ESOC Flight Dynamics included generating the troposphere calibration covering the period of the tracking pass. This file was delivered to JPL along with the tracking data.

3.2 Interferometric

Interferometric measurements of the MEX spacecraft were a critical component of the total navigation data set. The system that has been developed by the DSN for this measurement type is called Delta Differential One-way Range (ΔDOR). A detailed description of the ΔDOR measurement system can be found in [6]. While radiometric data types measure line of sight components of the spacecraft state, ΔDOR is more sensitive to the spacecraft position perpendicular to the line of sight. Hence, ΔDOR provides very accurate measurements of the spacecraft position in *plane of sky* coordinates.

The fundamental ΔDOR observable is the difference in arrival times of spacecraft signals (delay) at two widely separated antennas. This signal delay is determined by cross correlation of the signals recorded at each antenna at a central processing facility. In the case of MEX, the antenna pairs were those of the DSN complexes at Goldstone, California; Madrid, Spain; and Canberra, Australia. ΔDOR observations were made using either the Goldstone – Madrid, or the Goldstone – Canberra baseline. Data recorded at these sites were transmitted to a central processing facility at JPL where the basic delay observables were computed.

Thornton and Border [6] provide a detailed discussion of the error sources in ΔDOR measurements. Of particular relevance to the MEX measurements is the spanned bandwidth of the spacecraft signal. An important component of the ΔDOR error budget is inversely proportional to this quantity. The relatively narrow bandwidth of the MEX spacecraft signal spectrum limited the nominal accuracy of the ΔDOR delay observable to approximately 0.25 nsec, or the equivalent of 1.4 km in the spacecraft position at Martian distances. To take maximum advantage of the ΔDOR observable, spacecraft transponders may be designed to maximize the spanned bandwidth of the signal spectrum. This has been accomplished on earlier missions through the incorporation of widely separated "DOR tones" in the spectrum of the spacecraft signal.

Each of the 55 MEX ΔDOR measurements required preparation of a detailed sequence of events (SOE) to coordinate the activities at the DSN stations and onboard the MEX spacecraft. Prior to each measurement, the spacecraft transponder was commanded to enter a special telemetry mode. The widely spaced spacecraft signals, or "tones", necessary for forming the ΔDOR observable were available only in this configuration of the MEX telemetry system. The SOE also specified the events that had to occur simultaneously at each of the two ground stations including antenna pointing and signal recording times. A failure at either of these locations would have resulted in loss of the ΔDOR measurement.

4. TRACKING CAMPAIGN

Two months after launch, JPL and ESOC performed a final set of software and auxiliary file cross-verification tests during a two-week tracking campaign. The campaign was designed to verify the equivalence of the JPL and ESOC navigation solutions, test the file exchange interfaces, and ensure that the output products that would be used during final approach were compatible and complete.

Six solutions were exchanged, culminating in an end-to-end process check. Exhaustive comparisons of the pre- and post-fit residuals of 27 DSN and 21 IFMS Doppler and Range passes and eight sets of DDOR measurements were performed. Successful comparisons of MEX trajectory files confirmed file format conversion processes and software agreement. The format of solution summary files was solidified and error ellipse plots at the Mars B-plane were compared and found to be equivalent. The successful campaign provided confidence to both JPL and ESOC during the critical Mars approach phase.

5. APPROACH TO MARS

In the weeks leading up to MOI, MEX performed maneuvers to target the Beagle 2 release point, released Beagle 2, and then retargeted the spacecraft from an impact trajectory to one that would allow it to enter orbit around Mars. The accuracy of the orbit determination was critical to the trajectory prediction and maneuver design. Key elements of this process during Mars approach included performing ΔDOR measurements, comparing daily solutions between JPL and ESOC, observing the Doppler signature due to Beagle 2 release, and propagating the Beagle 2 trajectory from release to the surface.

5.1 ΔDOR Performance

The ΔDOR measurement system performed extremely well throughout the entire MEX cruise navigation campaign. Of 55 scheduled ΔDOR measurements only one failure was reported, which was due to an operation schedule change at the last minute. During the cruise phase of the mission, ΔDOR measurements were completed every three to four days, with nearly equal numbers on both the Goldstone-Canberra (25) and Goldstone-Madrid baselines (30). Average observation time for each ΔDOR measurement was approximately 90 minutes.

Immediately prior to critical mission events, such as the Beagle 2 separation and Mars orbit insertion, ΔDOR measurements were performed with much greater frequency, sometimes twice daily. For the most critical mission event, Mars orbit insertion, final ΔDOR observables were delivered to project navigation within 12 hours of measurement completion.

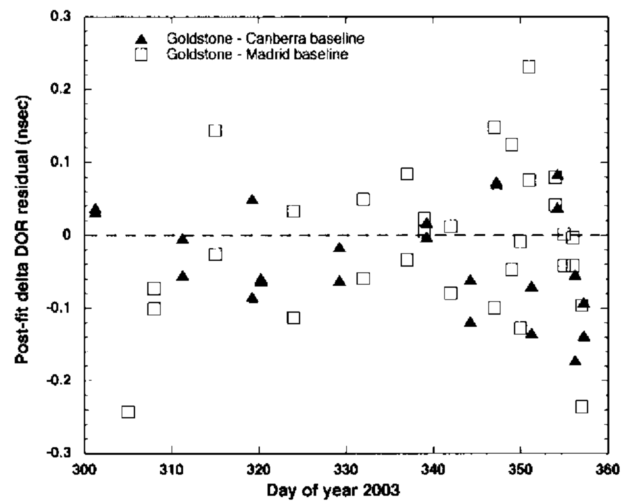

Figure 5-1. Post-fit delay residuals for all ΔDOR measurements completed during the period Oct. 29 – Dec. 25, 2003. The root-mean-square scatter of these residuals is less than 0.1 nsec.

Based upon post-flight analysis, the precision of ΔDOR measurements met or exceeded expectations. Figure 5-1 shows the post-fit ΔDOR residuals for all measurements completed between Oct. 29 and Dec. 25, 2003. The root-mean-square scatter in these residuals is less than 0.1 nsec, corresponding to a precision of ~0.6 km in the measured plane of sky spacecraft position at Mars.

5.2 Daily Solution Comparisons

During the last several weeks prior to MOI, JPL and ESOC exchanged orbit determination solutions on a daily basis. Each day included tracking passes from Madrid and New Norcia. Days that included ΔDOR measurements also included a limited amount of Doppler and range from Goldstone. Tracking data cutoff occurred after the NNO pass, at approximately 1600 GMT. At 1830 GMT, JPL Navigation and ESOC Flight Dynamics held a teleconference to discuss their respective orbit determination solutions and corresponding trajectory predictions. JPL Navigation also computed a daily intermediate solution based on tracking data from the Madrid pass that ended later that day (locally) at approximately 0000 GMT, as well as any ΔDOR measurements delivered after the 1600 GMT data cutoff. This solution was then available for comparison by ESOC when they arrived to work the next day. In addition, to address immediate concerns and facilitate the daily interactions, The lead author was the JPL navigation liaison present at the ESOC facility in Darmstadt, Germany, during this period.

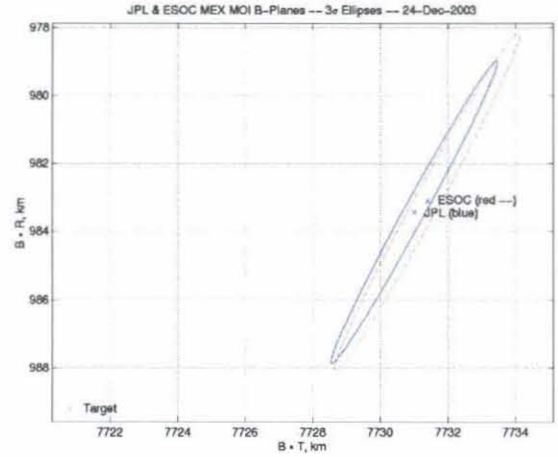

Figure 5-2. JPL and ESOC B-plane ellipses for the 24 Dec. 2003 solutions. Delivery requirement was +/-75 km from the target, so the solutions are well within that range. The two solutions are comparable, with the size and location difference due to slightly different data weights and error assumptions.

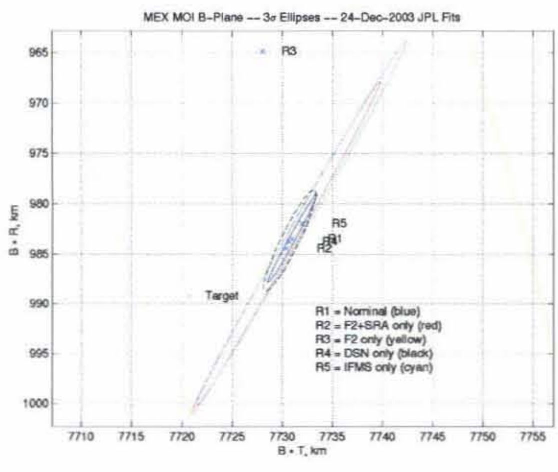

Figure 5-3. JPL solutions with different tracking data combinations to evaluate solution consistency and sensitivity to specific data types. Doppler only is the weakest solution, though its ellipse encompasses the other more accurate solutions.

The primary metric for solution comparison was the location and size of error ellipses in the Mars B-plane [7]. Figures 5-2 and 5-3 show examples from the last comparison prior to MOI. Figure 5-2 shows the error ellipses for the nominal solutions, which included Doppler, range, and ΔDOR tracking data. Figure 5-3 shows variations of the JPL solution using different tracking data combinations to determine solution consistency. These plots and a summary of the solution were compared on a daily basis to provide, in the context of the MOU, approach navigation support and relevant technical data. In the context of spacecraft operations, these comparisons provided additional confidence towards the ultimate goal of mission success.

5.3 Real-Time Doppler Display

An additional capability that JPL was able to provide involved real-time display of the Doppler residuals. This was especially useful during the Beagle 2 release event and Mars orbit insertion, providing an immediate indication of the performance of those events. Because the body-fixed HGA did not point at Earth during maneuvers, the spacecraft had to be tracked using the low gain S-band antenna from a DSN 70 m ground station. An example of the real-time display is shown in Figure 5-4, which shows the Doppler signature due to the ΔV caused by the spring release of Beagle 2. Though indirect, this capability provided an immediate indication of the successful release of the lander. Likewise, a similar indication of success was provided by the real-time display during MOI after the spacecraft emerged from behind the planet.

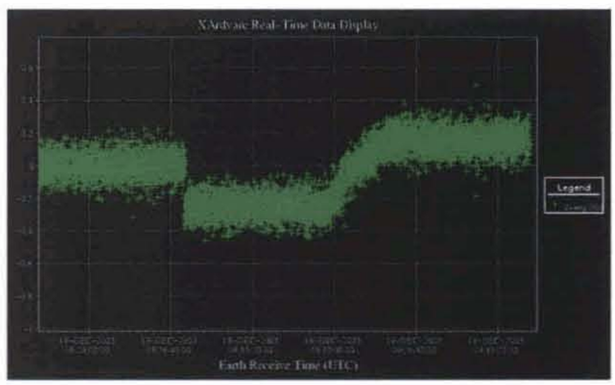

Figure 5-4. Real-time display of 2-Way S-band Doppler during Beagle 2 release, indicated by a –0.3 Hz step. The following 0.4 Hz increase was due to the thrusting of a momentum wheel offloading.

5.4 Beagle 2

In addition to targeting MEX MOI, the JPL team solved for the Beagle 2 trajectory after release for comparison with the ESOC solution. While there was no tracking of Beagle 2 itself after its release from Mars Express, the actual release ΔV was reconstructed by solving for the trajectory change on Mars Express and translating it into a change in the velocity of Beagle 2. The JPL and ESOC final solutions of the Beagle 2 state at atmospheric entry agreed to within 2.67 km and placed Beagle 2 about 6 km from the target and well within the 3-sigma flight path angle requirement of –15.8° ±1°. The JPL solution, with a data cutoff just before MEX MOI, can be seen in Figure 5-5 plotted with the ESOC ellipse from 23 December 2003.

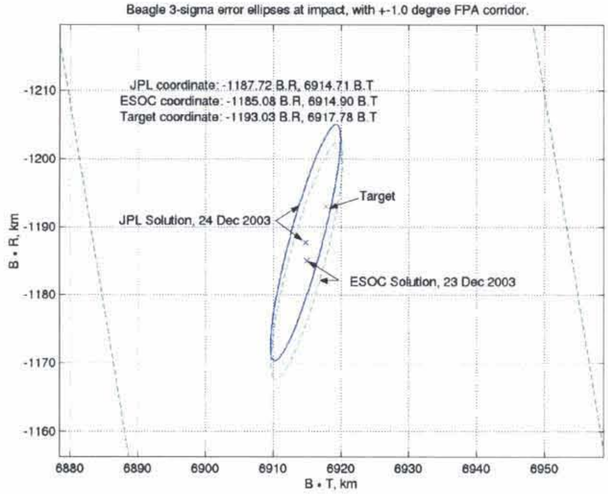

Figure 5-5. Final Beagle-2 error ellipses at the atmospheric entry interface (~ 125 km altitude).

To determine the suite of possible Beagle 2 landing locations, the final JPL entry state and its corresponding covariance were used to produce a set of 2000 dispersed entry states. These states, along with dispersed atmosphere and wind profiles for the Isidis region, were required as initial conditions for propagation through entry, descent, and landing (EDL). JPL's EDL propagation tool, the Atmospheric-Entry, Powered-Landing (AEPL) software package, was used to simulate the behavior of Beagle 2 upon entering the Martian atmosphere. This tool incorporated the nominal defined Beagle 2 EDL sequence of events and event triggers to determine the surface dispersions numerically via Monte Carlo analysis. The resulting landing error ellipse can be seen in Figure 5-6.

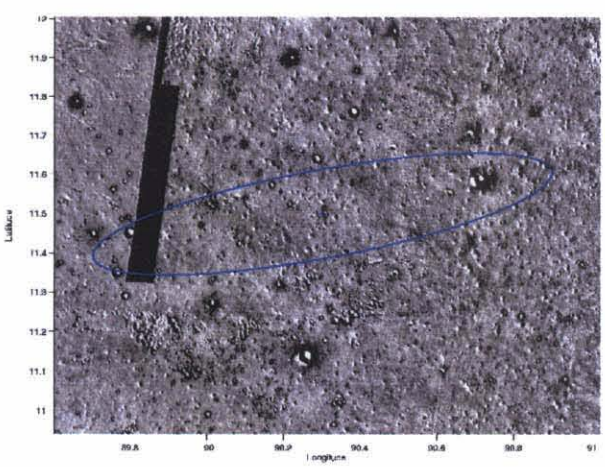

Figure 5-6. Final JPL Beagle 2 landing ellipse.

6. ACKNOWLEDGEMENTS

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