2001 MARS ODYSSEY ORBIT DETERMINATION DURING INTERPLANETARY CRUISE

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Abstract

On October 24, 2001 UTC, following a seven-month journey to Mars, Odyssey executed a nominal Orbit Insertion burn to be captured successfully into orbit around Mars. The excellent navigation performance during the interplanetary cruise resulted in arrival conditions over the North Pole of Mars well within 1–σ of the designed values. The achieved altitude above the North pole was less than 1 km away from the 300 km target altitude. Several sources of error made the orbit determination (OD) process for Odyssey challenging. The largest of these errors was caused by the periodic autonomous Angular Momentum Desaturation events. Several navigational aides were brought forth to mitigate the error sources and improve the accuracy of Odyssey's interplanetary cruise navigation. The most significant of these included the incorporation of Very Long Baseline Interferometry (VLBI), Delta-Differential One-way Range (ΔDOR) tracking data into the OD filtering process and the placement of the spacecraft into a "low-torque" attitude during the final two months of interplanetary cruise. OD solution consistency was routinely evaluated through a battery of filter strategies and data combinations. This paper will discuss the orbit determination processes and results of Mars Odyssey from launch to orbit insertion at Mars.

INTRODUCTION

NASA's Mars Odyssey spacecraft (S/C) was launched on April 7, 2001 into a Type I transfer orbit to Mars. Four Trajectory Correction Maneuvers (TCMs) were performed to achieve the required arrival conditions at Mars. On October 24, 2001 02:30 UTC, after the nearly seven-month journey, Odyssey executed a nominal Mars Orbit Insertion burn (MOI) to be captured into an 18.5-hour orbit. Aerobraking was then employed for nearly 3 months to reduce the spacecraft's orbital period to 2 hours and trim the orbit for science mapping. The Mars Odyssey project is managed at the Jet Propulsion Laboratory (JPL). The spacecraft was built by Lockheed Martin Astronautics (LMA) in Denver, CO. The flight team is split between the two institutions, as Navigation is performed at JPL, while the spacecraft subsystem analysts are located at LMA in Denver.

The Odyssey Mission

The Odyssey mission objectives are to globally map the chemical elements and mineral distributions that constitute the surface of Mars using the Thermal Emission Imaging System (THEMIS) and Gamma Ray Spectrometer (GRS) instruments. These instruments will search for evidence of subsurface water ice through the determination of hydrogen and minerals that are known to occur in the presence of water. The Mars Radiation Environment Experiment (MARIE) instrument will study the radiation environment in low Mars orbit to ascertain the radiation risk to future human explorers. Towards the end of its planned 2.5 year science mission, the orbiter will provide an important telecommunications link with Earth for US and international landers and rovers through its UHF relay.

This paper will focus on the details of the Orbit Determination (OD) that was performed during the cruise phase of the mission. A more general treatment of the Odyssey navigation approach including all mission phases from launch, through orbit insertion, aerobraking and mapping is given by Mase et al[1]. Smith & Bell[2] describe the detailed navigation processes and results during Odyssey's aerobraking phase. Note that all activities referred to in this document occurred in the year 2001.

MOI Targeting Requirements

After two failed attempts to explore Mars with the Mars Climate Orbiter (MCO) and the Mars Polar Lander (MPL), NASA was under tremendous pressure to succeed with Mars Odyssey. The success of Mars Odyssey navigation effort was primarily contingent upon accurately determining the spacecraft's orbit during the seven-month cruise and targeting the trajectory correction maneuvers (TCMs) to achieve the required Mars encounter conditions necessary for a safe and successful capture into orbit. The mission target requirements were to achieve an encounter periapsis altitude of 405 ± 25 km over the North Pole of Mars with an inclination with respect to the Mars Mean Equator of Date (MME) coordinate frame of 93.467° ± 0.2°.[1,3] Given that the periapsis altitude would drop by 105 km as a result of the constant pitch-rate MOI burn, the requirement was also given in terms of a *P2* periapsis altitude after the first orbit about Mars of 300 km.

Navigational Challenges

Several sources of error made the OD process during cruise challenging for Odyssey. The largest of these

errors was caused by the periodic thrusting events brought about by autonomous Angular Momentum Desaturation (AMD) events. AMDs or *desats* were performed every 16 – 25 hours to desaturate the momentum build-up on the reaction wheels primarily caused by solar pressure torque. The thrust vectors of the Reaction Control System (RCS) attitude thrusters with respect to the S/C's center of mass were not balanced and resulted in a net translational ΔV. These desats produced ΔV components orthogonal to the Earth–S/C direction that were not observable with traditional Doppler and range data. It was this source of error (along with the English–Metric units conversion) that contributed to the MCO navigation difficulties.

Another source of error affecting Odyssey navigation was caused by the noise and quality of the 2-way, X-Band Doppler and range tracking data from NASA's Deep Space Network (DSN) antennas. The extreme negative declination of the interplanetary trajectory constrained the tracking of Odyssey to DSN's Canberra, Australia complex for the first 2 months of cruise. During this time, several S/C activities were performed to check S/C health and calibrate science instruments and subsystems. These activities routinely corrupted the OD solutions and challenged the OD processes. Eventually, DSN's Goldstone, California and Madrid, Spain complexes could track Odyssey through the remainder of cruise but only at low elevations. Tracking data collected at such low elevations was more susceptible to uncalibrated ionospheric and tropospheric conditions, which also may have been exacerbated by higher than usual solar activity at the time. Apart from the occasional noisy tracking pass, the Doppler residual data frequently exhibited unusual structure that also had the potential of corrupting the OD solutions and producing inconsistent results. These signatures could not be attributed to any S/C activity.

Navigational Aides

Several navigational aides were brought forth to mitigate the aforementioned error sources and improve the accuracy of Odyssey's interplanetary cruise navigation. These include the incorporation of Delta-Differential One-way Range (ΔDOR) tracking data, a type of Very Long Baseline Interferometry (VLBI) measurement, into the OD filtering process, active and passive RCS thruster calibrations, solar pressure calibration, Differenced Range Versus Integrated Doppler (DRVID) measurements for media calibration and repositioning the S/C's final cruise attitude into a *low-torque* orientation. The most significant of these included the ΔDOR measurements and the *low-torque* configuration. The ΔDOR data type complements the traditional 2-way X-Band Doppler and range radio-metric measurements by constraining the S/C's position in the Earth plane-of-sky coordinate frame. In addition, the ΔDOR measurements are not dependent on modeling S/C dynamics. Thus, the out-of-the-ecliptic-plane component of Odyssey's position, which is weakly observable with Doppler and range, can be determined from the ΔDOR data. The reduction of the S/C's position uncertainty in this direction was important in meeting the altitude requirement above the North Pole of Mars for orbit insertion. The adjustment of the S/C's attitude and solar array to balance solar pressure torque with respect to the center of mass during the last 2 months of cruise significantly decreased the occurrence of AMDs, and effectively removed the desat ΔVs as being a significant error contributor in the OD solutions for the final targeting maneuver.

CRUISE NAVIGATION

Odyssey was launched into a Type I trajectory towards Mars aboard a Boeing Delta II 7925 launch vehicle from Kennedy Space Center. The Mars injection target was biased to miss Mars by approximately 450,000 km to insure that the S/C and the launch vehicle's upper third stage would not be on an impacting trajectory, thereby satisfying planetary quarantine requirements ($< 10^{-4}$ probability of impact). Four TCMs were scheduled during interplanetary cruise to guide Odyssey's flight path to the final B-plane[‡] aim point and meet the navigational requirements for MOI. Figure 1 shows Odyssey's interplanetary cruise trajectory with respect to Earth and Mars in a north ecliptic view. The Odyssey S/C is shown in Figure 2. In the case of a contingency, a fifth TCM was planned for, but not executed, in the final day before encounter.

Small Forces

The spacecraft is three-axis stabilized, with three orthogonally mounted reaction wheels (and a spare skew wheel) that spin to absorb excess angular momentum produced primarily by solar radiation pressure. When the wheel momentum threshold is reached, generally 2 N-m-s, this excess momentum must be unloaded. This AMD event is accomplished by firing the small attitude control thrusters to counteract

[‡] The B-plane coordinate frame is an asymptotic coordinate frame centered at the target body with axes S, T, and R used for targeting planetary encounters. In this system, the S vector is aligned parallel to the spacecraft approach asymptote, the T vector is normal to S and parallel to the Mars Mean Equator of Date, and R is orthogonal to both S and T, such that R = S x T. The B-vector, which lies in the R-T plane, defines the B-plane and points from the origin of the coordinate frame to the point where the incoming asymptote intercepts the R-T plane.

and unload the angular momentum. Because the thrusters are not coupled, the thrusting imparts a net translational ΔV to the S/C. These events are also referred to as small forces. The thruster suite used to desaturate the wheels consists of four 1 N (0.2 lbf) RCS thrusters, located at the corners of the S/C. These thrusters must provide torque authority in all body axes, so they are not axially mounted. The thrust-vector direction for each thruster is given in Table 1, in S/C coordinates. The thrusters fire in pairs to desaturate each S/C axis sequentially, but, as mentioned, are not balanced. Note in Table 1 that since each thruster has a vector component in the $-z$ direction, any RCS thruster firing will result in a net ΔV along the spacecraft z-axis.

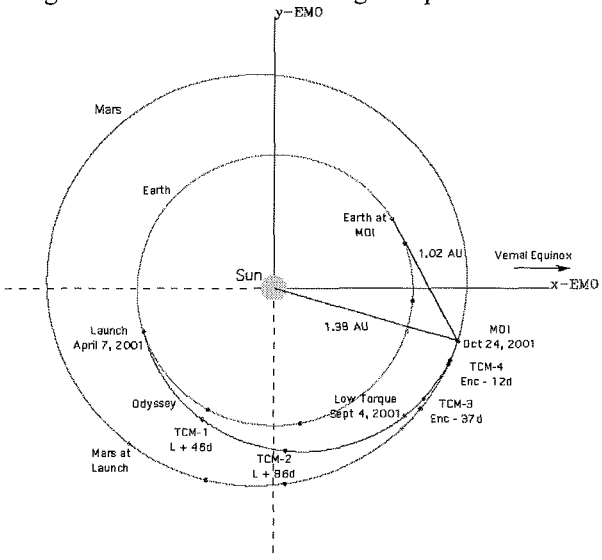

Figure 1: North ecliptic view of Odyssey's flight path.

Table 1: RCS Thrust Vectors in the S/C Coordinate Frame

Thruster	x	y	z
RCS-1	-0.8926	0.4162	-0.1736
RCS-2	-0.8926	-0.4162	-0.1736
RCS-3	0.8926	-0.4162	-0.1736
RCS-4	0.8926	0.4162	-0.1736

Although the RCS thruster configuration did not cancel the z-component (and the x-component for the y-axis desat), y and z-axis wheel desat were performed efficiently because of their relatively large moment arms and x-vector components. The x-axis wheel desats, however, had the smallest torque authority; they had the smallest moment arm and were also unbalanced in the y-axis direction. Since the S/C's x-axis was continuously pointed towards Earth during cruise to maintain telecommunications over the high gain antenna (HGA), the x-axis wheel desats produced unobservable ΔV components orthogonal to the Earth–S/C direction. Table 2 lists the thruster pairs required to dump momentum from a particular reaction wheel. Although the total translational ΔV from each desaturation event was small (see Figure 3) the cumulative trajectory perturbation was quite large, on the order of 10,000 km. So careful trending and calibration was required to meet the delivery accuracy requirements. This also meant that a predicted ΔV profile of all future AMD events had to be included in the trajectory propagation. All RCS thruster pulses during each AMD were recorded in the telemetry stream and downlinked at the beginning or ending of a tracking pass. This data was used in the propagation and determination of the orbit.

Table 2: RCS Thrusters Required Per Wheel Desat

To produce	Fire	Removes
$-x$ Torque	RCS-2, RCS-3	$+x$ Wheel torque
$+x$ Torque	RCS-1, RCS-4	$-x$ Wheel torque
$-y$ Torque	RCS-3, RCS-4	$+y$ Wheel torque
$+y$ Torque	RCS-1, RCS-2	$-y$ Wheel torque
$-z$ Torque	RCS-2, RCS-4	$+z$ Wheel torque
$+z$ Torque	RCS-1, RCS-3	$-z$ Wheel torque

The TCMs were performed using the four 22 N (5 lbf) monopropellant *TCM* thrusters, which are axially mounted along the z-axis such that they produce ΔV in the $+z$-axis direction. All TCMs were performed in a turn-and-burn mode, which enabled sufficient margin for telecom over the medium gain antenna (MGA). Turns to and from burn attitude are performed using the reaction wheels. Yaw and pitch control during the burns was enabled by off-pulsing the thrusters, while roll control was handled by the RCS thrusters. The MOI burn was performed using the bi-propellant main 695 N (158 lbf) engine. At launch, the S/C's total mass was 730 kg including 225 kg of fuel. The expected TCM execution errors are characterized as having a proportional 2% magnitude error with a fixed component of 20 cm/s for ΔV less than 5 m/s. The maneuvers also have a 10% proportional pointing error for ΔV less than 5 m/s, while ΔV greater than 5 m/s and less than 20 m/s scale linearly down to 2% for 20 m/s and greater.

Spacecraft Activities

After injection, the S/C was configured to remain in an initial-acquisition, safe-mode attitude. At this attitude, the S/C's low gain antenna was used to receive uplink signals while the MGA was used for transmission. Following subsystem checkout, the S/C was configured on April 9, 2001 for cruise by altering the attitude and solar array orientation. Almost immediately, the HGA gimbal was found to be growing hotter than expected, so the S/C was returned 8 hrs later to the safe-mode configuration. The S/C remained in this configuration

until it was believed that the solar distance grew far enough to reduce the heating; then the S/C was again reoriented for cruise on April 18. The gimbal temperatures were again found to exceed the designed values, so once more the S/C returned to the safe-mode attitude after an 8-hour checkout. Finally, on April 24-25, the S/C was configured (as shown in Figure 2) for cruise with the solar array normal offset 55° from the sun. An active thruster calibration took place on May 4, 2001 to characterize the RCS thruster firings used in the AMD events. Following the thruster calibration, the solar array was fixed relative to the S/C body such that the solar array normal sun-offset angle followed the sun-spacecraft-earth (SPE) angle within a few degrees. On August 10, a solar radiation pressure calibration was performed to determine the reflectivity (specular and diffuse) properties of the solar array. On September 4, 2001, the S/C's attitude and solar array was positioned into a *low-torque* configuration. The S/C held this attitude until two days before encounter, when the solar array was stowed for MOI, meaning that the solar was stowed against the body within the clasps. After each attitude change, the predicted AMD profile had to be recomputed as each new attitude changed the rate of momentum accumulation, and therefore the frequency and ΔV characteristics of the autonomous AMD events. Not only did these ΔV's affect Odyssey's trajectory, the changes in the solar radiation pressure due to these attitude/solar array changes also affected the trajectory. These changes resulted in significant differences in the expected arrival conditions at Mars.

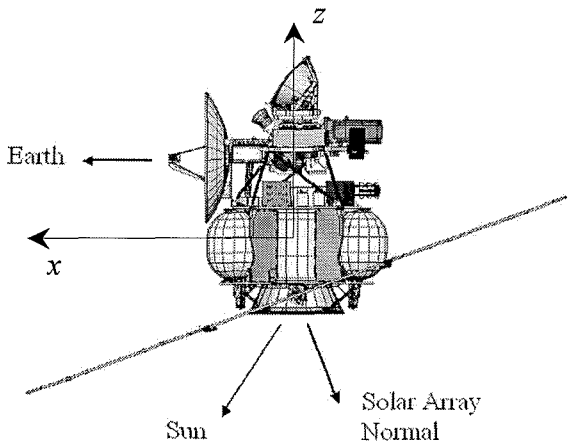

Figure 2: The S/C cruise configuration, HGA and x-body axis pointed towards Earth, *z*-axis pointed away from the sun and solar arrays 55° from sun.

Tracking Data Types

Navigation and telemetry data were obtained through the near continuous use of the Deep Space Network (DSN) antennas. Because of the trajectory's highly negative declination (-52° – -42°) for the first 2 months after injection, the S/C was only in view at the Canberra, Australia DSN complex. Eventually, the Goldstone, California, and finally the Madrid, Spain complexes were able to track the S/C (declinations, -42° – -23°), but tracking was constrained to relatively low elevations for the remainder of cruise (< 30°). In general, one DSN contact per day was established, with additional tracking scheduled around critical events. Continuous contact was maintained for the final 50 days of cruise.

The navigation tracking data used for OD included the 2-way coherent X-band Doppler (7.2 GHz up/8.4 GHz down), range, and ΔDOR data. The 2-way Doppler data measure line-of-sight velocity of the S/C relative to Earth via the Doppler frequency shift in the radio signal. For cruise, the Doppler data was collected using a 60 second count time. This data typically exhibited noise on the order of 0.02 – 0.2 mm/s and consequently was generally weighted at the 0.1mm/s level except for the noisier passes of data. The range data directly measures the relative Earth-S/C distance. The ranging signal was configured to give adequate range data from launch through MOI. The data noise was on the order of 1 m. This data was generally weighted at 3 m. Non-correlated stochastic range biases per tracking pass were also applied at 5 m to account for station-to-station differences.

In general, the Earth's troposphere and ionosphere delay the X-Band signal, so the radio-metric data must be calibrated to remove their effect. Daily ionospheric and tropospheric calibrations are provided by the Tracking Systems Analysis and Calibrations (TSAC) group at JPL, who measure the zenith path length delay through a network of GPS satellites and GPS receivers. Solar plasma can also affect the X-Band signal, but since the view of Odyssey from the DSN is away from the sun, no model was used. Since the media have a pronounced effect on the data at low elevations, the tracking station elevation cut-off was set at 10°. The range data are also affected by signal path-length delays at the tracking stations ground electronic systems and the various paths through either of two of Odyssey's Small Deep Space Transponders (SDST), depending on which S/C antennas are used for uplink and downlink. The SDST delays were calibrated before launch. The station delays are generally measured before and after a ranging pass.

ΔDOR Tracking

The ΔDOR data is formed by the near simultaneous observation of Odyssey from two DSN tracking stations separated by an intercontinental baseline. In a ΔDOR observation, the spacecraft signal is received at each of

two stations and the difference in arrival time is measured. This measurement is affected by station clocks, receiver electronics, transmission media, system noise, and other geometric factors. To calibrate systematic effects, an observation of the difference in signal arrival time, or delay, is also made for an angularly nearby quasar. The ΔDOR observable is then formed as the delta between the S/C and quasar signal delays. Instrumentation has been designed and receiver parameters are chosen so that systematic effects for the spacecraft and quasar measurements will nearly cancel. The resulting ΔDOR observable has an expected accuracy of 0.12 nsec, one sigma. The leading error sources are system noise, non-canceling instrumental phase shifts, and media fluctuations. A geometric delay accuracy of 0.12 nsec corresponds to an angular position accuracy of 4.5 nrad for two stations separated by 8000 km.[4] This corresponds to S/C position accuracies in the Earth plane-of-sky of approximately 90 – 680 meters for Earth-S/C cruise distances of 20 – 152 mkm. This measurement error is random for observations taken a day or more apart.

Shortly after Odyssey was observable at the Goldstone complex in June 2001, the ΔDOR observation campaign began using the Goldstone–Canberra baseline which is also known as the North–South (N–S) baseline because of its ability to ascertain accurate angular measurements in Earth's N–S direction. Because of the S/C-Earth geometry, the Goldstone–Madrid or East–West (E–W) baseline was unavailable since a certain amount of station-to-station overlap time is needed to complete the three 15 minute observations (S/C, quasar, S/C) which constitute a single ΔDOR measurement. Beginning on Sept. 30, this E–W baseline measurement was determined to be viable, but the observation times had to be reduced to ten minutes and the viewing was constrained to very low elevations. In addition, because the S/C or quasar could not be simultaneously observed during the third observation, the observations consisted of first observing one quasar, then the S/C and finally a quasar different from the first. The noisy data due to the low elevation that resulted had to deweighted such that no real benefit was gained by including it in the OD solutions. The ΔDOR campaign consisted of acquiring data at a rate of two points per week until the last three weeks before encounter where the rate went to four per week for a total of 46 measurements, (39 N–S and 7 E–W). Only one measurement was lost due to a station transmitter failure unrelated to the ΔDOR measurement.

Orbit Determination

The JPL Orbit Determination Program's (ODP) pseudo-epoch state least-squares filter was used for determining Odyssey's trajectory and predicting the Mars encounter conditions by estimating the S/C's epoch state and various parameters that model the dynamical environment that influences the S/C's motion. These dynamical influences include the thrusting events of TCMs or AMDs, solar radiation pressure, possible out-gassing events and the Mars ephemeris within the last several hours before encounter. Stochastic range biases and S/C accelerations were also included in the estimation filter. Once determined using the available tracking data, the trajectory was propagated using a schedule of future AMD ΔV events. The contributions of the following errors were considered in the OD covariance: ionosphere, troposphere, station locations, Earth and Mars ephemerides, and gravity, polar motion, UT1, quasar locations, solar pressure areas and future AMD ΔVs.

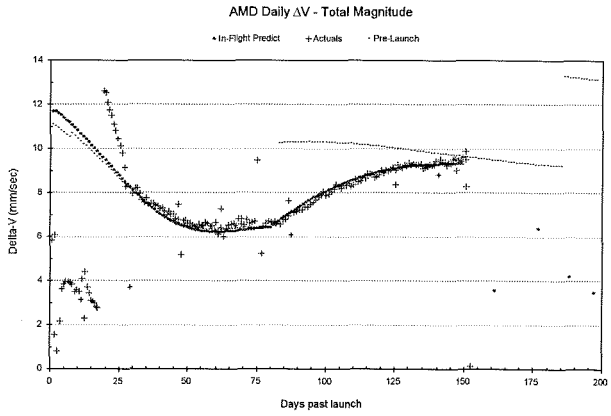

Figure 3: AMD ΔV magnitudes.

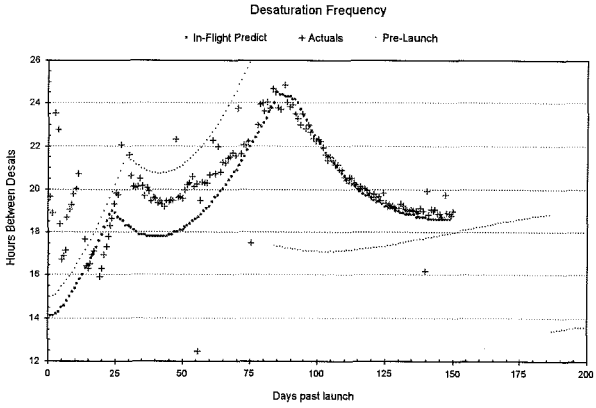

Figure 4: Frequency of AMD events during cruise. After the S/C *low-torque* attitude was configured (approx. 150 days after launch), no autonomous desats occurred.

Thruster Calibrations

Two in-flight thruster calibration activities (one active, one passive) were scheduled to ensure adequate modeling of the thruster perturbation on the trajectory. The calibration was envisioned first as a risk-reduction measure to ensure that no gross computation errors were introduced to the thruster modeling. The second benefit was an increase in the accuracy to which the thrust vector magnitude and direction could be calculated.

The active calibration occurred on May 4, 2001, just about a month after launch, This first effort involved slewing the spacecraft to view the thrusting from several different angles, and there were several operating constraints that affected the design of the calibration. The MGA was limited to 45° off Earth-point to maintain telecom, and thermal considerations also limited the choice of acceptable attitudes. To minimize changes in configuration, the solar array was constrained to stay in a fixed position for the duration of the event, which also limited the choice of acceptable attitudes from a power perspective. A reaction wheel momentum limit of 3 N-m-s was imposed to prevent the wheels from spinning up to an unsafe rate.

Through iteration, an acceptable design was developed that satisfied all of the constraints and met the objectives of the test. Three nearly orthogonal off-Earth attitudes were chosen to provide observability into the three components of the thrust vector. At each attitude, the thrusters were fired in pairs to sequentially spin up, then spin down each reaction wheel. The test totaled nine hours in duration to perform the profile at Earth-point, and the three off-Earth attitudes. The goal of this *active calibration* effort was to completely characterize the magnitude and direction of the thrust vector for each RCS thruster pair. The translational velocity change was measured with the Doppler, and the body and wheel rates were captured in telemetry. The results of the calibration indicated that the predicted models were consistent with the actual thruster performance to within 5%. This was confirmed with the Doppler analysis, as well as the dynamics analysis.

The *passive calibration* was performed three months prior to encounter. It involved all of the data collection, analysis, and interaction between the teams that was required for the active calibration, but was performed only at the Earth-point attitude. The goal of this test was to confirm that the character of the thrusting had not changed significantly over the course of the mission. Again the results indicated that the models were consistent with the observed performance to within 5%.

Low Torque Attitude

Once the modeling was shown to be consistent with the performance, an updated momentum management strategy was developed. As power margin was shown to be sufficient, the first step was to fix the solar array orientation to minimize the disturbance torque. Instead of a fixed sun-offset angle of 45° as planned before launch, the solar array was fixed with respect to the S/C body to follow the SPE angle, thereby reducing the solar torque. To further reduce the effects of the AMD events on orbit determination during the final two months of interplanetary cruise, the Navigation Team requested the attitude and solar array position be adjusted in order to place the center of pressure as close to the S/C's center of mass as possible. This *low-torque* attitude nearly eliminated the build-up of momentum, and thus minimized the number of AMD events during the most critical portion of cruise. The adoption of the *low-torque* attitude late in cruise reduced the desat frequency from twice per day to twice per month. This configuration worked so well that no autonomous desats occurred during this time, only forced desats occurred before the four following activities: MOI checkout (Sept. 6), TCM-3 (Sept. 17), TCM-4 (Oct. 12) and the S/C re-configuration into the MOI attitude (Oct. 22). In addition to minimizing the desat frequency, the ΔV per event was minimized (see Figure 3 and 4). Also shown in Figure 4. is the desat frequency that was predicted pre-launch. The pre-launch model was reasonably accurate, but the operations in flight changed significantly from the plan.

FILTER STRATEGY

In addition to a baseline filter case, OD solution consistency was routinely evaluated through a battery of filter strategies and data combinations. The approach to the orbit determination problem with regards to the challenges presented beforehand was to define a set of filtering configurations that would encompass the realm of possible modeling uncertainties. This approach also included unrealistic strategies. The goal of this approach was to understand how these filtering strategies influenced the solutions by determining the sources of solution differences. The unrealistic strategies were used to cover extreme possibilities which may reveal modeling problems that could have been masked by the nominal filtering strategies.

Software tools were built to visualize and trend the results of these many cases and to help decipher the causes of solution discrepancies. Finally, OD strategies and results also were regularly reviewed (up to daily) in the two months prior to MOI by the Navigation Advisory Group (NAG) at JPL.

Since launch, we observed that the beginning and end of the fit 2-way Doppler data would exhibit slopes. Much effort went into finding the cause of these patterns. The S/C dynamic models and media calibrations were re-evaluated. Solar pressure and the small force AMD events were found to be non-contributing factors. Media parameters were estimated, but found to be unrealistically large. A white-noise three-axis stochastic 'gas-leak' acceleration model was routinely estimated to account for possible unmodeled accelerations acting upon the S/C. Several batch lengths of 2 hrs to 2 days were used with an *a priori* uncertainty on the order of 10 – 20% of the solar radiation pressure value ($\approx$ 60 – 80 nm/s^2). The only significant gas-leak acceleration estimates were in the Earth-line component.

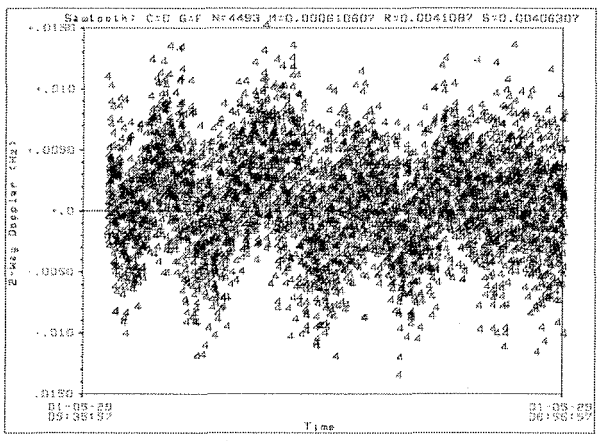

Figure 5: Sawtooth signature in 1-second 2-way Doppler residuals from Canberra DSN station.

During the TCM-2 data arc, a couple passes of Doppler residuals such as that shown in Figure 5 exhibited a peculiar *sawtooth* pattern. Because it appeared that we were having problems fitting the data without the gas-leak acceleration estimation, we became concerned that this may have been more evidence of serious problems in the S/C modeling, the SDST, DSN hardware or the ODP. Several DSN and NAG experts helped analyze these unusual patterns, but no definitive explanation was found. The DSN tracking procedures for Odyssey had been to follow the S/C's downlink frequency within a fairly tight bandwidth by periodically ramping the uplink signal. It was believed that this ramping of the signal could have contributed to this problem, especially if the values of the ramp rates were being truncated, but no evidence of this was found. In the case that this data was incorrect, our procedures were to remove the data, however, it was determined that the data had little effect on the OD solutions, especially due to the signatures' high frequency nature.

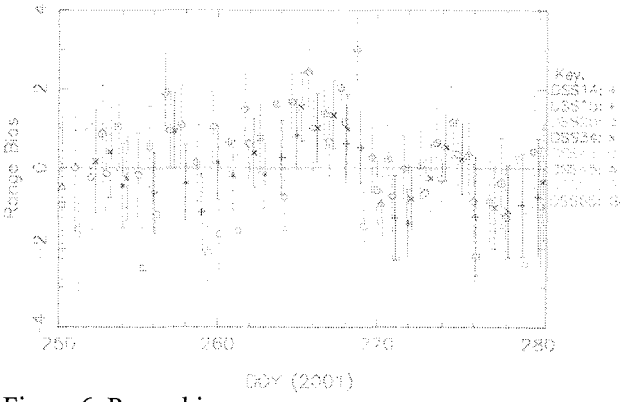

Figure 6: Range biases

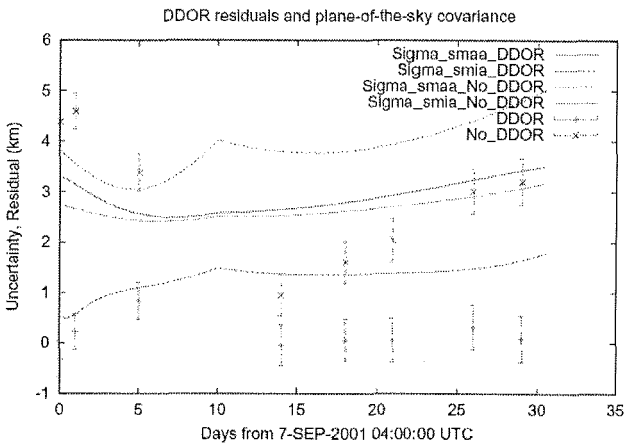

Figure 7: ΔDOR residuals with respect to the mapped Earth plane of sky covariance.

Several passes of Doppler residuals and fewer passes of range residuals were exhibiting more anomalous signatures. The low elevation data, especially at the Madrid complex, were suspected to strongly be influenced by media. Unlike the high frequency of the sawtooth pattern, these longer period fluctuations in the Doppler data were found to shift Odyssey's OD solutions by orders of 1-σ in the B-plane from one hour to the next. Tropospheric and ionospheric calibrations for Odyssey were generally computed and delivered twice per week and these products included predicted calibrations to cover the times between deliveries. During the time of the TCM-3 design (early Sept), inconsistencies on the order of 2σ in the B.R direction were found between OD solutions that included ΔDOR to those that did not. When a new troposphere calibration delivery (received just after the OD027 delivery for TCM-3 design) was used in the OD, these inconsistencies were removed. Furthermore, when these calibrations were included in the ΔDOR solutions, such as OD027, the shift was smaller, approximately 1-σ. Since there was a lack of media observations using the GPS survey in the line-of-sight direction to Odyssey from Madrid, the calibrations were

found to not correctly model the troposphere and ionosphere for the Madrid passes. To verify the media's affect on the radio signal, a few Differenced Range Versus Integrated Doppler (DRVID) measurements were taken using the S/C's ΔDOR tones to measure the media's total electron content (TEC). Because the ranging measurement's code modulated on the carrier signal experiences a positive group delay while the carrier phase experiences a negative phase delay, DRVID is a direct measurement of the TEC along the signal path.[5] This verified that the disturbances to the radio-metric data at Madrid were caused by media (ionosphere and/or solar plasma). It was also known that solar activity during this time was high and there were reports of several coronal mass ejections.

Figure 6 displays range biases of ± 3 meters estimated during a TCM-4 data arc. Madrid's Deep Space Station (DSS) 65 was found to have biases of 1 to 2 m while Canberra's DSS-43 exhibited biases of –1 to –2 m. The other DSS antennas generally showed biases of 1 m or less. Generally, all pass biases were resolved down to ±1 m. These station relative bias variations were typically seen in the OD solutions since the Madrid and Goldstone came into view of Odyssey.

The ΔDOR residuals for the N–S baseline generally fit down to the 0.12 nsec applied weight. The E–W baseline on the other hand could not fit down to this level. These data generally fit to an accuracy of 1 nsec. This data was determined to highly influenced by inadequate media coverage at the low elevations south of Madrid and thus, were not included in the OD solutions. Figure 7 compares a ΔDOR solution (including Doppler and range) residuals to a Doppler and Range only solution (No_DDOR). The ΔDOR residuals in Figure 7 have been mapped to Earth Plane-of-Sky distances in the second to last month before MOI. At the S/C-Earth distances during this time, ΔDOR fixes the S/C's position to under 500 m relative to the Earth's N–S direction. For comparison, the ΔDOR data was passed through the Doppler and range only solution. Here the S/C's trajectory shows N–S position residuals of 1 to 5 km from the ΔDOR measurements. The semimajor and semiminor axes of the S/C's state covariance mapped to the Earth's plane of sky is also shown for comparison. Aside from the first two points, the ΔDOR pass-through residuals of the Doppler and range solution show consistency with its plane-of-sky covariance.

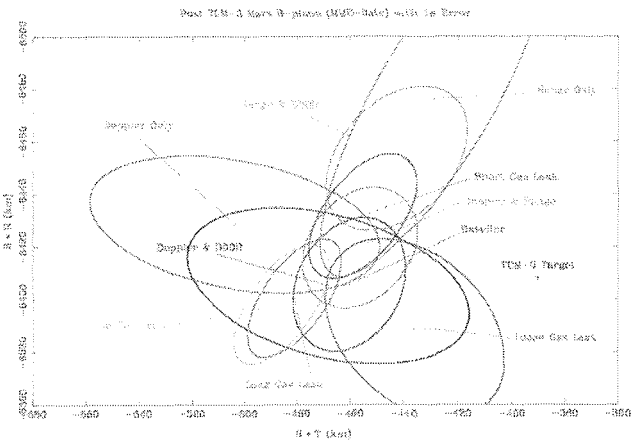

Figure 8: Comparison of filter strategies during post-TCM-3 analysis.

In the month before the design of TCM-3, several filter approach strategies were identified for routine inspection during the days leading up to MOI. A set of thirteen cases was developed to realistically encompass the realm of possible OD solutions by covering areas of concern. These concerns included mismodeling of non-gravitational accelerations or forces upon the S/C, data type inconsistencies, and data problems. The baseline filter strategy included the Doppler, range and ΔDOR data respectively using the nominal weights of 0.1 m/s, 5 m, and 0.12 nsec and an elevation cut-off of 10° (later updated for TCM-4 design to 15°). The filter set-up included estimating one scaling factor on the ΔV per axis desat, the white-noise stochastic gas-leak acceleration with a batch length of 12 hours and process noise of 5 nm/s^2 in the Earth-line component and 1 nm/s^2 in the orthogonal directions, 50 – 100% uncertainties applied to the specular & diffuse reflective properties of the solar array and bus in the solar radiation pressure model, white noise stochastic pass dependent range biases with process noise of 5 m. The following cases departed from the baseline only in the change of the concerned model or data. These included the loosening the *a priori* uncertainties on the desats, on the solar radiation pressure parameters, or stochastic gas-leaks, and changing the batch length (longer or shorter) or removing the gas-leak from the filter. The Appendix gives the nominal *a priori* uncertainties for the estimated and consider parameters in the baseline case. Tight and loose *a priori* uncertainties are also listed the Appendix for the alternative cases. Data type variations included the following cases: Doppler only, Doppler & range, Doppler & ΔDOR. The cases that addressed data problems included, deweighting the Doppler data by two times, changing the elevation cut-off to 15° and removing entire passes of Doppler data that exhibited unusual signatures.

With the continuous tracking data available during the last 2 months before MOI, trending of the 13 cases using short, medium and long data arc lengths of respectively, 1 – 4 weeks, 4 – 9 weeks and 9 – 12 weeks were performed on a near daily basis. Several other non-standard strategies were performed 2-3 times per week. These included the following cases: applying loose range bias a prioris, range only, range & ΔDOR, estimating Doppler biases and an *enhanced* filter set-up. The *enhanced* filter incorporates the estimation of Earth's polar motion and rotation and data errors from sources such as the ionosphere, troposphere, and station or S/C transponder biases into the filter as stochastic processes.[6]

Figure 8 shows an example of how the various filter strategies compare in the MME B-plane. Compared to the baseline during the time of the post-TCM-3 solutions the Doppler-only solutions were found to reside approximately 1-σ or more to the left (in the B.T direction), Doppler-and-range solutions were 1-σ above (in the B.R direction), range-only solutions were more than 1-σ □□□□□, no-gas and long gas-leak solutions drifted down to the left, and the short gas drifted up to the right approximately 1-σ. The addition of the ΔDOR to the Doppler or range-only cases brought the solution closer to the baseline.

RESULTS

After accumulating several minutes of Doppler data following separation from the launch vehicle's third stage, the Multi-Mission Navigation Team at JPL determined Odyssey's flight path and transferred the estimated state vector to the Odyssey Navigation Team. With several more hours of Doppler and Range measurements it was determined that the Delta-II launch vehicle had injected the spacecraft onto a trajectory that would take it nearly 2-σ away from the designed target.[1] This off-nominal performance fortuitously put Odyssey on a favorable trajectory. Instead of the expected ΔV 15.4 m/s to remove the bias and bring Odyssey closer towards Mars, TCM-1 only required approximately 3.6 m/s. Not only did it result in a substantial propellant savings, the first flight path correction, TCM-1, was delayed to 46 days (May 23) after launch instead of the planned launch + 8 days.

TCM-1 Design

To support the TCM-1 maneuver design, the OD team collected tracking data up to 13 days prior to the maneuver execution. Several S/C events perturbed the trajectory in the time leading up to the TCM-1 design. In addition to the 46 AMD events, these included the active RCS thruster calibration, the THEMIS Earth-Moon calibration and a safing event which lost a few packets of AMD data and produced a higher frequency of desats. In addition to an acceleration presumably caused by the escaping of trapped gas or surface material out-gassing experienced shortly after launch, a clear indication of out-gassing appeared during the turn for the THEMIS calibration. The equivalent ΔV amounted to approximately 1.5 mm/s. The epoch of the data arc was advanced past the final S/C transition to cruise orientation on April 25. A TCM-1 of 3.6 m/s was designed to move the S/C 65,000 km closer to Mars and change arrival time by 3.5 hrs earlier. Because TCM-1 and the next burn, TCM-2 were designed and optimized together, TCM-1 did not target the final encounter aim point. Based on radio-metric data and burn telemetry, the maneuver was determined to have accurately achieved the desired ΔV magnitude, but the pointing was off approximately 3°, about a 1-σ error (see Table 3 for maneuver statistics). Following the TCM-1 burn, the predicted attitude and thus, the predicted AMD events were changed to reflect new assumptions. This resulted in a B-plane shift of approx. 1000 km closer to the desired TCM-1 aim point. Table 4 compares the TCM-1 B-plane target against that achieved through the TCM-1 reconstruction. Figure 9 shows the movement of the S/C's trajectory resulting from the TCM-1 burn mapped to the time of encounter in the MME B-plane. In this figure, the TCM-1 target and expected 3-σ maneuver uncertainties are compared to that achieved.

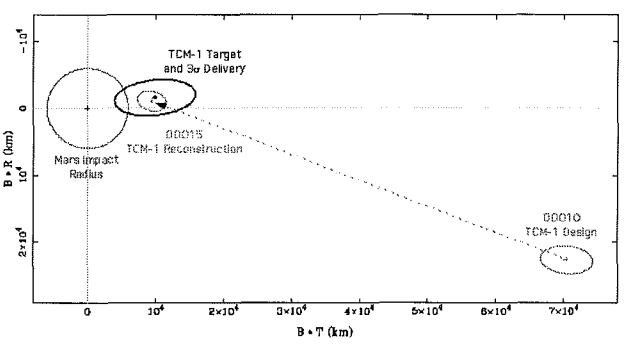

Figure 9. TCM-1 target and 3-σ delivery dispersion and achieved results.

TCM-2 Design

The data cut-off for the TCM-2 design solution (OD015) was 11 days before TCM-2's execution on July 2. The data arc began after the TCM-1 burn and included five N–S ΔDOR measurements, several passes of Goldstone and three passes of Madrid. Since considering the error contributions from the predicted AMD ΔVs inflated the B-plane statistics by approximately six times, these errors were removed in

the comparison of the various OD solutions strategies. With these errors removed, it was found that the inclusion of the ΔDOR data into the OD baseline strategy consistently moved the solution approximately 1-σ away from the Doppler and range solution.

TCM-2 executed with a ΔV of 0.9 m/s to move the S/C's mapped B-plane encounter conditions closer to the final aim point over the North Pole of Mars. Because of the expected maneuver errors, TCM-2 was designed to lessen the probability of impact by biasing the trajectory away from the final aim point by approximately 1000 km. The maneuver in Table 3 was reconstructed to be an overburn of approximately 1% in ΔV magnitude and 1° error in pointing. Figure 10 displays the change in arrival conditions in the B-plane due to TCM-2. TCM-2 achieved its target with 0.2σ of the delivered statistics listed as the post-TCM-2 solution in Table 4.

TCM-3 Design

After the design of TCM-2, two changes for the remaining AMD ΔV profile were adopted. These included the changes to the future ΔVs from the fixing of the solar array orientation with respect to the S/C body and changing the S/C configuration into the *low-torque* attitude after Sept. 4. These changes, especially the *low-torque*, caused the OD solutions to migrate upwards away from the TCM-2 target about 840 km. The analysis of the active thruster calibration had computed small RCS thruster misalignments and differences in thrust levels from the nominal values. This analysis was used to adjust the AMD ΔV values from telemetry. Further analysis through the OD process showed that these adjustments were closer to those observed, so this small force formulation, referred to as '3aeR2', was used in the solutions. Later, after the passive thruster calibration took place, the thruster vectors were again adjusted in version '3aeR2-ptcal'.

The OD solution (OD027) for the design of TCM-3 used data up to seven days before the burn executed. TCM-3 executed on Sept 17 with a ΔV of 0.5 m/s to move the S/C's trajectory to the final aim point for MOI as shown in Figure 11. The desired inclination and altitude corridors are illustrated in this figure. The direction of the ΔV was nearly orthogonal to the Earth-line direction which made it challenging for the OD team to quickly determine the performance. After a few days of tracking, the burn was determined to be 3% over in magnitude and nearly 2° off in pointing. The error in the pointing may have been caused by the rate damping of the attitude control system after the maneuver. Although TCM-3 achieved the upper boundary requirement on the altitude corridor, it missed the target by approximately 1.5–σ, mainly in the B.T or inclination direction.

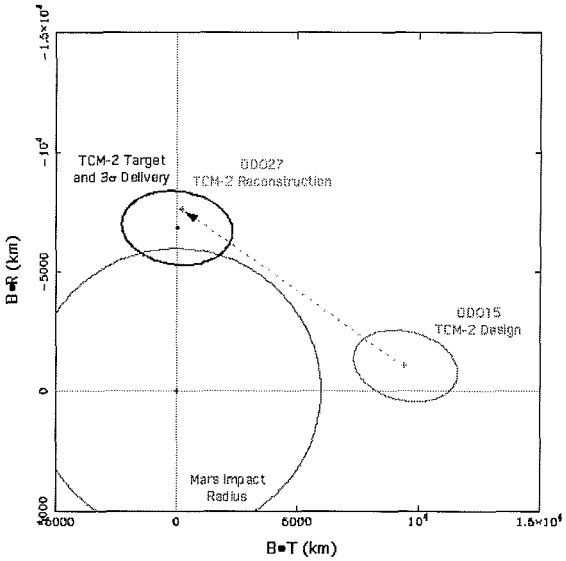

Figure 10: TCM-2 target and 3-σ delivery dispersion and achieved results.

TCM-4 Design

The tracking data of solution for the design of TCM-4 (OD034) was cut-off five days before the burn executed. Eighty-two solutions were computed to support TCM-4. From the time since the TCM-3 design, eight hundred solutions had been generated. The epoch of the baseline solution used for TCM-4 design began on Sept. 7 after the transition to the *low-torque* configuration and the MOI check-out activity on Sept. 6. Aside from estimating the TCM-3 burn and its associated RCS firings (forced desat before, and rate damping afterwards), this data arc maximized the amount of tracking data while the S/C was minimally influenced by dynamical events. The various OD solutions showed remarkably good agreement. A small 8 cm/s TCM-4 was designed to achieve the final aim point. Figure 12 shows the path of TCM-4 to the final aim point in the MME B-plane with the expected 3-σ delivery statistics fitting well inside the targeted corridor.

TCM-5 Go/No-go Decision

There were concerns that TCM-4 was too small to be adequately executed on Odyssey because of quantization effects in the propulsion system, however, TCM-4 performed flawlessly with negligible error (Table 3). Following the execution of TCM-4, the Navigation Team presented daily OD updates to the Project and NAG. Figure 13 illustrates the process of determining Odyssey's final delivery at Mars by

showing the consecutive B-plane results following TCM-4 on Oct 12, 18, MOI – 36 hours, MOI – 12 hours and finally at encounter.

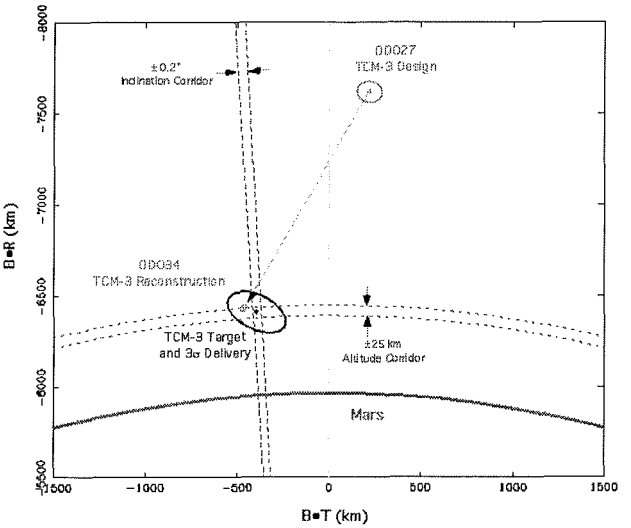

Figure 11: TCM-3 target and 3-σ delivery dispersion and achieved results.

The decision of whether to perform a TCM-5 maneuver was based on the *P2* altitude. The periapsis altitude during MOI was expected to be 328 km, which was well out of the Martian atmosphere. Due to the natural drop in periapsis radius due to the pitchover MOI burn, the target periapsis altitude at *P2* was 300 km, with an expected altitude uncertainty of 15 km 3σ. To provide ample margin, a reasonably large uncertainty of 50 km was used to define the TCM-5 go/no-go criteria. The region of concern was an altitude below 200 km, which would place the spacecraft within the sensible Mars atmosphere. So the criteria stated that if the solution plus the 50 km uncertainty dipped below 200 km at *P2*, then a TCM-5 maneuver would be executed to raise the periapsis altitude. Two opportunities for TCM-5 were scheduled at MOI – 24 hours and MOI –6.5 hours. The decisions on whether to perform the burn were respectively made 2.5 and 2 hours beforehand. These decisions were based on OD updates with the data cut off, respectively, 9.5 (MOI –36 hrs) and 4.5 (MOI –12 hrs) hours earlier. As the estimated periapsis altitude remained within 1 km of the 300 km target (at *P2*) during these times, the 50 km altitude margin never approached the 200 km limit, and as a result, TCM-5 was not executed at either opportunity.

With respect to the TCM-4 delivery statistics, the achieved conditions were approximately 0.2σ (-1 km) high in the B.R and 0.5σ (-4 km) to the left in the B.T directions and 0.4σ (0.6 sec) late (Table 4). The achieved altitude at P2 was 0.7 km high while the inclination was off 0.04° (Table 5).

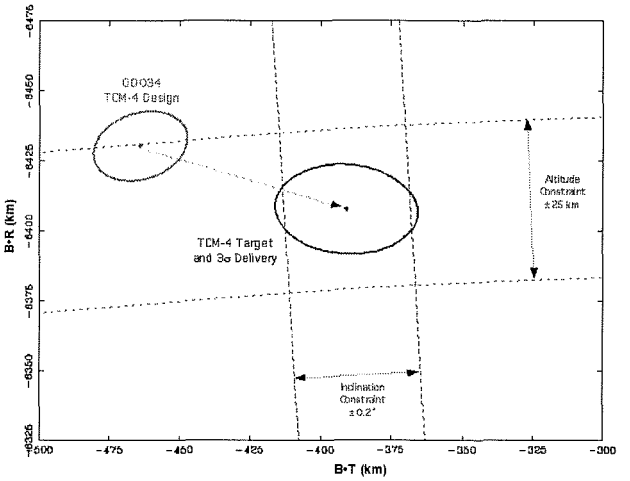

Figure 12: TCM-4 target and 3-σ delivery dispersion.

CONCLUSIONS

With the help from the ΔDOR data, and the *low-torque* attitude, the Odyssey's navigation was able to overcome the challenges presented to the OD processes. These challenges included the affect of the routine AMD small forces, and the tracking data problems on the OD solutions. The ΔDOR measurements complimented the traditional Doppler and range data by improving the S/C's out-of-ecliptic plane position component which was necessary for achieving the encounter conditions. The *low-torque* attitude effectively removed the *desat* ΔVs as being a significant error contributor in the OD solutions, especially for the final targeting maneuver, TCM-4. The inspection of the final TCM design solutions through the routine evaluation of the many filter strategies helped our understanding of how the dynamical models and radio metric data quality can affect the OD solutions. These improvements resulted in arrival conditions over the North Pole of Mars well within 1–σ of the designed values. The achieved altitude above the North Pole was less than 1 km away from the 300 km target altitude.

ACKNOWLEDGMENT

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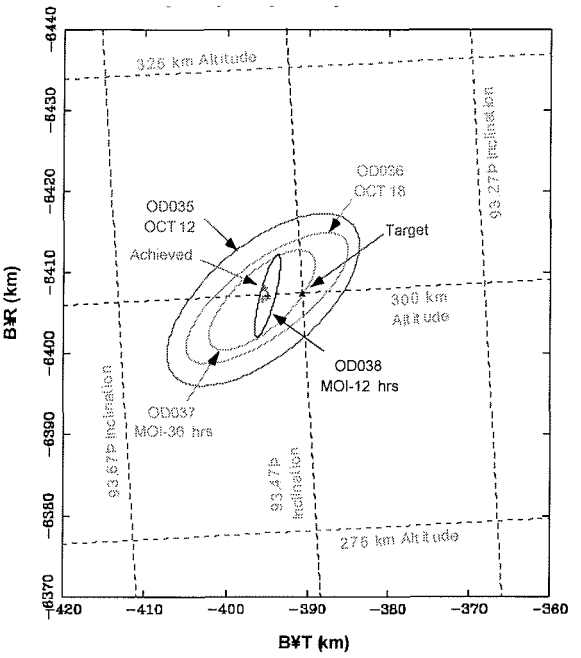

Figure 13: TCM-4 target and 3-σ delivery dispersion and achieved results.

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Table 3: Maneuver Reconstructions

Maneuver	Date Executed (UTC-SCET)	Design (EME-2000)	Reconstruction	Sigma	Deviation from Design
TCM-1	23-May-2001 17:30				
	ΔV (m/s)	3.5578	3.5628	0.014 (0.40%)	0.14%
	α(deg)	-28.9760	-29.3478	0.209	-0.372
	δ(deg)	-0.5539	-3.3952	0.204	-2.841
	Total Pointing Error				2.87 deg
TCM-2	02-Jul-2001 16:30				
	ΔV (m/s)	0.8992	0.9093	0.073(0.25%)	1.12%
	α (deg)	-21.171	-22.094	0.121	-0.927
	δ (deg)	8.343	8.619	0.171	0.276
	Total Pointing Error				0.95 deg
TCM-3	17-Sep-2001 04:00				
	ΔV (m/s)	0.4496	0.4630	0.002(0.37%)	2.98%
	α (deg)	87.9686	84.1285	0.548	-3.840
	δ (deg)	-63.5344	-63.3219	0.079	0.213
	Total Pointing Error				1.73 deg
TCM-4	12-Oct-2001 04:00				
	ΔV (m/s)	0.0772	0.0772	0.001(1.2%)	-0.04%
	α (deg)	-174.5770	-174.5536	0.197	-0.023
	δ (deg)	10.8916	10.8298	0.199	-0.062
	Total Pointing Error				0.066 deg

Table 4: Mars B-Plane Aim Point & (1-σ) Delivery Results (Mars Centered, MME Date: 24-OCT-2001 ET)

Maneuver	B•R (km)	B•T (km)	TOF (ET-SCET)
Injection			
Target & Delivery	45,572 ± 75,000	439,690 ± 190,000	25-OCT-01 23:43:40
Post Injection / TCM-1 Design (OD010)	22,646 ± 693	70,496 ± 1291	06:28:09 ± 404 sec
TCM-1			
Target & Delivery	-1565 ± 904	9972 ± 1977	02:56:58 ± 730 sec
Post-TCM-1	-693 ± 652	8178 ± 1061	02:46:10 ± 356 sec
Difference	871(+0.96 □)	−1794(-0.91□)	−648 sec (-0.89 □)
TCM-2 Design (OD015)	-1064 ± 1496	9459 ± 2140	02:49:15 ± 696 sec
TCM-2			
Target & Delivery	-6825 ± 518	46 ± 998	02:30:00.3 ± 214 sec
Post-TCM-2	-6913 ± 363	-98.0 ± 480	02:29:51.7 ± 145 sec
Difference	-88 (-0.17 □)	-144 (-0.14□)	-8.6 sec (-0.04 □)
TCM-3 Design (OD027)	-7619 ± 19	221 ± 23	02:30:41 ± 7 sec
TCM-3			
Target & Delivery	-6408 ± 38	-391 ± 53	02:30:00 ± 14 sec
Post-TCM-3/ TCM-4 Design (OD034)	-6430.2 ± 4.2	-463.9 ± 5.6	02:30:08.1 ± 1.3 sec
Difference	-22.2 (0.58□	-72.9 (1.4□)	8.1 sec (0.58□
TCM-4			
Target & Delivery	-6407.00 ± 5.3	-391.00 ± 8.3	02:29:57.7 ± 1.7 sec
Achieved	-6408.00 ± 0.04	-395.39 ± 0.06	02:29:58.3 ± 0.004
Difference	-1.0 0(-0.19□	˜□□9□□□	˜□sec ˜□□

Table 5: Comparing Achieved Altitude and Inclination conditions to target (1-σ).

	Altitude (km)	Inclination (deg)
Flyby target	404.50 ± 5	93.4690 ± 0.07
Achieved	405.23 ± 0.043	93.5102 ± 0.0006
Difference	0.73 (0.14 σ	˜□10.6 σ
P2 target	300.00 ± 5	93.4670 ± 0. 07
Achieved	300.73 ± 0.043	93.5102 ± 0.0006
Difference	0.73 (0.14 σ	˜□30.6 σ

APPENDIX

Filter Parameters			A priori Uncertainties				
			Nominal	Tight	Loose	Nominal Value	Prelaunch Value
Estimated Parameters							
Position			10^{-6} km				
Velocity			1.0 km/s				
Solar Pressure							
	Solar Array	Specularity	50%	25%	100%	0.0900	0.0068
		Diffusivity	30%	15%	100%	0.0670	0.2814
	Drag Flap	Specularity	50%	25%	100%	0.0900	0.0000
		Diffusivity	50%	25%	100%	0.1500	0.3330
	Bus - X face	Specularity	100%	50%	200%	0.0300	0.0000
		Diffusivity	50%	25%	100%	0.2500	0.3330
	Bus - Y face	Specularity	100%	50%	200%	0.0300	0.0000
		Diffusivity	50%	25%	100%	0.2500	0.3330
	Bus - Z face	Specularity	100%	50%	200%	0.0300	0.0000
		Diffusivity	50%	25%	100%	0.2500	0.3330
	HGA	Specularity	100%	50%	200%	0.0300	0.0000
		Diffusivity	50%	25%	100%	0.2500	0.3330
TCMs							
	Magnitude		2% + 0.020 m/s				
	Direction	0.04 < ²V < 5 m/s 5 < ²V < 20 m/s ²V > 20 m/s	10% 10% – 2% (linear) 2%				
AMD ²Vs*	Impulsive ²Vs in S/C coord	1 per entire S/C x-y-z desat	20%	10%	100%	3σR2	
Stochastic Parameters							
3-Axis Acceleration (gas leak) in S/C coord.	Spherical		5e-12 km/s²	1e-12 km/s²	1e-11 km/s²	0	
	Correlation Time		0				
	Batch Length		2 hr - 2 day				
Range Bias			5 m	4 m	1000 m	0	
	Correlation Time		0				
	Batch Length		per pass				
AMD ²Vs*	Small force file	DVFSCL per S/C axis desat	20%	10%	100%	3σR2	
AMD ²Vs*	Small force file	DVFX, DVFY, DVFZ per S/C axis desat	20%	10%	100%	3σR2	
Consider Parameters							
Predicted AMD ²V's in S/C coord.	X Y Z	Acceleration per day	1.1 mm/s = 13 e-12 km/s² 0.8 mm/s = 9.3 e-12 km/s² 0.9 mm/s = 10 e-12 km/s²				
Ionosphere							
	Day		3 cm				
	Night		1 cm				
Troposphere							
	Wet		2 cm				
	Dry		1 cm				
Polar Motion	X, Y coord.		5 cm (7.5 nrad)				
UT1			15 cm (0.32 ms)				
Ephemerides							
	Earth		DE405 covariance				
	Mars		DE405 covariance				
Station Locations			Full covariance				
Quasar Locations	RA, Dec		5 nrad (2.778e-7 deg=1mas)				
Solar Pressure							
	Solar Array	Area (m²)	2.50%			7.39	
	Drag Flap	Area (m²)	2.50%			3.2	
	Bus - X face	Area (m²)	2.50%			1.58	
	Bus - Y face	Area (m²)	2.50%			3.93	
	Bus - Z face	Area (m²)	2.50%			2.41	
	HGA	Area (m²)	2.50%			1.3273	
Gravity Parameter							
	Earth (km³/s²)		2.500000E-03			3.986004E+05	
	Moon (km³/s²)		1.476000E-06			4.902798E+03	
	Mars (km³/s²)		2.621440E-03			4.282837E+04	
Data Weights							
2-Way X-Band	Doppler		0.1 mm/s	0.05 mm/s	0.2 mm/s		
	Range		3 m	1 m	100 m		
	²DOR		0.12 nsec	0.12 nsec	0.36 nsec		
Data Arc Length	Short		1–4 weeks				
	Medium		4–9 weeks				
	Long		9–12 weeks				

* AMD ²Vs: one method used (Impulsive ²Vs, stochastic DVFSCL, or stochastic DVFX,Y,Z)