ODYSSEY MARS ORBITER – THIRTEEN YEARS OF ON-ORBIT NAVIGATION

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***Abstract**: The Odyssey spacecraft has been in Mars orbit since October 24, 2001 and has nearly completed 61,490 orbits. Navigation operational objectives include the following: Control the local mean solar time for science observations; for most of the mission, this varied from 3:45 pm to 5:20 pm. Currently, an orbit trim maneuver planned for November 10, 2015 will place Odyssey at 6:45 pm/6:45 am at equator crossings in order to observe early morning ground frost, fog and clouds. Initially, Odyssey was late by 42 minutes for an over-flight of the critical seven minutes of Phoenix's entry, descent and landing (EDL). Odyssey was successfully positioned for this over-flight using the ∆V from angular momentum desaturations (AMD). Similar results for the Mars Science Laboratory's EDL and Comet Siding Spring's minimum risk location will be presented. Odyssey has and continues to relay significant quantities of rover data. Navigation successfully models frequent AMD ∆Vs in order to generate accurate sixty-day trajectory predictions; a typical timing error is 25 seconds after 60 days. However, unexpected events, such as safe-mode entries with their larger and more frequent thrusting, severely impact that trajectory accuracy. Impacted trajectories can have timing errors ranging from a few minutes to ten-to-fifteen minutes after sixty-days. Other analyses (briefly stated) include: a) the offset of the orbital ground track pattern after an initial cycle of 30 days or 362 orbits and b) an operations environment of continuous thrusting if/when one of the three remaining reaction wheels fails.*

***Keywords**: Odyssey Mars orbiter navigation, Phoenix and MSL over-flights, angular momentum desaturation, trajectory accuracy, Comet Siding Spring.*

1. Introduction

The Odyssey spacecraft was launched on April 7, 2001, entered Mars orbit on October 24, 2001, began the Mars mapping or science phase on February 19, 2002 and has continued until the present day. The initial science orbit was short period (1.96 hours), low altitude (388 km at periapsis-passage and 450 km at apoapsis-passage), near polar (I = 93.1 deg), sun-synchronous (3:55 pm/3:55 am at the equator crossings) and remains in a frozen orbit with periapsis-passage over Mars' south pole. As of October 24, 2015, Odyssey will have completed 61,490 orbits of Mars.

Navigation's primary responsibilities are to a) generate accurate predicted (over sixty-days) and reconstructed trajectories, b) plan and execute orbit trim maneuvers and c) generate long term planning trajectories over several years.

For accurate trajectory predictions, all forces acting on the spacecraft must be modeled. Among these is the generation of an AMD ∆V (Angular Momentum Desaturation) or small forces model. These ∆V perturbations are caused when the spacecraft must de-saturate or reduce excess angular momentum by thrusting. Typical ∆Vs are 3-4 mm/sec with a frequency ranging from every 6 hours to every 48 hours. These models are developed from three sources: recent telemetry data, current Doppler data analysis and long-term predicted ∆V estimates. On average, approximately once per year, Odyssey entered a safe mode configuration due to an unexpected event. The ΔVs generated under this condition are larger and more frequent than nominal conditions. This had a significant impact on the predicted trajectories. Trajectory accuracy under both conditions will be presented.

Two types of orbit trim maneuvers (OTM) have been executed. Inclination changes control the local mean solar time (LMST) and rate or equivalently the longitude of the ascending node and rate. Period changes control the time of future events, the ground-track-walk and provide additional margin for our planetary protection requirement. The LMST optimizes science data acquisition, however eclipse durations, which impact battery lifetime and solar array energy generation, are also considered. Period control was used to adjust Odyssey's arrival over critical events such as Phoenix and Mars Science Laboratory's (MSL) entry, descent and landing (EDL). This allowed for the transmission of real-time telemetry data to Earth during a critical phase of the lander and rover missions. A period-change was also implemented on August 5, 2014 in order to avoid any potential danger due to Comet Siding Spring's flyby of Mars on October 19, 2014.

In addition, small period changes refined Odyssey's ground-track-walk (GTW). These were necessary to insure that the mapping orbit repeat cycle (for example, 312 orbits over 26 days or 362 orbits over 30 days) did not exactly repeat or else surface imaging would cover the same ground. This would hinder the accumulation of a global map of Mars and leave gaps. Finally, the accumulation of small positive changes to the mean semi-major axis (SMA) provided additional margin to our planetary protection requirement. Both of these were implemented by the AMD ΔVs which can be considered as micro-maneuvers.

Initial results from the beginning of Odyssey's primary mission and a description of the science instruments are presented in [1,2,3].

2. Local Mean and True Solar Time Variation – Science and Spacecraft Implications

The local mean solar time (LMST) and local true solar time (LTST) are key parameters for Odyssey's science data acquisition and spacecraft health and safety. At the beginning of the science phase, February 19, 2002, the LMST was 15:54 at the descending equator crossing (DEQX) with a positive drift rate of 39.15 minutes (LMST) per year. On September 24, 2003, our first orbit trim maneuver (OTM) was performed, with an inclination change (ΔI) of -0.16 degrees, in order to stabilize this rate as shown in Fig. 1. This maneuver was executed primarily to satisfy the various science instrument requirements for data acquisition. Although the LMST was initially constant, a positive drift developed due to third-body perturbations acting on the orbit. On September 30, 2008, another OTM was executed, with an inclination change of -0.56 degrees, in order to arrive at a very early LMST to support the MSL EDL as a relay satellite. As an example, the ΔI for this OTM can be estimated from the longitude of ascending node (LAN) rate or equivalently LMST-rate variation

$$\dot{\Omega} = -1.5\ J_2\ (R/p)^2\ n\ \cos(I) \tag{1}$$

$$\Delta(\dot{\Omega}) = -\dot{\Omega}\ \tan(I)\ \Delta I \tag{2}$$

Equation 2, the variation of the nodal rate, gives the effect of only the inclination variation. However, there is also a semi-major axis and eccentricity dependence through both $p=a(1-e^2)$ and n (the mean motion) as shown in Eq. 1. J_2 and R refer to the oblateness and mean equatorial radius of Mars. Quantities related to the OTM on 09/30/2008 are given in Tab. 1.

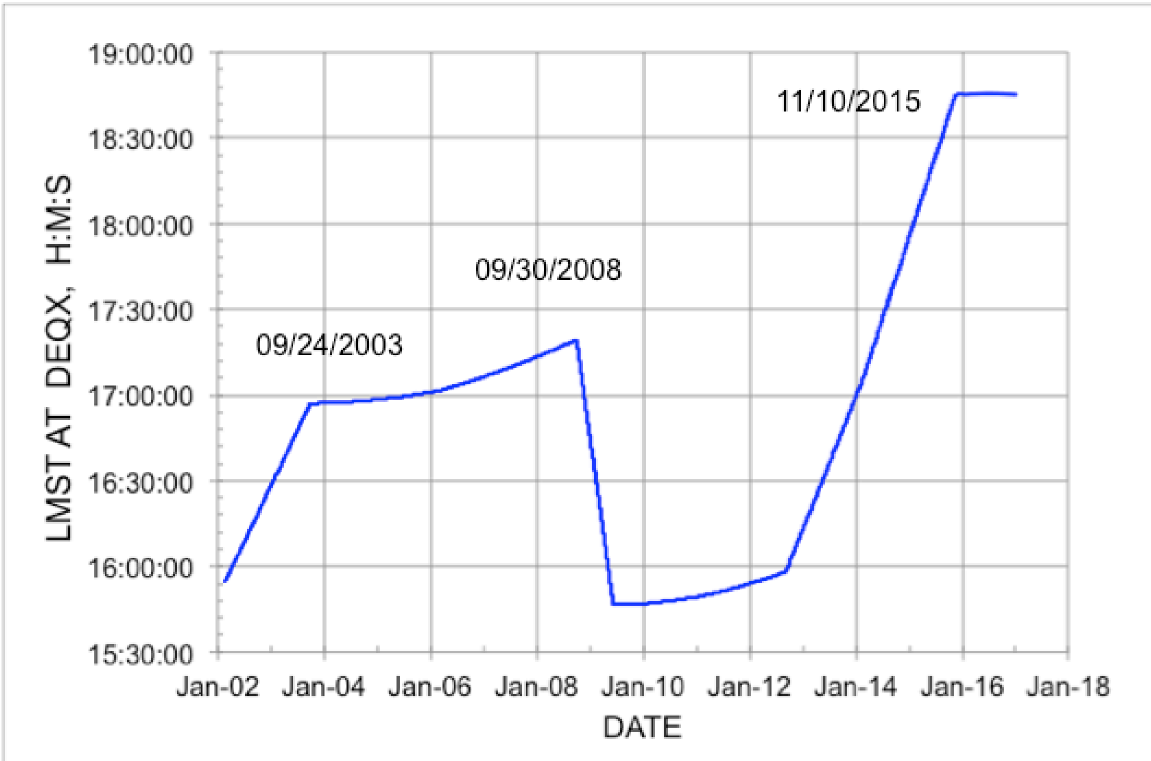

Figure 1. Variation of the LMST Throughout the Mapping Mission

Table 1. LAN and LMST Rates For OTM-5 on 09/30/2008

Parameter	LAN, deg/day	LMST at DEQX, min/year
Rate before OTM	0.529519	7.994
Rate after OTM	0.431819	-134.773
Variation	-0.097701	-142.767

The inclination and LAN before this maneuver were 93.033 deg and 267.019 deg respectively which gives a ΔI of -0.56 deg. Because of Odyssey's near circular orbit, the velocity change can be estimated from $\Delta v/v = \Delta I$ where v is 3.33 km/sec leading to $\Delta V = 33.0$ m/s.

In preparation for the mid-November, 2015 OTM, we can estimate the ΔI and Δv from the LMST variation. Propagated trajectories show that the LMST-rate will be 56.6443 minutes per year before this maneuver also as indicated in Fig.1. Since we require the LMST-rate after this simulated OTM to be at or near zero minutes per year, the total variation is available. Using the

LMST results in Tab. 1 and the -0.56 deg inclination-change, the scaled ΔI was estimated to be ΔI = -0.22 deg and also Δv = 13.1 m/sec.

In Fig. 2 we have the results of a simulated OTM on 11/10/2015. The initial LMST is 18:44:30 at the DEQX (or 06:44:30 at the AEQX) with a slight upward trend of one minute per year. The maximum and minimum LTSTs are 40 minutes later and 50 minutes earlier as shown. This variation is significant for the Thermal Emission Imaging System instrument. During these early morning hours (6:45 am to 7:25 am to 5:55 am at the AEQX), science is searching for the presence frost, haze, fog and clouds.

Also during this time, the Spacecraft Team is interested in the eclipse duration and the effect on the amount of sunlight on the solar array, battery charging and corresponding operational strategies. Because of this nearly 6:45 pm – 6:45 am orbit, as seen from the sun, the orbit is almost face-on. On November 15, 2015, the angle at Mars between the orbit angular momentum vector and the direction to the sun is 156 degrees and there is no eclipse.

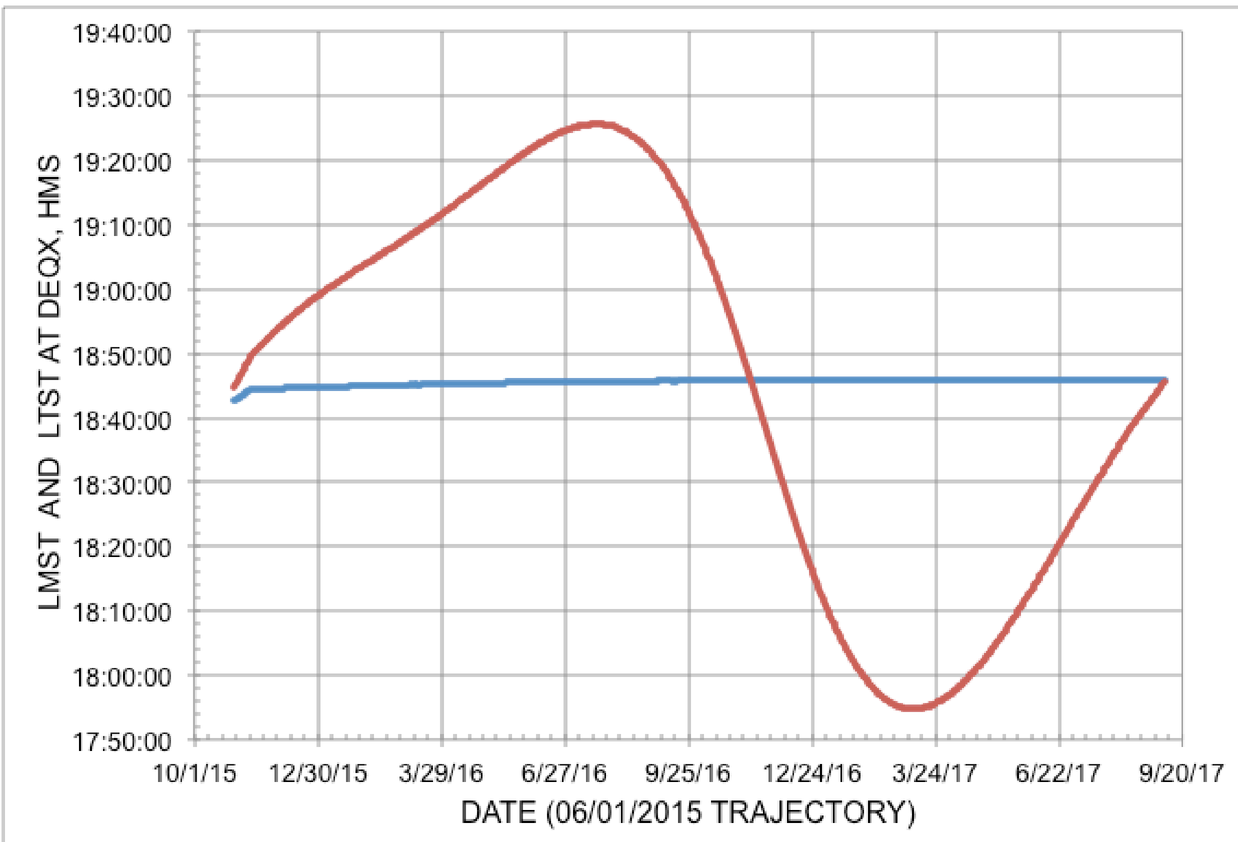

Figure 2. LMST and LTST Variation After the Mid-November, 2015 OTM

3. Orbit Trim Maneuvers (OTM)

Since mapping began, nine orbit trim maneuvers have been executed; an additional two were developed as contingencies but never executed. The next OTM is scheduled for November 10, 2015 and will adjust the inclination in order to stabilize the LMST or nodal rate. These are summarized in the following table in which the inclination and period change OTMs have been separated.

Table 2. Orbit Trim Maneuver Summary

OTM - LMST Control	1	5	6	9	10	12
Date	9/24/03	9/30/08	6/09/09	9/05/12	2/11/14	11/10/15
ΔI, deg	-0.16	-0.56	0.52	0.15	0.043	-0.22
ΔV, m/sec	9.3	32.7	30.6	8.7	2.5	12.6
Fuel, kg	1.8	5.8	5.6	1.6	0.5	2.3

OTM-Over-Flights	2	7	8	11
Date	11/22/03	7/11/12	7/24/12	8/05/14
ΔP, sec	3.25	0.41	-2.53	2.31
ΔV, m/sec	0.50	0.063	0.38	0.36
Fuel, kg	0.17	0.03	0.09	0.09
Over-flight	Spirit-MER	MSL	MSL	CSS

Inclination adjustment OTMs were used to control the LMST-rate as indicated in Fig. 1. For these maneuvers, the ΔV direction was perpendicular to the orbit plane and could be executed either at DEQX or AEQX. The orientation of the thrusters on the spacecraft was a consideration when selecting the orbital location. On several occasions, this led to a simplification in the steps necessary to orient the spacecraft to the maneuver attitude. As shown in the table, the largest and smallest OTMs were 32.7 and 2.5 m/sec (corresponding to burn durations of approximately 360 and 30 seconds) respectively. All of these maneuvers were successfully executed, both with respect to the attitude and ΔV magnitude (or thruster firing duration), and achieved their objective.

Period adjustment OTMs were used to achieve targeted locations. These were either along or opposite the spacecraft’s velocity resulting either in an increase or decrease in the orbital period. On occasion, unforeseen events, such as a safe mode entry (SME) could disrupt the nominal plan. Such an event occurred on 10/29/2003 which necessitated an OTM on 11/22/2003 in order to maintain Odyssey's over-flight of the Spirit rover on 01/04/2004. Although there was an over-burn, the over-flight of Spirit was successful.

OTM-7 was executed on July 11, 2012 with a ΔP of 0.41 seconds, because Odyssey was projected to arrive too early, by 125 seconds, for its scheduled over-flight of the MSL EDL. Prior to this, Odyssey entered safe mode on June 8 (described in Section 5) resulting in this early arrival. Immediately after this OTM, safe mode was entered again. As a result, Odyssey was instead going to be late for the over-flight by 361 seconds.

OTM-8 on July 24, with a ΔP of -2.53 seconds, corrected the above late arrival. Odyssey was now accurately positioned, within twenty-five seconds of the target time, and successfully over-flew MSL during its EDL on August 6, 2012.

Rare events, such as the Comet Siding Spring (CSS) flyby of Mars on 10/19/2014, required a maneuver. OTM-11 was essentially a time-phasing maneuver with a ΔP of 2.31 seconds. This placed Odyssey in a minimum-risk location as explained in Section 8. OTM-11 appeared to have executed as planned but immediately afterwards there was unexpected "attitude rate damping" and the associated thrusting. The initial assessment was that an extra ΔV of approximately 20 mm/sec was generated which added an additional 0.13 seconds to the planned period change. When integrated over 75 days, or 913 orbits, our arrival time at the target declination was late by two minutes and forty-five seconds. However, this was within the allowable tolerance on the target time.

The two contingency OTMs refer to the following. A close approach between Odyssey and ESA's Mars Express (MEX) spacecraft was predicted for 05/07/2005. The separation distance and radial separation were 8.3 km and 2.7 km respectively. There were larger uncertainties associated with the MEX trajectory because of the scheduled deployment of the MARSIS antenna on May 4. Based on that information, the MEX project proposed to execute a collision avoidance maneuver on April 28. The maneuver was successful and substantially increased the separation distance thus avoiding any possibility of a collision.

OTM-4 was proposed as a contingency to further ensure Odyssey's over-flight during Phoenix's EDL. Fortunately, no unexpected event occurred and the contingency OTM was never executed.

4. Time-Phasing Strategy for Phoenix and Mars Science Laboratory EDL

Before the Phoenix launch (August 4, 2007), the Odyssey and Phoenix projects discussed an Odyssey over-flight of Phoenix during the critical entry, descent and landing (EDL) phase. This was required so that real-time Phoenix telemetry data would be relayed to Earth during the seven minutes of EDL. An initial set of EDL targets was provided by the Phoenix project. That is, Odyssey was to be at a specific location (52.34º longitude and 80.27º latitude; Mars mean equator and prime meridian of epoch) at a target time (05/25/2008, 23:32:07 ET) and within a tolerance of ±30 seconds. This over-flight could have been accomplished with an OTM but the time-phasing approach presented a fuel savings and other advantages.

For an initial estimate, an Odyssey trajectory was generated on 07/30/2007 without an angular momentum desaturation (AMD) delta-velocity model. This refers to spacecraft generated, velocity perturbations due to thrusting to maintain spacecraft attitude. This is the major error source affecting the orbital period and the time of future events. Based on this trajectory, it was estimated that Odyssey would be at the target location 42 minutes and 8 seconds too early with respect to the target epoch. With this information, a time-phasing capability analysis was initiated with the objective of increasing the orbit period. Time-phasing refers to controlling or modifying the arrival time over the target location using the velocity perturbations (ΔVs) generated by reaction wheel desaturations. When reaction wheel angular speeds approach an unsafe limit, thrusting occurs (by sequence commands) in order to reduce these speeds. This results in a net ΔV imparted to the spacecraft which in particular changes the orbit period. Individually, these perturbations are very small but when integrated over many orbits they have an appreciable effect. Since the reaction wheels must be desaturated, the resultant ΔV can be used for a beneficial navigation purpose.

The size and frequency of these ΔVs are a function of the spacecraft configuration, perturbing forces acting on the spacecraft and the orbital geometry. Representative initial ΔV magnitudes were within three to four mm per sec and at a frequency of twenty-four hours for the Phoenix analysis. For an initial estimate of the time-phasing capability, we assumed the following: a desaturation ΔV of 1.0 mm/sec gradually decreasing to 0.25 mm/sec, acting along the spacecraft's velocity direction. This one mm/sec ΔV resulted in a period change of 0.0064 seconds. Starting on 08/26/2007, this single ΔV integrated over 274 days or 3326 orbits resulted in a time-phasing or change in event-times of 21.2 seconds later on 05/25/2008.

The total or integrated effect of these daily desats at the Phoenix EDL amounted to 44 minutes of time-phasing capability. Since we had initially estimated that Odyssey would be at the target latitude about 42 minutes early, this result indicated that there was enough time-phasing capability to have Odyssey arrive at the target latitude on schedule.

Although much of this work was accomplished by trajectory integrations, the following equations provide insight and accurate initial estimates. The ΔP can be estimated from the tangential component of the desaturation ΔV by

$$\Delta P = (3avP/\mu)\ \Delta V_t \qquad (3)$$

where a, v, P and μ refer to the semi-major axis, velocity, period and Mars' gravitational constant respectively. With the start and end dates of the operational plan established, the time-phasing or time-delay due to a single desat at the end date is given by

$$\Delta t = (N - 12 * i)\ \Delta P \qquad (4)$$

where N = 3326 or the total number of orbits. For the first desat, i=0. Since we assumed a desat every 24 hours (or approximately every 12 orbits), the second desat integrates over twelve fewer orbits therefore i=1. Continuing along, the total time-phasing result on 05/25/2008 is

$$\Delta T = \sum \Delta t(j) \qquad (5)$$

where j goes from zero to the total number of daily desats or velocity perturbations (i.e. 274).

As navigation progressed with the time-phasing capability, the following operational considerations and impacts needed to be understood and addressed:

a) The target information provided by the Phoenix Project was subject to change and update. If known sufficiently in advance, the impact was small.

b) In particular, there was an important flow of information between the navigation and attitude control engineers. An initial set of AMD ΔVs was provided by the Spacecraft Team, covering the entire time-phasing interval, however uncertainties could be as large as 25 percent. In addition, an option was available for selecting AMD ΔVs with a component either along or opposite the spacecraft's velocity direction. This capability allowed positive or negative period changes and was important because it gave some control for achieving the EDL over-flight within the 30 seconds of tolerance.

c) Operational command files, called sequences of activity, up-linked to the spacecraft impacted the desat planning. The sequence schedule required a 28-day development and a 28-day operational cycle. Navigation recommendations for the type of desat, either along or opposite the spacecraft's velocity, were required at the start of this cycle. Effectively, Navigation was recommending desats over 56 days and analyzing their effect at the EDL time.

d) An accommodation needed to be made for unexpected events. During time-phasing, the spacecraft experienced a safe mode entry (SME) which lasted from Sept 14 to Sept 18, 2007. Because the SME required a change in the spacecraft's configuration and attitude, thrusting and the resultant ΔVs were completely different than in the nominal nadir attitude. For example, the desat frequency increased to every 2-3 hours and the ΔV magnitude was between 12 to 20 mm/sec. In addition, there was a large initial ΔV, 155 mm/sec, as the spacecraft turned to the SME attitude.

Throughout time-phasing for the Phoenix EDL, adjustments were made for the above considerations.

Figure 3 provides an overview of the AMD ΔVx, derived from telemetry, from Phoenix's launch to EDL. This component is along the spacecraft's body axis, is in the orbit plane and is offset from the velocity direction by 73 degrees. Because the Z-body axis is perpendicular to the orbit plane, ΔVz does not contribute to the period change and ΔVy is always zero mm/sec due to the implementation of the desaturation. As shown, initially the ΔVx perturbations were positive leading to a small increase in the orbital period and thus delaying Odyssey's arrival at the target location. By 01/10/2008, Odyssey was on target for the EDL. During the remaining 137 days, systematic velocity perturbations would have taken Odyssey away from the target specification. The plan was to implement the desaturations such that the velocity perturbations oscillated as shown. This strategy canceled out any additional changes to Odyssey's arrival time at Phoenix's EDL.

The final result was that Odyssey was on target and within two seconds of the target time for the Phoenix EDL leading to a successful real-time transmission of telemetry data.

Note that Fig. 3 provides a summary of the time-phasing process from the viewpoint of the AMD ΔVs and the corresponding period changes. When Navigation provided monthly desaturation recommendations, the information available at that time was: a) the previous several weeks of telemetry data, b) current Doppler data analysis to assess the models used in previous trajectories and c) the long term ΔV predictions. This process is described in detail in Section 7.

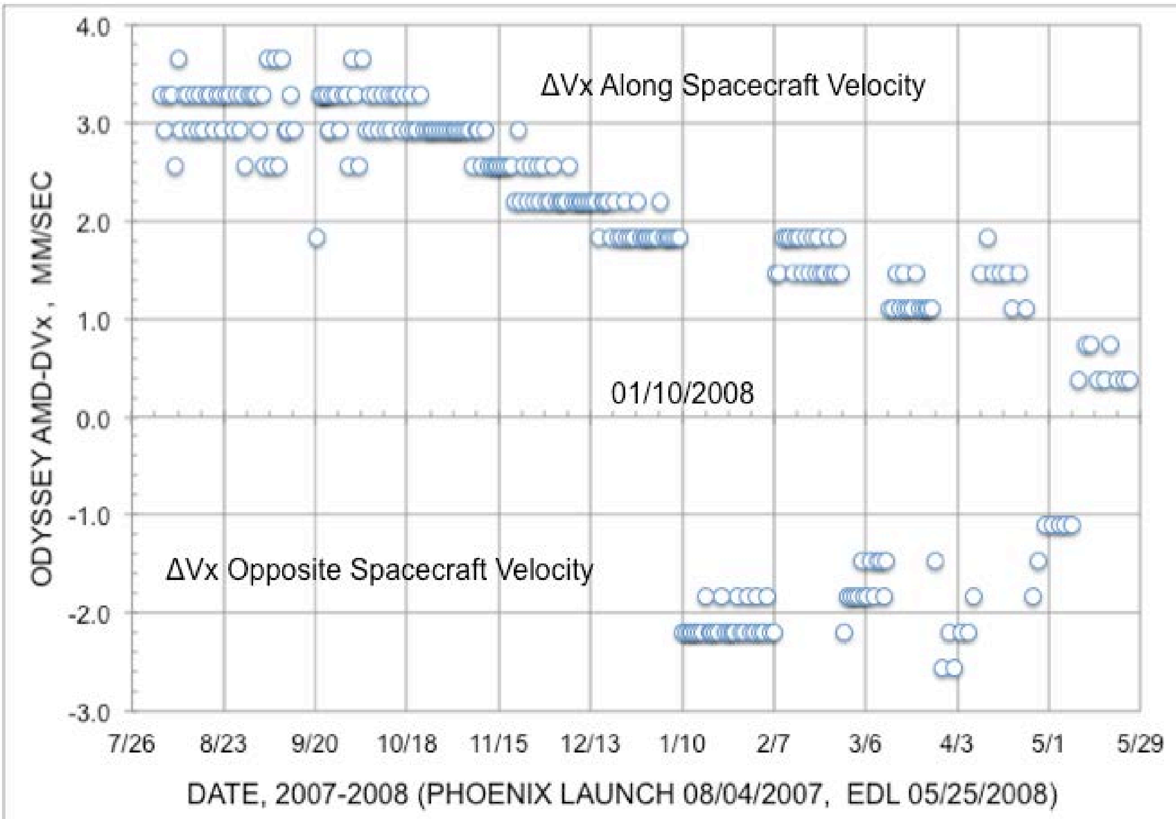

Figure 3. Overview of Odyssey's AMD-ΔVx During Phoenix's Time-Phasing

With the success of the Phoenix EDL over-flight, Navigation continued to apply this methodology to the upcoming Odyssey over-flight of MSL's EDL on 08/06/2012. The launch date was 11/26/2011 so the interplanetary phase covered 253 days. MSL provided a preliminary set of targets for Odyssey prior to launch. These specified the required time and location that Odyssey must achieve in order to be in the correct position to relay MSL telemetry during the critical entry-descent-landing phase. Thus, Odyssey was to provide real-time relay support from MSL's atmospheric-entry-point to several minutes after landing.

Table 3. Preliminary Odyssey Location for the MSL EDL Over-flight

Epoch, ET	08/06/2012, 05:13:17
Longitude, deg	153.45 (equivalently 15:56:33 LMST at the DEQX)
Latitude, deg	23.04
Coordinates	2000 IAU, Mars fixed frame

For an initial assessment, Odyssey Navigation generated a trajectory on 10/17/2011 which was propagated to 08/06/2012. The AMD ΔV model covered 10/17/2011 to 01/12/2012 (80 days) with desats occurring every eight hours each with a magnitude of 3.0 to 3.4 mm/sec. Prior to 11/10/2011, the desat model was simulated for spacecraft operational considerations. From 11/10/2011 to 01/12/2012, the AMD ΔV model analysis was conducted with a goal of closing in on the target conditions specified in Tab. 3. As indicated previously, there were two types of AMD ΔVs which were used to control Odyssey's arrival at the target: one to increase the period and allow for a later arrival and the other to decrease the period and allow for an earlier arrival.

In this simulated trajectory, no desats were modeled after 01/12/2012. The result of this trajectory propagation was that Odyssey was close to the target location on 08/06/2012 but arriving 13 minutes and 9 seconds too early. Since there was plenty of time-phasing capability after 01/12/2012, the remaining time offset could be easily accommodated. For comparison with the Phoenix analysis, Fig. 4 gives an overview of the AMD ΔVx derived from telemetry data. Note that in Fig. 3 the desats occurred every 24 hours initially (launch to 02/14/2008) and decreased to every 48 hours thereafter. In Fig. 4, the desats occurred every 8 hours (launch to 02/02/2012) and decreased to every 12 and then 16 hours thereafter. Since the launch-to-encounter intervals were almost the same (273 days for Phoenix and 253 days for MSL), time-phasing for MSL had almost three times more capability than for Phoenix.

As shown in Fig. 4, systematic desats continued until 02/02/2012. Thereafter, the plan was to oscillate the desats between the two options in order to gradually achieve and maintain the correct targeting. For example, a trajectory generated on 12/12/2011 modeled desats up until 03/29/2012 with the result that Odyssey would be late by 5 minutes and 20 seconds at EDL. Another trajectory generated on 03/19/2012, with desats modeled until 05/24/2012 indicated that Odyssey would be right on target, that is, only 4 seconds late, at EDL. Note that on May 24, the AMD-ΔVx decreased to almost zero mm/sec because of a solar array configuration change. This decreased the rate of spacecraft angular momentum accumulation resulting in infrequent desaturations, namely one desat every three days. Thus, it was necessary that Odyssey be on target for EDL as of this date because of the significantly reduced time-phasing capability. Thus far, the planning and execution was precise until unexpected events occurred.

On June 8, Odyssey entered safe mode due to a degraded performance of a reaction wheel which impacted the attitude control. The safe mode condition lasted until June 17 during which thrusting was frequent, every 2-3 hours, and the AMD ΔVs ranged from 16 to 25 mm/sec. A description of this process is given in Section 5. A trajectory generated on June 18 indicated that Odyssey was no longer on target for EDL but early by 125 seconds. Time-phasing, with the small and infrequent desats and only 49 days remaining until EDL was unable to compensate for the offset. Planning for an OTM, which had always been an option, was started immediately.

The OTM was executed on July 11, 26 days before EDL, and appeared to have been successful. However, immediately after this OTM, entry into safe mode was autonomously initiated by the spacecraft; it lasted for almost one day. A trajectory generated on July 16 indicated that the results of the safe mode thrusting was that Odyssey was now 361 seconds late with respect to the EDL targets and outside the ±30 seconds of tolerance.

Another OTM plan was rapidly developed and executed on July 24, 13 days before EDL. A propagated trajectory confirmed that Odyssey would be early by 25 seconds and within the target requirements.

On 08/06/2012, Odyssey was in place and on-target for the critical seven minutes of MSL's EDL. During that interval, MSL telemetry data was received by Odyssey and immediately transmitted to a DSN receiving station. This telemetry and Mars' surface imaging confirmed the successful entry, descent and landing.

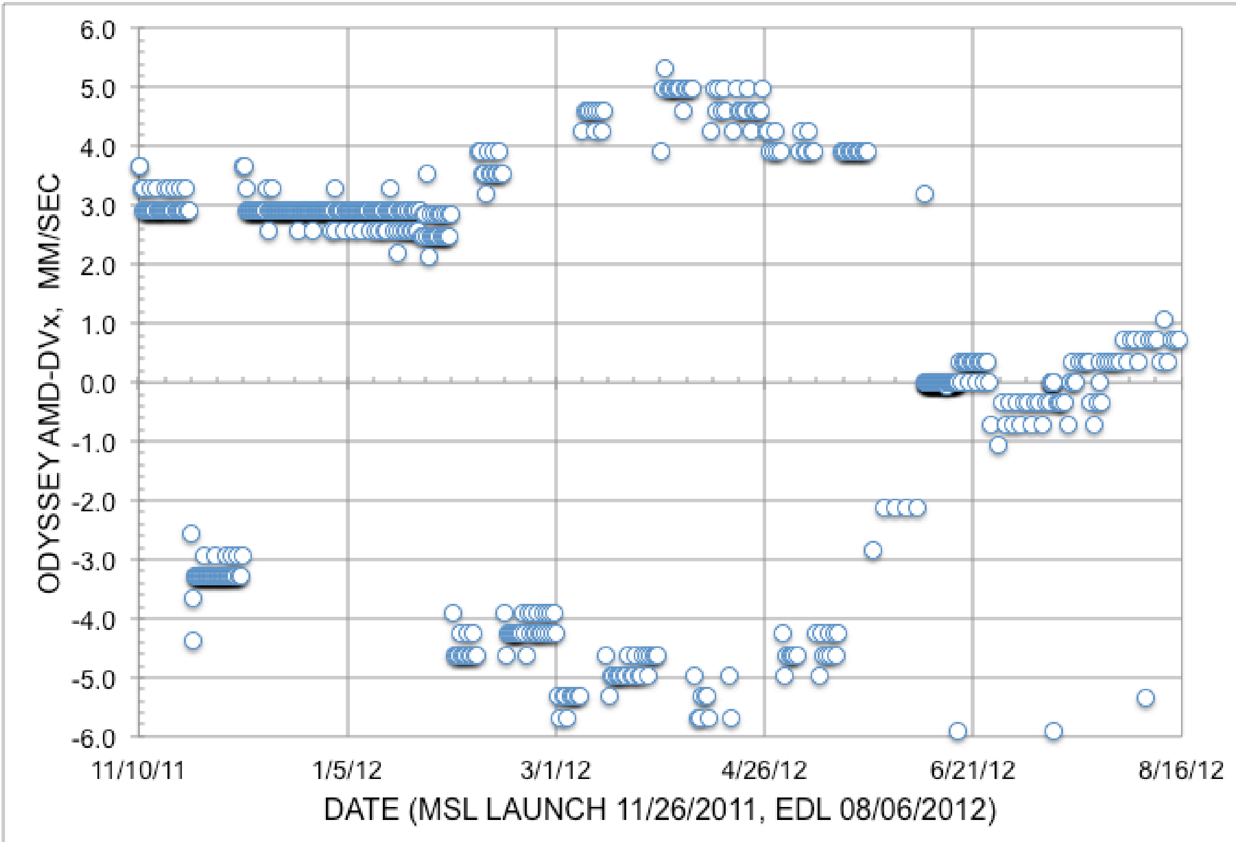

Figure 4. Overview of Odyssey's AMD ΔVx During Time-Phasing for MSL's EDL

5. Safe Mode Entry (SME) and Impact on Trajectory Accuracy

Nominally, Odyssey is in the mapping orbit configuration collecting science data and acquiring and transmitting rover data to Earth. Occasionally, the spacecraft will detect an anomalous condition and autonomously place itself in a safe state called safe mode. In safe mode, science observations are terminated, the solar array is sun-pointed to assure adequate power and the high gain antenna is Earth-pointed to maintain communications. As the spacecraft changes its orientation (from nominal mapping to safe mode on thrusters), there is an initial, large ΔV along with a series of smaller velocity perturbations. A representative example, giving the AMD ΔV magnitude as received from telemetry data, is given in Fig. 5. As shown, the small forces generated are frequent, every 2-3 hours, and significantly larger when compared to nominal nadir operations. This safe mode occurred due to degradation of a reaction-wheel-assembly performance. Safe mode durations can be short (1-2 days) if the source is easily identified or long (7 to 9 days) if complex.

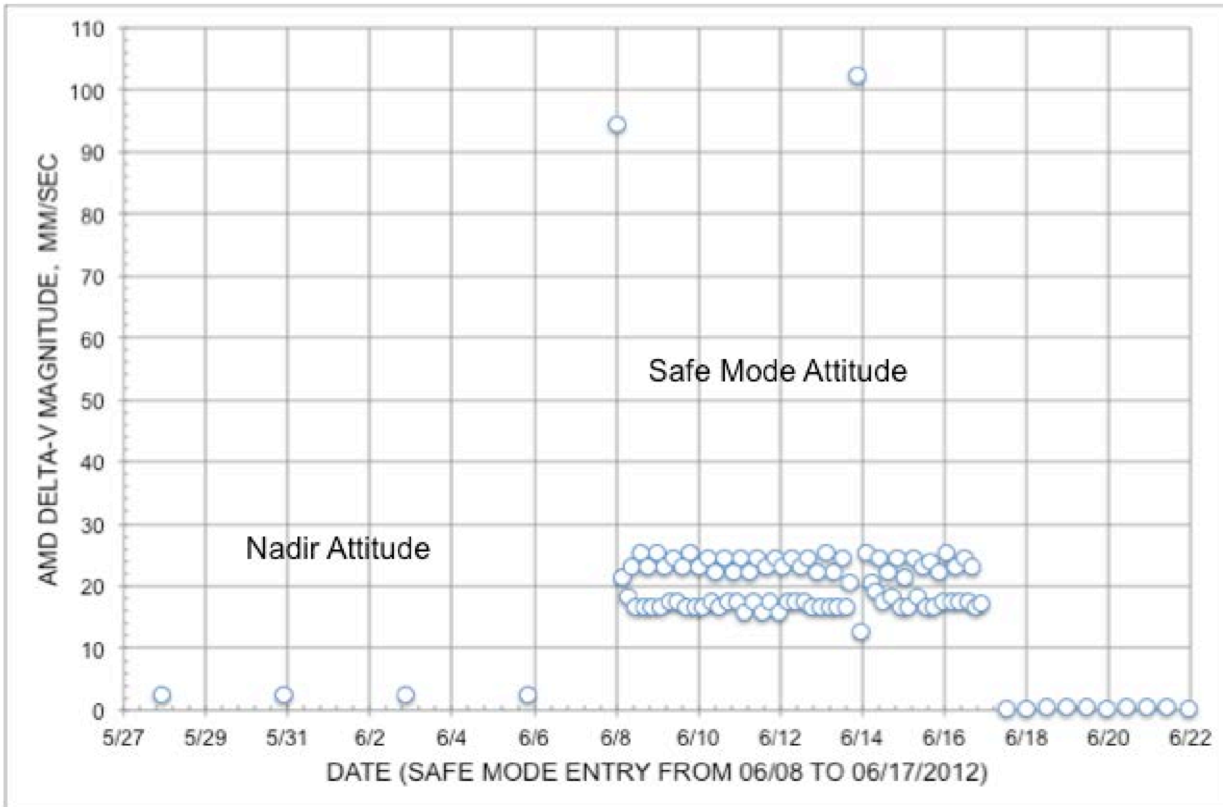

Figure 5. Representative Velocity Perturbations Resulting from a Safe Mode Entry

Trajectories generated prior to the unexpected SME will experience a significant degradation in the time-of-descending-equator-crossing (Tdeqx) accuracy. Navigation's immediate objective is to assess the timing error and develop interim trajectories thereby reducing the error accumulation. Each SME is unique with respect to the ΔVs generated and so are the resulting errors in the Tdeqx in the affected trajectories. Since the start of mapping, there have been fourteen SMEs with a partial list summarized in Tab. 4. The integrated effect of the SME is summarized by the rate-of-error growth in predicted timing in trajectories generated prior to the SME. In Fig. 6, we give the Tdeqx error for the five trajectories shown in Tab. 4. Prior to these SMEs, the Tdeqx error is less than one second.

Table 4. Odyssey Safe Mode Entry and Resulting Timing Error

SME Date (duration)	Trajectory Date, To (Days Past To)	Tdeqx Error Rate, sec/day
2010 July 14 (2 days)	06/28/2010 (16)	-4.7
2011	No SMEs	---
2012 June 8 (9 days)	05/29/2012 (9)	2.7
2012 July 11 (1 day)	07/02/2012 (9)	-14.1
2012 Nov 5 (2.5 days)	10/15/2012 (21)	16.3 and 4.0
2013 Dec 8 (2 days)	12/02/2013 (6)	2.9
2014	No SMEs	---

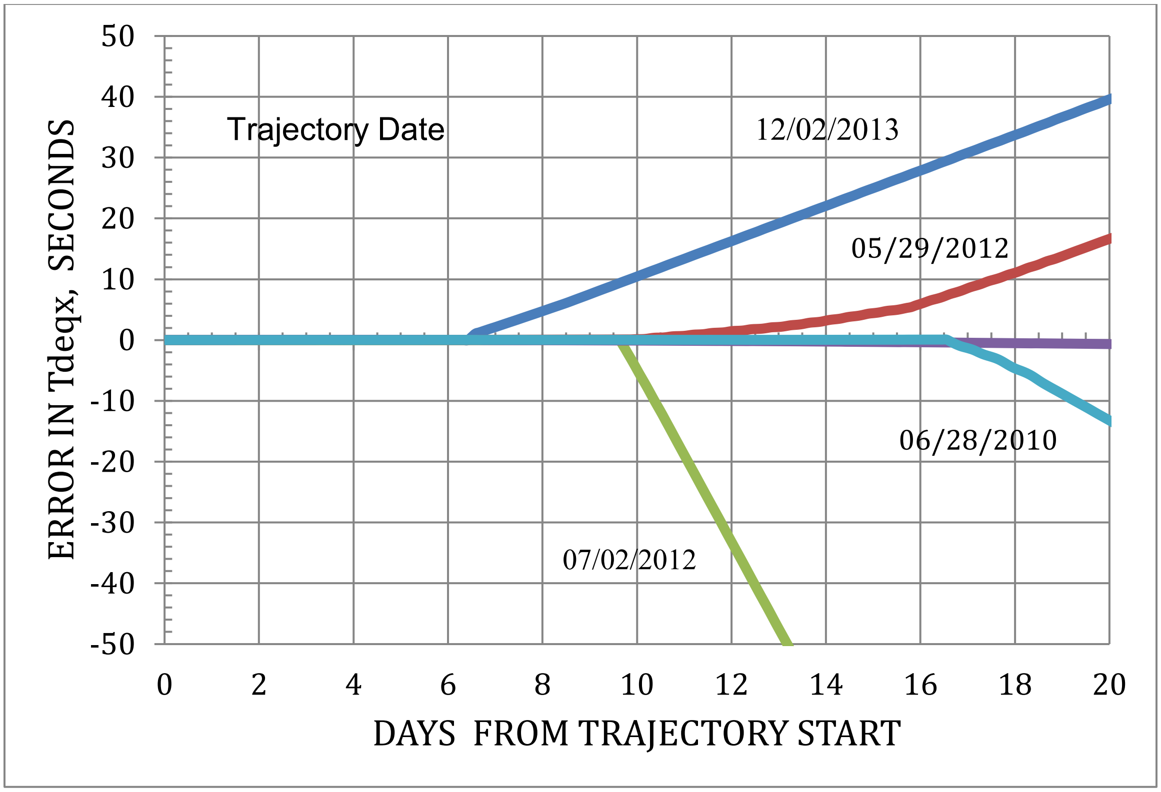

Figure 6. Error in the Tdeqx Due to SMEs

In Fig. 7, we summarize the Tdeqx-error-rate for trajectories impacted by twelve of the fourteen SMEs experienced since the start of mapping. As indicated, each safe mode has a different impact. The largest error-growth occurred with the SME on 11/29/2009 and reached a rate of -19.7 sec/day. At this rate, the error in the predicted Tdeqx would be at or near -60 seconds in only three days. In particular, this impacted trajectory cannot be used for sequence development and operations since it would exceed the Tdeqx accuracy requirement.

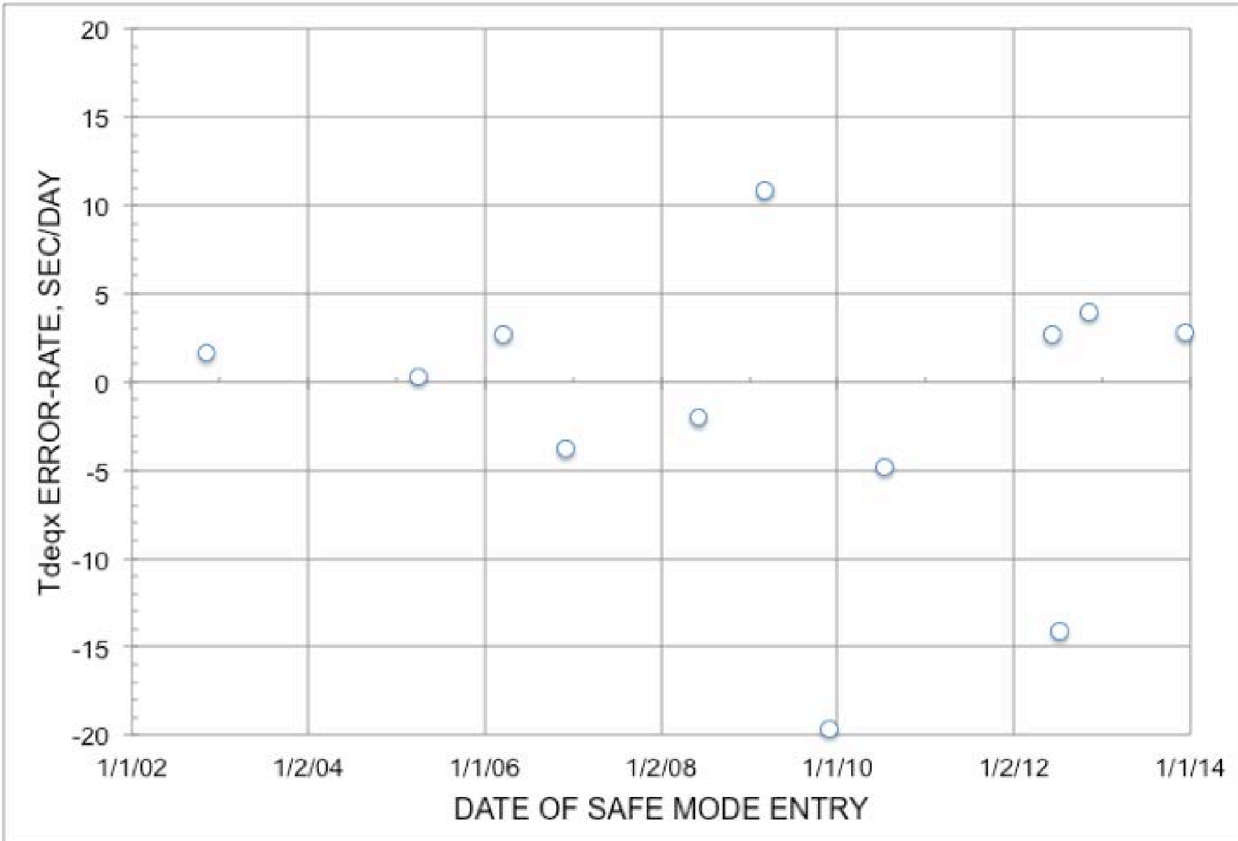

Figure 7. Tdeqx Error Rates Due To Trajectories Impacted By SMEs

6. Trajectory Accuracy and Timing Requirements

Every week, usually on Mondays, Navigation generates trajectories covering the following prediction intervals: 21 days, three times per month and 90 days, once per month. The former are primarily used for up-linking spacecraft ephemerides to Odyssey, science image targeting and observation refinements and DSN signal acquisition. The latter are used for sequence-of-events (SOE) file development and operational usage onboard Odyssey and science and relay over-flight planning for the MER and MSL rovers. The propagated trajectories are usually based on analysis of two to three orbits of Doppler data.

Each on-board SOE file, usually of 28-day duration with a 28-day development cycle, is used to direct some aspects of spacecraft activity. Navigation monitors the accuracy of event-times as predicted by the trajectory used to generate a particular sequence. A key event is the Tdeqx as predicted by each trajectory. The requirement is that the error in the predicted Tdeqx, after 56 days of trajectory prediction, must be less than or equal to sixty seconds.

Every Thursday, navigation generates reconstructed trajectories, based on Doppler data analysis, spanning the past 5-6 days (61 to 73 orbits). These represent our most accurate knowledge of orbital information. In particular, each Tdeqx is accurate to within 0.005 to 0.01 seconds under nominal operations. This accuracy is dependent on Doppler data analysis, orbital conditions and spacecraft configurations. With this information, the error for each Tdeqx in every prediction-trajectory can be determined simply by differencing the predicted and reconstructed Tdeqx. These results are summarized in Tab. 5: a) after seven days, the predicted times are accurate to 0.15 seconds or less with a single exception and b) after 56 days of trajectory propagation, the Tdeqx error is within 24 seconds except for non-nominal conditions related to the three trajectories shown.

Table 5. Long-Term Propagated Trajectories and their Tdeqx Error During 2014

Traj Date	After 7 days, sec	After 56 days, sec
1/21/14	0.01	-21.2
2/3/14	0.019	-19.7
3/3/14	0.059	14.9
3/31/14	0.097	19.6
4/28/14	0.11	14.3
5/27/14	-0.15	-14.9
6/23/14	0.014	-23.4
7/21/14	-0.104	-73.8
8/18/14	-0.034	-9.72
9/15/14	-0.009	58.8
10/13/14	1.0	114.9
10/27/14	-0.019	-0.12
11/24/14	0.083	6.55
12/8/14	0.074	15.9

The trajectory generated on July 21 was affected by the execution error associated with OTM-11 on August 5, 2014. This maneuver was necessary in order to place Odyssey in a minimum risk location during Comet Siding Spring's (CSS) Mars flyby as described in Section 8. Trajectories generated on Sept 15 and Oct 13 were influenced by a series of five spacecraft slews, the resultant thrusting and the associated velocity perturbations, in order to image CSS during Oct 19 to 21. Five separate imaging sessions were executed with the related ΔVs ranging from 13 to 30 mm/sec.

Error propagation for the last seven trajectories given in Tab. 5 is shown in Fig. 8. As indicated, after seven days of propagation, the October 13 trajectory was strongly perturbed by the CSS ΔVs. The October 27 trajectory was exceptionally accurate since the Tdeqx error was bounded by $\pm$0.15 seconds throughout the entire sixty days of propagation. During this time, AMD ΔVs were executed twice per day and were modeled very precisely.

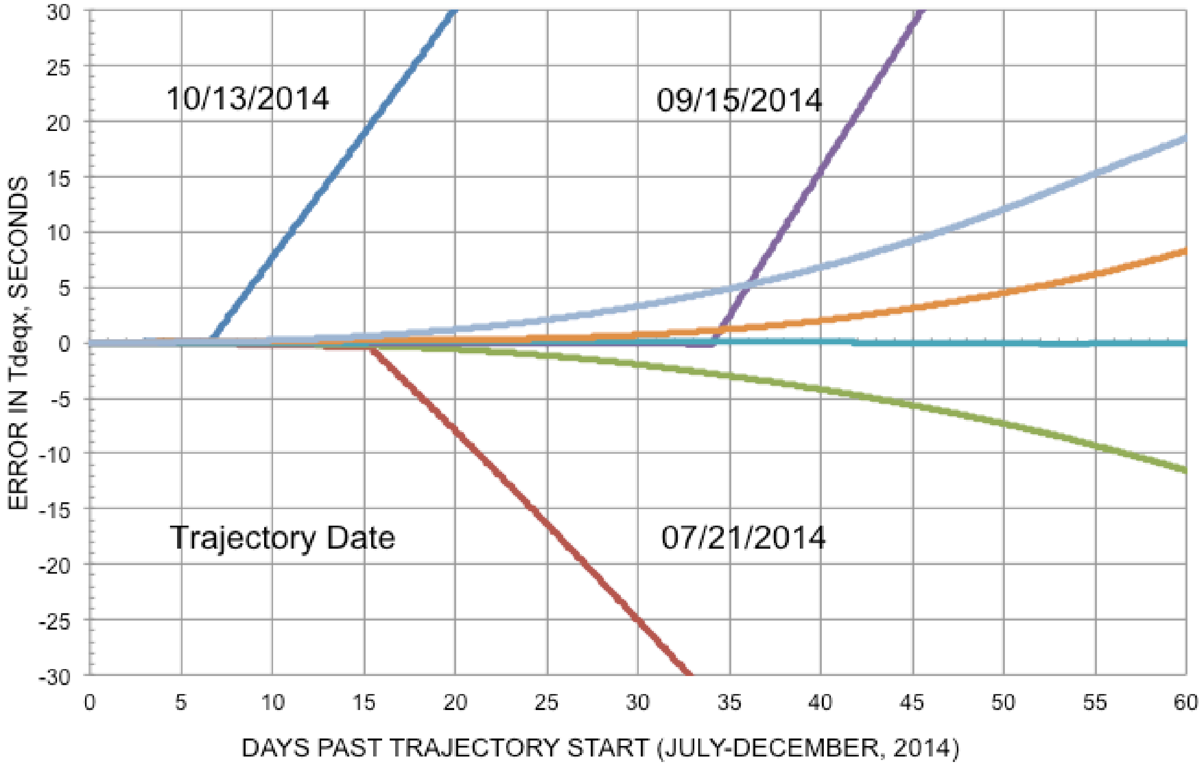

Figure 8. Nominal Trajectory Accuracy and Impact of Special Events

7. Angular Momentum Desaturation ΔV Model For Trajectory Predictions

7.1. Background

The largest error source in developing a predicted trajectory for the Odyssey spacecraft is the delta-V (ΔV) perturbations caused by angular momentum desaturations (AMDs). As the spacecraft orbits Mars, angular momentum is accumulated and is counteracted by the reaction wheels. Odyssey had one reaction wheel assembly (RWA) for each orthogonal spacecraft body axis, and one "skew" wheel for redundancy. RWA-1 failed on 12/08/2013 and was replaced by the skew-RWA. When the RWAs have reached their maximum spin rate, they are considered to be saturated, and must be *de*saturated to return to their nominal, lowest spin state. As a result of each desaturation, a ΔV (small force) is imparted to the spacecraft that modifies its orbit. The timing and magnitude of these ΔV's must be modeled in order to more accurately predict the spacecraft's trajectory. Examples of two-way X-band Doppler residuals from reconstructed data analysis, with and without desats estimated, are shown in Figs. 9a and 9b.

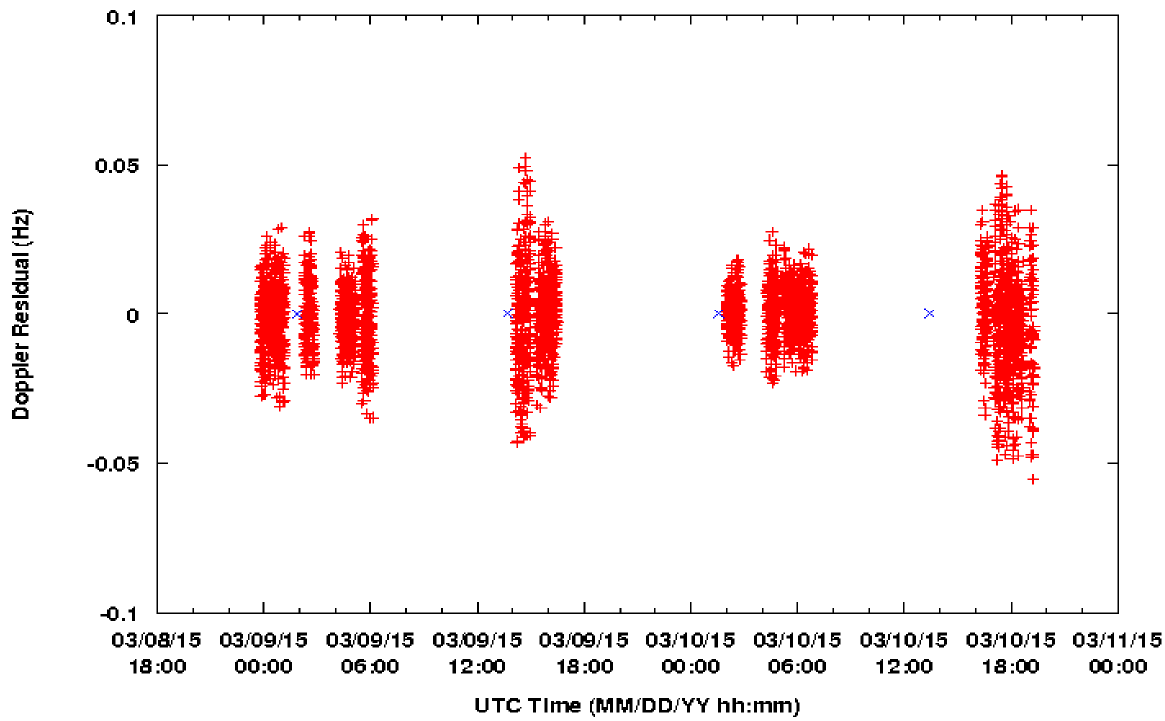

Figure 9a. Converged two-way Doppler residuals and four estimated AMDs (as indicated with an x)

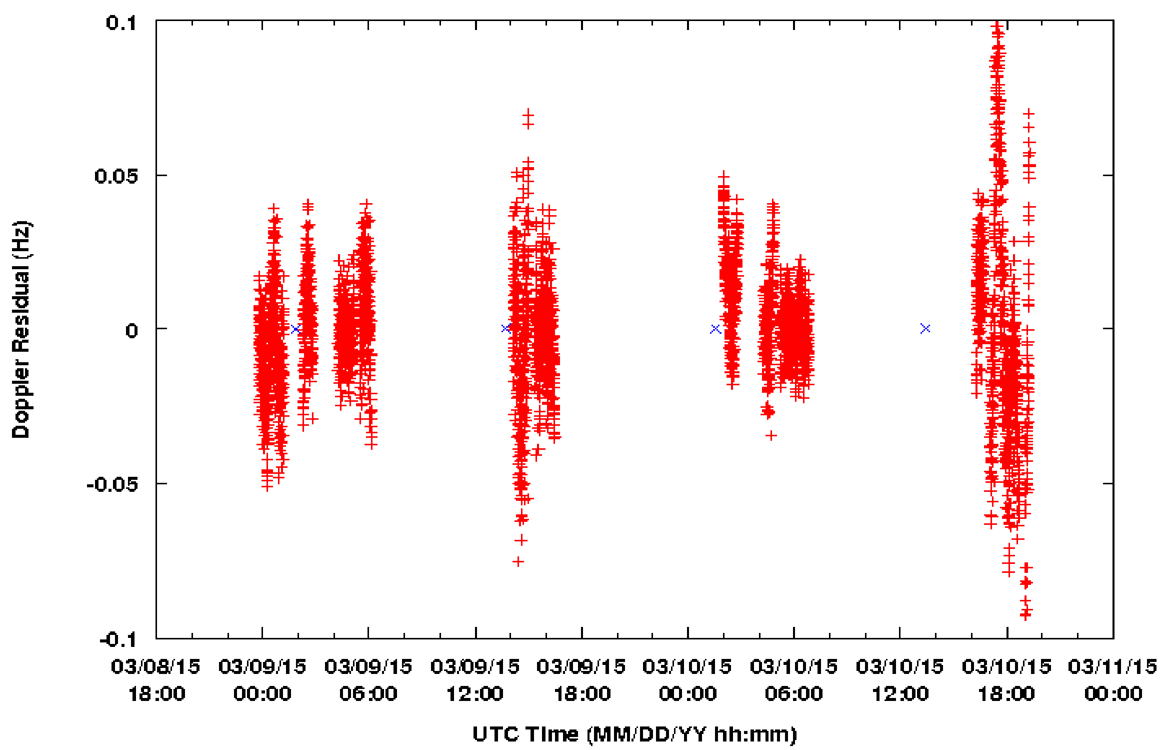

Figure 9b. Converged two-way Doppler residuals, no AMD ΔV modeled

Examples of predicted orbit timing accuracy, as measured at the descending equator crossing when compared with reconstructed orbits, are shown in Figs. 10a and 10b.

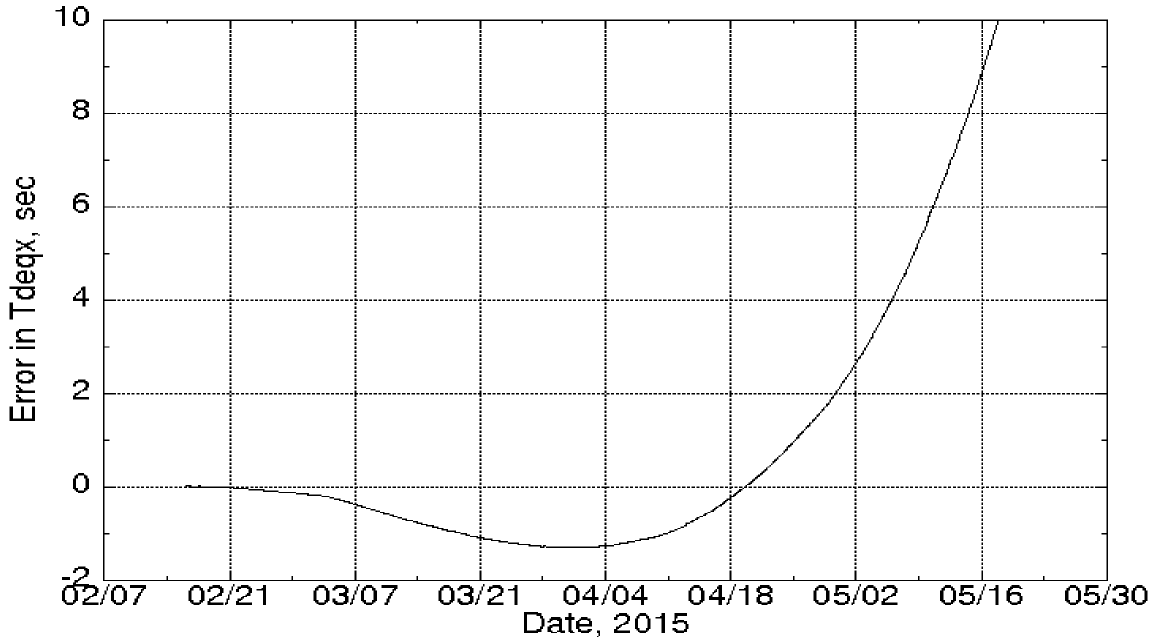

Figure 10a. Error in Tdeqx, AMDs modeled (2/17/2015, 90-day trajectory)

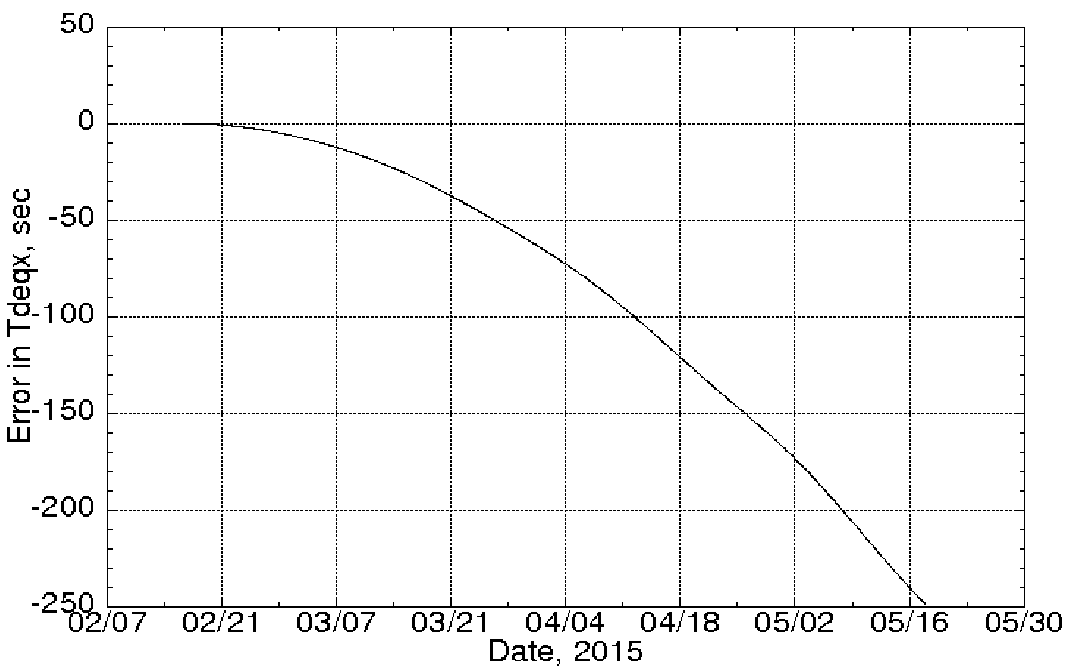

Figure 10b. Error in Tdeqx, no AMDs modeled (2/17/2015, 90-day trajectory)

A discussion of our current AMD modeling methods follows.

7.2. AMD ΔV Model Process

7.2.1. Scale Factor Analysis

Spacecraft telemetry data (thruster firing information) are available which allow us to estimate the ΔV imparted to the spacecraft during each angular momentum desaturation. It is understandable to expect that modeling these ΔVs exactly as they are given from the telemetry would result in a reasonable prediction. However, from experience, we have learned that these ΔV's need adjustment in order to improve the prediction, the idea being that there remain other trajectory perturbations that are not completely accounted for by other models (primarily gravity, atmospheric, and solar radiation pressure) used in the orbit determination process. Thus, we apply a scale factor to our modeled ΔVs in order to account for some of the remaining mis-modeling.

The AMD scale factor is determined by incorporating spacecraft telemetry data (discrete ΔVs) in the trajectory for about a week-long trajectory prediction, initialized from state information from the previous week's trajectory analysis. A metric of the quality of any given trajectory is how well it models any future tracking data observations that are "passed through" it (see Fig. 11a).

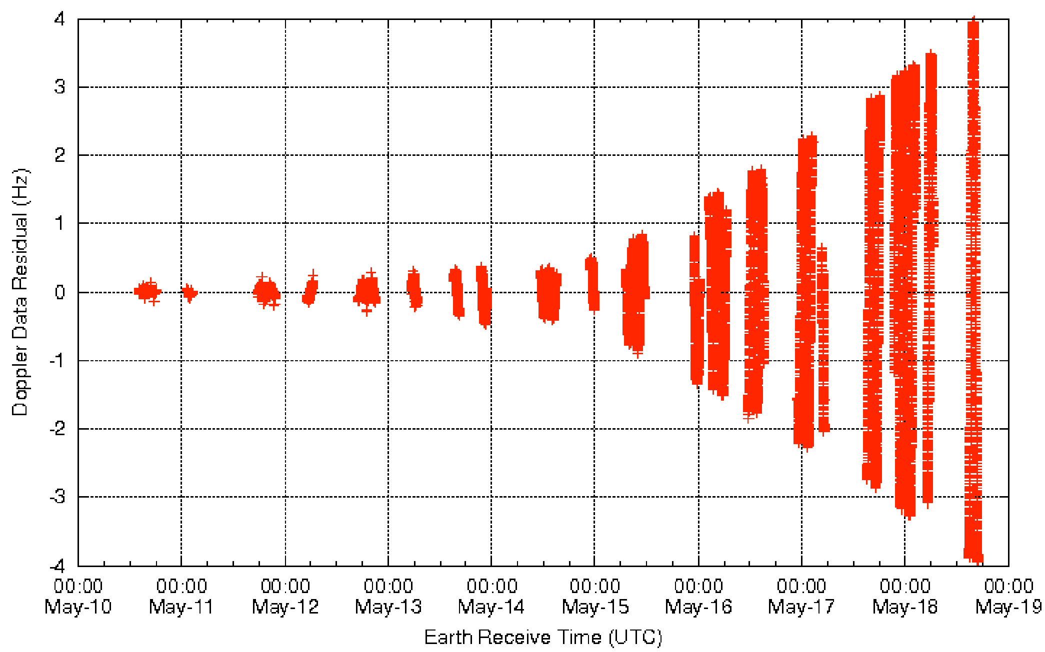

Figure 11a. Nominal pass-through of 5/11/2015 trajectory using only the AMD model determined at that time

After applying an initial estimate of the scale factor (again, based on results from the previous week), this factor is varied parametrically until the "pass through" pre-fit Doppler residuals are minimized. Figure 11b shows the pre-fit Doppler residuals achieved after incorporating desaturation ΔVs from telemetry, each of which has been scaled by a factor of 0.81. These residuals reflected the most accurate prediction, based on the observed improvement in the data residuals, indicating 0.81 was the most feasible scale factor to choose for the upcoming week's prediction (epoch on 5/18/2015).

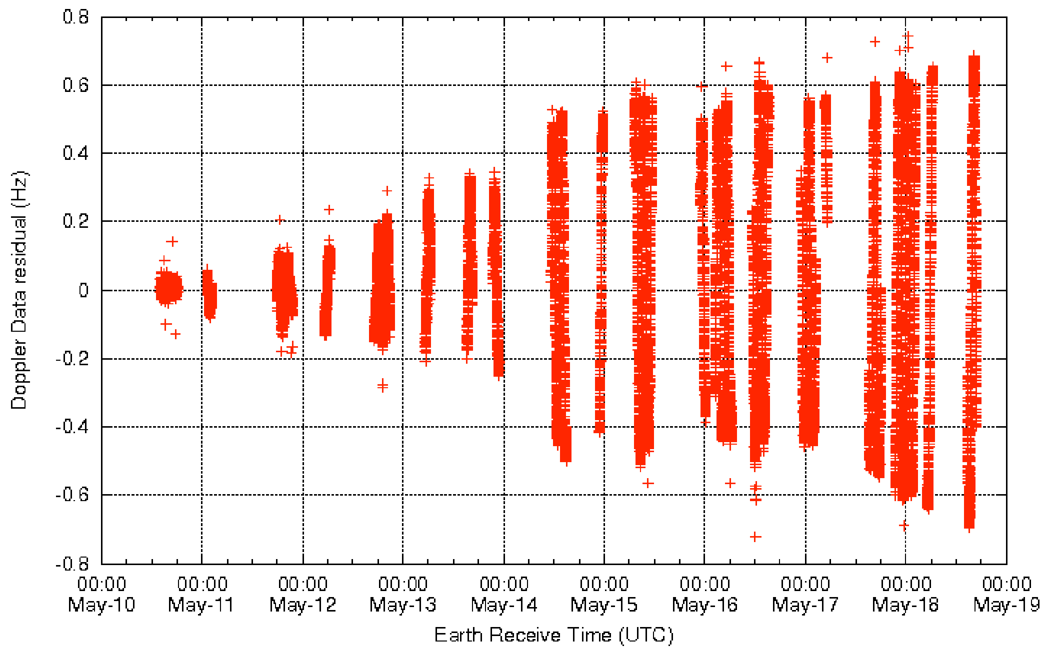

Figure 11b. Pass-through of 5/11/2015 trajectory using updated desat ΔVs from telemetry scaled by 0.81

7.2.2. Timing, Magnitudes, and Rates

The desaturations occur periodically on-board the spacecraft, and execute on a schedule that is known in advance. Desaturation initiation times, their expected frequency and their estimated ΔV vector for each flight sequence are provided to the Navigation Team by the Sequencing and Spacecraft Teams. For example, the reaction wheels were desaturated every 12 hours in February-March 2015, and every 20 hours during April-May 2015. Also, a subset of recently acquired telemetry values (typically over the previous week) is examined in order to obtain the average ΔV for each spacecraft body axis, as well as the average time between desats. This average time is used as the frequency throughout the designed predict model. If the trajectory prediction interval is long enough to span multiple flight sequences (which are typically 28 days each) with differing desat frequencies, the originally chosen timing value is scaled appropriately for each sequence.

Similarly, the average ΔV is used as the initial value of the first desaturation in the model. The rate of the changes in desaturation magnitude, discussed in the next section, is not constant, as shown in Fig. 12.

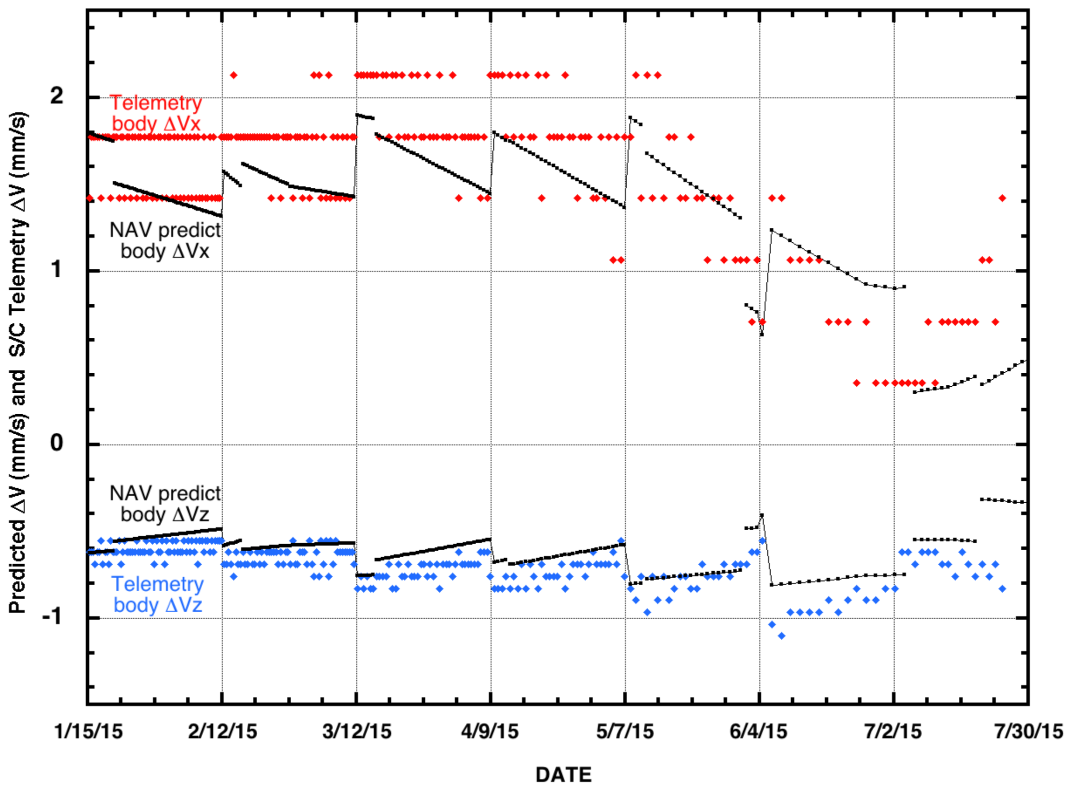

Figure 12. Predicted (NAV) and observed (telemetry) desaturation ΔV profiles

However, we have observed that the changes in average ΔVs are typically on the order of a few percent from week to week. The initial ΔV is entered in our model on a per-component basis, for spacecraft body axes X and Z. Due to the sinusoidal nature of the reaction wheel angular speeds, the desaturations occur when the ΔVy is estimated to be at zero mm/sec.

In order to model the changes in the imparted ΔVs arising from the changing angular momentum build-up as the spacecraft orbits Mars, a linear rate is applied to the desaturations at the frequency described above. Determining this linear rate can be challenging. Navigation trajectory predictions are usually 21-days in duration, with a 90-day prediction delivered once per month for sequence planning. Because of the discretized and short-term nature of the desaturation ΔVs gleaned from telemetry, these data alone are not always sufficient to estimate the most realistic per-component rates of change for the desaturation model over longer periods of time. For these trends, it has proved helpful to also consider desaturation ΔV predictions determined by the Spacecraft Team. These are provided on a monthly/per-sequence basis, with occasional longer term (year-long) predictions made available when requested.

Taking these multiple data sources into account, desaturation ΔV rates are determined and included in the model. Typically, there may be different rates (possibly with different signs, reflecting increasing or decreasing ΔV magnitudes) for each flight sequence, though often it may even be necessary to use different desaturation rates *within* a sequence to reflect all of the trends expected to occur throughout the trajectory prediction interval.

Combining the overall ΔV scale factor and desaturation rates results in the final AMD model. These final ΔVs are applied to the trajectory propagation, which is then delivered to the project teams as one of our final navigation products. We continue to monitor the accuracy of each trajectory propagation as our future reconstructed orbit analyses are completed and become available for comparison.

8. Comet Siding Spring and Odyssey's Minimum Risk Analysis

8.1 Comet Siding Spring (CSS) Background

On October 19, 2014, Comet Siding Spring (C/2013 A1) made a close approach to Mars within 135,200 km ± 4500km (3-σ) at 18:29 ± 00:03 UTC. That is roughly one third of the distance between Earth and its moon. This comet traveled from the Oort cloud and was discovered during January 2013 by Robert H. McNaught at Siding Spring Observatory in Australia. CSS was 7.2 AU from the Sun at the time of discovery and reached the perihelion of its retrograde orbit at 1.399 AU, just inside of Mars' orbit, on October 25, 2014. JPL's orbital solution 46 [4] provided the heliocentric ephemeris of the comet used for this analysis. Table 6 and Fig. 13 provide a summary of the comet's orbit in the heliocentric, ecliptic J2000 frame. As shown, CSS was traveling from below the ecliptic plane, northward as it passed sunward by Mars.

Table 6. C/2013 A1 Orbital Elements at August 1, 2013

Element	Value
Eccentricity	1.001
Perihelion distance, AU	1.399
Longitude of ascending node, degree	300.974
Argument of perihelion, degree	2.435
Inclination, degree	129.027

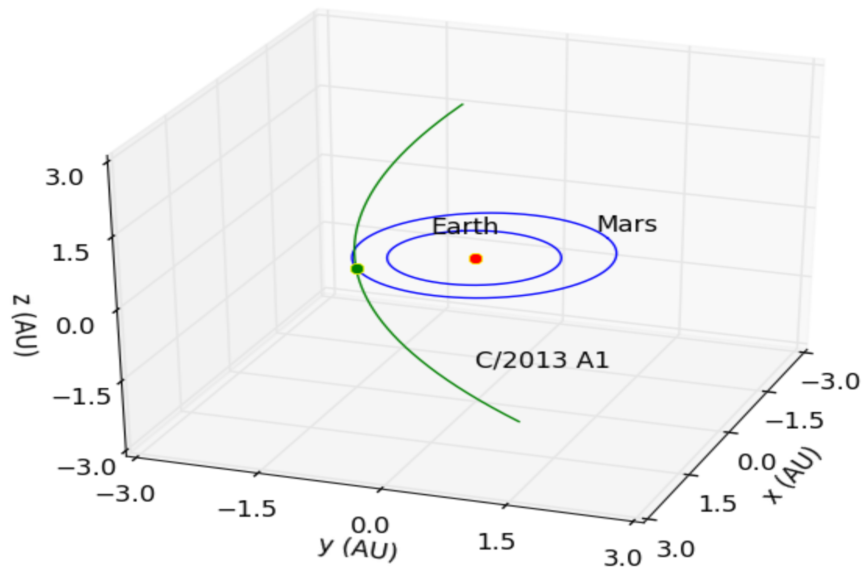

Figure 13. CSS's Orbit During the Close Approach to Mars

Though the comet's nucleus passed by Mars at a safe distance, preliminary modeling estimated that the comet fluence, the number of particles encountered during passage through the cometary debris, could put Mars orbiters at risk. Three groups of comet specialists [5,6] modeled the comet-produced dust distribution as function of time. In addition, they determined the arrival time and duration of the comet-associated particle flux at Mars and characterized the size and density of dust particles.

8.2 Odyssey's Minimum Risk Target and OTM Planning

A Comet Encounter Target File (CETF) was provided by the JPL Mars Program on April 25, 2014. It identified the minimum risk location for Odyssey as shown in Tab. 7. The time of the maximum flux reaching Mars (time of particle fluence center) was estimated as 98 minutes after the comet's close approach to Mars. Initially, the tolerance on achieving the target epoch was ±2 minutes but later was relaxed to ±4 minutes.

Table 7. Minimum Risk Target (Mars Mean Equator of J2000 reference frame)

Right Ascension, degree	165.4
Declination, degree	8.5
Time of particle fluence center, ET	2014 Oct 19, 20:08:07

The relative velocity between C/2013 A1 and Mars, 98 minutes after the close approach epoch, was used as a preliminary representation of the velocity of the comet particles around the time of close approach. The possibly hazardous dust particles were estimated to be ejected from the nucleus more than a year ago as these particles have low ejection velocity and would stay along their nucleus' trajectory with similar velocity. The dust particles that are larger than 0.5 mm were estimated to reach Mars while smaller particles would get pushed away by solar radiation pressure. At the close approach epoch, the comet was approaching its perihelion and the velocity direction, of the nucleus and dust particles, changes would be minimal (<0.001 degree/day). The reverse direction represents the path that dust particles traveled when viewed from Odyssey.

The location of the spacecraft, during its 1.96 hour orbital period, centered on the minimum risk location is given in Fig. 14. As indicated, at the target time, Odyssey was 8.2 degrees above the target location. Equivalently, Odyssey arrived at the target declination 2 minutes and 45 seconds later than the target time. This was within the project's guideline of ±4 minutes of tolerance in the target time. Odyssey was outside the target right ascension by 7.2 degrees; this was reviewed and accepted as close enough. Also shown is CSS's location over a 140-minute interval and starting at 110 minutes before the target time.

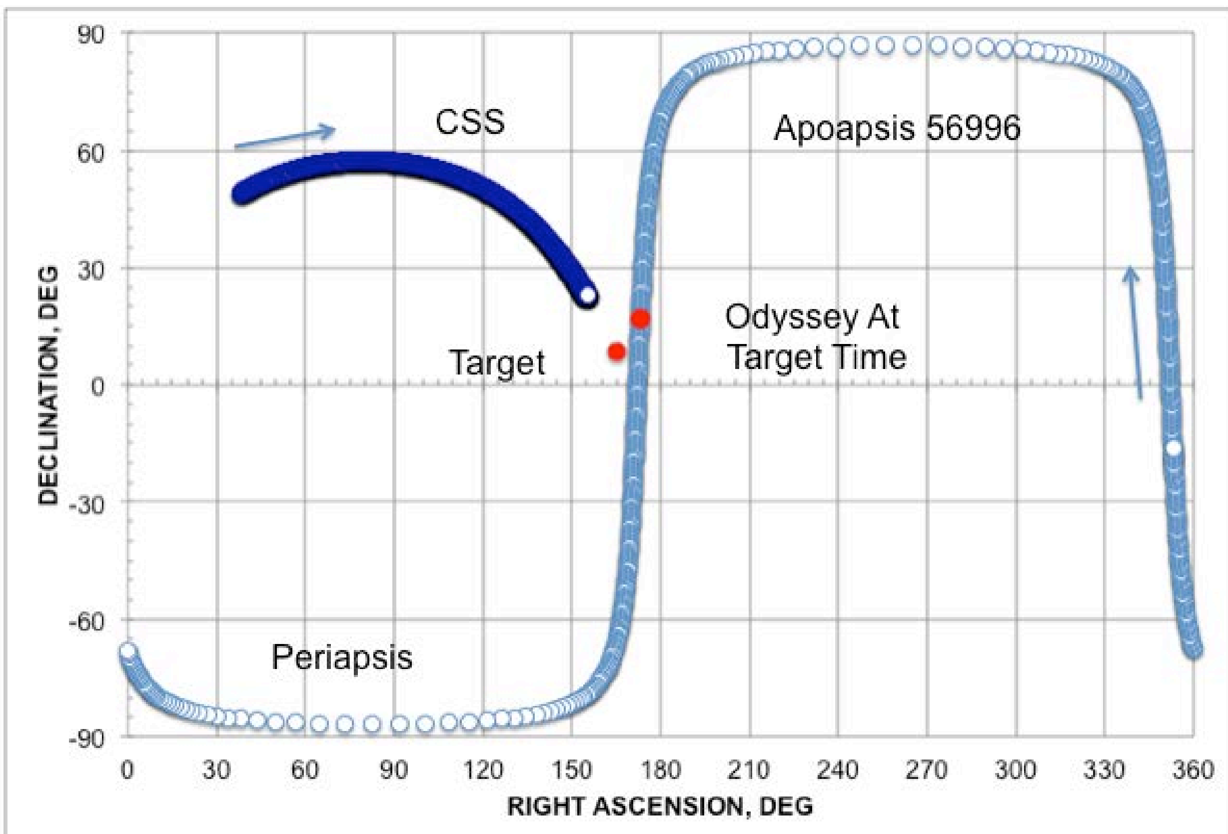

Figure 14. Minimum Risk Target and Odyssey's Location at the Target Time

Navigation verified the CETF target by analyzing the velocity of the comet at several epochs. By locating Odyssey in the dust particle's velocity direction, the orbiter can be maneuvered behind the planet and protected from dust and particles emanating from CSS.

To position Odyssey at the minimum risk location, Navigation developed OTM-11 which was executed on August 5, 2014, 75 days or 913 orbits prior to the target epoch. The maneuver was designed to increase the orbit period by 2.3 seconds and achieve the target time and declination. As discussed in Section 3, this late arrival was due to an additional ΔV of approximately 20 mm/sec, due to thrusting by the spacecraft, immediately after OTM-11. If this maneuver was not executed, we estimated that Odyssey would have arrived 35 minutes and 18 seconds too early at the target location. Equivalently, Odyssey would have been a little more than one-quarter of an orbit past the target location at the target time.

The net result of this effort was that Odyssey was shielded by Mars from possibly hazardous comet dust particles, no component of the spacecraft was damaged and imaging of Comet Siding Spring was performed as scheduled.

9. Solar Conjunction and X-Band Doppler Data Quality

Since the start of mapping, Mars/Odyssey have experienced seven superior/solar conjunctions as shown in the following table.

Table 8. Solar Conjunction Date and the Minimum Sun-Earth-Mars Angle

Solar Conjunction	SEM Angle, deg
06/14/2015	0.62
04/18/2013	0.40
02/04/2011	1.08
12/05/2008	0.46
10/23/2006	0.39
09/15/2004	0.96
08/10/2002	1.15

During this time, the X-band (7145-7190 MHz uplink) signal's ray-path, transmitted to Odyssey by the Deep Space Network (DSN), passed close to the Sun. Under these conditions, some degradation of the received-frequency was expected on both the up-link and down-link. The quality of the Doppler data, as well as the resulting orbital information, was assessed during the orbit determination process. This involved iterating and converging initial conditions (e. g. the spacecraft's position and velocity at epoch) and minimizing the Doppler residuals (DSN measured Doppler data – Navigation computed Doppler data) as shown, for example, in Fig. 9a in Section 7. A tracking pass usually lasts for several hours with the Doppler data sampled every ten seconds. Thus, there is enough data to determine statistical quantities, such as the mean and standard deviation of the residuals, for each tracking pass. The results of this analysis, the one-sigma Doppler residuals, are summarized in Figs. 15 and 16 for our most recent solar conjunction. The Doppler data accuracy is at the 3-5 mHz level away from solar conjunction; it degrades to about 450 mHz close to solar conjunction as shown in both figures (10 mHz = 0.18 mm/sec).

When comparing the solar conjunctions in Tab. 8, as expected, there is much variation in the Doppler data "noise" (i.e. the one-sigma results). However, when the SEM angle is within 3 to 10 degrees there appears to be reasonable similarity in the upward trend as shown in the figures.

Within 1 to 3 degrees, the variation grows and each solar conjunction is unique. As a rough guide, the Doppler "noise" varied between 150 to 800 mHz.

Our last data analysis and trajectory distribution before solar conjunction was on June 1 when the SEM angle was 3.6 degrees. Four weeks later, on June 29, the error in the predicted Tdeqx was 2.3 seconds and within requirements. The first trajectory analysis and distribution after solar conjunction was on June 29 when the SEM angle was 4.2 degrees. After 21 days of trajectory prediction, the error in the Tdeqx was 0.9 seconds and within requirements. The only impact on navigation was the reconstruction of orbits within approximately three degrees of the Sun. The trajectory degradation was as expected and had only a minor influence on science objectives.

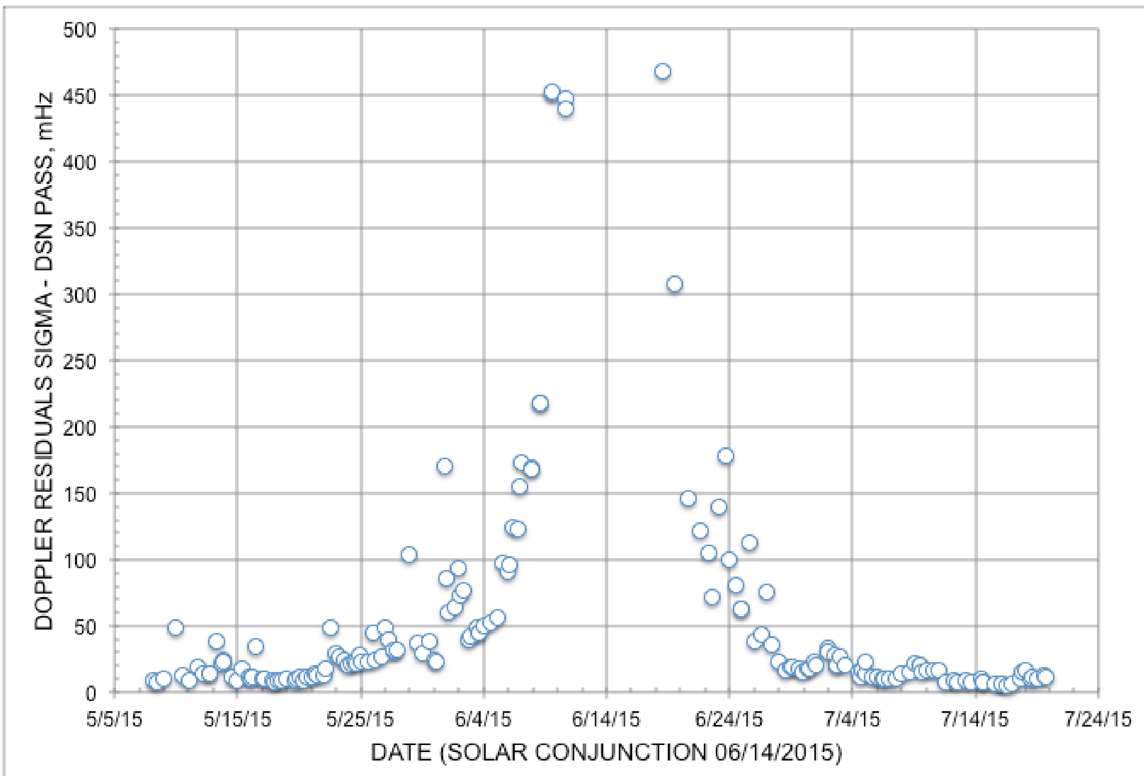

Figure 15. Doppler Data Degradation. The start and end (data) dates correspond to ten degrees SEM angle.

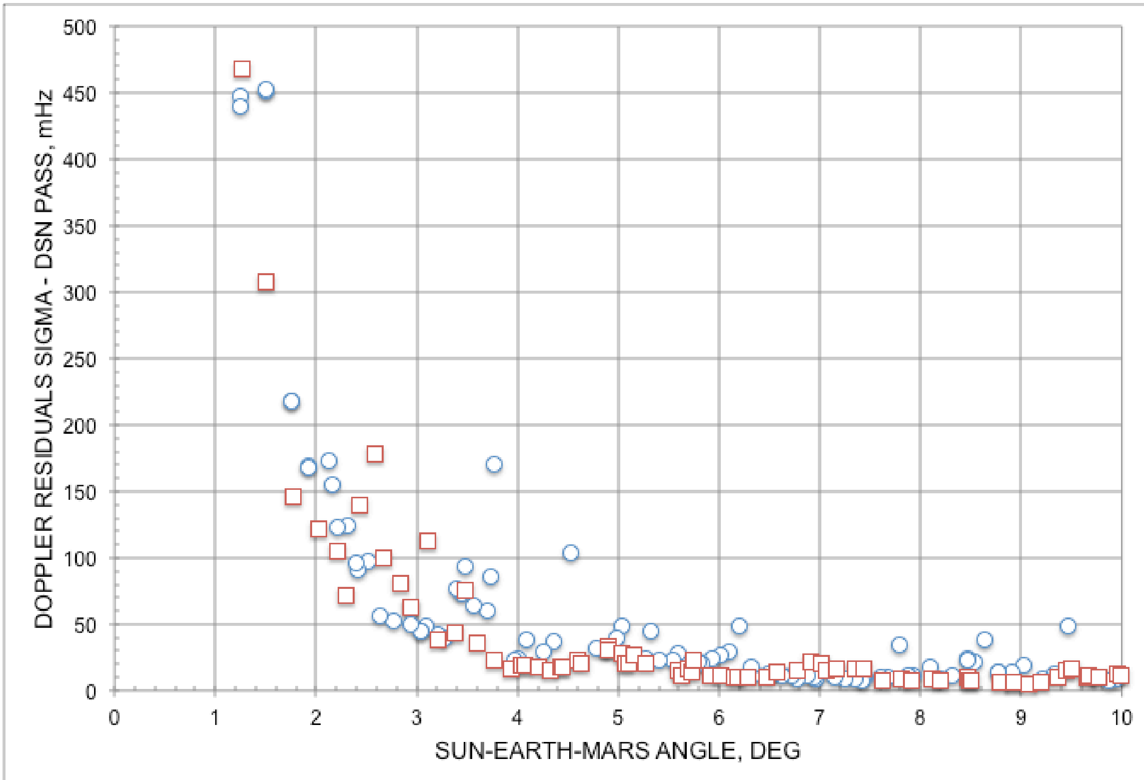

Figure 16. Doppler data degradation as the X-band signal passes within ten degrees of the Sun

10. Acknowledgment

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11. References

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[4] The CSS orbital information is available on the Solar System Dynamics Group public ftp server: ftp://ssd.jpl.nasa.gov/pub/xfr/c2013a1_s46_merged_DE431.bsp (Binary SPK format). (Also http://ssd.jpl.nasa.gov).

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