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MARS ODYSSEY MAPPING ORBIT DETERMINATION
(Draft Version)

Jason Stauch, et. al.

This paper presents the orbit determination (OD) strategy employed by the Odyssey navigation team, as well as the major navigation challenges and accomplishments. The most significant challenge in the OD process has been the trending and modeling of angular momentum desaturation (AMD) events, which significantly perturb the orbit. The predictable nature of the Odyssey momentum management strategy has allowed the navigation team to accurately model the trajectory perturbations due to the AMD thruster firings. In addition, the AMD perturbations have been used to control the desired orbit characteristics, mitigating the need for orbit maintenance maneuvers.

INTRODUCTION

Since February 2002, the Mars Odyssey Mission has successfully returned a wealth of exciting science data. Each of the three primary science payloads are on track to exceed the science-return goals set forth in the planning stages of the mission. The Gamma Ray Spectrometer (GRS) has gathered evidence of a tremendous amount of water trapped in the polar ice caps, far more than previously suspected. The thermal and visible imager (THEMIS) has been able to globally image the planet, and the radiation monitor (MARIE) has developed a previously undocumented radiation map of Mars. The excellent orbit determination performance of the navigation team has greatly contributed to this successful science output.

This paper is a continuation in a series of papers documenting the Odyssey navigation effort. Past papers include Mase, et. al. [ref. NAV EXP, NAV STRAT], which documented the entire navigation design and experience through the start of mapping; Antresian, et. al. [ref CRUISE OD], which detailed the navigation experience during the interplanetary cruise phase; and Smith and Bell [ref AEROBRAKE], which detailed the navigation experience during the aerobraking phase of the mission.

OVERVIEW

Mission Overview

The 2001 Mars Odyssey spacecraft was launched on April 17, 2001. After the launch, cruise, orbit insertion, and aerobraking phases of its journey, including the

various trajectory correction, orbit trim, and transition maneuvers required during each phase, Odyssey entered it's mapping orbit around Mars on January 30, 2002 [ref NAV EXP]. Following a brief spacecraft check-out period, Odyssey began its primary science mapping mission on February 19, 2002. The science mission is planned to extend for 917 days, concluding in August 2005.

In early June 2002, the GRS boom was deployed, putting Odyssey in its final science configuration, shown in Figure SC CONFIG. In this configuration, the spacecraft and onboard instruments can carry out the primary objectives of this mission, which are to further investigate the mineral and chemical composition of the Martian surface (particularly relevant to the detection of water) and the radioactive properties of the spacecraft's orbital environment.

Only two maneuvers are planned for the remainder of the mission. The first will establish a Sun-synchronous orbit desirable for an extended mission. The second will occur at the end of the mission. This final maneuver will raise Odyssey's orbit in order to comply with planetary quarantine requirements.

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, sequencing and mission management is performed at JPL, while the spacecraft subsystem analysts are located at LMA.

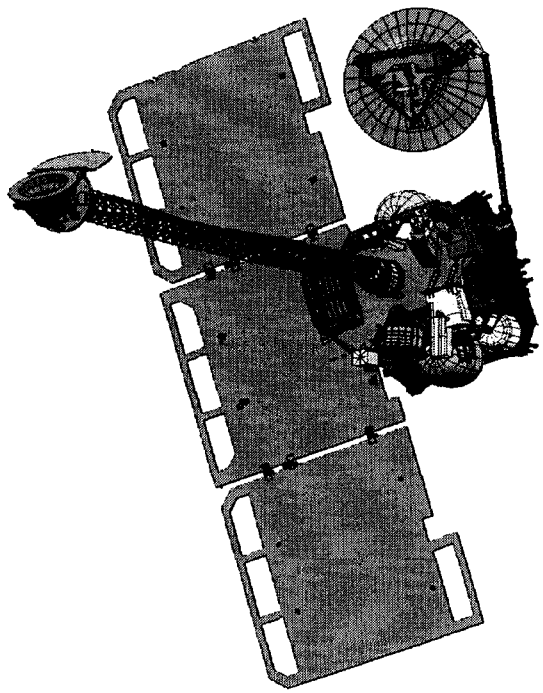

Figure SC CONFIG

Mapping Orbit Design

The 400 km, near-circular, frozen mapping orbit provides the observational geometry desired by the science instruments. The orbit is nearly polar at an inclination of 93.1°. The orbit period of just under 2 hours results in roughly 12.5 revolutions per Martian day, or sol. Successive ground tracks are separated in longitude at the equator by approximately 28.8° and the entire ground track pattern nearly repeats every 2 sols (25 orbits), with a 1° shift to the west. The ground track has another near repeat every 30 sols (362 orbits), with a 1/4° shift to the east.

The science orbit design was negotiated to balance the observational desires of THEMIS with those of GRS. The MARIE investigation is insensitive to the orbit design. The somewhat conflicting requirements that drive the orbit design are that high-quality THEMIS infrared data can be obtained only at local true solar times (LTST) earlier than 5 PM, while high-quality GRS data is only obtained for beta angles less than –57.5°. The LTST and beta angle profiles are controlled by the orbit inclination, which affects the orbit nodal precession rate (the rate at which the orbit plane rotates in inertial space). Figure LMST BETA displays the time-history of the science orbit LTST and beta angle for the planned science mission. The figure also includes local mean solar time (LMST), and Mars to Earth range.

The frozen orbit condition maintains a relatively fixed eccentricity and argument of periapsis for a given semi-major axis. The periapsis point is "frozen" at the South Pole, and the orbit altitude at any given latitude is constant at all longitudes. The real benefit of a frozen orbit for the Odyssey mission is that it keeps the Odyssey orbit away from the orbit of the Mars Global Surveyor, which is also in a similar frozen orbit.

The initial orbit is frozen, but long-term perturbations will cause the orbit to wander from the frozen condition. The primary source of orbit perturbation is the angular momentum desaturations that are performed daily on the spacecraft. Each event imparts several millimeters per second to the trajectory. The events tend to occur at the same relative point in the orbit, so over time, the perturbation can build to the point where the cumulative effect is similar to an orbit trim maneuver.

Another spacecraft concurrently orbiting Mars with Odyssey is Mars Global Surveyor (MGS), launched November 7, 1996. The orbit of MGS is very similar to that of Odyssey in that it is also frozen, polar, and near-circular at an altitude of about 400 km., however, its velocity is in the opposite direction. The MGS/Odyssey Navigation Team has been monitoring the separation between these two spacecraft since October 2002. The minimum distance observed to date is 16.2 km, which occurred on May 7, 2003.

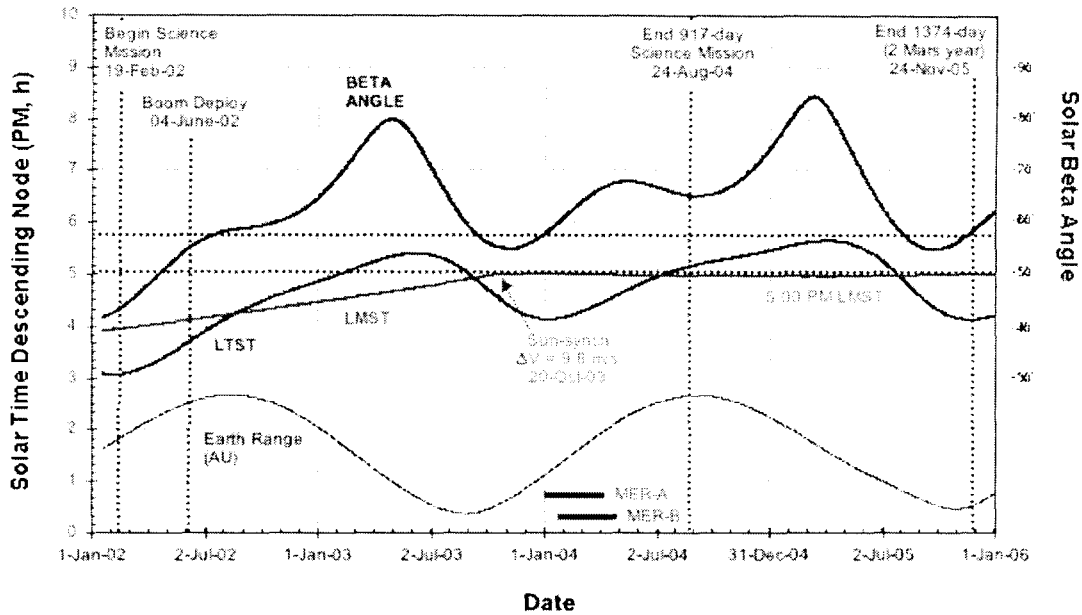

Figure LMST BETA

OD Requirements

The navigation task during the mapping phase is to provide high-accuracy trajectory predicts and reconstructions for science observations and background sequence development. The driving requirement is to provide predicted trajectories that are better than 6 seconds (3σ) [ref. REQ DOC]. There is not a formal requirement on the reconstructed trajectory accuracy.

In order to meet strict position and pointing requirements of the high-resolution camera, trajectory predicts are delivered once per week. In order to provide the science team with quick OD results, trajectory reconstructions are also provided once per week. The Odyssey navigation team has been able to provide excellent orbit determination generating both trajectory predictions and reconstructions throughout the mapping phase.

ORBIT DETERMINATION STRATEGY

This section presents a description of the orbit determination models used for mapping operations. Orbit determination involves three aspects: the observations and their respective models, the dynamics and associated models, and the filter.

Observations

The observations, or observables, are the measurements used to track the spacecraft, such as range and Doppler shift. Several phenomena affect the characteristics of the

observations. Such phenomena include those that affect the path length, such as Earth orientation parameters, as well as those that affect the perceived path length, such as ionosphere and troposphere delays, station transmitter biases, and spacecraft transponder biases. For accurate orbit determination, all of these effects must be compensated for using observation models.

The tracking data used for each orbit solution consists of X-band Doppler data collected at 10-second samples. Plans for mapping operations originally called for Deep Space Network (DSN) coverage of XXX. The actual tracking of Odyssey has exceeded the planned coverage, often reaching 16 hours per day. Tracking data quality is typically better than 0.08 mm/s for the two-way and three-way Doppler data. Odyssey does not have an ultra stable oscillator on board and thus one-way Doppler data is not useful for orbit determination purposes.

Signal path deviations due to the Earth's ionosphere and troposphere are applied in the orbit determination process with model updates occurring once and twice per week, respectively. Information providing corrections to the Earth rotation and pole orientation are updated twice each week.

Dynamic Models

In addition to observation models, dynamic models are used to represent the physical forces acting on the spacecraft. The dynamic models include the gravitational forces, drag, solar radiation pressure, and thruster activity.

A 75th degree and order spherical harmonic Mars gravity field model, identified as MGS75E, truncated to 55x55 is employed in the orbit determination process. MGS75E was developed by the MGS radio science team and is based upon analysis of one-way, two-way and three-way Doppler and range tracking data. These data were acquired during the science phasing orbits, gravity calibration orbits and the mapping phase of the MGS mission until September 2000[ref. MGS75E]. Navigation utilizes the IAU 1991 definition of the Mars astrodynamic constants, and the MGS75E model is consistent with these constants as well. In addition, we use the USGS Mars reference spheroid (a = 3393.4 km and f = 0.0052083) and the JPL planet and Mars satellite ephemerides DE405 and MAR033, respectively [Ref. DE405].

For the mapping mission, the spacecraft coordinate system is defined as shown in Figure SC CONFIG. First, a coordinate system, X', Y', Z' must be defined. X' is in the anti-nadir direction. Z' is the cross product of the velocity vector and the nadir vector. Y' completes the triad. This coordinate frame is rotated by 17° about the Z' axis in order to form the X, Y, Z coordinate system.

To account for solar radiation pressure (SRP), the spacecraft is modeled using a collection of five flat plates. These components can be independently oriented with respect to the Sun, the Earth, or the spacecraft coordinate system. The area, specular

reflectivity (μ) and diffuse reflectivity (ν) of each component have been calculated from information supplied by LMA. Table SRP summarizes the physical properties of these components. The HGA is modeled as a flat plate that points towards the Earth. The solar power array assembly and drag flap are modeled as another flat plate. Their orientation is defined by the vector normal to the flat plate, expressed in the spacecraft coordinates. The orientation of the solar power array occasionally changes (every couple of months) in order to lubricate joints and minimize torques on the spacecraft, but they are otherwise fixed with respect to the spacecraft frame. Lastly, the three remaining flat plates are affixed to the spacecraft +X, +Y and +Z axes to model the equipment bus.

Table SRP
MGS SRP MODEL PARAMETERS

Component	μ	ν	Area
HGA	0.010	0.2100	1.327 m^2
SA / Drag Flap	0.049	0.0720	10.590 m^2
+X Bus	0.026	0.2573	3.270 m^2
+Y Bus	0.026	0.2573	3.930 m^2
+Z Bus	0.026	0.2573	2.410 m^2

For reconstruction analysis, an exponential atmospheric drag model is used. The exponential model parameters are as follows: the base altitude is 381 km, the scale height is 65 km, and the base density varies between 10^{-15} to 3×10^{-14} kg/m^3. Odyssey's coefficient of drag is modeled to be 1.99. The cross-sectional area is modeled using the attitude of the spacecraft along with the component definitions described above. The atmospheric drag is ignored for prediction analyses.

Filter

The final component to the orbit determination process is the filter. The filter adjusts parameters of the observation and dynamic models in order to produce the best statistical fit of the dynamic model to the observed tracking measurements. These adjusted, or estimated, parameters can be used to propagate the trajectory forward in time in order to form a trajectory prediction.

The orbit determination filter for mapping operations uses a single batch, weighted least squares, square-root information algorithm. The parameters estimated in an orbit solution include the spacecraft epoch state (position and velocity), a subset of the gravity field coefficients, the base density of the exponential atmospheric drag model, the SRP force scale factor, once-per-rev accelerations, and the scale factor on ΔVs associated with AMD events. The subset gravity coefficients that are estimated are the 7th, 8th, 9th, 12th, and 13th order coefficients, which are chosen to optimize the performance of the filter. The once-per-rev accelerations estimated are two sinusoidal accelerations that are 90° out of phase with each other. These help alleviate the effect of unmodeled dynamics. The

scale factor on the AMD ΔVs are stochastically estimated (see the AMD Reconstruction Section). Table FILTER summarizes the a priori uncertainties of the estimated parameters.

Table FILTER
FILTER A PRIORI MODEL UNCERTAINTIES

Parameter	A Priori Uncertainty (1-σ)
Position: X, Y, Z (km)	100, 100, 100
Velocity: ΔX, ΔY, ΔZ (m/s)	10, 10, 10
Gravity Coefficients	30 times the formal MGS75C uncertainties
Base Density (kg/m^3)	$10^{-15} - 10^{-14}$
SRP Scale Factor	10%
Once Per Rev. Accel. (km/s^2)	3×10^{-11}
AMD ΔV Scale Factor	50%

ANGULAR MOMENTUM DESATURATIONS

One of the key factors in the mapping orbit prediction accuracy resides in the understanding of the AMDs. This insight is limited not only to the relationship between build-up of reaction wheel speeds and the thrusters, but also to how AMDs relate to other non-gravitational forces, such as solar radiation pressure (SRP) and atmospheric density, and the impact of all these non-gravitational forces on the mapping orbit trajectory. Therefore, the Navigation team's ability to comprehend, and properly model, the AMDs is crucial to the success of the mission.

Odyssey is three-axis stabilized using three orthogonally mounted reaction wheels (and a spare skew wheel). The reaction wheels build up angular momentum in order to counteract the torques induced by SRP, drag and gravity gradient effects. The momentum in the reaction wheels must be unloaded periodically. This event, known as an angular momentum desaturation (AMD), is accomplished by firing a pair of the 0.2 lbf (1N) Reaction Control System (RCS) thrusters. There are four RCS thrusters, which are aligned such that momentum in each axis of the spacecraft can be desaturated using a specific pair of the thrusters. The thruster pairs are not coupled, thus each AMD thruster event imparts a translational ΔV to the spacecraft.

As mentioned, besides desaturating the momentum build up in the reaction wheels, these Odyssey AMDs also impart a ΔV, which is nominally less than 5 mm/s. Even though these changes in the spacecraft velocity are small (6 orders of magnitude less than the orbital velocity), if poorly modeled, they can have a profound effect on the spacecraft trajectory.

AMD Strategy

One of the significant lessons learned from the Mars Global Surveyor (MGS) mission was in regard to the AMD strategy. The AMD strategy for MGS involves desaturating one axis at a time when the wheel speed exceeds some threshold. Given the autonomous nature of this strategy and that momentum build up is not entirely consistent, the timing of the AMDs are very difficult to predict. Due to the inability to accurately predict AMD timing using this strategy, and the fact that impulsive ΔVs are very sensitive to timing errors, MGS employs a constant acceleration model rather than an impulsive maneuver model for trajectory prediction generation. Using a constant acceleration model does allow MGS to also produce very accurate mapping orbit predictions, but the value for acceleration does have to be closely monitored and maintained.

Odyssey's momentum management strategy allows for more control upon the timing of the desaturations, while employing autonomous methods that ensure the most efficient AMDs possible. The configuration of the RCS thrusters provides much more torque authority for Y-axis wheel desaturations than X-axis wheel desaturations. Since the X and Y axes are aligned in the orbit plane and the angular momentum vector is fixed in inertial space, the momentum exchanges between the X and Y wheels during an orbit. Due to this exchange of momentum and the favorable torque authority for Y wheel desaturations, the AMDs are performed at a point in the orbit where the momentum in the X wheel goes to zero. During each AMD event, all axes of the spacecraft are desaturated (but since the AMDs occur at X wheel zero-crossings, only the Y and Z wheels are actually desaturated).

Although the exact timing of the AMDs are determined autonomously on board the spacecraft (i.e. when the X wheel momentum goes to zero), two parameters are used to control approximately when the AMD will occur: 1) the orbit during which the AMD will occur and 2) on which side of the orbit the AMD will occur. These parameters are determined while each sequence is being generated. The number of orbits between each AMD is chosen to ensure that none of the momentum wheels will accumulate momentum past a certain threshold (XXX Nms, or YYY rad/sec). During the first portion of the science phase, the AMDs were scheduled to occur about twice per day. In June 2002, the AMD frequency was changed to approximately once per day due to the fact that momentum accumulation did not approach the threshold until well over one day after an AMD. The actual time between AMDs is about 23 hours, 42 minutes, which is very close to once every 12 orbits (but not exactly 12 orbits due to the fact that the location of the AMDs drifts within the orbit over time, see figure ORB PLOT).

The high gain antenna is not Earth pointed for approximately 45 minutes surrounding an AMD. Thus, tracking data loss is minimized by choosing the first AMD of each sequence in order to avoid AMDs during tracking passes. The remainder of the AMDs occur at a daily intervals.

The X wheel momentum passes through zero twice per orbit on opposite sides of the orbit. The zero-crossing during which the AMD is triggered must be determined ahead of time. Based on orbit perturbations caused by the AMD ΔV, the navigation team

recommends a preferred side of the orbit for each sequence build (see figure GTW PLOT).

In this manner, the orbit and side of the orbit are used to produce a 20-minute window during which the AMD is to occur. The AMD is autonomously performed by the spacecraft when the X wheel momentum goes to zero during this 20-minute window. Given the orbit during which the AMD will occur and the side of the orbit on which the AMD will trigger, the timing of the actual AMD event is quite predictable.

AMD History

The location of the AMD events within the orbit drift over time. Figure ORB PLOT shows the orbital location of several AMDs throughout the mapping phase. The AMDs shown are separated by about two weeks. Throughout the mapping phase, the apoapsis AMDs have drifted from near the descending node clockwise, past apoapsis towards the ascending node, then back towards the ascending node. The total variation of the AMD location is about 75 degrees around the orbit. A similar behavior is exhibited in the periapsis AMD locations, except on the opposite side of the orbit.

Figure ORB PLOT also demonstrates the orientation of the AMD ΔV vectors. As can be seen from the edge-on plots, the majority of the ΔV vectors are in the orbit plane. Furthermore, the face-on plot shows that the vectors also lie mostly in the radial direction. The orientation of the ΔV vectors is fortuitous in the fact that they cause minimal perturbation to the orbit. The largest perturbation that the Navigation team is concerned with is the component of the vectors that lie in the direction of motion. These ΔVs increase or decrease the semi-major axis of the orbit, and thus change the period of the orbit. These timing perturbations translate into an along-track position error, which are by far the largest error in the prediction solutions.

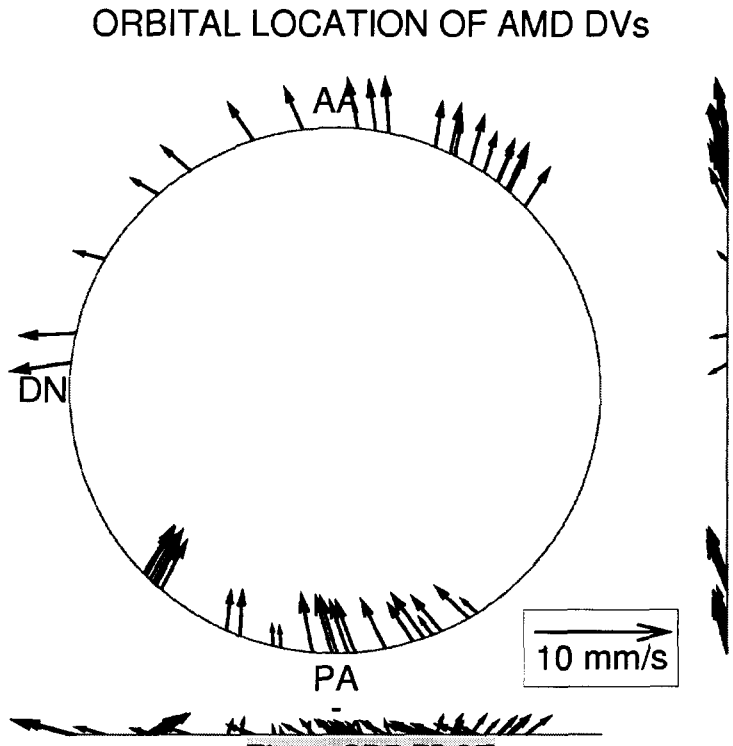

Figure ORB PLOT

AMD Reconstruction

Odyssey's telemetry contains information on each AMD, which is used to develop a model of the associated ΔV. The telemetry information identifies the number of pulses each RCS thruster performed in order to complete the desaturation. This information is then translated into a ΔV vector using LMA software. In order to ensure the best reconstruction solutions, the AMD ΔV is modeled using this telemetry information and its magnitude is estimated. Figure RECON AMD shows the post-fit 2-way Doppler residuals with the AMD ΔV modeled and not modeled. As can be seen, the post-fit residuals are noisier and demonstrate considerably more signature when the AMD ΔV is not modeled. This increase in noise and signature is a strong indication of mis-modeling. Figure OVERLAP AMD shows the difference between the reconstruct solution modeling AMDs and without modeling AMDs. Although the residuals are noiser without AMD modeling, the difference plot indicates that the reconstruct solution without modeled AMDs is still quite accurate.

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Figure RECON AMD

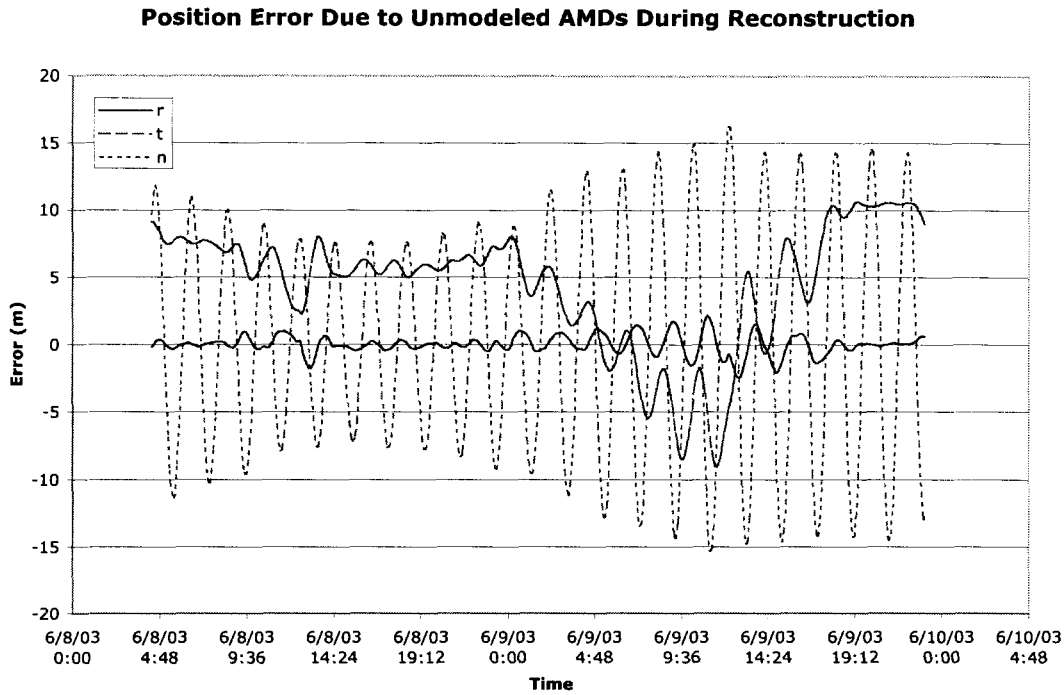

Figure OVERLAP AMD

Beyond simply modeling the AMD ΔV, a scale factor for each AMD event is estimated using a stochastic parameter, meaning that the value of the parameter changes with time. At the time of each AMD, the parameter changes according to the best fit of the data arc. Figure DVFSCL HIST shows a histogram of the value of the AMD ΔV scale factor. There is a significant variation in the scale factor value, however a majority of the values lie between plus-and-minus 20%.

It is unlikely that the actual ΔV of the AMDs varies as much as the histogram demonstrates. Rather, the AMD ΔV scale factor is more likely aliasing drag and solar radiation mis-modeling. SRP and drag forces that tend to line up with the direction of the AMD ΔV vectors will tend to be masked as variations in the AMD ΔV. The main reason that the filter solution indicates that the AMD ΔV is the cause of the orbit perturbation is due to the nature of stochastic parameters. The filter has more flexibility with the stochastic parameter than the SRP and drag parameters since the SRP and drag parameters can not change over the data arc. Thus the AMD ΔV scale factor is likely to be soaking up some of the errors in the SRP and drag models, as well as any errors in the AMD ΔV model.

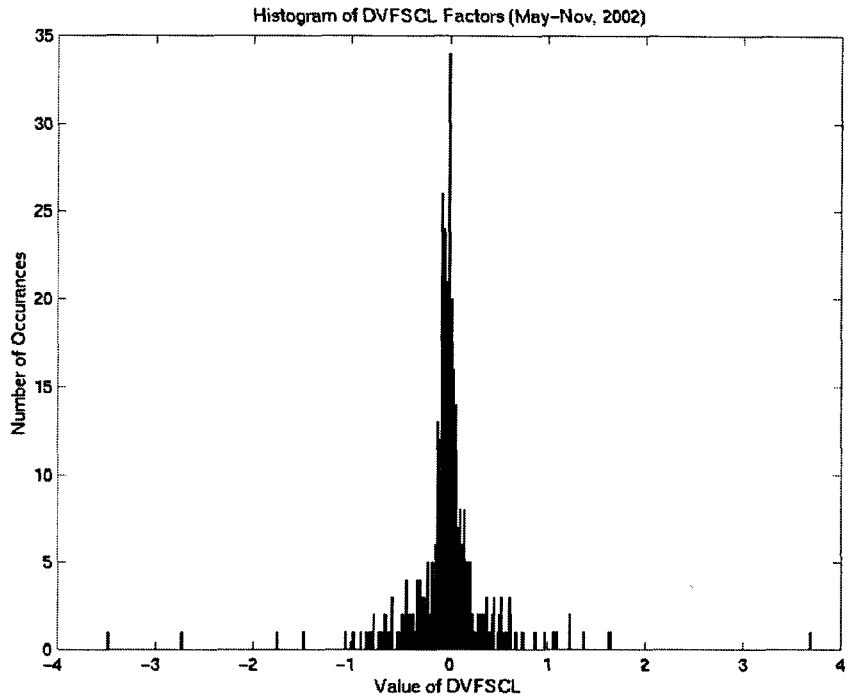

Figure DVFSCL HIST

AMD Prediction

The AMD ΔVs have a considerable effect on Odyssey's trajectory, and thus need to be predicted when generated a prediction trajectory. Mis-modeling of AMD ΔVs is the largest source of error in the predictions produced by the navigation team.

As mentioned previously, the proactive AMD strategy that Odyssey employs allows the navigation team to predict the timing of the AMD events quite well. In addition to timing, the magnitude of the ΔV vector of future AMD events must also be predicted when generating a prediction trajectory. Based on experience, the direction of the ΔV vector is the same for a given thruster pair, and the thruster pair that will be used for future AMDs is known based on knowledge of which axis will need to be desaturated at the time of the AMD. Table AMD RCS indicates which thrusters are used in order to desaturate momentum in each axis. The navigation team is generally able to predict the timing of the AMDs to within 30 seconds, and predict the ΔV to within 20% over one week.

TABLE AMD RCS
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A combination of predicted reaction wheel performance and actual thruster performance is used in order to predict the AMD ΔV. The Attitude Control analyst at LMA generates a predicted model of the momentum build up for all the reaction wheels. This information is then used to determine the estimated number of thruster pulses that are required to desaturate the momentum of the y- & z-reaction wheels. Finally, the number of thruster pulses can be used to yield a ΔV vector that can be used by the navigation team in order to develop a prediction model. Telemetry analysis indicates that the ΔV per thruster pulse is very consistent (i.e., the 3σ ΔV per pulse that is less than 0.004% of the average). The ΔV per pulse is shown in Table AMD RCS. During a prediction analysis, the past several AMDs are used to verify the thruster pulse plot provided by the Attitude Control team, and the prediction model is adjusted accordingly.

Figure PREDICT AMD demonstrates the value of accurately modeling the AMD ΔVs during a prediction solution. The Doppler residuals (i.e. predicted Doppler shift minus the observed Doppler shift), and the timing errors for two cases is presented: 1) When AMD ΔVs are appropriately predicted and 2) when AMD ΔVs are not included in the prediction model at all. After 7 days, the prediction using an AMD ΔV model yields a Doppler error of about 10 Hz and at iming error of about 0.05 seconds, while the prediction without an AMD ΔV model yields a Doppler error of about 100 Hz, and a timing error of about 0.55 seconds. This demonstrates an order of magnitude improvement can be obtained by properly modeling the AMD ΔV events when developing a trajectory prediction model.

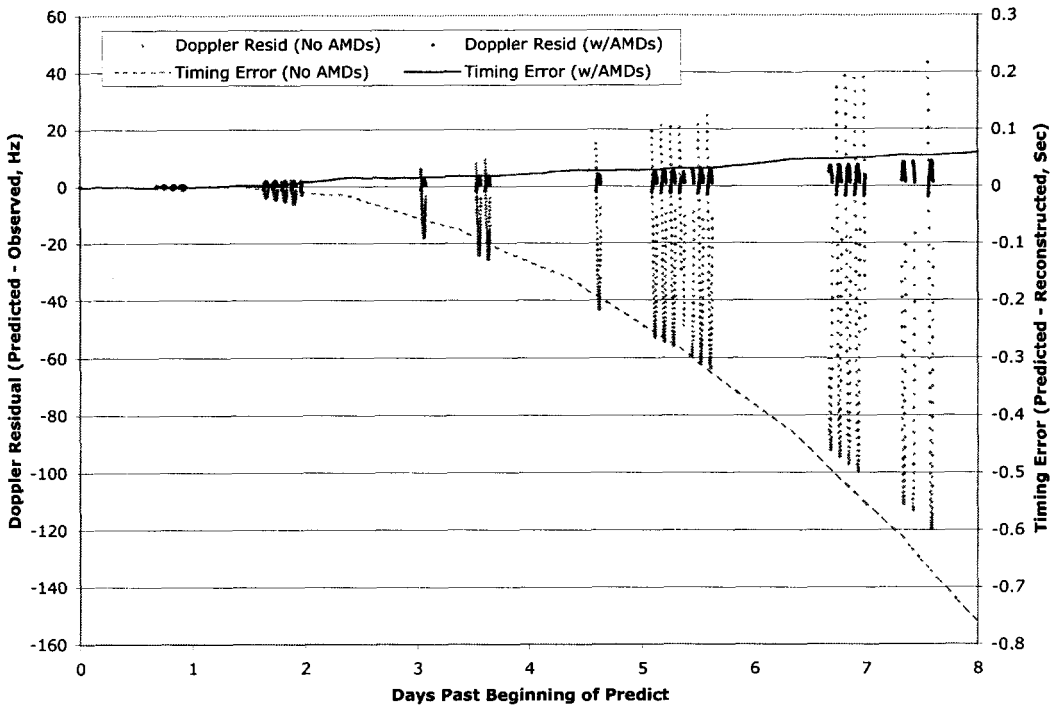

Figure PREDICT AMD

Due to non-truths in the AMD ΔV model, such as solar array impingement, the predicted ΔV for future AMD events must be scaled. Previous to February 2003, the predicted ΔV did not need to be scaled. However, following a solar array re-orientation in February, it was discovered that the prediction trajectories were significantly degraded. It was found that applying a scale factor to the ΔV helped to alleviate this degradation. Figure AMD SCALE shows a history of the value of the scale factor since March 2003, when the scale factor was first invoked during the mapping phase of the mission. As is clearly shown, periapsis AMD ΔVs need to be scaled up, while apoapsis AMD ΔVs need to be scaled down. Each week, the previous weeks worth of data, in conjunction with AMD telemetry, is used to determine a new scale factor that is to be used for the following week. In order to predict what the scale factor will need to be for a new sequence, a linear fit of the previous sequence's scale factors is extrapolated to the date of the new sequence. Due to the limited amount of data that is available concerning the predicted AMD ΔV scale factor, it is unclear, at this point, if a linear fit is appropriate.

Recent findings indicate that the AMD scale factor may be accounting for mis-modeling in the SRP or atmospheric drag model. The largest effect that the AMD ΔV vector has on the prediction model is in the along-track direction. Some of the SRP force and all of the drag force align with the along-track direction. This allows the AMD model to compensate for SRP and drag force mis-modeling. Reconstruction analysis has shown that the atmospheric density has been increasing over the last several months. Atmospheric drag is not considered in the prediction model, thus an increasing atmospheric density is likely being compensated for with the AMD scale factor.

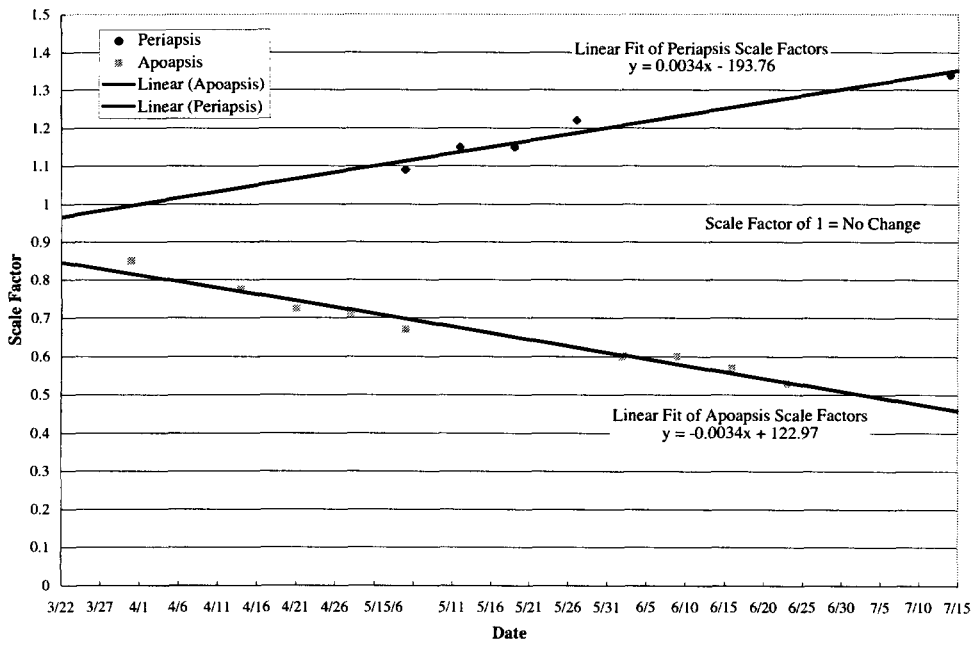

Figure AMD SCALE

Ground Track Walk Management Using AMD Perturbation

Because the AMD events are well understood, the Odyssey AMD strategy has also been used to control the orbit ground track walk. Towards the beginning of mapping, it was observed that the AMD events were causing the ground track walk to drift away from the desired repeat cycle. It was then determined that if the AMD events were forced to occur on the opposite side of the orbit (i.e., near periapsis, rather than near apoapsis), the drift in the ground track walk could be reversed. As shown in Figure GTWPLOT, this phenomenon has been used to control the ground track walk without the use of orbit maintenance maneuvers.

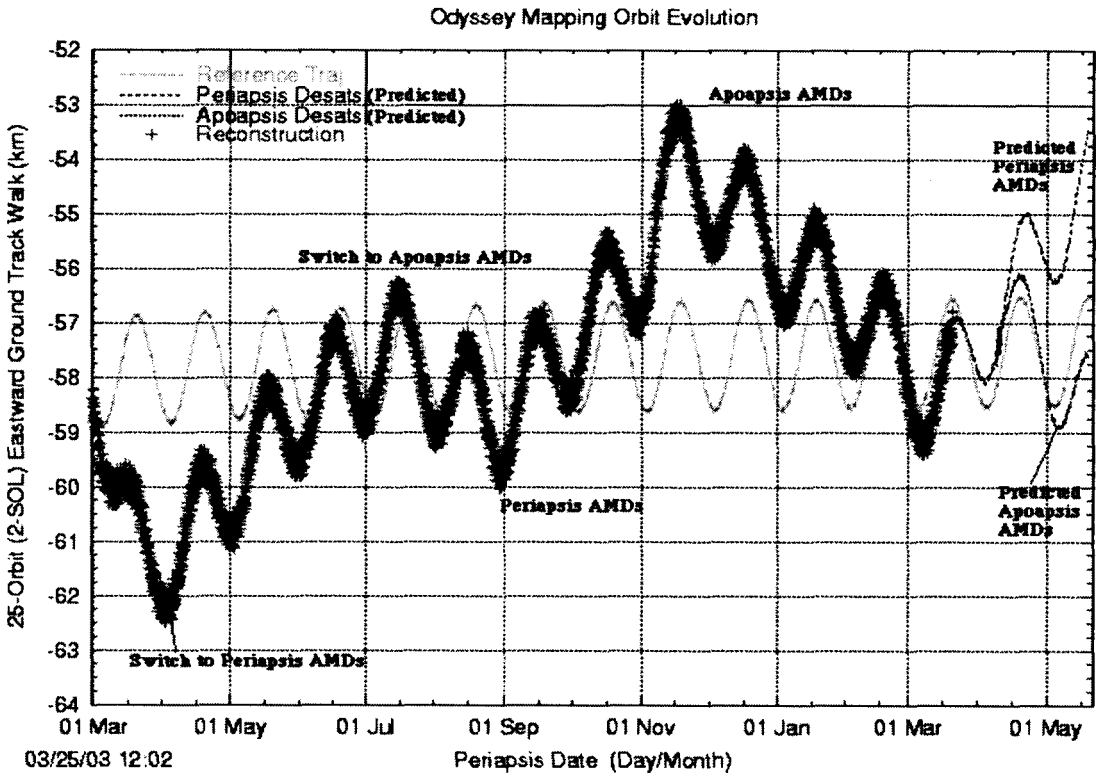

Figure GTW PLOT: As shown in the above plot, the ground track walk can be controlled by choosing which side of the orbit the AMDs are triggered.

ORBIT DETERMINATION RESULTS

Trajectory Reconstruction Analysis

The Navigation team delivers trajectory reconstructions once per week. The reconstruction deliveries are typically broken up into 20-25 orbit batches. Given the nearly 2-hour orbit period, these batches reconstruct the trajectory using 40-50 hours of data, and thus 3-5 batches are combined for each delivery. The start and end time of the

batches are selected such that at least 2-3 orbits of tracking data are present at the beginning and end of the batch. This ensures that all orbits that do not occur during tracking passes are bracketed by orbits that are tracked. This strategy is similar to that used by the MGS Navigation team [Ref. MGSOD]. The batches typically overlap by at least 1-2 hours, which allows for accuracy analysis by differencing overlapping portion of two subsequent reconstruction batches.

It is difficult to assess the precision of the navigation team's trajectory reconstruction results. As mentioned above, one method of assessing reconstruction accuracy is to difference two overlapping reconstruction batches. As part of the Navigation team's reconstruction analysis, overlap plots are generated. Figure TYP OVERLAP shows a typical overlap plot. Note that the down-track and cross-track components demonstrate the largest error, while the radial error is significantly smaller. The RMS overlap difference in the radial, down-track, and cross-track directions are typically less than XX m, YY m, and ZZ m RMS, respectively. Figure OVERLAP HIST shows a histogram of the radial, cross-track and along-track RMS of by all of the mapping phase reconstruction overlaps.

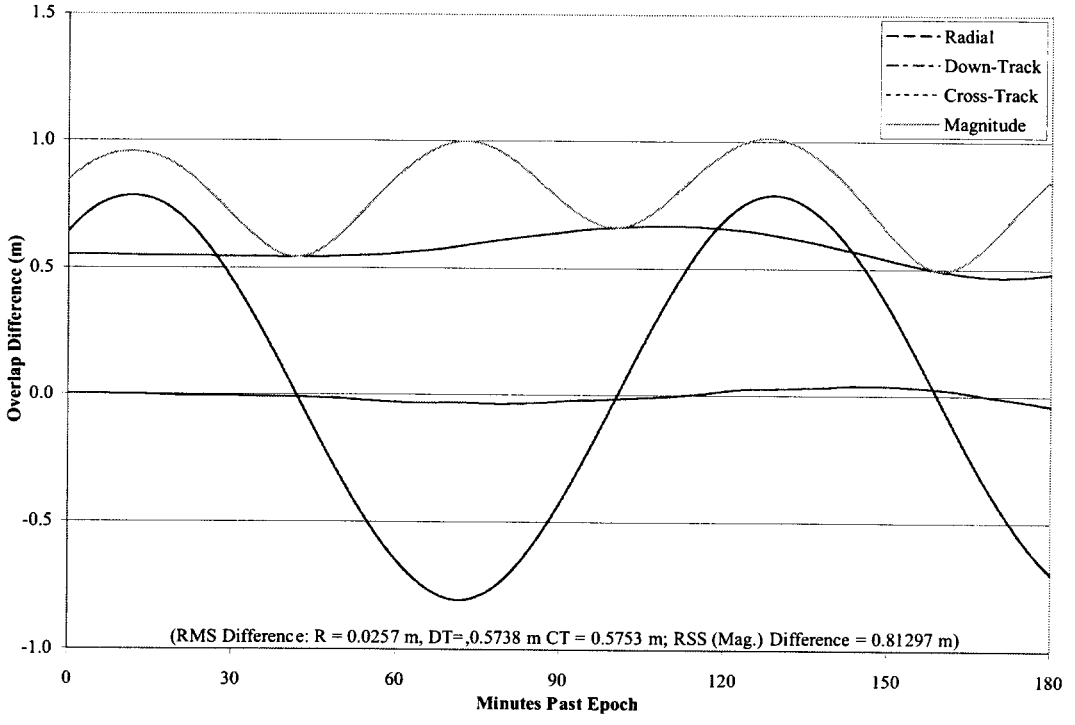

Figure TYP OVERLAP: Typical Reconstruction Overlap Plot

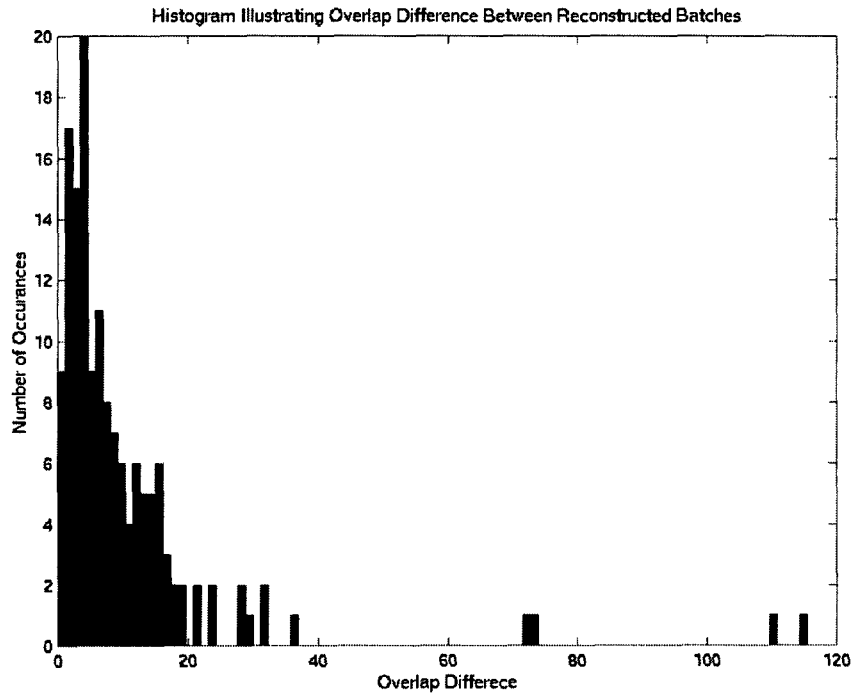

Figure OVERLAP HIST

The overlap plot method is generally a somewhat optimistic evaluation of accuracy and precision. There are two reasons for this: 1) most overlapping segments occur during tracking passes, and 2) the same dynamic model, observation, and filter techniques are used for all of the reconstruction analyses. A better indication of the solution accuracy and prediction would be a comparison with an independent set of orbit determination solutions. The JPL radio science team has produced an independent set of OD solutions which have been used to demonstrate the accuracy of the Navigation team solutions.

Prediction Accuracy

The Navigation team delivers trajectory predicts once per week. Earlier in the mapping mission, predicts were delivered twice per week, but the navigation team was able to demonstrate that requirements could be met consistently with weekly predicts. The delivered solutions typically provide 21 days worth of trajectory prediction, which is used by the science team to plan their data collection activities. Once per month, a 60-day runout is generated in order to support development of a new background sequence. In order to determine an accurate dynamic model for the trajectory integration, several orbits worth of data are reconstructed. It has been shown that two orbits of data, or more, can be used to determine a suitable prediction integration model, however up to 24 hours (12 orbits) of data is typically used in order to ensure that the dynamic model accurately

reflects longer-term trends in the dynamics. The start and end times of the reconstructed portion of the analysis are chosen using the same guidelines as are used for reconstruction solutions.

Once the dynamic models have been determined, the AMD prediction model is developed as described in the previous section. At this point, the trajectory is integrated forward until the desired end time.

There are two ways in which to evaluate the accuracy of prediction solutions. Once a prediction solution has been generated, the Navigation team can evaluate it's accuracy in real time using incoming Doppler residuals from the DSN. Figure X shows a plot of the Doppler residuals for the first week of a typical predicted trajectory. It is very difficult to attach a physical meaning to the Doppler residuals, however based on experience, the Navigation team can use this type of plot to quickly assess if a predict is going astray.

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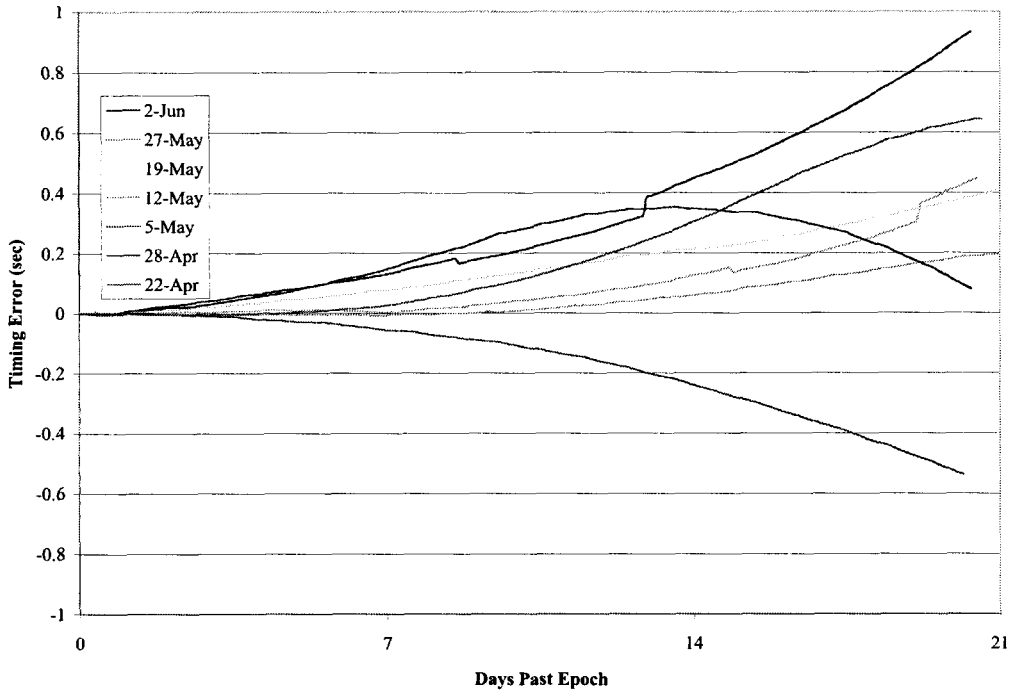
The accuracy of prediction solutions can also be determined by comparing them to the reconstructed solutions, which are obtained once the prediction time span has passed. This method can not be used in real time since reconstruction batches are not typically generated until a couple of days after the data is available. However, the results of this method are much more physical. The descending equator crossing time is generally used as the key measure of prediction accuracy. Timing errors are generally less than X seconds over 7 days, and XX seconds over 21 days. Typical position errors after 7 days are less than X km, Y km, and Z km in the radial , down-track, and across-track directions, respectively after 7 days, and X km, Y km, and Z km after 21 days. The 60-day predictions are generally accurate to within XX seconds. (Note that the reconstruction accuracies described previously correspond to a timing accuracy of 0.002 to 0.06 seconds). Figure PRED TIME shows the timing accuracy of several prediction trajectories as a function of time since the beginning of the predicted portion of the run out.



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CONCLUSIONS

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ACKNOWLEDGEMENTS

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6. Ref MGS75E: MGS75E Document?
7. Ref MGSOD: Mars Global Surveyor Mapping Orbit Determination
8. Ref REQ DOC: Mars Odyssey Navigation Requirements Document.