Orbit Determination and Navigation Software Testing for the Mars Reconnaissance Orbiter

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Contents

1 Introduction **3**

2 Background & Objectives **4**
2.1 Implementation of Orbit Determination Process 4
2.2 Motivation for Summer Work 6

3 Approach **7**
3.1 Orbit Trim Maneuver Support 8
3.2 MONTE Testing 9

4 Results & Discussion **12**
4.1 Orbit Trim Maneuver Support 12
4.2 MONTE Testing 13

5 Conclusions & Future Work **17**

6 Acknowledgements **19**

List of Figures

2.1 Data Residuals vs. Time (Before and After Filtering Process) 5

3.1 Differences in Trajectory Overlaps Across Reconstruction Interval 8
3.2 Summary of MONTE Test Configurations and Comparisons Made 10

4.1 Pre-fit Residuals Spanning OTM-24 Execution 12
4.2 Differences in Trajectory Overlaps Across Reconstruction Interval 14
4.3 Differences in Trajectory Overlaps Over 28-Day Prediction 15
4.4 Differences in Descending Equator Crossing Times Over 28-Day Prediction . 16

Section 1

Introduction

During the extended science phase of the Mars Reconnaissance Orbiter's lifecycle, the operational duties pertaining to navigation primarily involve orbit determination. The orbit determination process utilizes radiometric tracking data and is used for the prediction and reconstruction of MRO's trajectories. Predictions are done twice per week for ephemeris updates on-board the spacecraft and for planning purposes. Orbit Trim Maneuvers (OTMs) are also designed using the predicted trajectory. Reconstructions, which incorporate a batch estimator, provide precise information about the spacecraft state to be synchronized with scientific measurements. These tasks were conducted regularly to validate the results obtained by the MRO Navigation Team. Additionally, the team is in the process of converting to newer versions of the navigation software and operating system. The capability to model multiple densities in the Martian atmosphere is also being implemented. However, testing outputs among these different configurations was necessary to ensure compliance to a satisfactory degree.

Section 2

Background & Objectives

A fundamental element of every space mission is the orbit determination process. Orbit determination is generally conducted in an iterative manner and utilizes both radiometric tracking data from ground stations and dynamic models for the satellite's motion [1]. The difference between the observed and predicted data, referred to as the residual, is minimized (in a weighted least-squares sense) through filtering to obtain higher accuracy orbit information about the satellite. Since the quality of the resulting prediction is directly dependent on the observation data (among other things), a high-fidelity tracking technique is essential for an accurate representation of the satellite's behavior.

2.1 Implementation of Orbit Determination Process

Currently, some of the most accurate ranging measurements are obtained using two-way Doppler [1]. For this reason, two-way Doppler is the primary source of tracking data used for the orbit determination of the Mars Reconnaissance Orbiter [2]. When the raw tracking data is received, the residual is computed by differencing the observational value with the nominal computed value. For reconstructions, two-way Doppler is the most common data type used, but one-way and sometimes three-way are also beneficial.

When these residuals are plotted as a function of time, a sinusoidal pattern emerges, as shown below:

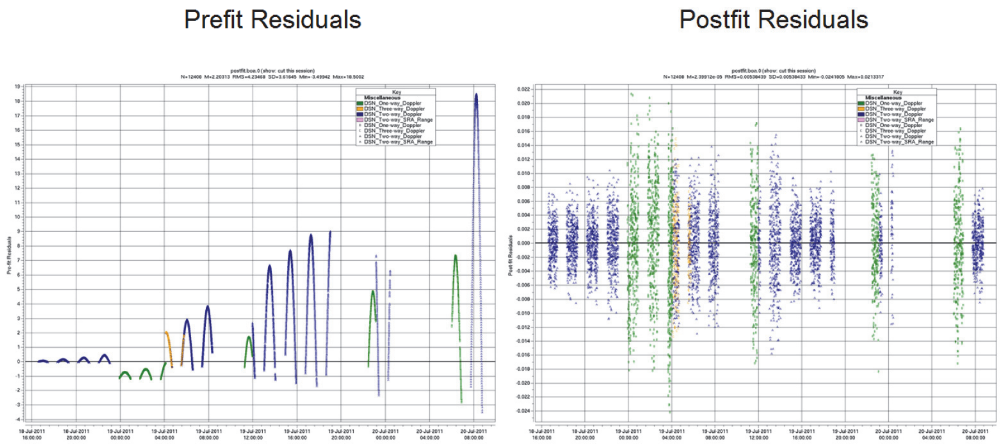

Figure 2.1: Data Residuals vs. Time (Before and After Filtering Process)

The blue points in Figure 2.1 represent two-way Doppler data, the green points indicate one-way Doppler data, and the orange points signify three-way Doppler data. Each "peak" of the sine wave corresponds to a Doppler pass, which is roughly one orbit's worth of data. In the "pre-fit" residual plot shown at left, the sinusoidal signature grows with time, which indicates that the predicted trajectory is slowly degrading. Also, the portions of the sine wave that are missing correspond to occultations, which are times where MRO passes behind Mars and is out of sight to an Earth observer. The magnitude of the residuals before they are filtered is on the order of 10 Hz, which is a relatively high value. Once the data has been filtered and the nominal trajectory has been altered through an iterative process, "post-fit" residuals are formed, as shown in the plot on the right of Figure 2.1. The size of the post-fit residuals are a few orders of magnitude lower than the pre-fit data and the data resembles a much cleaner Gaussian distribution with close to a zero mean. This filtering technique is incorporated in all of the orbit determination procedures that the MRO Navigation Team utilizes.

For MRO, the orbit determination duties are separated into two categories: reconstruction and prediction. The orbit reconstructions are mostly of use to the science team because they provide information about the satellite's state at the time of scientific measurements. Doppler data spanning about 36 hours is processed through a batch estimator and a new nominal trajectory is calculated over multiple iterations to form the reconstructed orbits.

Alternatively, predictions are obtained by propagating MRO's orbit over the course of a few weeks. This propagation is achieved by numerically integrating the satellite's equations of motion using a few orbits' worth of *a priori* data to enhance the prediction. As necessary, orbit trim maneuvers are designed and relevant information such as magnitude, right ascension, and declination of the OTM is provided to the spacecraft team.

2.2 Motivation for Summer Work

Over the course of the summer, proficiency has been gained in the orbit determination process for MRO. This was mainly achieved by repeating the procedure for predictions and reconstructions to validate the results obtained by the regular MRO Navigation Team. The MRO Navigation Team has just recently implemented an updated version of the navigation software (MONTE 46) that fixes several bugs associated with the previous release. Also, the conversion to a newer operating system (Redhat Enterprise Linux 5) is in progress in order to stay current with the rest of the Navigation and Mission Design section. Finally, the capability to model the Martian atmosphere as multiple densities is desired to better determine MRO's behavior, especially during the Mars high-density season. In order to have confidence in the transitions to the newer versions of software, testing occurred to examine how the orbit determination solution results varied with the different software configurations.

Section 3

Approach

A useful method of learning the orbit determination process is to independently generate solutions that aim to replicate the official delivered results produced by the MRO Navigation Team. This also serves as a way to validate the Navigation Team's work. To compare trajectories, the differences in each of the three components of position are computed and plotted as a function of time. An example of this plot is shown on the next page:

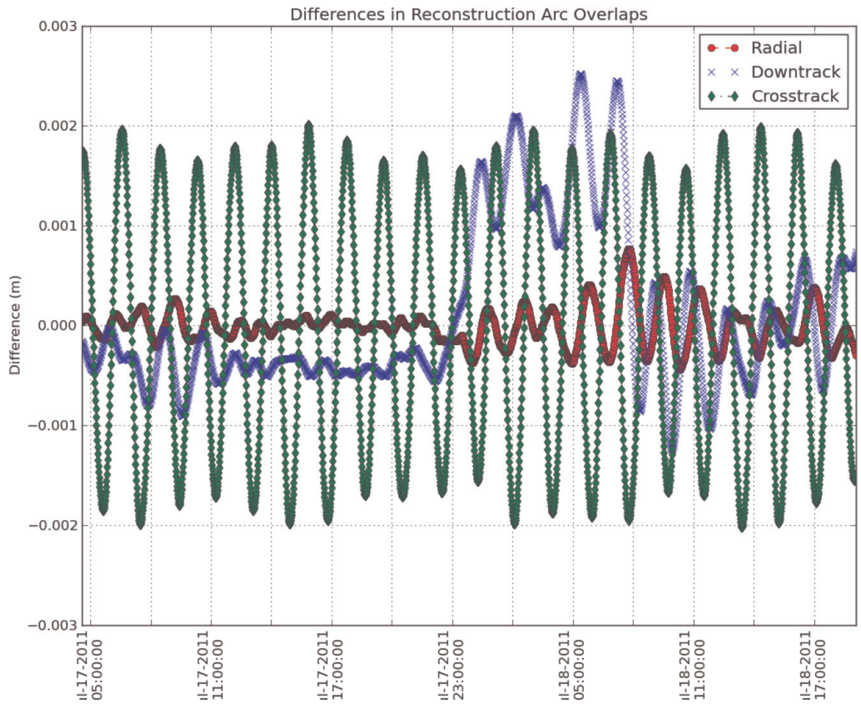

Figure 3.1: Differences in Trajectory Overlaps Across Reconstruction Interval

The behavior displayed in Figure 3.1 indicates that there was an agreement in the positional components of the two trajectories to the millimeter level, which is exceptional. Generally, the comparisons stayed within about one meter, which is well within the navigation requirements for the mission. The skills obtained through repeated checks of the Navigation Team's results were used to help monitor the behavior of MRO during its orbit trim maneuver on July 20.

3.1 Orbit Trim Maneuver Support

For MRO, an orbit trim maneuver (OTM) is usually executed to raise the semi-major axis of the orbit, although they are sometimes used to change the inclination. These maneuvers occur roughly every eight weeks and are necessary to fulfill certain mission requirements. The expected Δv and direction associated with the maneuver must be modeled into the satellite's equations of motion in order to accurately predict the resulting trajectory soon after the OTM occurs.

To monitor the OTM's performance, the satellite's trajectory was computed according to two scenarios: with and without the maneuver accounted for. On the day of the maneuver, near real-time residuals were formed by comparing the incoming tracking data to the two different predicted solutions. The plot with the smaller data residuals indicated that the corresponding solution was a better reflection of the satellite's true behavior. These results will be discussed in the next section.

Additionally, a common operations task on the day of an OTM is to periodically perform orbit predictions shortly after the maneuver to determine if an ephemeris time update to the satellite is necessary. While the official predictions were performed by a member of the MRO Navigation Team, other trajectories were calculated in tandem using MONTE 46 to examine the effects of using a different version of the navigation software.

3.2 MONTE Testing

To ensure that the anticipated software updates produce comparable results to the accepted operations configuration, testing was necessary. The effects of using each piece of software were isolated by carefully designing the testing process, which is summarized in the diagram on the next page:

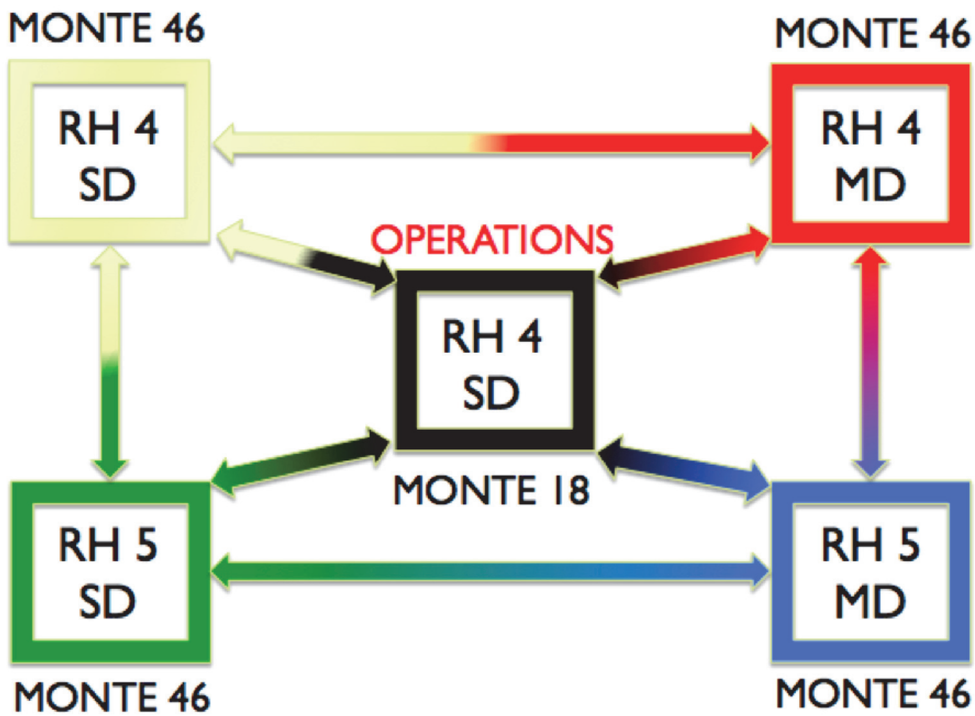

Figure 3.2: Summary of MONTE Test Configurations and Comparisons Made

The black square in the center of Figure 3.2 corresponds to the baseline configuration and represents the nominal results for comparison. The four outer squares denote the four other cases that were considered to illustrate how the results vary with software. MONTE 46 was used in all four cases because a change from MONTE 18 to version 46 was previously determined to have a minimal result on the generated solutions. However, different combinations of the operating system (Redhat Linux 4 & 5) and Martian density model (Single and Multi-Density) were tested and the results were compared to the operations case. Additionally, there were auxiliary comparisons made between the four test cases to help visualize the effect that changing only one type of software had on the solutions.

To cover the entire spectrum of possibilities, these tests were conducted for reconstructions and predictions. For reconstructions, comparisons between the two cases were made using the same overlap method described earlier to validate the results of the MRO Navigation Team. Predictions utilized two different metrics to assess how well the trajectories coincided. First, the three positional components of the propagated trajectory were differenced in a similar fashion to the overlap technique used for reconstructions. Also, the difference in time of descending equator crossing at each orbit provided another means of comparison.

Section 4

Results & Discussion

4.1 Orbit Trim Maneuver Support

The results involving the support of OTM-24 represent a demonstration of the proficiency achieved in the orbit determination process throughout the summer. As mentioned in the previous section, predicted solutions were generated while accounting for and neglecting the Δv's associated with the maneuver. On the day of the maneuver, near real-time tracking data was used to form residuals from each calculated trajectory as follows:

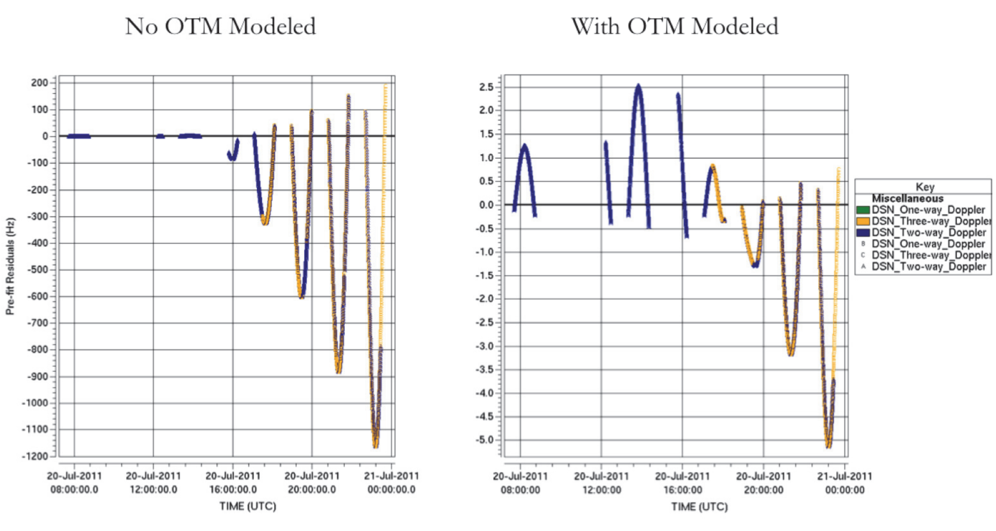

Figure 4.1: Pre-fit Residuals Spanning OTM-24 Execution

This technique is helpful to determine if the maneuver actually occurred. From Figure 4.1, the residuals are much larger (about 1000 Hz) in the solution that doesn't account for the maneuver, but the plot on the right included the maneuver and has a much smaller difference between the observed and computed values. The residuals in the two plots are similar until about 14:30 UTC, which is when the maneuver was scheduled to be executed. After that, the residuals in both of the plots start to diverge, but at different rates. This is an indication that the actual OTM was executed differently in the line of sight direction than both of the solutions predicted. However, the execution error for the trajectory on the right (which was used by the Navigation Team) was determined to be only 2.5 mm/s, which is small enough not to require any corrections.

4.2 MONTE Testing

The MONTE Testing involving reconstructions was not expected to vary significantly between the test cases and baseline because the entire trajectories were run through a filter and iterated until convergence. This means that any variations that arose due to software differences were essentially negated by the iterative process imposed within the batch estimator. The overlap plot between the operations trajectory and the solution created using Redhat Linux 5 and the multi-density model (which should represent the biggest variation) is shown on the next page:

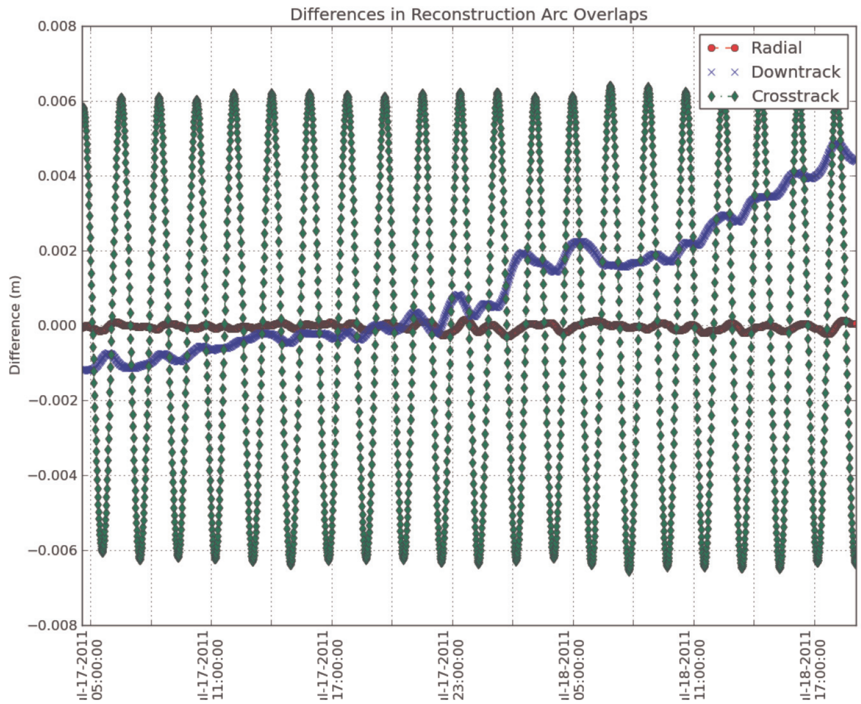

Figure 4.2: Differences in Trajectory Overlaps Across Reconstruction Interval

Even in the case that is expected to show the greatest differences, the two solutions comply to the millimeter level, as demonstrated in Figure 4.2. These tests were conducted for different orbit intervals and the corresponding solutions are fairly consistent. These results verify that a conversion to MONTE 46, Redhat Linux 5, and the multi-density model will have no adverse affect on trajectory reconstructions, which is expected. However, such close agreement is not anticipated when considering predictions. This is due to the fact that trajectory predictions are very sensitive to initial conditions because the equations of motion are integrated over either a 28-day or 60-day span. This allows for small changes in the initial state of the satellite to lead to a large divergence in final position. An example of this behavior follows on the next page:

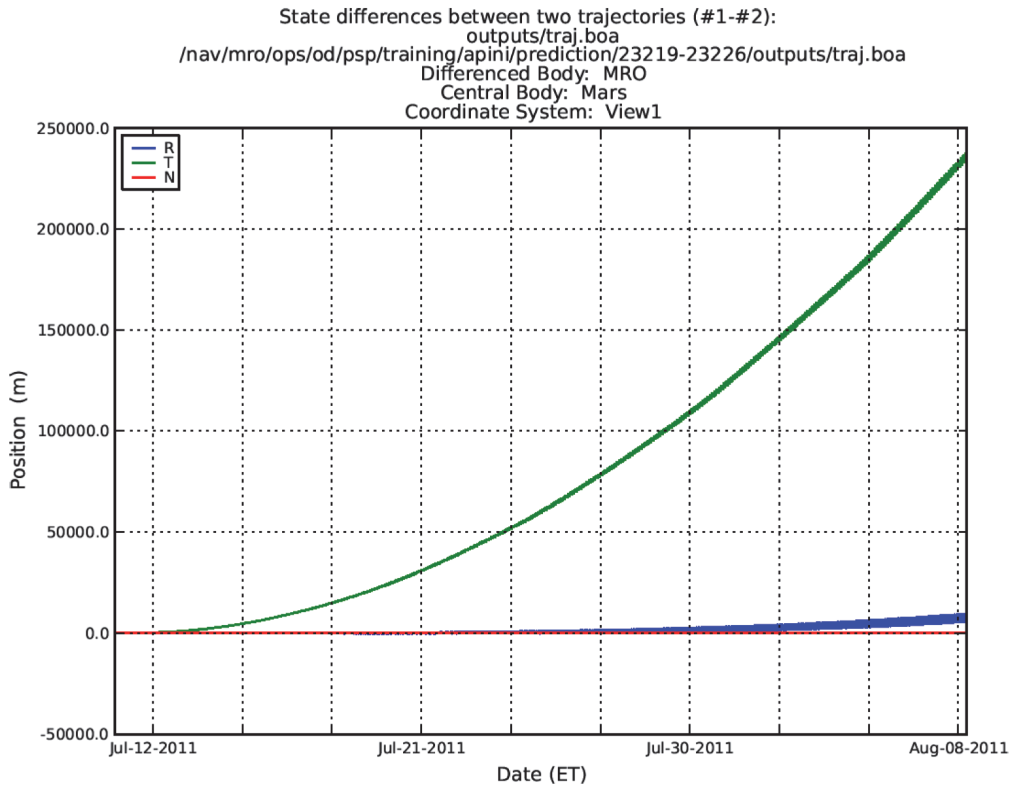

Figure 4.3: Differences in Trajectory Overlaps Over 28-Day Prediction

It can be clearly seen in Figure 4.3 that a large difference, roughly 250 km, is encountered between the test case and operations trajectory in the transverse position component. This case is also utilizing Redhat Linux 5 and the multi-density model, so this plot represents the largest expected deviation among the test cases. The auxiliary comparisons suggest that this large discrepancy arises because of the multi-density model. This conclusion is intuitive because the transverse component of position is greatly affected by the atmosphere via the drag Δv. As a result, using an inaccurate representation of the Martian atmosphere will lead to erroneous estimates of the transverse position and velocity. The significant differences between this test case and the operations case are also apparent when examining the descending equator crossing times, as shown on the next page:

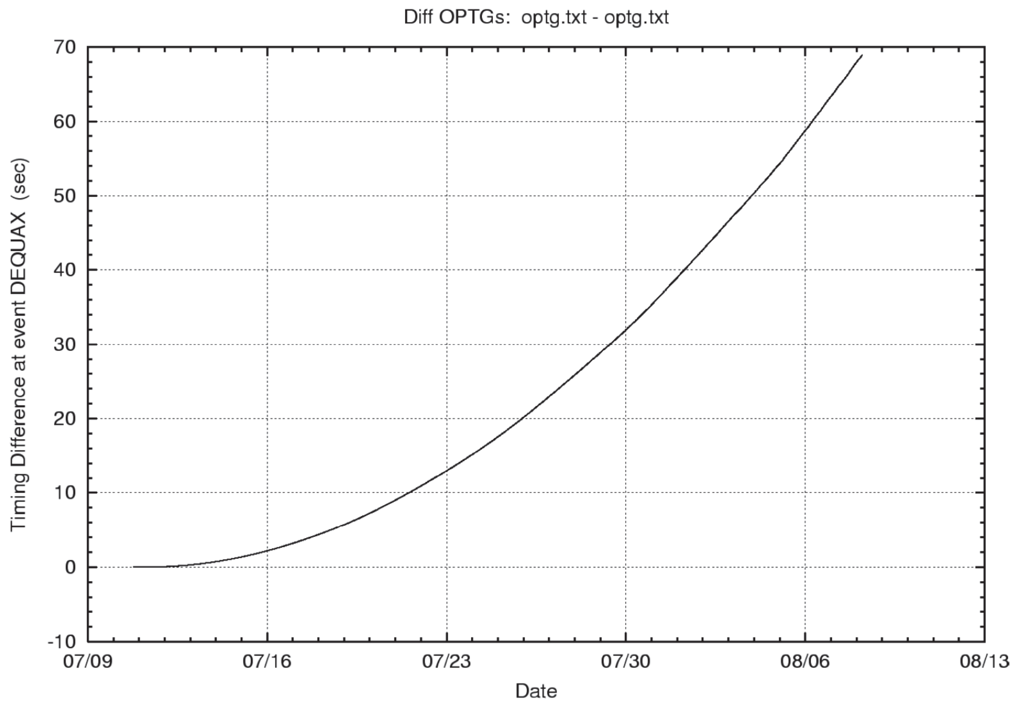

Figure 4.4: Differences in Descending Equator Crossing Times Over 28-Day Prediction

It can be seen in Figure 4.4 that the difference in equator crossing times between the two trajectories approaches 70 seconds after about a month of orbit propagation time. Considering that the maximum tolerance for equator crossing time error before an ephemeris update is necessary is 0.43 seconds, the solution produced by the Redhat 5 multi-density configuration is completely unacceptable. The predicted orbit trajectories were expected to have the highest chance of being problematic, but the exact nature of these errors is yet to be determined. The test results show that the multi-density modeling may not have been correctly implemented in this version of MONTE and further analysis is required to pinpoint the issues.

Section 5

Conclusions & Future Work

This summer experience provided a valuable opportunity to witness and participate in the daily navigation operations involving a significant interplanetary orbiter. Additionally, learning the orbit determination process from those who do it best has helped to build a strong foundation and apply the theory that was encountered in the classroom. In the end, a comfortable skill level has been reached when performing the ”basic” tasks pertaining to orbit determination. This includes the generation of reconstructions and predictions without having to account for more advanced capabilities offered by MONTE, such as estimating several bias and rate parameters for one-way Doppler.

When this skillset with the navigation software was established, it was applied to help support the orbit trim maneuver occurring on July 20. By allowing for near real-time residuals to be formed representing the ”correct” and ”incorrect” solutions, the Navigation Team was able to verify that the maneuver occurred. Also, the maneuver was determined to be accurate enough that an ephemeris update was unnecessary.

The extensive testing of the MONTE software yielded a few different conclusions. First, MONTE 46 was shown to have a negligible effect on the results when compared to the previous operations version (MONTE 18). Because this was verified through the testing, the MRO Navigation Team officially updated to MONTE 46 on August 9, 2011. However, the tests regarding Redhat Linux 5 and the multi-density capability are inconclusive thus far. Redhat Linux 5 has shown some fairly significant differences when compared to Redhat 4, partially due to the different versions of the AutoEditor feature to eliminate outlying data points. The multi-density model is still quite problematic. The differences in the single and multi-density solutions, particularly in the transverse component of position, are far too large to ignore. Further testing is recommended to help diagnose the source of these errors.

Section 6

Acknowledgements

First, I would like to thank Allen Halsell for bringing me to JPL. He did an excellent job of getting me situated and showing me around the lab, but more importantly, he introduced me to many amazing people that I would never have dreamed of meeting five years ago. I've wanted to experience a summer at JPL for as long as I can remember, and it was everything I hoped it would turn out to be. Without him, this paper would not exist.

Also, I would like to thank Prem Menon for "adopting" me and becoming my co-mentor. He may or may not have known ahead of time that he was getting interns, but he managed to handle us very well and cater to our needs. Although he is the Navigation Team lead, he was much more accessible than I anticipated and he promoted a great environment for becoming acclimated to this process. Even if some of my work was a late scratch from the MONTE 46 transition presentation, it feels good to know that my contributions were originally considered. I've come to realize that doing exactly what I want to do on an internship is very rare, and I've definitely cherished the last ten weeks working under him as part of the MRO Navigation Team. His actions are greatly appreciated.

Eric Graat and Stuart Demcak are also deserving of individual recognition for all of their help while I was learning the orbit determination process. The system is very complex, but with their help I was able to get up to speed for the most part within the first half of the summer and produce some results. They are both very busy people, but they handled my barrage of questions and were invaluable assets when dealing with my MONTE growing pains (even though they may not think they were that helpful!).

Finally, I would like to thank the rest of the MRO Navigation Team. At one point in the summer I was glaring over each of their shoulders and bugging them with questions while they tried to go about their jobs. Their patience during this whole process has encouraged me to ask more questions (probably to their dismay) and obtain a better understanding. More importantly, they took me in and made me feel like part of the team. That means a lot to interns, has made this summer much more enjoyable, and will not soon be forgotten.

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Bibliography

[1] Thornton, C. L., and J. S. Border. *Radiometric Tracking Techniques for Deep-Space Navigation*. Pasadena: California Institute of Technology, 2000.

[2] You, T. H., et al. *Mars Reconnaissance Orbiter Navigation Plan (Revision B)*. Pasadena: California Institute of Technology, 2005.