AAS 02-164

THE EFFECT OF USO STABILITY ON ONE-WAY DOPPLER NAVIGATION OF THE MARS RECONNAISSANCE ORBITER

Dolan E. Highsmith

This paper provides a summary of a study to assess the effect of the stability of the ultra-stable oscillator (USO) on board MRO (Mars '05) on navigation accuracy when using one-way Doppler to the Deep Space Network. Subject to the assumptions of the covariance analysis, the results indicate that an oscillator with 1×10^{-12} short-term stability would provide navigation performance sufficient to meet the ephemeris requirements, but a 1×10^{-13} oscillator would ensure minimal loss of performance versus the nominal two-way Doppler.

INTRODUCTION

A key navigation capability of the Mars Reconnaissance Orbiter (MRO), the NASA mission to Mars to be launched in 2005, will be one-way Doppler transmission driven by an ultra-stable oscillator (USO). The one-way Doppler navigation functionality becomes a critical asset in the 2007 to 2008 time frame when the Deep Space Network (DSN) will experience a veritable traffic jam of vehicles at Mars. To highlight, missions being launched to Mars in 2007 include the CNES orbiter and Netlanders, ASI/NASA Marconi orbiter, and possibly NASA Scout missions. MRO will still be in its primary mapping mission in '07, and Mars Odyssey ('01) and Mars Express ('03) could still be active in extended missions. In addition to the Mars missions, there are other deep space missions that overlap with the Mars view periods, such as Cassini, Chandra, STEREO, MESSENGER, and the Europa orbiter [1].

Figure 1 from the DSN forecast (Ref. [1]) depicts the difference between DSN coverage requested by the MRO project and the coverage availability projected by the DSN, accounting for the overlap of the aforementioned missions. Clearly, there will be a need during the '07-'08 time frame to maintain MRO science mission performance while sharing DSN uplink time. Given the likely dearth of two-way communications to MRO during those periods, multiple spacecraft per aperture (MSPA) tracking provides a potential solution for maintaining navigation accuracy. Through MSPA tracking, the DSN can receive signals from multiple satellites on a single antenna while uplinking to only one of the satellites. To generate a highly-stable frequency on board for one-way navigation, MRO must have a USO. Through covariance analysis, this study assesses the effect of various oscillator stabilities on MRO navigation performance when assuming one-way Doppler tracking.

MISSION OVERVIEW

MRO will include a suite of five primary science instruments, including a high-resolution imager, context imager, shallow sub-surface radar, spectrometer, and climate

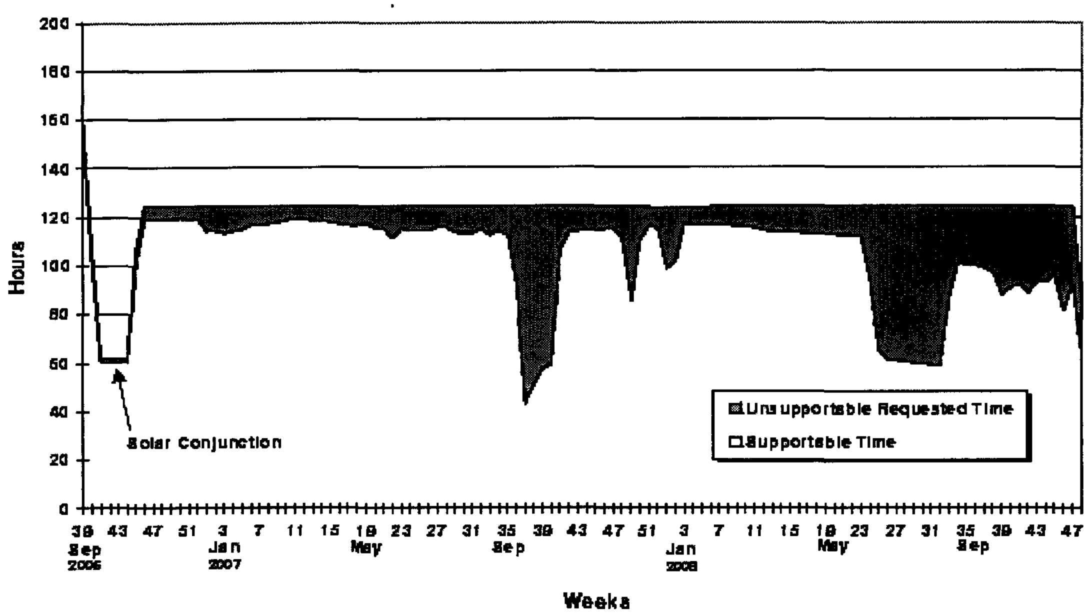

Figure 1: Requested versus projected DSN coverage for MRO primary science orbit phase. The significant dips in projected coverage are due to 2007 Mars launches and their arrivals in 2008. Note that these estimates include the launch of the NASA Smart Lander in 2007 (now 2009), so the DSN burden depicted is conservative [1].

sounder. In addition, the MRO spacecraft will include a targeting capability to allow crosstrack pointing to 30 deg off-nadir. The unique navigation aspect of this mission is that MRO will fly in a 200 × 400 km, sun-synchronous orbit, rather than the customary 400 km frozen, sun-synchronous orbit inhabited by Mars Global Surveyor (MGS) and Mars Odyssey (and planned for the ill-fated Mars Observer and Mars Climate Orbiter). The change is due to the desire by scientists for low-periapsis opportunities to obtain ultra-high resolution imagery (25 cm/pixel at 200 km) for identification of potential landing sites, as well as for a closer look at the geology (*areology?*) of Mars.

The baseline primary science orbit is designed with an apsidal rotation approximately every 64 days to allow global low-altitude viewing opportunities over the course of the primary science phase of one Mars year. The particular behavior of the altitude of periapsis and apoapsis is plotted in Figure 2. The figure shows that the periapses altitudes vary from about 200 to 260 km (with the lowest altitudes always in the southern hemisphere). With respect to navigation, the low altitudes present a new challenge for Mars spacecraft orbit determination: accounting for atmospheric drag above aerobraking regimes. Current conventional wisdom is that the atmospheric density can change randomly on a per-rev basis by as much as a factor of two. Given that assumption, atmospheric drag by far dominates the orbit prediction errors for the 200 × 400 orbit. Therefore, it is especially important for MRO to have the best possible reconstructed orbit solutions in order to provide the most accurate starting point for prediction.

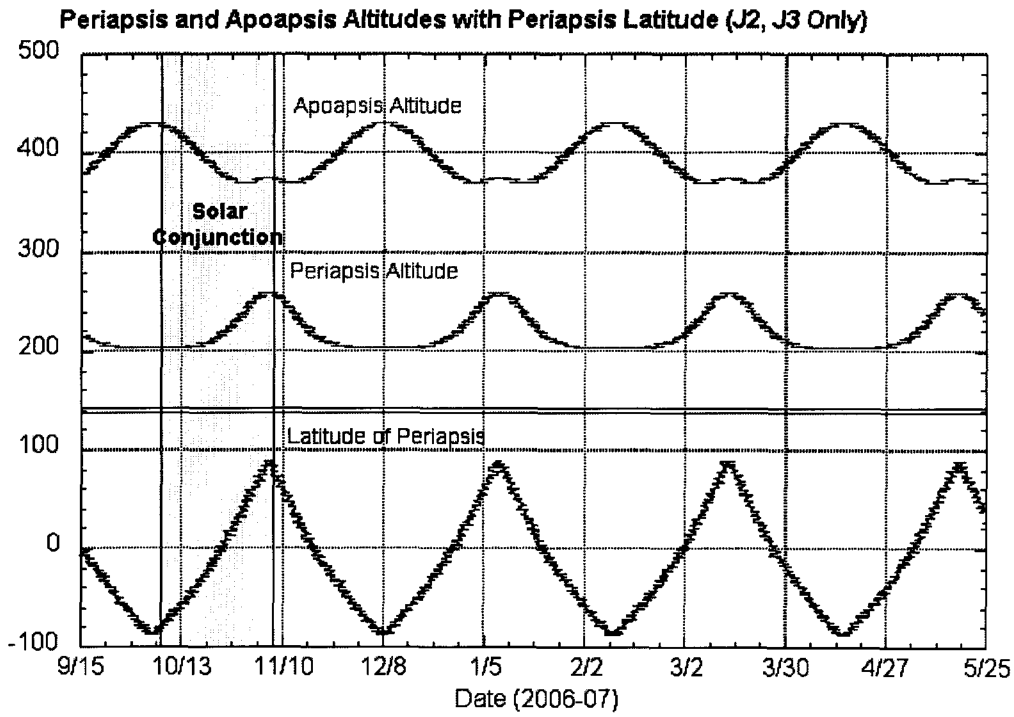

Figure 2: MRO periapsis and apoapsis altitudes and periapsis latitudes derived using J2 and J3 terms only [2]. Notice that the lowest periapses are always in the southern hemisphere.

The MRO ephemeris requirements are given in Table 1. Due to the demands of a targeted mission, these requirements are more stringent than for previous Mars missions. Mars Odyssey, for example, has 3σ prediction requirements of 10 km radial, 20 km downtrack, and 10 km crosstrack [3]. The following sections describe the investigation into the capability to meet the reconstruction requirements with one-way Doppler solutions, while keeping in mind the desire to minimize reconstruction errors for the purposes of prediction.

Table 1:
PREDICTION AND RECONSTRUCTION REQUIREMENTS

	Radial (km)	Downtrack (km)	Crosstrack(km)
7-Day Prediction	0.04	1.50	0.05
Reconstruction	0.01	0.30	0.04

Table 2:
REFERENCE TRAJECTORY INITIAL CONDITIONS

$a = 3683.588$ km	$e = 0.02827$	$i = 92.764$ deg
$\omega = 278.627$ deg	$\Omega = 65.024$ deg	$M = 20.069$ deg
t_0 = December 9, 2006 10:00:00 ET		
S/C Mass = 1000 kg	S/C Area = 37.7 m^2	

REFERENCE TRAJECTORY

The reference trajectory initial conditions with osculating elements are specified in Table 2. Referring to Figure 2, the arc is chosen to occur near the minimum periapsis altitude and maximum apoapsis altitude in early December 2006. The lowest periapsis is chosen as a stressing case for the magnitude of atmospheric drag.

The trajectory is integrated with the JPL Double Precision Trajectory Program (DPTRAJ) [4]. The primary dynamic model inputs include the Mars Global Reference Atmospheric Model 2000 (Mars-GRAM 2000), the MGS75D gravity field, solar radiation pressure (SRP), and angular momentum desaturations (AMD). Mars-GRAM 2000 is a global atmospheric model that uses a modified Stewart-type thermosphere model for altitudes above 170 km [5]. The spacecraft mass and area shown in Table 2 produce a ballistic coefficient of 13.3 kg/m^2, assuming $C_d = 2.0$. The 37.7 m^2 represents the area for aerobraking drag passes, but it is used in this analysis as a potential stressing orientation. Likewise, the SRP model acts on the 37.7 m^2 area. (In this preliminary covariance analysis, the spacecraft is modeled as a sphere, so the same area is presented to drag and SRP.) The MGS75D gravity field is a full 75th degree and order model based upon DSN radiometric tracking data from Mariner 9, Viking 1 and 2 orbiters, and MGS [6]. Finally, small forces with zero magnitude are included in the trajectory at discrete intervals in order to simulate the occurance of AMD events. The size (or lack thereof) of the AMDs in the reference trajectory is not important because the filter analysis accounts for the *uncertainty* associated with each event.

COVARIANCE ANALYSIS

The covariance analysis approach uses an OASIS-heritage software suite called LEXUS to identify the relevant partial derivatives of the reference trajectory from DPTRAJ and evaluate the effect of uncertainties in estimated and considered parameters (listed in Table 3). Notable assumptions listed in Table 3 include AMD uncertainty and frequency, atmospheric drag uncertainty, gravity errors, and spacecraft clock drift.

The desaturation maneuvers are designed to have much smaller errors and to occur less frequently than on previous missions. On MGS, for example, AMDs are the dominant orbit error source [7]. Hence, MRO mission designers and navigators required a "quieter" spacecraft in order to realize the tighter navigation performance requirements.

The uncertainty in the drag acceleration is due to poorly known and potentially highly variable atmospheric density. For the purposes of the covariance analysis, this un-

Table 3:
COVARIANCE ANALYSIS A PRIORI ASSUMPTIONS

Measurement Types	Noise (1σ)
Doppler	0.1 mm/s
Range	Not used
Estimated Parameters	**Initial Uncertainty (1σ)**
Position	10 km
Velocity	1 m/s
Angular Momentum Desats (AMD)	0.1 mm/s spherical every 48 hr
Atmospheric Drag (C_d)	100% init., 35% per rev stochastic
Outgassing	1×10^{-13} km/s^2
S/C Clock Drift (1-way cases only)	$\sigma_y = 1 \times 10^{-13}/10^{-12}/10^{-11}/10^{-10}$
Considered Parameters	**Uncertainty (1σ)**
Gravity	$3\times$ subset of MGS75D formal errors
Solar Coefficient	10%
UT1-UTC	0.35 ms
X & Y Pole Motion	15 nrad
Wet Troposphere (zenith)	2 cm
Dry Troposphere (zenith)	2 cm
Ionosphere (zenith)	0.278×10^{17} elec/m^2
DSN Station, Dist. Spin Axis	10 cm
DSN Station, Longitude	16 nrad
DSN Station, Z	10 cm
Planetary Ephemeris	DE405+ covariance
GM	0.008581 km^3/s^2 (MGS75C value)

certainty is accounted for in the drag coefficient term C_d. The resulting uncertainty in the drag acceleration is the same as if the uncertain parameter were density because the acceleration is formed by the equation $a_{drag} = \rho V^2 C_d A/2m$, where ρ represents density, V is the spacecraft velocity, A is the surface area presented to the flow, and m is the spacecraft mass. The 1σ 35% per rev stochastic white noise on the drag accounts for the effect of a time-varying, random change in density between each periapsis pass that could result in a change in density by as much as a factor of two (a 3σ case).

Table 3 shows that gravity terms are considered. Considered parameters are not estimated, but the effect of their uncertainties on the trajectory is computed in a sensitivity matrix. The total error covariance is then the sum of the sensitivity matrix and the filter covariance for estimated parameters. Gravity is considered under the presumption that the solution to the gravity field is optimized, such that further estimation for relatively short arcs is unnecessary.

The full 75×75 gravity field, however, is not considered. In order to keep the number of terms manageable in the software, Kaula's method (see Ref. [8]) is used to identify the most significant perturbation terms for the 75×75 field given mean elements for MRO. The reduced set includes 108 terms, including all the zonals. To be conservative, the subset of MGS75D formal errors is increased by a factor of three. It should be noted that GM is considered separately from the gravity field, where the apriori uncertainty listed in Table 3 is conservatively estimated at the MGS75C formal error value.

For the one-way Doppler cases, the spacecraft clock drift is estimated as a random walk dynamic stochastic with short-term Allan deviation stabilities $\sigma_y(\tau = 60\,\text{sec})$ ranging from 1×10^{-13} up to 1×10^{-10}. The stochastic update rate is set to 60 sec in order to match the Doppler measurement interval. Note that the Doppler noise value listed in Table 3 remains the same because the deleterious effect of spacecraft oscillator drift on one-way Doppler is handled separately as an estimated parameter.

Given the a priori assumptions listed in Table 3, the total covariance for a reconstructed fit is determined by forward filtering and backward smoothing. The nominal case is a two-day fit assuming two eight-hour DSN passes per day. Three-day fits are also computed for the noisiest cases to assess clock noise reduction with longer data arcs.

RESULTS

Covariance results for the smoothed two- and three-day fits are shown in Figures 3-5, depicting the radial, alongtrack, and crosstrack 3σ errors, respectively. In the figures, one-way Doppler cases with the four oscillator stabilities listed in Table 3 are compared to the nominal 2-way Doppler case and the MRO ephemeris reconstruction requirements listed in Table 1. Note that the more accurate cases in the radial and downtrack figures (Figures 3 and 4) show an increase in error during an eight-hour period surrounding Day 1 that is due to a DSN tracking gap.

In all cases, the oscillator noise dominates the errors for the 1×10^{-11} and 1×10^{-10} cases. Not one of the 1×10^{-10} cases meets the requirements in any direction. The 1×10^{-11} two-day fit meets the requirement only in the downtrack direction, and the three-day fit does not improve the performance enough in the radial and crosstrack directions. Fitting the 1×10^{-11} data over longer arcs may provide enough noise reduction to meet the requirements in all directions. However, fitting very long arcs may be operationally cumbersome, especially given the likelihood of frequent drag make-up maneuvers in the MRO orbit. A more likely scenario is the mixture of two-way and one-way Doppler for a given fit span. The proper proportion of each is the subject of a future study.

Figures 3-5 show that the one-way cases with 1×10^{-12} and 1×10^{-13} stability meet the MRO reconstruction requirements in all three directions. The 1×10^{-13} case, in particular, approaches the performance floor defined by the two-way case. In Figure 3, the two-way radial errors are held up by GM uncertainty at about 0.7 m, with drag and gravity errors dominating during the tracking gap. In Figures 4 and 5, the two-way downtrack and crosstrack errors are held up by gravity to approximately 20 m in both cases. Once MRO has been on orbit for a while, updated solutions to the gravity field from the new 200×400 km orbit should improve the two-way and 1×10^{-13} one-way performance.

To illustrate, another set of analyses were performed using $1\times$ the MGS75D formal errors for the gravity and GM. Only the 2-way case and one-way cases with 1×10^{-12} and 1×10^{-13} stabilities are evaluated. Recall from Table 3 that the initial analysis used $3\times$

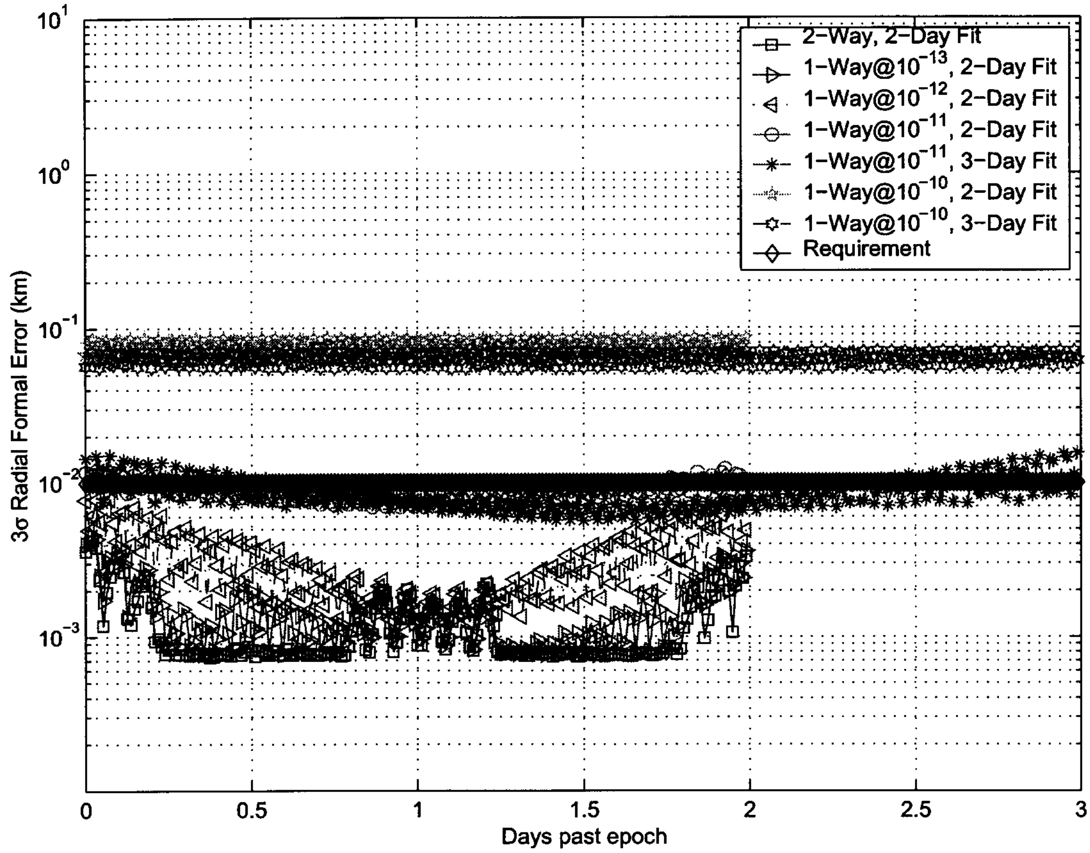

Figure 3: Smoothed 3σ radial formal errors for two- or three-day reconstructions. The MRO reconstruction requirement of 0.01 km is also indicated.

the MGS75D formal errors and the GM uncertainty from the MGS75*C* field. Reducing the gravity and GM uncertainties to the nominal MGS75D values, where $\sigma_{GM} = 0.0008$, results in the 3σ errors shown in Figure 6. The order of magnitude improvement in GM uncertainty dramatically improves the radial errors for the two-way case, and further distinguishes the differences in performance between one-way and two-way. Likewise, the factor of three improvement in gravity uncertainty results in reduced errors in the downtrack and crosstrack directions. For example, comparison of the downtrack plots in Figures 4 and 6 shows that the 2-way and 1×10^{-13} one-way errors improved by approximately a factor of three (20 m to 7 m), while the 1×10^{-12} one-way errors improved by approximately a factor of two (30 m to 15 m).

Therefore, under the assumption of improvement in the knowledge of the gravity field, Figure 6 shows that a USO with 1×10^{-13} short-term stability can still achieve one-way navigation performance similar to two-way in the downtrack and crosstrack directions. The clock noise does, however, show up in the radial errors, with about a 50 cm error compared to 15 cm for two-way. Figure 6 also shows a more significant increase in reconstruction errors

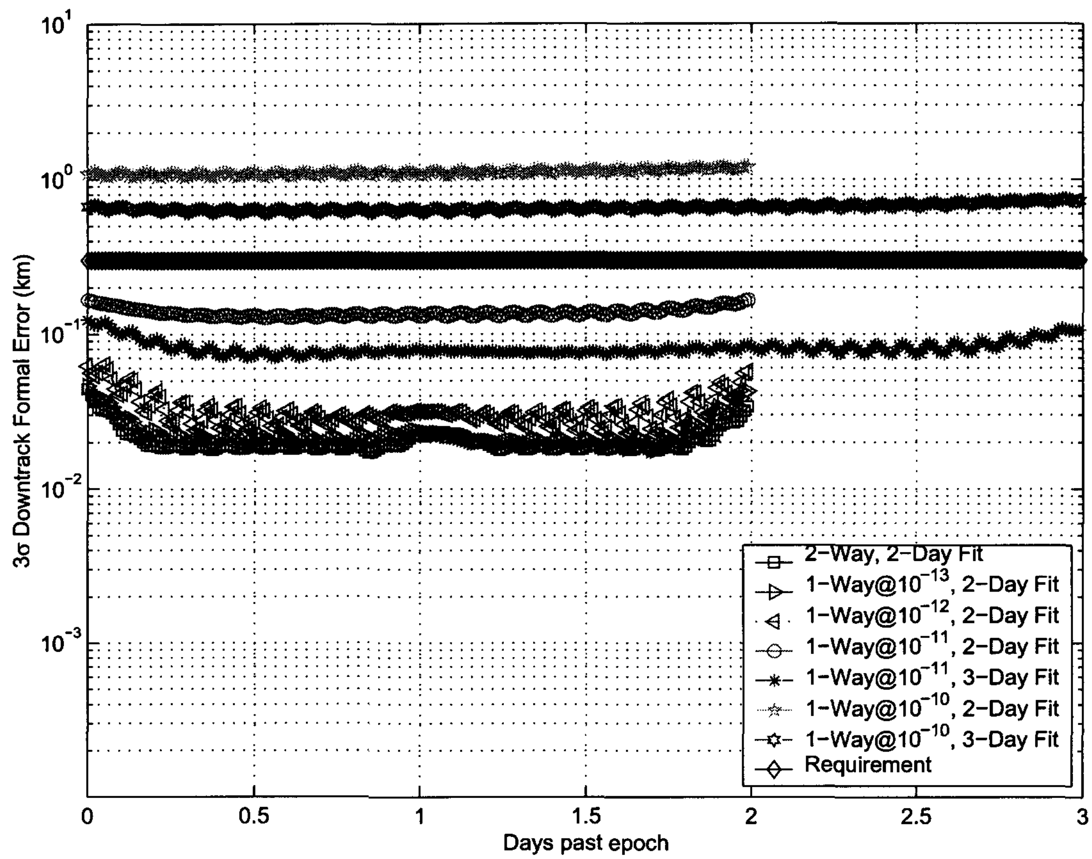

Figure 4: Smoothed 3σ downtrack formal errors for two- or three-day reconstructions. The MRO reconstruction requirement of 0.3 km is also indicated.

for the 1×10^{-12} case versus the nominal two-way performance. Such differences become amplified when these reconstructed solutions are used to initialize a predicted trajectory. This is generally true, however, only for the first several days of prediction. By the end of a one-week prediction, the 35% stochastic uncertainty in atmospheric drag dominates all error sources, including initial condition offsets. Prediction results are not presented here because the Mars-GRAM density model at orbital altitudes is under question and is currently being validated with Mars Odyssey flight data. The fact remains, though, that reconstructed orbits with the smallest errors will produce better overall predictions.

CONCLUSIONS

A targeted mission in a new, more dynamic orbit than its predecessors, MRO provides a challenging navigation opportunity under the best conditions. When faced with multiple spacecraft per aperture tracking, the use of one-way Doppler tracking adds another significant error source to the orbit determination process. This analysis has shown

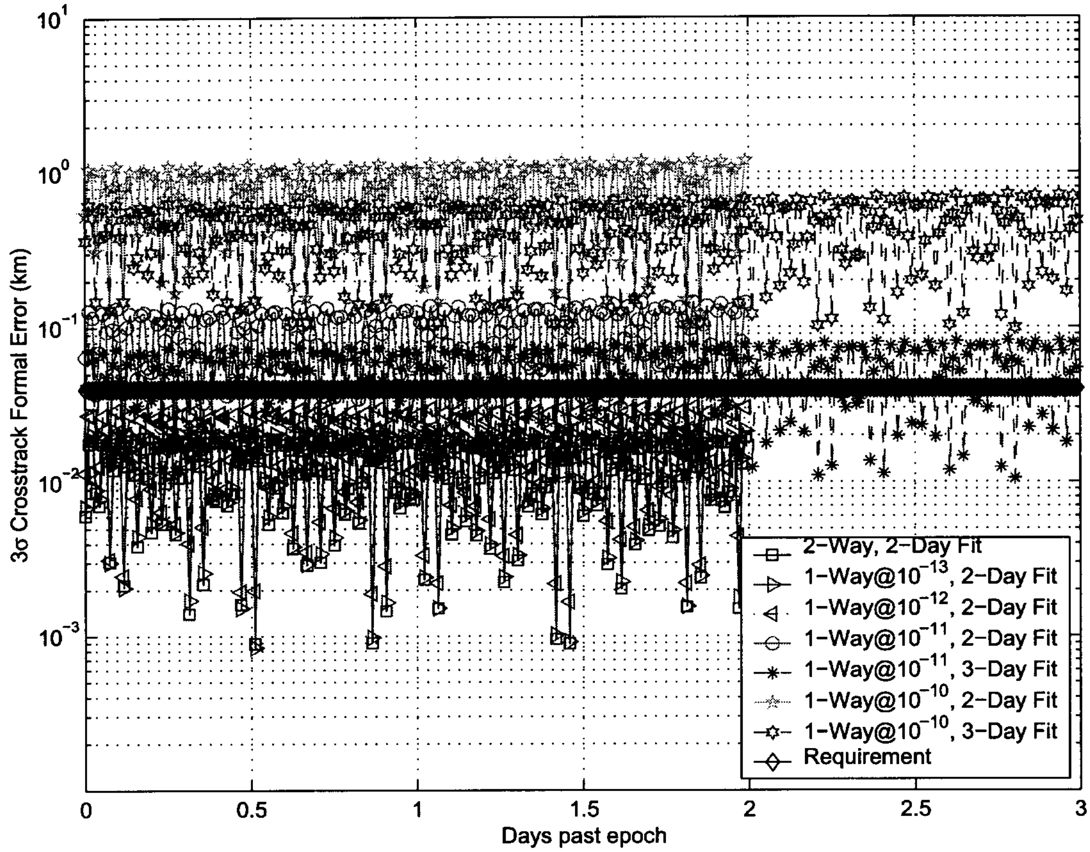

Figure 5: Smoothed 3σ crosstrack formal errors for two- or three-day reconstructions. The MRO reconstruction requirement of 0.04 km is also indicated.

that a USO with a short-term stability of 1×10^{-12} is the minimum required to meet the MRO reconstruction requirements during times of one-way tracking only. However, a 1×10^{-13} stability or better oscillator would be more desirable in order to maximize the one-way navigation accuracy for the purposes of both reconstruction and prediction.

ACKNOWLEDGEMENTS

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The author would like to acknowledge the contributions of Joe Guinn, Todd Ely, Shyam Bhaskaran, and the MRO Mission and Navigation Design Team at JPL.

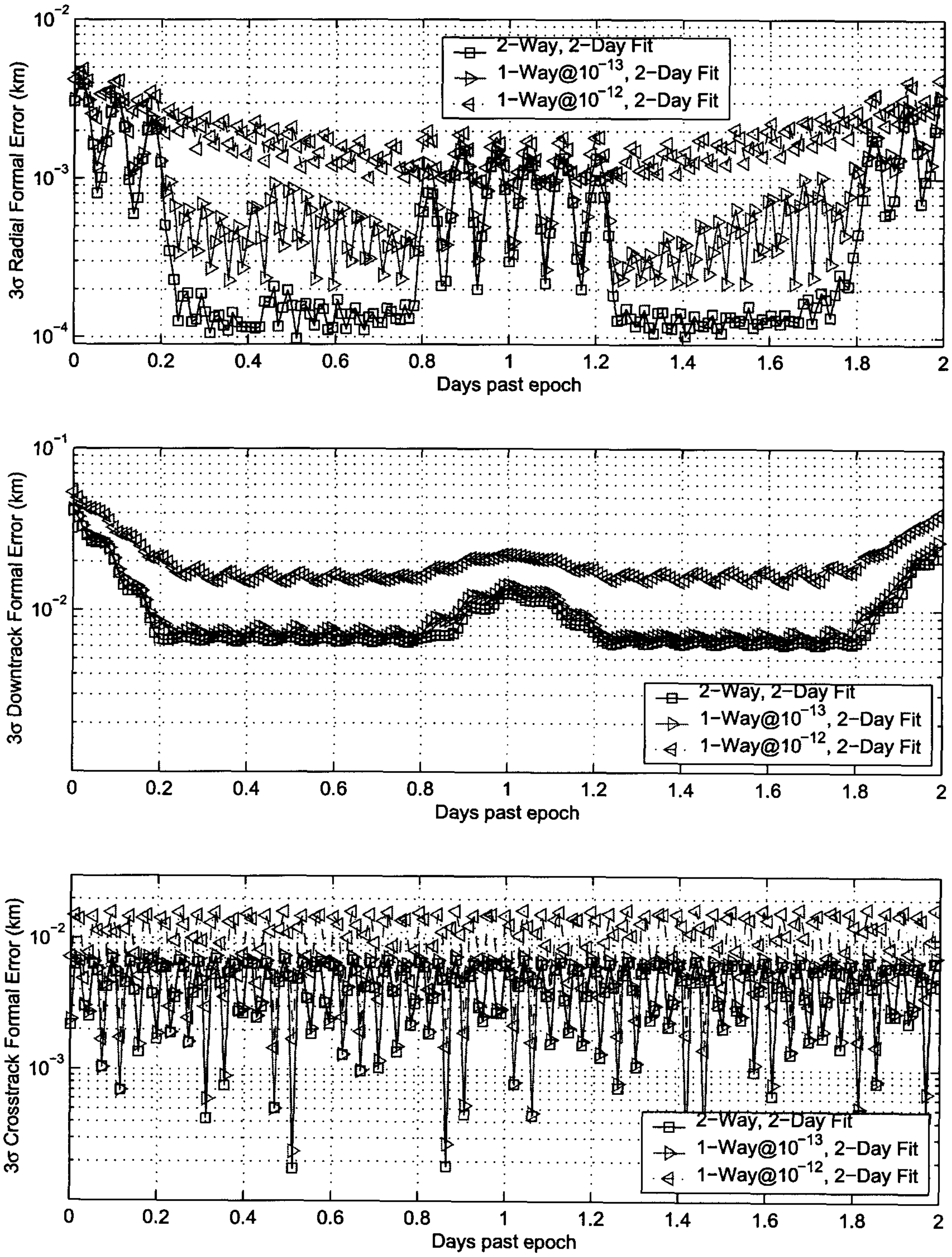

Figure 6: Smoothed 3σ formal errors for two-day reconstructions using $1\times$ MGS75D formal covariances for gravity and GM.

REFERENCES

[1] S. Lineaweaver, "Mars Reconnaissance Orbiter 2005 Support Evaluation," JPL Interoffice Memorandum, SL:368-1101-002, Jet Propulsion Laboratory, Pasadena, CA, November 12, 2001.

[2] R. Lock and P. Xaypraseuth, "Mars Reconnaissance Orbiter Project Mission Plan: PMSR Release," JPL D-22239 (JPL internal document), Jet Propulsion Laboratory, Pasadena, CA, January 2002.

[3] R. A. Mase, "2001 Mars Odyssey Navigation Plan and Trajectory Characteristics," JPL D-16001 (JPL internal document), Jet Propulsion Laboratory, Pasadena, CA, March 2001.

[4] *DPTRAJ/ODP User's Reference Manual, Volume 1*, JPL D-18671 (JPL internal document), Jet Propulsion Laboratory, Pasadena, CA, March 22, 1996.

[5] C. G. Justus and B. F. James, "Mars Global Reference Atmospheric Model 2000 Version (Mars-GRAM 2000): Users Guide," NASA/TM-2000-210279, National Aeronautics and Space Administration, Marshall Space Flight Center, AL, May 2000.

[6] D. Yuan, W. L. Sjogren, A. S. Konopliv, and A. B. Kucinskas, "Gravity Field of Mars: A 75th Degree and Order Model," *Journal of Geophysical Research*, Vol. 106, No. E10, pp. 23,377-23,401, October 25, 2001.

[7] S. Demcak, P. B. Esposito, D. Baird, and E. Graat, "Mars Global Surveyor Mapping Orbit Determination," Paper AAS 01-100, AAS/AIAA Space Flight Mechanics Meeting, Santa Barbara, CA, February 11-15, 2001.

[8] W. M. Kaula, *Theory of Satellite Geodesy*, Blaisdell Publishing Company, Waltham, MA, 1966.