Navigation Services of the Mars Network

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BIOGRAPHY

Dr. Todd Ely received his B.S.A.A.E. in 1986, M.S.A.A. in 1988, and Ph.D. in 1996 all from Purdue University. Dr. Ely is currently a senior engineer at the Jet Propulsion Laboratory in the Navigation and Mission Design Section where he works on the Mars Network and a variety of other technology development projects. He has been on the Mars Network project since its inception in 1999 conducting mission design and navigation studies, and formulating system requirements for the network's navigation services. Prior to JPL, he was a Visiting Assistant Professor at Purdue University, and an officer in the United States Air Force. Dr. Ely's published research is in astrodynamics, adaptive estimation, constellation design, and satellite navigation.

Joseph Guinn has been involved with tracking and navigation of planetary and Earth orbiting spacecraft for over 19 years at JPL. Most recently, he supervises the Inner Planet Navigation group that primarily provides development and operations support to NASA's Mars Exploration Program. He also has published works on autonomous navigation for Mars orbital rendezvous, entry, descent, and landing, and surface positioning.

Elizabeth Quintanilla is currently an academic part time employee within the EDL/Aero Applications Group in JPL's Navigation and Mission Design section. She started to investigate the orbit beacon navigation problem as part of graduate research at the University of Texas at Austin in summer of 2001 as a JPL technical co-op. She is currently finishing her Master's degree from UT-Austin while working at JPL. She is also a NSF fellow.

ABSTRACT

The Mars Network (MN) provides proximity based communications and navigation services to support Mars exploration. The network will be comprised of science orbiters with a MN relay transceiver, and, potentially, dedicated telecommunication orbiters. The common MN transceiver, called Electra, is currently in development, and is being designed for both communications and radiometric tracking.

MN navigation services will utilize Electra radiometric data to support surface asset positioning, approach navigation, orbit determination, and entry/descent/landing (EDL) trajectory determination. These services and the anticipated performance of the MN at providing them are discussed.

INTRODUCTION

The Mars Network (MN) provides Mars in-situ communication and navigation services to landed and space-based users at Mars. More on MN's communication services can be found in References [1], [2], and [3]. A fundamental component of the Network's navigation services include collection of radiometric tracking data on links between a Network asset and a user, which might include a Mar's surface asset, another orbiter, or an approaching/landing spacecraft. Initially, this data will be post-processed at Earth to determine positions or trajectories of user vehicles. Later, these services could be expanded to include in-situ processing because the Network is being built around a reconfigurable transceiver, called Electra, with its own processing unit.

Electra is currently in development and is being designed for dual use as a communication and radiometric tracking device. It will reside on MN elements and its users. The first MN element to carry Electra is the Mars Reconnaissance Orbiter (MRO) that will launch in 2005. MRO's will have a dual role as a science orbiter and as a Mars Network orbiter. In fact, each NASA Mars science orbiter launched after MRO will carry some version of the Electra transceiver and participate in the MN. Mars Exploration Program also has plans to place a dedicated communications and navigation satellite in orbit at Mars after 2009, called the Mars Telesat Orbiter (MTO).

The Electra design currently includes the ability to formulate and collect 1-Way and 2-Way coherent integrated carrier phase data (which can be converted into equivalent Doppler data). Another capability, useful for critical events or scenarios with very low signal-to-noise ratios (SNRs), is open loop recording of a selected frequency band. The recorded data is sent back to Earth for signal processing to extract phase and/or Doppler data. The reconstructed data is, by definition, 1-Way, and can be processed like other 1-Way radiometric data. Since Electra's radiometric tracking capabilities are implemented in software, it will be possible to add other radiometric tracking data types (such as ranging using a pseudo-noise sequence) in the future and update existing Electra transceivers already at Mars.

The navigation services that are supported by the Mars Network fall into several categories and include the following:

1. Position determination of a Mars lander or rover;
2. Trajectory determination of a Mars approaching spacecraft
3. Orbit determination of a Mars orbiting spacecraft;
4. Trajectory determination of a Mars landing spacecraft during its entry, descent, and landing.

Details of each of these services will be discussed with results from representative scenarios presented. The results are illustrative only, and are not meant to be construed as definitive for every possible scenario.

SURFACE ASSET POSITIONING

The Mars Network will accomplish position determination of surface assets on Mars using either 1-Way or 2-Way coherent Doppler data from the proximity link. In the 1-Way mode, one end of the link transmits and the other end tracks the received signal and collects the carrier phase data. Use of 2-Way data implies that one end of the link is using Electra as a coherent transponder– typically the surface asset, and the other end of link transmits and collects the data on reception. 2-Way data is the more accurate of the two types because it is formulated to minimize the impact of oscillator instabilities. These data can be augmented with direct-to-Earth (DTE) Doppler and range taken by the Deep Space Network (DSN) to any of the assets with a DTE capability. The combination of the proximity data and the DTE provides good observation geometry such that with 2-Way links it is possible to achieve position accuracies of 10 m (1-σ) or less.

The utility of 1-Way data is dependent on the quality of the oscillators that are used to transmit and to receive. That is, since 1-Way Doppler is based on frequency differences derived from two independent oscillators, their stability can be a significant error source. Oscillator stability is reported as an Allan deviation measured over a specified time, for 1-Way Doppler this is the Doppler count interval. In general, the Allan deviation at time T, $\sigma_A(T)$, measures the accumulated fractional frequency drift over that interval. It can be related to a range rate error as follows,

$$\sigma_{\dot{r}} = c\sqrt{\sigma_A(T)\big|^2_{\text{Transmitter}} + \sigma_A(T)\big|^2_{\text{Reciever}}} \qquad (1)$$

where c is the speed of light and the Allan deviations of the transmitter and receiver are RSS'ed.. Now, most missions use quartz crystal oscillators, and for drift times longer than tens of seconds, the Allan variance for quartz oscillators behave like a random walk, that is,

$$\sigma_A(\tau) = \sigma_A(T)\sqrt{\frac{\tau}{T}}, \qquad (2)$$

where τ is another time of interest. This is the error model used to represent oscillator instability in the subsequent simulations. Consider, the case of 1-Way Doppler taken on a 20 sec count interval with the oscillators at each of the link with a 10^{-9} Allan deviation. Using these values in Eq. (1) yields an error of 424 mm/sec. Compare this with a typical 2-Way Doppler error of 0.1 mm/sec. Clearly, 2-Way Doppler is more accurate; however it does require a more complex transceiver. For some small Scout missions this could be prohibitive.

The following three cases illustrate the performance of a Mars Network asset at providing positioning services to a surface asset under different tracking assumptions.

1. In the first case, MRO is in its primary science orbit (255 x 320k m, Sun-Synchronous) collecting 2-Way Doppler data to a lander located at 15° N, 160° E, or 1-Way Doppler where the lander has an oscillator with Allan Deviation statistics of 10^{-7}, 10^{-8}, 10^{-9} at a 20 sec count time. Tracking is allowed only during the daytime and the elevation angle cutoff has been set to 20°. Additionally, there is 2-Way Doppler tracking between MRO and the Goldstone DSN station.
2. The second case is same as the first except now the Mars Network orbiter is MTO in its baseline orbit (4450 x 4450 km,Su n-Synchronous).
3. The third case illustrates the benefit of near simultaneous tracking using 1-Way Doppler from both MRO and MTO to the lander. This case is similar to the first two except here the lander location has been changed to obtain overlapping viewperiods. The new location of the lander is at 19° N, 19° E. The lander's oscillator stability is 10^{-7} and each orbiter's oscillator stability is 10^{-12} at 20 seconds. All other assumptions for the scenario are the same as with cases 1 and 2.

It should be noted that the following high fidelity simulations include the effects of significant error sources that impact the orbit of MRO. However, they do not include some key error sources including the effects of multipath errors on the proximity link, and error in the time tag on the proximity data as compared to UTC. These two effects are currently under investigation. Multipath errors are being characterized in simulations and in experiments; the results of these tests will determine an appropriate model to apply to these covariance studies. Time tag errors have been investigated separately and position errors have been found to be relatively insensitive to time tag errors, as long as the navigation filter includes clock parameters in its estimation vector. Preliminary results suggest that the position accuracy can be maintained at levels below 10 m in the presence of time tag errors. Detailed results are forthcoming in a follow on paper.

Results for the first scenario are shown in Figure 1 for Case 1. At the bottom of the figure are time spans indicating tracking between the lander and MRO, and time spans for tracking between DSS 15 (Goldstone)a nd MRO. Note that in this 9 day period there are only 6 tracking passes between MRO and the lander, which typically last about 6 mins. Because of MRO's low altitude there is an example of a gap in tracking that lasts for over 3 days. For the case of 2-Way Doppler the position accuracy after 2 proximity passes yields an accuracy of better than 1 m. The results for the proximity 1-Way Doppler with the stability of the lander's oscillator indicated in the legend are significantly worse, indicating that oscillator quality is a key factor.

Results for Case 2 are shown in Figure 2. MTO is in view of the lander much more frequently than MRO, and the tracking passes are much longer, usually on the order of an hour. As before, the 2-Way performance is far

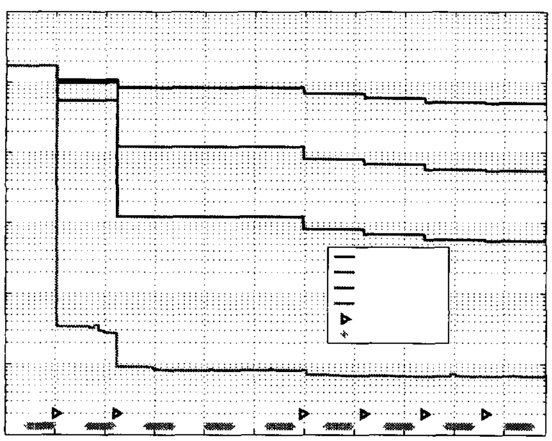

Figure 1: Case 1 results for MRO tracking the surface asset with either 1 Way Doppler (and various oscillator stabilities) or 2-Way Doppler.

superior to 1-Way with the indicated oscillator stabilities. Indeed, the 2-Way result is even better than MRO's. The 1-Way results, on the other hand, are worse. This is because MTO's smaller Doppler signature coupled with a longer period for oscillator instability to accumulate leads to less information in the 1-Way data as compared to MRO.

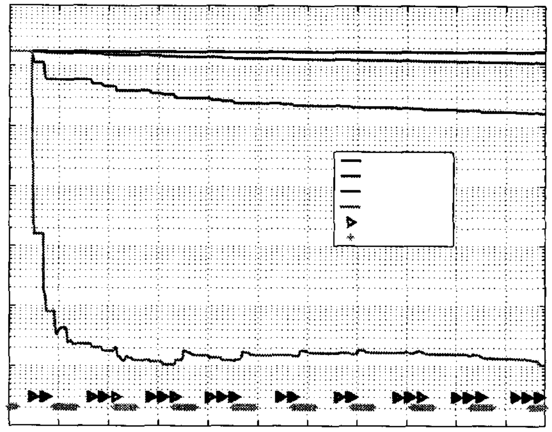

Figure 2: Case 2 results for MTO tracking the surface asset with either 1-Way Doppler (with various oscillator stabilities) or 2-Way Doppler

Case 3 results are shown in Figure 3. At the bottom of the figure are the tracking periods of the various links in the scenario (1-Way Doppler between lander and MRO, lander and MTO, 2-Way Doppler and range between MRO and DSN 15, MTO and DSN 15). Recall the results from Case 1, for a lander with a 10^{-7} oscillator the position accuracy reached about 5 km. In this case with MRO and MTO data, the position accuracy is a little over 400 m. This results stems from the fact that the two links are observing relatively the same frequency error transmitted from the surface, so the combination of the two pieces of Doppler data is sufficient to minimize the impact of this error.

In 2004 a demonstration of surface asset positioning at Mars usingp roximity Doppler data between the Mars Exploration Rovers (MER) and Mars Odyssey Orbiter will take place. Both MER and Odyssey will carry a precursor to Electra, a Cincinatti Electronics UHF transceiver that can collect Doppler data. Odyssey will track MER after landing in January 2004 with the goal of being able to determine MER's position to within 10 m after 3 Sols of tracking.[4] This will be a first ever demonstration of surface positioning at another planet (besides Earth) using proximity data.

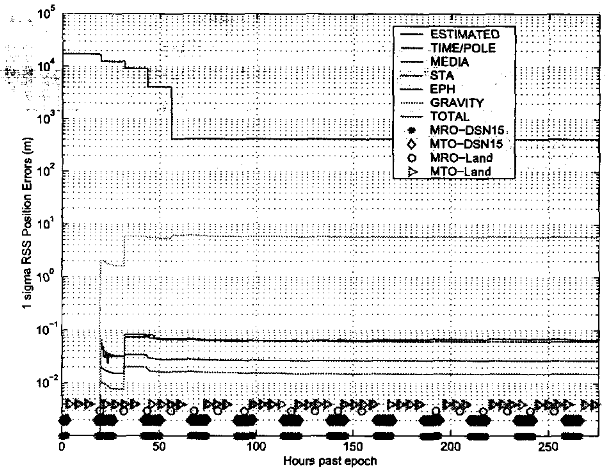

Figure 3: Case 3 results for MTO and MRO simultaneously tracking the surface asset with 1-Way Doppler.

APPROACH NAVIGATION

The Mars Network can aid with navigating a Mars approaching vehicle using 1-Way Doppler data between a MN asset and the other spacecraft. The MN observations can augment standard DTE Doppler and range data taken by the DSN in support of approach phase trajectory correction maneuver (TCM). The data can also be used for trajectory knowledge updates after the TCMs to support Mars lander entry guidance. In order to collect this data, Electra must have an optional 1-Way X-Band receive capability (referred to as the 'X-Band slice'). The X-Band configured Electra can be resident on either the network orbiter or the approaching vehicle. Currently, the X-Band slice is planned for the Electra transceiver that will be on MTO. Whichever vehicle is receiving the signal will, given sufficient signal power, lock onto it and take 1-Way carrier phase measurements. Using this link to formulate an observable requires both spacecraft to point their respective antennas towards each other (which could be either with gimbals or changing the attitude of the spacecraft). Doing so represents a significant operational activity that should be minimized so as to not interfere with the approaching spacecraft's DTE communications. Furthermore, both spacecraft need to use ultra stable oscillators (USO) that have Allan deviations of at least 10^{-12} at 60 seconds for the data to be useful requires. Once collected, the measurements are nominally transmitted back to Earth and processed with the DTE Doppler and range to update the trajectory.

The following results illustrate the performance of a Mars Network asset at providing approach navigation services given realistic assumptions on tracking capabilities (i.e., maximum ranges, short pass length, USO stability) and major error sources affecting approach vehicle trajectories (i.e., unmodelled nongravitational accelerations). The scenario uses a candidate approach trajectory that was at one time considered by the, now cancelled, CNES Premier orbiter mission. There is 30 days of tracking between the MN orbiter and Premier, corresponding to an initial slant range of 6.1 million km and a received signal power of −138 dBm given the link properties identified in Table 1. This is well within Electra's X-band carrier only acquisition and tracking threshold of −160 dBm.

Table 1: Approach Navigation Scenario Link Component Parameters

Link Hardware Component	*Power/Gain*
Transmitter Power on Orbiter	100W
Antenna Gain (3m dish) on the Orbiter	46 dB
Antenna Gain on Approach Vehicle	18 dB

The MN orbiter is in a 200 x 400 km altitude, Sun-synchronous orbit ($i = 92.9°$), at one time a candidate orbit for MRO. The baseline errors assumed represent standard values used by Mars missions (details can be found in Ref. [5]).

A practical issue pertaining to oscillator stability is that ultra stable oscillators are expensive. Thus, an important question to be addressed is what minimum stability is needed for the 1-Way Doppler to be useful at aiding approach navigation? The results compare approach navigation performance from the MRO orbit with different oscillator stabilities. These include Allan deviations of:

1. 10^{-11} at6 0 seconds. This is representative of the class of oscillator currently on Mars Odyssey,
2. 10^{-12} at6 0 seconds. This is representative of the class of oscillator currently being examined for use by MRO and MTO.
3. 10^{-13} at 60 seconds. This represents the current state of the art capability for quartz crystal oscillators. An oscillator of this quality is on the Mars Global Surveyor.

As already mentioned, collecting the 1-Way Doppler data requires a significant operational commitment for both the network orbiter and the approach vehicle. For a low altitude orbiter with a period of less than 2 hrs, collecting a 30 min pass of data once per day represents a realistic scenario. This is the baseline-tracking scenario for all the results using the MRO orbiter.

Figure 4 shows values for the semi-major axis (SMAA) of the entry B-plane error ellipse with the approach vehicle tracking MRO. Specifically, the cases, as indicated in the legend are,

1. The first case is the standard case with 2-Way Doppler and range tracking from three DSN stations (located at Canberra in Australia, Goldstone in California, and Madrid in Spain). There is no tracking from MRO.
2. The next three cases represent 1-Way Doppler tracking from MRO where the oscillator stability takes values of 10^{-11}, 10^{-12}, and 10^{-13}. Note that for each case, the identified oscillator stability applies to both MRO and the approaching vehicle. There is also 2-Way Doppler and range from DSN stations at Canberra and Goldstone.

Comparing the results for the 10^{-12} and 10^{-13} cases to the DSN only tracking case (the standard) show that MRO assisted approach navigation yields significant improvement in the knowledge of the approach trajectory. For instance, at 1 day prior to entry the DSN only case yields a 10.8 km value for SMAA, while both the 10^{-12} and 10^{-13} cases produce SMAAs smaller than 700 m. Also the 10^{-13} case performsco nsistently better than the 10^{-12} case for the entire simulation. Both cases indicate MRO assisted approach navigation could significantly reduce trajectory correction maneuver magnitudes, and improve the overall performance of Mars approach navigation. The results for the 10^{-11} case show that this data is not very useful at improving trajectory knowledge as compared to the DSN only case. There is some improvement in the last 2 days, but it is marginal and does not justify the operational and hardware costs associated with collecting this data. It is clear that for the approach data to be valuable, the minimum oscillator stability required on both the network orbiter and the approach vehicle is 10^{-12}.

The final set of results compare the performance of the MRO tracking (with a 10^{-12} oscillator stability) to tracking with doubly-differenced 1-way range (ΔDOR) and to optical navigation data taken from a camera on-board the approach vehicle. Since the unfortunate demise of the Mars Climate Orbiter and the Mars Polar Lander, ΔDOR has become a standard data type that is collected to augment DSN 2-Way Doppler and range. ΔDOR measurements provide information on the angular data of the approaching spacecraft relative to the tracking stations (i.e., "plane-of-sky" data). However, since it is a coordinated measurement from two DSN stations that can view the spacecraft at the same time, they are taken infrequently. In this scenario, one measurement is taken every other day. But, since plane-of-sky information augments line-of-sight information (range and range rate), this small amount of data is still very powerful at improving trajectory knowledge.

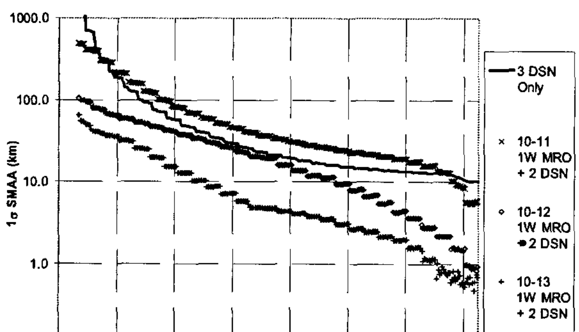

Figure 4: 1 sigma SMAA of the B-plane uncertainty ellipse for approach tracking from MRO with different oscillator stabilities.

The optical navigation (Op Nav) data are pictures taken of the Mars' satellites, Phobos and Deimos, taken on-board the approach spacecraft, and can be used to determine angular displacement of the approach vehicle relative to Mars.

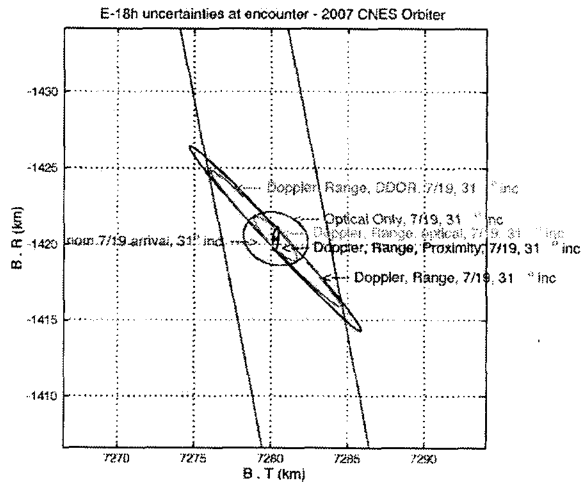

Figure 5: B-plane 1σ uncertainty ellipse for the approach spacecraft with the different tracking scenarios. The canted lines represent boundaries for achieving acceptable flight path angles for orbit insertion.

Note that both the ΔDOR and the Op Nav data are taken in the last 15 days prior to entry. Results comparing the B-plane uncertainty ellipses at 18 hours prior to orbit insertion between DSN Doppler and Range, DSN Doppler and Range and ΔDOR, DSN Doppler and Range and MRO 1-Way Doppler data (i.e., labeled 'proximity data') and Op Nav data (both with and without DSN data) are shown in Figure 5. The best performing case is the proximity case with MRO tracking (SMAA ~ 700 m). The next best case is Op Nav data with DSN Doppler and range (SMAA ~ 2 km).T he ΔDOR (with DSN Doppler and range) case produces a SMAA ~ 6.2 km. Finally, the DSN Doppler and range only case yields a SMAA of 8.2 km. The slanted lines represent the entry corridor for the

CNES orbiter to achieve its entry flight path angle constraint. All cases meet the requirements except the DSN Doppler and range only case. These results illustrate the significant improvements that MN aided approach navigation can have other measurement scenarios.

ENTRY, DESCENT, AND LANDING TRAJECTORY DETERMINATION

This is a critical event service that can be supported by the Mars Network provided that the network asset has been positioned to view the EDL event at the appropriate time. If so, it is envisioned that a 1-Way signal could be transmitted from the entry vehicle and tracked by the Mars Network asset. The data would then be sent back to Earth for post-processing to determine the entry trajectory. Another scenario could be to turn this link around where the entry vehicle could collect and process the 1-Way data in conjunction with its IMU data for its EDL navigation and guidance. Furthermore, provided a sufficient SNR, this data could be 2-Way rather than 1-Way, consequently improving the accuracy of the navigation results.

In this scenario a Mars Network orbiter is tracking a lander during its EDL phase with 1-Way Doppler data. The entry vehicle is on a ballistic trajectory (i.e., such as the Mars Exploration Rover) and the orbiter is in a typical 400 km altitude science orbit (i.e., such as MGS). The entire EDL event lasts for 5 mins and 20 secs and starts when the lander is at the top of the atmosphere (~ 127 km altitude). The magnitude of the initial uncertainty for the

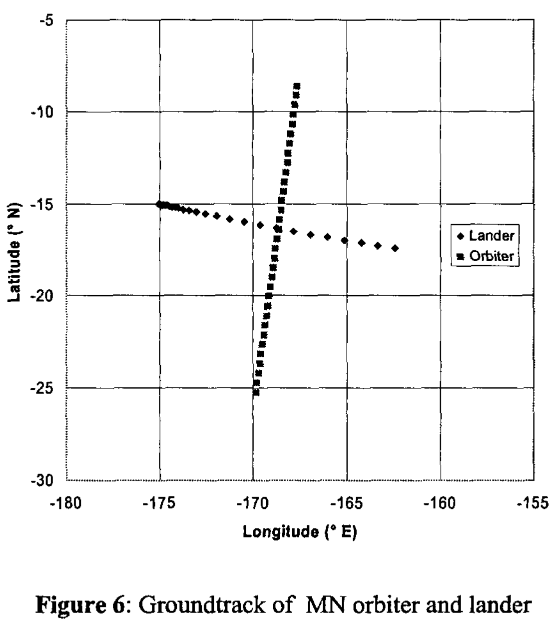

Figure 6: Groundtrack of MN orbiter and lander

lander is ~ 17 km, which is large compared to the typical delivery uncertainty that is based on DSN tracking with a data cut off a few hours prior to entry. A plot of the lander's and orbiter's groundtracks is shown in Figure 6. A plot of the altitude time history of the lander and orbiter is shown in Figure 7.

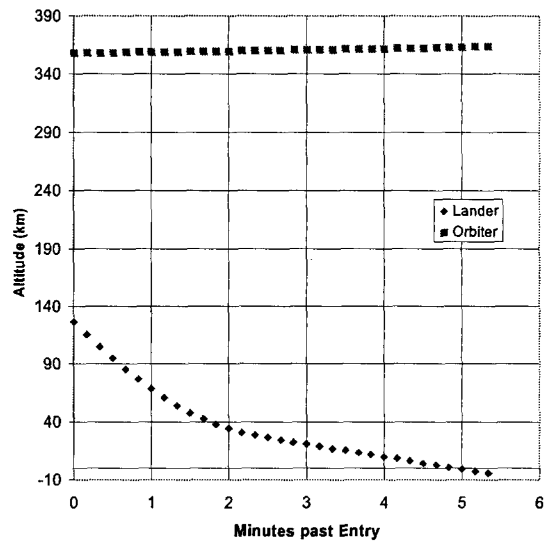

Figure 7: Altitude time history of MN orbiter and lander

The orbiter is tracking the lander for the entire event with data taken on 5 sec intervals, resulting in a total of 65 measurements. To illustrate the effect of the oscillator instability on the trajectory determination process the atmosphere density is assumed to perfectly known (the next set of results will include more realistic atmosphere model assumptions), the Allan Deviation on the lander's oscillator is set to various values including 10^{-6}, 10^{-7}, 10^{-9}, and 10^{-12} at 60 seconds. The magnitudes of the position uncertainties for the lander with these oscillators are shown in Figure 8. Also shown is the result of propagating the error when there are no measurements – at landing (t = 5 min, 20 sec) the error is around 95 km (1-σ). In all cases with data, the results improve knowledge ranging from 30 km for the 10^{-6} oscillator down to 4.6 km for the 10^{-12} oscillator. Note that the largest marginal improvement is made when going from the 10^{-6} oscillator to the 10^{-7} oscillator.

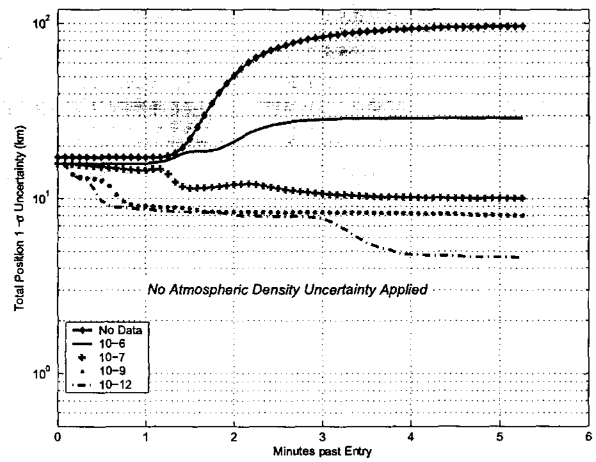

Figure 8: Lander 1-sigma total position uncertainty for different oscillator instabilities given perfect knowledge of the drag acceleration

Now compare these results when drag uncertainties are active, these results are shown in Figure 9. Note that the 10^{-6} case error grew to 43 km from the previous value of 30 km. Most noteworthy, is that a floor performance level of ~ 16 km is achieved with a 10^{-9} oscillator stability, where beyond this improvements in oscillator stability are overwhelmed by the additional uncertainty introduced by atmospheric drag.

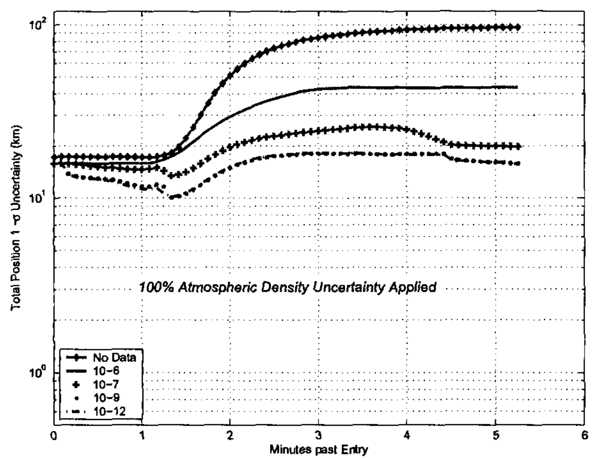

Figure 9: Lander 1-sigma total position uncertainty for different oscillator instabilities given 100% drag uncertainty

These results have been obtained using a generic scenario with large a priori uncertainties. Currently, these simulations are being updated to reflect specific delivery errors and uncertainties associated with the Mars Exploration Rovers. This simulation is in anticipation of a planned technical demonstration in 2004 where 1-Way UHF Doppler data will be collected by Mars Global Surveyor to MER during its EDL phase. This data will be telemetered back to Earth for MER EDL trajectory reconstruction.

ORBIT DETERMINATION

In this final case, the user is in orbit and one or several MN orbiter(s) participate in tracking the user vehicle. The specific scenario examined represents a technology demonstration to validate search and rendezvous with a small Orbital Sample (OS) representative of a future Mars Sample Return mission. During the early parts of the rendezvous demonstration the OS can transmit a carrier that can be tracked by MN assets and 1-Way Doppler can be collected for post processing back at Earth. The Doppler data is intended to serve as a redundant data type to the baseline optical navigation data.

The OS sample is in a 500 km circular orbit and the tracking vehicles include the rendezvous orbiter (RO) that carries Electra, and MTO. Figure 10 illustrates orbit determination (OD) results with 1-Way Doppler tracking from just the RO, and simultaneous tracking from the RO and MTO. The relative range between the RO and OS is shown in red. Initially the range is 300 km, which represents the intermediate phase of the rendezvous. Around 3 days in the simulation the RO passes underneath the OS and enters the terminal phase (a co-elliptic orbit around the OS). The different tracking cases illustrate OD sensitivity to oscillator stability. The simplest case is that of 1-Way Doppler between the RO with a 10^{-14} oscillator and the OS with a 10^{-7} oscillator. Not unexpectedly, the solution is poor with the error significantly larger than the range. This scenario indicates that a simple 1-Way link with a poor oscillator is not sufficient for rendezvous with the OS. On the other hand, if the OS oscillator is 10^{-14} (yielding data quality comparable to 2-Way Doppler), then the orbit error drops to 20 – 30 m during the terminal phase. The cases with simultaneous tracking fall between these two extremes. In the first example the oscillator stability on the RO and MTO are 10^{-10}, and results in orbit error that is commensurate with the range (a marginally usable scenario). In the second case the oscillators improve to 10^{-12}, and orbit error drops well below the range (except in the final day). The results illustrate the same phenomenon that was seen with simultaneous tracking of a surface asset; that simultaneity of the link minimizes the impact of a poor oscillator stability. The results also point to a threshold stability needed by the orbiters, namely 10^{-12}.

CONCLUSION

The Mars Network will be a significant and capable resource for navigating at Mars. The results show that, when using MN services, navigating at Mars is improved in most cases by orders of magnitude as compared to DTE

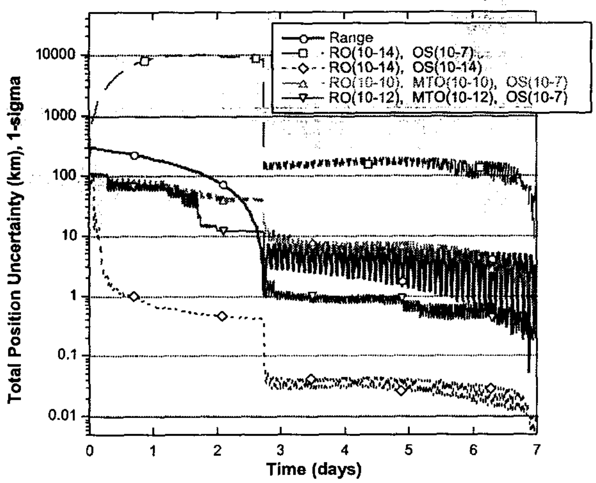

Figure 10: OS support with tracking from RO, or RO and MTO.

based navigation services. MN aided navigation increases mission robustness and safety. It is also enabling. For instance, entry guidance coupled with beacon navigation enables EDL to be "fly-by-wire" (i.e., closed loop trajectory guidance). It is anticipated that the next decade of Mars exploration will increasingly rely on the navigation services provided by the Mars Network.

ACKNOWLEDGMENTS

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