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Application of Noncoherent Doppler and Range Data for Mars Approach Navigation

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The use of noncoherent radio tracking data to perform position determination for the approach phase of a Mars lander mission is examined in light of recent improvements in spacecraft onboard clocks. Clock characteristics required to achieve tracking performance similar to coherent Doppler and range are discussed.

I. Introduction

The use of radiometric data from noncoherent (one-way) signal links for spacecraft position determination in place of coherent (two-way) data can simplify ground operations and provide better reception of spacecraft telemetry. The recent development of a space-capable, high-precision ion-clock [1] warrants the reconsideration of the use of one-way data for navigation. Navigation performance using noncoherent Doppler data was previously analyzed [2]. The current study shows that replacing the coherent Doppler and range tracking with noncoherent data for a hypothetical mission similar to Mars Science Laboratory (MSL) with an onboard Doppler reference oscillator similar to the ion space clock, along with current DSN ground capabilities, can meet mission navigation requirements.

The MSL mission plans to use a combination of coherent Doppler data, coherent range, and delta-differential one-way range (ΔDOR) to meet its cruise and Mars approach navigation requirements including a stringent entry requirement of a 0.2-deg (3-sigma) delivered entry flight path angle imposed by the complex entry, descent, and landing (EDL) scenario. The requirement implies long periods with continuous tracking for months prior to entry in which the use of one-way data could be an attractive option.

II. Launch, Cruise, and Arrival Geometry

Figure 1 shows a representative trajectory for MSL at the start of the 2009 launch opportunity showing expected Earth-to-spacecraft distance at launch and entry of 1.15 AU and 1.86 AU, respectively. There are five planned trajectory-correction maneuvers (TCMs) of

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magnitudes of 5.1 m/s, 0.8 m/s, 0.2 m/s, 0.1 m/s, and 0.04 m/s at times shown. A nominal entry flight path angle (EFPA) of –15.5 deg is used.

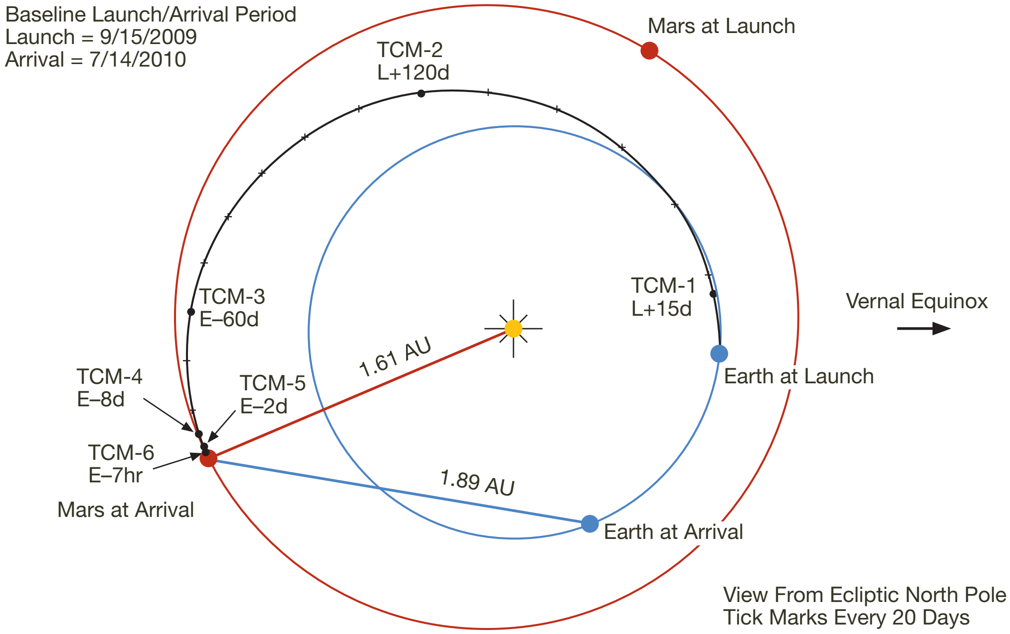

Figure 1. Launch and arrival geometry for 2009 Mars missions.

III. Orbit Determination Error Assumptions

This study uses the JPL's Double-Precision Trajectory/Orbit Determination Program (DPTRAJ/ODP) program suite, which uses parametric models of dynamic influences on a spacecraft trajectory and models radiometric data between the spacecraft and an Earth station. Partial derivatives of the model parameters with respect to the radiometric measurements are also computed and used to solve for model parameters, including the spacecraft state, and their errors by filtering a real or simulated observable set. For this study, the error sources modeled and their a priori uncertainties follow the MSL Preliminary Navigation Plan, where details can be found.[1] A synopsis of the error sources is given in Table 1.

IV. Tracking Data

The tracking data used for the baseline approach navigation study were a combination of two-way Doppler and range plus ΔDOR (an inherently one-way data type) with the frequency expected for a typical Martian cruise. This study follows the same tracking schedule substituting one-way Doppler and range. The tracking schedule reflects a presently typical tracking plan for a Mars lander mission and is shown in Table 2. During tracking passes, it is assumed that either two-way or one-way Doppler and range data are continuously col-

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[1] L. D'Amario et al., *Mars Science Laboratory Preliminary Navigation Plan*, JPL D-33445 (internal document), Jet Propulsion Laboratory, Pasadena, California, September 2006.

Table 1. A priori uncertainties of filter parameters.

Parameter	A priori Uncertainty	Correlation Time
Spacecraft state		
Position	1000 km	—
Velocity	1 km/s	—
Solar radiation pressure	5%	—
Unmodeled accelerations	3×10^{-12}	10 days
Maneuvers	5% of nominal + 2 mm/s	—
Spacecraft turns *	1 mm/s per axis	—
Station locations	~ 3 cm	—
Troposphere (wet/dry)	1 cm/1 cm	—
Ionosphere (day/night)	55 cm/15 cm	—
Earth orientation		
Pole X,Y **	1 cm	2 days
UT †	2 cm	2 days

* Spacecraft attitude control system (ACS) events expected once per week.
** Grows to 4 cm for predicted pole position after 2 days.
† Grows to 15 cm for predicted UT series after 6 days.

Table 2. Tracking schedule during launch, cruise, and Mars approach.

DSN Tracking Coverage	
Launch to L + 30 days	Continuous 34-m coverage
L + 30 days to E – 45 days	Three 34-m 8-hr passes per week
± 2 days about TCMs 2 and 3	Continuous 34-m coverage
E – 45 days to entry	Continuous 34-m coverage

lected, according to the case being discussed. In addition to Doppler and range data, simulated data include a few ΔDOR data near the times of TCMs, two points per week between 45 days (E–45d) and 28 days (E–28d) prior to entry and two points per day from E–28d to Mars entry. Statistics are generated for both cases including and excluding the ΔDOR data points.

One-way Doppler data noise resulting from reference clock short-term instability is approximately sqrt(2)$c\sigma(\tau)$ where $\sigma(\tau)$ is the Allen sigma (square root of the Allen variance) of the reference clock for count time τ [3]. One-way Doppler data noise values examined here are between 0.01 mm/s corresponding to a clock stability sigma of 2×10^{-14} at 60 s (a typical Doppler count time) and 0.5 mm/s corresponding to 1×10^{-12}. Note that there are other sources of noise-like error for a Doppler measurement such as space media, so the Doppler data precisions used here are slightly optimistic for clock stability sigma values better than 1×10^{-13}, especially. For reference, current Deep Space Network (DSN) two-way Doppler noise error can be as good as 0.03 mm/s. Two-way Doppler data noise of 0.1 mm/s was used in the MSL Navigation Plan and this study based on Mars Exploration Rover (MER) performance and expectations of solar activity. For the one-way Doppler data, in addition to the short-term noise error, a one-day clock drift is modeled as a random-walk bias parameter. Ten-hour Allen sigma values of 1×10^{-13} and 1×10^{-14} were examined for each case.

Currently, range data noise errors from sources other than reference clock dominate the short-term error, so the one-way study uses the same short-term data noise (3m) as the two-way case. The impact of the clock instability on one-way range data over a month is modeled by solving for a bias parameter with an a priori value equal to the accumulated clock error over that time (75 m for 1×10^{-13} s/s clock, 7.5 m for 1×10^{-14} s/s clock). It is assumed that there will be some two-way communication with the spacecraft at least monthly for commanding purposes that can be used to calibrate the spacecraft clock offset. Therefore, accumulated clock errors over periods longer than a month are not considered. For the stability values considered, no discernible impact in the approach navigation results was seen due to solving for the additional bias.

V. Results and Conclusions

For a lander mission, two statistics of particular interest are the entry state knowledge a few hours prior to entry and the entry flight path angle (EFPA) delivery error at the time of the last TCM, in this case TCM-5 at 2 days prior to entry (E–2d). Figure 2 shows the position knowledge uncertainty that can be expected using one-way tracking data given a reference clock stability value. Figure 3 shows the EFPA delivery error that can be expected using one-way tracking data given a reference clock stability value. Both figures show lines indicating the expected value using two-way data including and excluding ΔDOR data. While mission navigation requirements of 0.2 deg EFPA error and 2.8 km position knowledge uncertainty cannot be met without the inclusion of ΔDOR data, the results excluding ΔDOR are useful in comparing the performance of two-way Doppler and range with one-way Doppler and range.

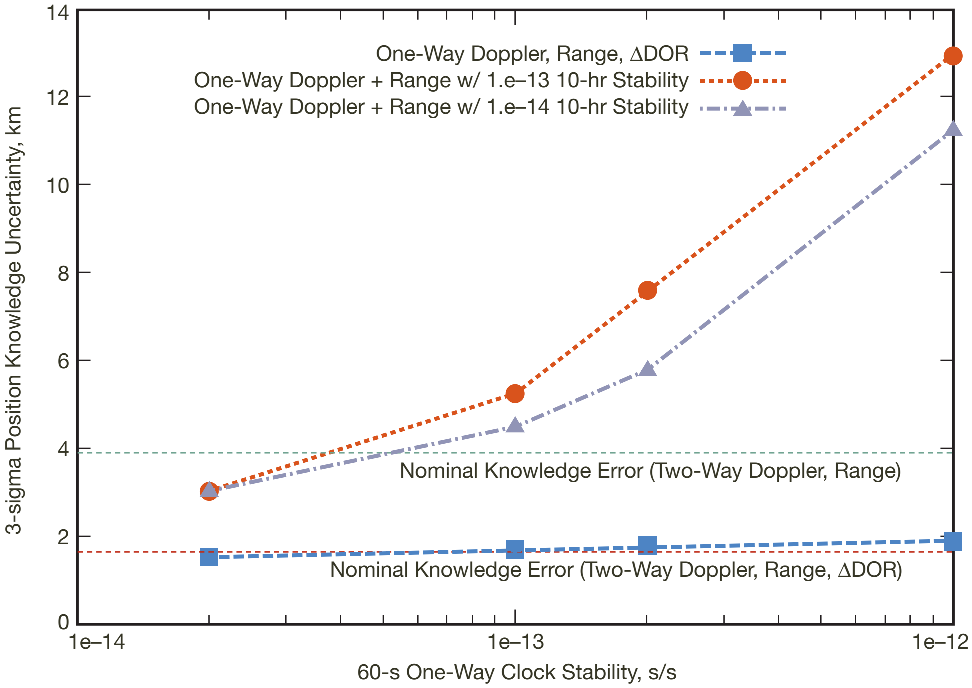

Figure 2. Position knowledge uncertainty at entry –6 hr as a function of one-way Doppler reference oscillator stability.

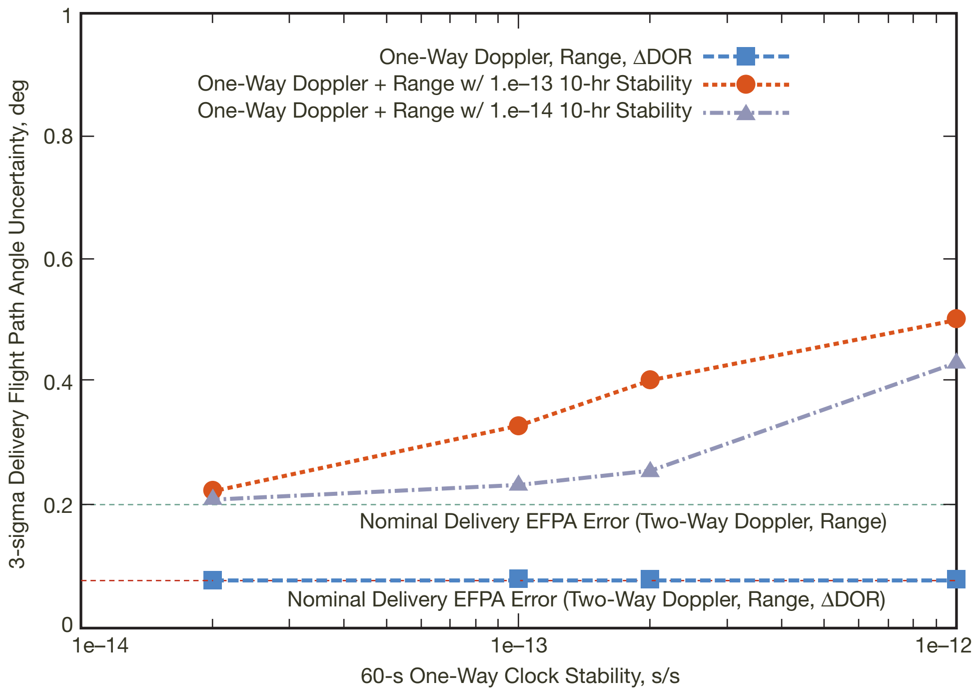

Figure 3. EFPA uncertainty for TCM-5 delivery (E–2.5 days) as a function of one-way Doppler reference oscillator stability.

Statistical results for an earlier last trajectory correction using either two-way or one-way data can often be of interest. Table 3 shows results of the delivery errors from both TCM-4 (E-8 days) and TCM-5 (E-2 days) data cutoffs. Both cases of Doppler and range combined with or without ΔDOR are shown. It can be readily seen that when ΔDOR data are used, with the dense scheduled that has been planned, Doppler precision does not influence the covariance results noticeably. The ΔDOR-free results show that noncoherent radiometric Doppler and range derived from a space clock with stability around 1×10^{-13} at 60 s and a longer-term stability better than 1×10^{-14} produces navigation results very comparable with those obtained with coherent radiometric Doppler and range.

Table 3. Approach navigation results for several data combinations.

Doppler Data Type	Two-Way	One-Way	One-Way	Two-Way	One-Way	One-Way	One-Way
Doppler Data Weight	0.1 mm/s	0.05 mm/s	0.5 mm/s	0.1 mm/s	0.05 mm/s	0.05 mm/s	0.5 mm/s
Clock 10-hr Stability	—	10^{-14} s/s	10^{-14} s/s	—	10^{-13} s/s	10^{-14} s/s	10^{-14} s/s
ΔDOR data used	Yes	Yes	Yes	No	No	No	No
TCM-4 Delivery (3σ) @ E– 8.5d:							
Flight Path Angle (3σ)	±0.21°	±0.21°	±0.21°	±0.32°	±0.43°	±0.35°	±0.62°
Position Knowledge @ E–6hr (3σ)	1.59 km	1.62 km	1.72 km	3.85 km	5.05 km	4.22 km	11.82 km
Velocity Knowledge @ E–6hr (3σ)	1.16 m/s	1.17 m/s	1.24 m/s	2.80 m/s	3.67 m/s	3.15 m/s	8.59 m/s
TCM-5 Delivery (3σ) @ E– 2.5d:							
Flight Path Angle (3σ)	±0.08°	±0.08°	±0.08°	±0.20°	±0.33°	±0.23°	±0.50°
Position Knowledge @ E–6hr (3σ)	1.66 km	1.73 km	1.90 km	3.91 km	5.24 km	4.49 km	12.94 km
Velocity Knowledge @ E–6hr (3σ)	1.21 m/s	1.26 m/s	1.37 m/s	2.84 m/s	3.81 m/s	3.26 m/s	9.41 m/s

References

[1] J. Prestage and G. Weaver, "Atomic Clocks and Oscillators for Deep-Space Navigation and Radio Science," *Proceedings of the IEEE*, vol. 95, no. 11, pp. 2235–2247, November 2007.

[2] S. Bhaskaran, "The Application of Noncoherent Doppler Data Types for Deep Space Navigation," *The Tracking and Data Acquisition Progress Report*, vol. 42-121, Jet Propulsion Laboratory, Pasadena, California, pp. 1–12, May 15, 1995.
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[3] Catherine L. Thornton and James S. Border, *Radiometric Tracking Techniques for Deep-Space Navigation*, Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO) Monograph 1 (JPL Publication 00-11), Jet Propulsion Laboratory, Pasadena, California, October 2000.