



## Reducing antenna mechanical noise in precision spacecraft tracking

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[1] Doppler tracking of deep space probes is central to spacecraft navigation and many radio science investigations. The most sensitive Doppler observations to date were taken using the NASA/JPL Deep Space Network antenna DSS 25 (a 34 m diameter beam-waveguide station instrumented with simultaneous X- and Ka-band uplink and tropospheric scintillation calibration equipment) tracking the Cassini spacecraft. Those observations achieved Doppler fractional frequency stability (Doppler frequency fluctuation divided by center frequency,  $\Delta f/f_0$ )  $\approx 3 \times 10^{-15}$  at 1000 s integration time. The leading noise in these very-high-sensitivity tracks was time-dependent unmodeled motion of the ground antenna's phase center (caused, e.g., by antenna sag as elevation angle changes, unmodeled subreflector motion, wind loading, bulk motion of the antenna as it rolled over irregularities in its azimuth ring, etc.). This antenna mechanical noise has seemed irreducible since it is not clear how to build a large, moving, steel structure with intrinsic mechanical stability better than that of current tracking stations. Here we show how intrinsic mechanical noise of a large tracking antenna can be suppressed when two-way Doppler tracking data and receive-only Doppler data from a stiffer antenna are combined with suitable delays. Using this time delay correction procedure, the mechanical noise in the final Doppler observable can be reduced to that of the stiffer antenna. We demonstrate proof-of-concept experimentally and briefly discuss some practical considerations.

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### 1. Introduction

[2] Precision Doppler tracking of deep space probes is used for spacecraft navigation and radio science. Examples of the latter include determinations of planetary masses and mass moments, measurements of planetary atmospheres/ionospheres/rings, studies of the solar wind, solar system tests of relativistic gravity, and searches for low-frequency gravitational radiation [e.g., Tyler *et al.*, 2001; Kliore *et al.*, 2004].

[3] Data quality for navigation and radio science is limited by noise in the Doppler system. Typical Doppler tracks at X-band ( $\approx 8.4$  GHz downlink) are limited by a

combination of plasma or tropospheric scintillation noise at  $\approx 1000$  s integration times [Woo and Armstrong, 1979; Keihm, 1995; Asmar *et al.*, 2005]. However, very high precision observations using a NASA Deep Space Network antenna and the Cassini spacecraft [Bertotti *et al.*, 2003; Armstrong *et al.*, 2003; Iess *et al.*, 2003; Tortora *et al.*, 2004] calibrated and largely removed these propagation noises. Those observations achieved fractional Doppler sensitivity (Doppler frequency fluctuation divided by radio center frequency) of  $\approx 3 \times 10^{-15}$  in 1000 s integrations. The leading residual noises in those high-precision two-way Doppler tracks were antenna mechanical noise, uncalibrated tropospheric scintillation, and frequency standard noise. The Allan deviations for these noises were  $\approx 2 \times 10^{-15}$  (antenna mechanical),  $\approx 1 \times 10^{-15}$  (residual tropospheric scintillation noise after water-vapor-radiometer based corrections), and  $\approx 8 \times 10^{-16}$  (frequency standard and its distribution) [Asmar *et al.*, 2005]. Other noises (such as unmodeled motion of the spacecraft, finite signal-to-noise ratio in the radio links, ground electronics noise, etc.)

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have, in current-generation observations, Allan deviations of a few times  $10^{-16}$  or smaller. (Noise levels are characterized by Allan deviation [Barnes *et al.*, 1971], a measure of fractional frequency fluctuation  $\Delta f/f_0$  ( $\Delta f$  = Doppler fluctuation in a specified integration time,  $f_0$  = radio center frequency) as a function of integration time  $\tau$ . All Allan deviations given here are for an integration time of 1000 s.)

[4] Antenna mechanical noise has appeared particularly difficult to reduce. Tracking antennas for deep space communications are necessarily large, moving, steel structures; it is difficult to see how to build such a structure having intrinsically better mechanical stability than is currently achieved. Here we show how the intrinsic mechanical noise in a large tracking antenna can, however, effectively be removed when conventional two-way Doppler tracking data are combined, with time delays, with tracking data from a second stiffer receive-only antenna. Using this time delay mechanical-noise cancellation (TDMC) method, the mechanical noise in the final Doppler observable can be reduced, substantially, to that of the stiffer antenna.

## 2. Antenna Mechanical Noise Reduction Procedure

[5] The idea for time delay mechanical-noise cancellation was originally proposed by Armstrong *et al.* [2006]. The motivation for TDMC, the transfer-function-based description of the Doppler observations upon which TDMC is based, and the algebraic description of TDMC are briefly summarized in this section for completeness. Discussion of the proof-of-concept observations is in section 3.

[6] In two-way Doppler tracking a single antenna is used to transmit an almost monochromatic radio signal to a deep space probe (the uplink) and to receive the phase-coherently transponded signal from that spacecraft (the downlink). Two-way Doppler is the difference between the frequencies of the transmitted and received signals, each referenced to the same frequency standard, but at different times because of the two-way light time between the earth and spacecraft. Three-way Doppler tracking uses one antenna to transmit the uplink and a separate antenna to receive the downlink. Three-way Doppler is the difference between the frequency of the received signal at the auxiliary antenna and the frequency of the signal which was transmitted from the other antenna a two-way light time earlier.

[7] Simultaneous two-and three way Doppler data can be combined such that the leading noises in the combined observable (in particular the antenna mechanical noise of the two-way station) are those as if the auxiliary three-way antenna provided both the up- and downlink.

Because the proposed receive-only three-way antenna can be smaller and stiffer, its antenna mechanical noise can be made small. This ancillary antenna can be situated near a tropospheric scintillation calibration system (or it can be the same as the antenna used for the tropospheric calibration system) so its output can in principle also have significantly reduced scintillation noise. The result is that significant suppression of leading noises is possible.

[8] Suppose the relative velocity between the earth and spacecraft gives rise to a two-way fractional Doppler shift  $y_S$ . Let the two-way time-of-flight of the radio signal to the spacecraft and back be  $T$ . Noises enter the two- and three-way observations via transfer functions [e.g., Estabrook and Wahlquist, 1975; Asmar *et al.*, 2005; Armstrong, 2006]. Let  $y_2(t)$  be the time series of fractional Doppler variation measured at the two-way station and  $y_3(t)$  be the fractional Doppler time series measured at a collocated three-way station. If  $M_2(t)$  and  $M_3(t)$  are the antenna mechanical noises at the two stations,  $T_2(t)$  and  $T_3(t)$  are the tropospheric scintillation noises, and  $C_2(t)$  and  $C_3(t)$  are the frequency standard (clock) noises, then these three noises and the signal enter the two- and three-way Doppler time series according to:

$$y_2(t) = [M_2(t) + M_2(t - T)] + [T_2(t) + T_2(t - T)] + [C_2(t) - C_2(t - T)] + y_S \quad (1)$$

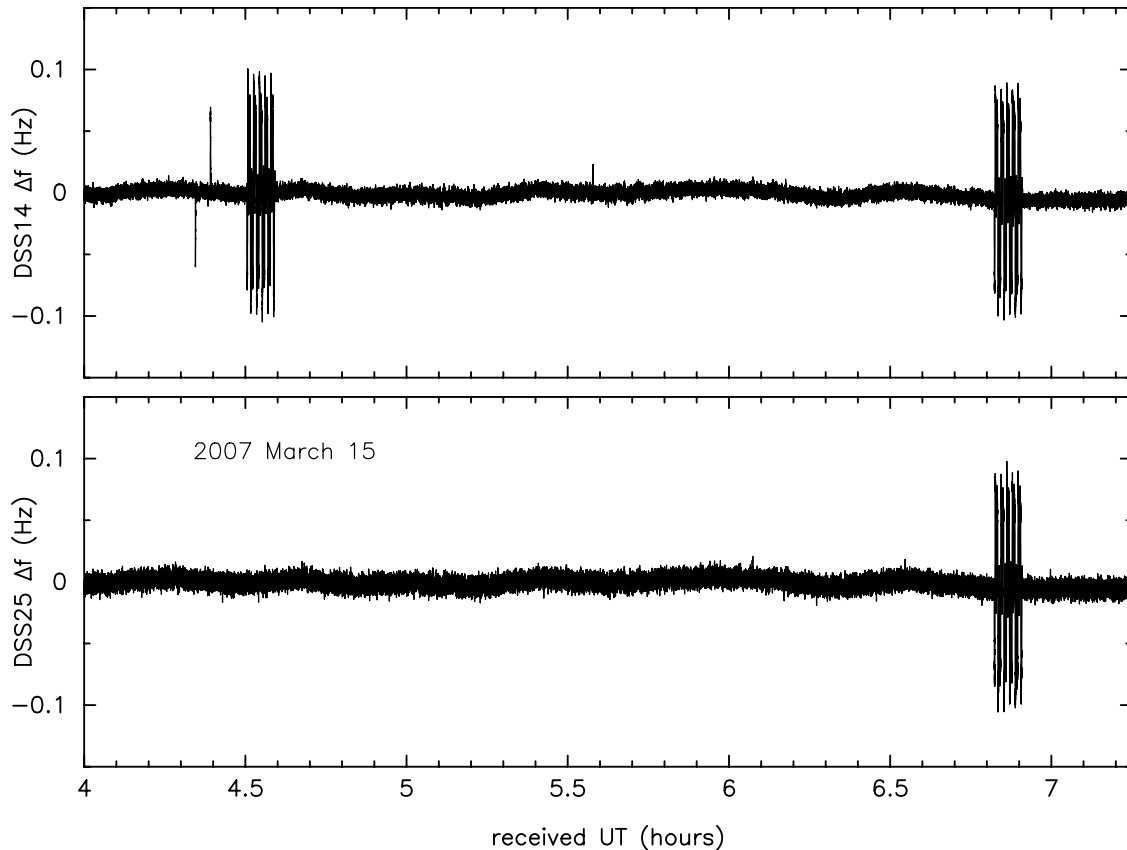
$$y_3(t) = [M_3(t) + M_3(t - T)] + [T_3(t) + T_3(t - T)] + [C_3(t) - C_3(t - T)] + y_S. \quad (2)$$

The time series of the two-way data depends only on  $M_2$ ,  $T_2$ , and  $C_2$ ; the time series of the three-way Doppler contains the mechanical, tropospheric, and clock noises of both stations. Combining  $y_2(t)$  and  $y_3(t)$  with appropriate delays [Estabrook and Armstrong, 1983; Armstrong *et al.*, 2006] gives the TDMC data combination  $E(t)$ :

$$E(t) = y_3(t) + y_3(t - T) - y_2(t - T) \quad (3)$$

$$= [M_3(t) + M_3(t - T)] + [T_3(t) + T_3(t - T)] + [C_3(t) + C_3(t - T) - 2C_2(t - T)] + y_S \quad (4)$$

This data combination has the signal content of the two-way time series but antenna mechanical and tropospheric noises as if the three-way station were both transmitting and receiving. (Indeed this data combination was originally proposed to suppress tropospheric scintillation noise in precision Doppler tracking observations



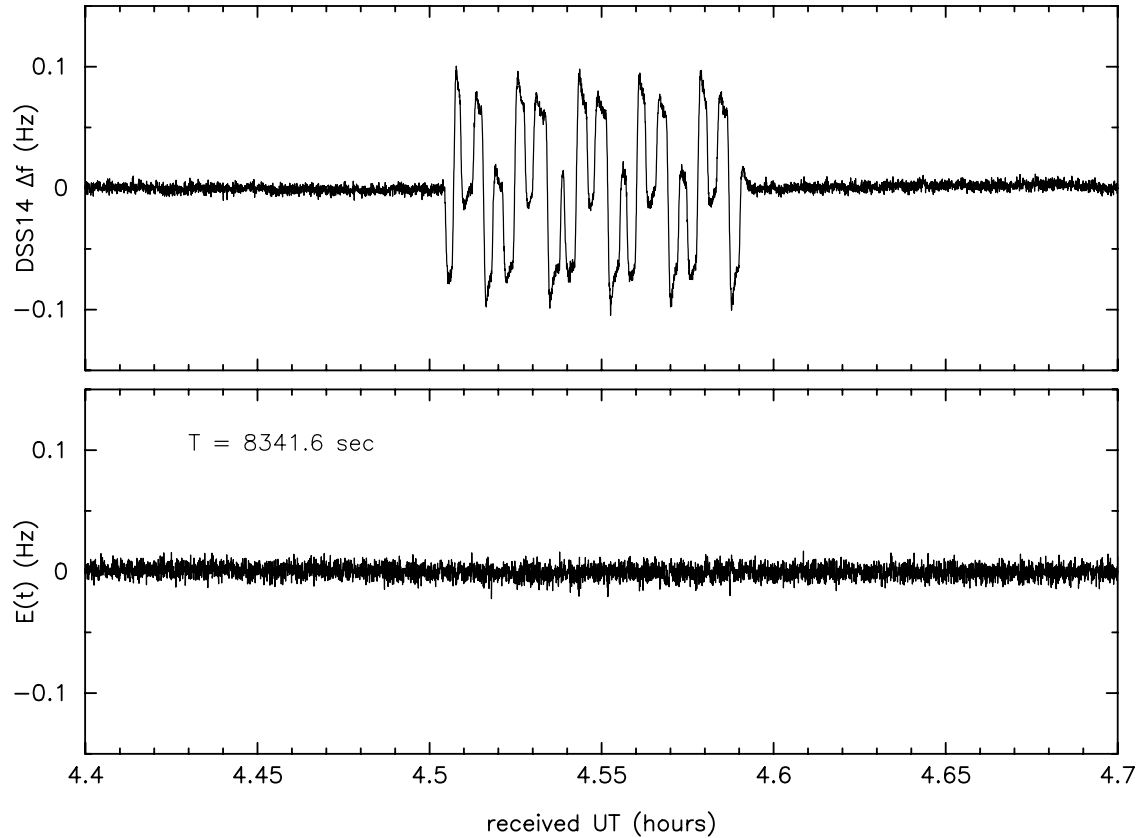
**Figure 1.** Time series of Doppler frequency during the single-frequency (X-band) antenna mechanical noise reduction test, 15 March 2007. Because these data are single-frequency, the noise level is set by plasma scintillation rather than antenna mechanical noise. We thus introduced large mechanical noise for the purpose of this test. (top) Two-way Doppler at DSS14. The large signature for 5 min starting slightly after 04:30 UT is caused by our deliberate articulation of the subreflector. This introduced exaggerated Doppler variability (mimicking exaggerated Doppler noise) immediately and at a two way light time ( $T = 8341.6$  s) later; see equation (1). The two impulsive events near 04:20 UT and the impulsive event near 05:35 UT in the DSS14 time series have unknown origin but are unrelated to the test. (bottom) Simultaneous three-way (i.e., receive-only) Doppler observations at DSS25. The echo of the DSS14 subreflector motion event after a two-way light time is clear in the DSS25 time series (equation (2)).

[Estabrook and Armstrong, 1983]. The idea was to put the three-way antenna at a troposphericly benign site, or in orbit, so that  $T_3 \ll T_2$ . This idea was never implemented for tropospheric scintillation correction, however. Instead, separate instruments – co-located water-vapor radiometers to estimate independently the time-variable tropospheric delay – were built to give the required tropospheric calibration [Tanner and Riley, 2003].)

### 3. Proof-of-Concept

[9] We took data for a demonstration of the method on 2007 March 15. The 70-m Deep Space Network

antenna at Goldstone (DSS14) tracked Cassini in two-way mode at X-band only. Because data for this test were taken at a single frequency, the dominant variability in the time series was caused by plasma and tropospheric scintillation noise [Asmar et al., 2005]. We simultaneously took receive-only (three-way) observations at the nearby 34-m antenna, DSS25. The data were recorded with the pre-detection radio science receivers and the frequency residuals of the two- and three-way data were detected in software with a time constant of about 1 s. Since the noise in the data was dominated by scintillation, we had to artificially introduce antenna mechanical noise for the test. To do this,



**Figure 2.** Time series of raw and TDMC-corrected Doppler frequency during the 15 March 2007 antenna mechanical noise reduction test. (top) Blowup of the two-way Doppler at DSS14, detected with a one-second time constant, near the exaggerated mechanical variation. (bottom) TDMC data combination  $E(t)$  (equation (3)), which has the antenna mechanical noise of the three-way station DSS25, has accurately removed the deliberate mechanical variation in the DSS14 data. Secondary noises are slightly increased by this procedure (equation (4) and the discussion in section 4).

at about 04:30 UT we artificially produced large “antenna mechanical noise” at DSS14 by deliberately articulating its subreflector along the antenna-spacecraft direction for 5 min. This introduced clear antenna mechanical variability in the Doppler signal at DSS14, which was echoed a two-way light time ( $T = 8341.6$  s) later (Figure 1, top). At the time of the DSS14 subreflector motion DSS25 was receiving a signal coherent with one uplinked a two-way light time earlier. Thus at  $\approx 04:30$  UT DSS25 was insensitive to the deliberate DSS14 antenna mechanical motion, but clearly observed its “echo” a two-way light time later (equation (2) and Figure 1, bottom). Forming the linear combination  $E(t)$  canceled the exaggerated DSS14 antenna mechanical motion to the level of secondary noises (Figure 2, bottom), which (as expected from equation (4)) were larger than the secondary noises in

the two-way tracking alone (compare the noise at the start of the plot in the top and bottom panels of Figure 2).

#### 4. Some Practical Considerations

[10] Some considerations for a practical TDMC implementation were outlined by *Armstrong et al.* [2006]. Here we briefly discuss limitations on the applicability of the method, signal-to-noise ratio considerations for the smaller antenna, the required stability for frequency and timing, the effect of tropospheric and other noises, and the achievable mechanical stability of the three-way antenna.

[11] Of course the TDMC method would only be useful in cases where antenna mechanical fluctuations dominate the total noise. The Doppler quality of current-

generation deep space probe tracking at a single microwave frequency is typically limited by propagation noise [Asmar *et al.*, 2005]. Only in precision deep space tracking (e.g., five-link Cassini tracks used to cancel the plasma noise and water vapor radiometers used to correct for tropospheric scintillation) is mechanical noise the leading effect. Indeed even Cassini-era precision tracks have antenna mechanical noise only about two times larger than other noises in the current tracking system. To achieve the full potential of TDMC the non-mechanical noise levels would have to be reduced in future deep space tracking.

[12] Downlink power received and ground station system noise temperature set a level of white phase noise. Suppose the two-way antenna is a 34m DSN station and the receive-only antenna has 10-times smaller diameter, but with both antennas having the same quality receiver electronics. The received downlink power at the smaller station will then be 20dB weaker than for the 34m antenna. The Allan deviation for the white phase noise associated with a finite SNR thermal noise component is [Barnes *et al.*, 1971]  $\sigma_y(\tau) \approx (3 B S_\phi)^{0.5} / (2 \pi f_o \tau)$ , where B is the bandwidth of the phase detector and  $S_\phi$  is the one-sided phase noise spectral density  $\approx 1/(\text{SNR in a one Hertz bandwidth})$ . For Cassini observations at X- and Ka-band the SNR in 1 Hz received at a 34m station can be 50dB or larger-with corresponding Allan deviation ( $\tau = 1000$  s,  $B = 1$  Hz) of  $\sim 10^{-16}$  or smaller. So thermal noise is not limiting the 34m antenna observations at  $\tau \approx 1000$  s. For the ancillary antenna, however, the smaller collecting area would give an unacceptably high thermal noise contribution for the same integration time and bandwidth. One way to bring the thermal noise component for the smaller antenna to  $\sim 10^{-16}$  would be to reduce the detection bandwidth to  $\approx 0.01$  Hz. This could be done with open-loop pre-tuning of the signal prior to phase detection using an a priori spacecraft orbit or recording the pre-detection signal in a wide band and then pre-tuning the signal in software before final phase detection. A reduced detection bandwidth would then restrict the utility of TDMC to timescales which depend on the size of the three-way antenna. In this example (10X smaller diameter three-way antenna) the mechanical noise corrections, and thus the scientific relevance of the corrected observations, would be restricted to timescales  $\approx 100$  s or longer. Making the three-way antenna even smaller would restrict the utility of TDMC-corrected data to even longer timescales. TDMC is appropriate only for mechanical-noise-limited observations and only over timescales where the other noises can be made suitably small.

[13] The data combination E(t) has not only the mechanical noise of the smaller antenna but also its tropospheric noise. The current generation tropospheric

correction method (the Advanced Media Calibration system, AMC) uses a separate water-vapor-radiometer (WVR) based antenna located close to DSS25 to provide the calibration [Tanner and Riley, 2003]. The tropospheric calibration is limited in part by beam mismatch (the tracking antenna beam and the AMC's beam do not quite sample the same tropospheric volume). In principle, the smaller TDMC antenna could also be instrumented for the tropospheric calibration, i.e., be the same as the WVR antenna, minimizing beam mismatch and simultaneously providing the tropospheric correction. To improve the tropospheric scintillation correction to the  $10^{-16}$  level would, however, require development.

[14] To reach the sensitivity where antenna mechanical noise dominates also requires negligible plasma noise, either through observations at very high radio frequencies or via accurate calibration and removal of this noise. Prior to the failure of the on-board Ka-band translator (KaT), Cassini tracking used a multilink radio system to estimate and effectively remove plasma scintillation noise [Bertotti *et al.*, 2003; Jess *et al.*, 2003; Tortora *et al.*, 2004]. If the larger two-way antenna were to provide the plasma scintillation correction, the three-way antenna must be located close enough to the two-way antenna that the same plasma correction applies.

[15] From equation (4), frequency and timing standard (FTS) noise enters E(t) as  $C_3(t) + C_3(t - T) - 2 C_2(t - T)$ . The resulting FTS noise in E(t) would in general be larger than in two-way Doppler. Reducing the FTS contribution in E(t) to  $\approx 10^{-16}$  would require about an order of magnitude improvement in as-implemented FTS stability. Such ten-fold improvements may be difficult, although published reports [e.g., Takamoto *et al.*, 2005] suggest even better frequency stability is possible in principle.

[16] For the total noise in E(t) to be  $\sim 10^{-16}$ , formerly minor contributors to the error budget need to be reconsidered. The Cassini spacecraft's unmodeled motion was measured by L. Won, G. Hanover, R. Belenky, and A. Lee (private communication, 2001) to be  $\approx 2 \times 10^{-16}$  (their power spectrum of unmodeled spacecraft motion is reproduced in Armstrong [2006]). This component of the error model thus almost reaches  $10^{-16}$  in an existing spacecraft. Ground electronics were measured to be  $\approx 2 \times 10^{-16}$  [Abbate *et al.*, 2003], thus also currently almost at the  $10^{-16}$  level. At least for microwave observations having large sun-earth-spacecraft angle, Cassini-class multilink plasma calibrations, which are based on geometrical optics, are probably accurate to  $10^{-16}$  or better for  $\sim 1000$  s integrations.

[17] TDMC fundamentally requires the three-way antenna to have excellent mechanical stability. Measurements of path-delay stability of prototype 12 m Atacama Large Millimeter Array (ALMA) antennas have been published by Mangum *et al.* [2006] and Snel *et al.*



[2007]. The stability of the ALMA prototypes depends on test conditions but is typically <15 microns for one-way path delay variations over timescales  $\sim 10$  min. This can be compared with measurements on the operational 34 m DSS25 antenna as follows. DSS25's two-sided spectrum of two-way fractional Doppler,  $S_y(f)$ , was published by *Armstrong et al.* [2003]. Since two-way fractional Doppler is twice the station-spacecraft velocity divided by the speed of light, the derivative theorem for Fourier transforms can be used to connect  $S_y$  with the spectrum of one-way path-delay variation,  $S_x$ :  $S_x(f) = c^2 S_y(f)/(16 \pi^2 f^2)$ , where  $c$  is the speed of light and  $f$  is the Fourier frequency. Integrating  $2 S_x(f)$  for Fourier frequencies between  $1/(10 \text{ min})$  and  $0.01 \text{ Hz}$  (antenna mechanical noise dominates DSS25 variability in this band) and taking the square root gives an RMS one-way path variation of 190 microns. (This result does not depend sensitively on the high-frequency cutoff; increasing the upper limit of integration by a factor of 50 to  $0.5 \text{ Hz}$  – a frequency where other noise dominates–gives 240 microns.) The ALMA prototype 12 m antennas thus have mechanical stability an order-of-magnitude better than that of DSS25; such antennas could enable order-of-magnitude mechanical noise corrections using TDMC.

## 5. Summary

[18] We demonstrated a time delay mechanical-noise cancellation (TDMC) method whereby antenna mechanical noise–currently the leading noise source in best-quality deep-space Doppler tracking–can be substantially reduced. Our method uses time delayed two- and three-way tracking, with the three-way station having a stiff, highly mechanically stable antenna. Using TDMC, antenna mechanical (and tropospheric) noises in the final Doppler data combination are those of the more stable receive-only antenna. If frequency/timing and tropospheric noises can be reduced suitably, the procedure given here could produce order-of-magnitude improvements in end-to-end fractional Doppler data quality to the  $\sim 10^{-16}$  level. This sensitivity would offer new opportunities for solar system radio science observations and precision spacecraft navigation.

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