Reducing Antenna Mechanical Noise in Precision Doppler Tracking

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Precision Doppler tracking of deep-space probes is central to spacecraft navigation and many radio science investigations. The most sensitive Doppler observations to date have been taken using the NASA/JPL Deep Space Network (DSN) antenna DSS 25—a 34-m-diameter beam-waveguide station especially instrumented with simultaneous X-band (≈8.4-GHz) and Ka-band (≈32-GHz) links and tropospheric scintillation calibration equipment—tracking the Cassini spacecraft. These Cassini observations achieved Doppler fractional frequency stability (Doppler frequency fluctuation divided by center frequency, $\Delta f/f_o$) of $\approx 3\times10^{-15}$ at $\tau = 1000$ s integration. In those very-high-sensitivity tracks, the leading disturbance was antenna mechanical noise: time-dependent unmodeled physical motion of the ground antenna's phase center caused by antenna sag as the elevation angle changed, unmodeled subreflector motion, wind loading, bulk motion of the antenna as it rolled over irregularities in the supporting azimuth ring, differential thermal expansion of the structure, etc. This noise has seemed irreducible at reasonable cost, since it is unclear how to build a practical, large, moving, steel structure having mechanical stability significantly better than that of current tracking stations. Here we show how the mechanical noise of a large tracking antenna can effectively be removed when two-way Doppler tracking data from an existing DSN antenna are suitably combined with simultaneous tracking data using an ancillary (smaller and stiffer) antenna. Using our method, the mechanical noise in the final Doppler observable can be reduced, substantially, to that of the stiffer antenna.

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I. Introduction

Precision Doppler tracking of deep-space probes is used for both spacecraft navigation and radio science. Examples of the latter include determination of planetary masses and mass moments, measurements of planetary atmospheres/ionospheres/rings, studies of the solar wind, precision tests of relativistic gravity, and searches for low-frequency gravitational radiation (see, e.g., [9,15]).

Both navigation and radio science are limited by noise in the Doppler system. Typical Doppler tracks at X-band ($\approx$8.4-GHz downlink) have a noise threshold, at $\approx$1000-s integration times, set by either plasma (e.g., [16]) or tropospheric (e.g., [8]) scintillation (see Fig. 2 of [4]). By contrast, recent very high precision observations using NASA's Deep Space Network (DSN) antennas and the Cassini spacecraft [3,6,14] calibrated and largely removed these propagation noises, achieving fractional Doppler sensitivity (Doppler frequency fluctuation divided by radio center frequency) of $\approx 3 \times 10^{-15}$ in 1000-s integrations. The noise threshold in these high-precision two-way coherent Doppler tracks was set principally by three sources. The Allan deviations[6] at $\tau = 1000$ s for these leading noises [4] were $\approx 2 \times 10^{-15}$ for antenna mechanical noise, $\approx 1 \times 10^{-15}$ for residual tropospheric scintillation noise after water-vapor-radiometer (WVR)-based corrections, and $\approx 8 \times 10^{-16}$ for frequency standard plus frequency distribution noise. Other noise sources—e.g., unmodeled motion of the spacecraft, finite signal-to-noise ratio (SNR) in the radio links, ground electronics—in current-generation observations have Allan deviations of a few times 10^{-16} or smaller.

Cost-effective reduction of antenna mechanical noise has appeared particularly difficult. Tracking antennas for deep-space communications are necessarily large, moving, steel structures; it has been difficult to see how to build a large structure having better mechanical stability than is currently achieved. Here we show how mechanical noise in a large tracking antenna can effectively be removed if conventional two-way Doppler tracking data from a large antenna are combined with simultaneously-taken tracking data from a second, considerably smaller and stiffer, receive-only antenna. Using our method, the mechanical noise in the final Doppler observable can be substantially reduced to that of the stiffer antenna.

II. Reducing Antenna Mechanical Noise

In two-way Doppler tracking observations, a single antenna is used to transmit a 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 finite two-way light-time between the Earth and spacecraft). Three-way Doppler tracking uses one antenna to transmit the uplink and an auxiliary antenna to receive the downlink. As we show in the following, simultaneous two- and three-way Doppler data can be processed such that antenna mechanical noise in the combined observable is *as if the auxiliary three-way antenna provided both the uplink 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 antenna used for the tropospheric calibration system) so its output can also in principle have significantly reduced tropospheric scintillation noise. The result is that marked suppression of leading noises is possible.

To illustrate the method, assume we wish to measure the relative velocity, v, between the Earth and a distant spacecraft. The two-way signal, fractional Doppler shift, is $y_S = 2\ v/c$. Suppose that the spacecraft has unity transponder ratio (i.e., the frequency re-transmitted by the spacecraft is the same as that it received) and that the two-way light-time-of-flight to the spacecraft and back is T. The noises

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[6] Noise levels are characterized by Allan deviation [5], a measure of fractional frequency fluctuation $\Delta f/f_o$ (Δf = Doppler fluctuation in a specified integration time; f_o = radio center frequency) as a function of integration time τ. Unless otherwise specified, all Allan deviations given here are for an integration time of 1000 s.

enter the two- and three-way observations according to well-known transfer functions [7]. 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 at the three-way station (assumed in this example to be colocated with the two-way station). If $M_2(t)$ and $M_3(t)$ are the time series of 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) fluctuations, then these noise contributions enter the measured two- and three-way Doppler time series as

$$y_2(t) = \left[M_2(t) + M_2(t-T)\right] + \left[T_2(t) + T_2(t-T)\right] + \left[C_2(t) - C_2(t-T)\right] + y_S \tag{1}$$

$$y_3(t) = \left[M_3(t) + M_2(t-T)\right] + \left[T_3(t) + T_2(t-T)\right] + \left[C_3(t) - C_2(t-T)\right] + y_S \tag{2}$$

Combining these two time series with appropriate delays gives a data combination,[7] $E(t)$:

$$E(t) = y_3(t) + y_3(t-T) - y_2(t-T) = y_S + E_{\rm noise}(t) \tag{3}$$

This data stream has the signal content of the two-way time series but the antenna mechanical and tropospheric noises as if the three-way station were both transmitting and receiving; its leading noises are

$$E_{\rm noise}(t) = \left[M_3(t) + M_3(t-T)\right] + \left[T_3(t) + T_3(t-T)\right] + \left[C_3(t) + C_3(t-T) - 2C_2(t-T)\right] \tag{4}$$

Note that $M_2(t)$ does not enter into $E(t)$. *The essential observation is that, with the three-way antenna smaller and stiffer,* $M_3 \ll M_2$, *this procedure significantly reduces the leading noise compared with purely two-way Doppler tracking.*

III. Some Practical Considerations

A detailed discussion of practical problems with the implementation (and also benefits to navigation and radio science investigations) will be discussed elsewhere. Here we just outline some of the considerations for an actual implementation.

A. Signal-to-Noise Ratio for the Smaller Antenna

Received downlink power and system noise temperature determine whether white phase noise (thermal noise) is significant. Suppose the larger antenna is a 34-m station and the ancillary antenna has a diameter 10 times smaller, so that the received downlink power at the smaller station will be 20-dB smaller. The Allan deviation for white phase noise associated with the finite SNR thermal noise component [5] is $\sigma_y(\tau) \approx (3BS_\phi)^{0.5}/(2\pi f_o \tau)$, where B is the bandwidth of the phase detector, τ is the integration time, and S_ϕ is the one-sided phase noise spectral density, $\approx$1/(SNR in a 1-Hz bandwidth). For Cassini observations at X- and Ka-band ($\approx$32 GHz), the SNR in 1-Hz received at a 34-m station can be >50 dB, with a corresponding Allan deviation ($\tau = 1000$ s, $B = 1$ Hz) of $\approx 10^{-16}$ or smaller, so thermal noise is not limiting at $\tau \approx 1000$ s. For the ancillary antenna, however, the thermal noise limit at the same τ and B

[7] This data combination was originally proposed to reduce (or eliminate) tropospheric scintillation noise in Doppler tracking observations searching for low-frequency gravitational radiation (F. B. Estabrook and J. W. Armstrong, "Three-Way Doppler Data for Gravitational Wave Searches," JPL Interoffice Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, April 4, 1983). The idea there was to put the three-way ancillary receive-only antenna at a high, dry site (or in orbit) so that $T_3 \ll T_2$.

would be unacceptably high.[8] One way to bring the thermal noise component for the smaller antenna to the 10^{-16} level is to reduce the detection bandwidth to $\approx$0.01 Hz. This might be implemented by open-loop pre-tuning the signal prior to phase detection using an a priori spacecraft orbit or by recording the pre-detection signal in a wide band and then carefully pre-tuning the signal in software before final phase detection. The detection bandwidth reduction to $\approx$0.01 Hz may restrict the utility of the method to radio science observations having time scales of interest >100 s.

B. Colocation and Plasma Scintillation Corrections

The Cassini spacecraft tracked with DSS 25 used a multi-frequency, but still fundamentally two-way, radio system to remove plasma scintillation noise [6,14]. Except for two-way Ka-band observations very close to solar opposition, this plasma correction was essential to reducing plasma scintillation noise to the level where the antenna mechanical noise became important [4]. If the 34-m antenna were to provide the plasma scintillation correction, this would put a constraint on the separation of the two antennas: the plasma calibration would have to be valid for the smaller antenna too.

C. Improved Tropospheric Scintillation Corrections

With a suitably stiff small antenna, we can probably reduce antenna mechanical noise to $\approx 10^{-16}$, thus leaving residual tropospheric scintillation as the leading noise source. The current-generation tropospheric correction method—the advanced media calibration system (AMC)—uses a separate WVR-based antenna located tens of meters from DSS 25 to provide a very high-quality calibration [11,13]. The AMC cannot perfectly calibrate the Doppler data, however, due in part to beam offset and mismatch (the DSS-25 antenna beam and the AMC beams do not quite sample the same volume of the troposphere, e.g., see [10]) and in part to subtleties in relating brightness temperatures (what the AMC measures) to tropospheric path delay (what is desired to correct the Doppler data).

In principle, the smaller antenna could also be used for tropospheric calibration, i.e., be the same as the WVR antenna. In Eq. (4), the tropospheric contribution is that of the small antenna so beam mismatch and offset could be minimized. As stated above, though, to get a WVR-based tropospheric correction significantly better than 10^{-15} may require an improved understanding of the relationship between microwave tropospheric brightness temperature and path delay.

D. Improved Frequency Standard Stability

Frequency and timing system (FTS) noise enters $E(t)$ as $C_3(t) + C_3(t-T) - 2C_2(t-T)$. Assuming the two FTS systems are uncorrelated, the FTS noise in $E(t)$ is larger than in conventional two- or three-way Doppler. Reducing the FTS contribution in $E(t)$ to $\approx 10^{-16}$ would require an order-of-magnitude improvement in as-implemented FTS stability. Such improvements are likely to be difficult to achieve but are not thought to be impossible. Indeed, there are published reports [e.g., 12], suggesting 10^{-18} or better FTS performance may be possible.

E. Other Noise Sources

For the total noise in $E(t)$ to be 10^{-16} or smaller, formerly minor contributors to the error budget need to be reconsidered. Unmodeled motion of the Cassini spacecraft has been measured independently[9] to be $\approx 2\times10^{-16}$. This component of the error model is thus almost good enough with a current spacecraft. Ground electronics are measured to be $\approx 2\times10^{-16}$ [1], thus also currently almost good enough. Plasma

[8] Of course this assumes that the low-noise amplifier—the first microwave amplifier in the receiver chain, which sets the downlink noise performance—at the smaller station has the same performance as that used by the two-way station. The constraint on the detection bandwidth for the smaller station could be relaxed if the SNR there were improved using a higher-performance amplifier.

[9] L. Won, G. Hanover, R. Belenky, and A. Lee, "Cassini Project Presentation," JPL internal document, Jet Propulsion Laboratory, Pasadena, California, October 18, 2001; their spectrum of stochastic spacecraft motion is reproduced with permission in [2].

calibration is already better than 10^{-16} [14] so, subject to the caveat regarding station colocation above, plasma corrections are already good enough.

F. Applications

If the FTS and tropospheric noises can be reduced suitably, our technique can reduce the total Doppler noise to $\sim 10^{-16}$. This sensitivity would offer new opportunities in solar system radio science and other spacecraft radio measurements. We will address these applications for navigation, mass and mass moment determinations, solar system tests of relativistic gravity, low-frequency gravitational wave searches, etc., in a future article.

IV. Summary

We have given a method whereby antenna mechanical noise, currently the leading noise source in precision deep-space Doppler tracking, can be substantially reduced. Our method is based on simultaneous two- and three-way tracking, with the ancillary receive-only station having a small, stiff, very mechanically stable antenna. Using this method, the antenna mechanical (and tropospheric) noises in the final Doppler data combination are those of the more mechanically stable receive-only antenna. We outlined some practical implementation problems (principally SNR limits on the small antenna, tropospheric scintillation calibration, and frequency standard stability) in the context of achieving total system Doppler performance at the 10^{-16} level.

An expanded version of this article, including a more complete discussion of practical issues in the method's implementation and quantification of scientific and other benefits of the improved measurement capability, is in preparation.

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