National Aeronautics and Space Administration

Advancing Solar System Dynamics Investigations from Calibrated Precision Doppler Tracking

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Program: FY21 R&TD Innovative Spontaneous Concepts

Objectives

The objective of this task was to develop the tools to demonstrate the time-delay mechanical-noise cancellation (TDMC) concept, a method of reducing the noise contribution of the intrinsic mechanical instability of the large tracking antennas used in precision Doppler measurements [1]. We aimed to combine two-way tracking data from BepiColombo from ESA's 35 m Malargüe antenna in Argentina and receive-only tracking data provided by smaller and stiffer 13.2 m diameter VLBI antenna at the RAEGE station of Santa Maria off the coast of Portugal, which has the capability to receive X- and Ka-band links and had an overlap in the view-period [2].

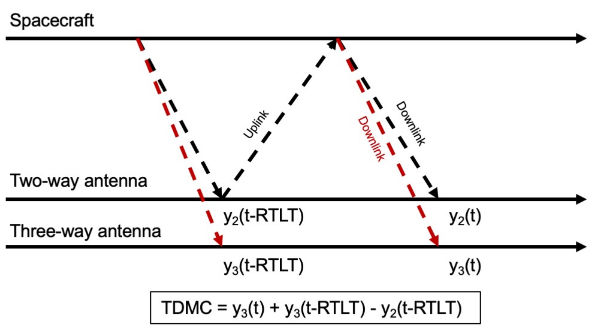

Figure 1. A schematic of the two-way and three-way (receive-only) observations adapted from Notaro et. al (2020) [6], where y is the Doppler observable and RTLT is the roundtrip light time. The TDMC is a linear-combination of the two- and three-way datasets [1].

Background

Planetary gravitation and solar system dynamics investigations rely on precision Doppler tracking of spacecraft [3]. In the most sensitive Doppler measurements carried out by the Deep Space Network (Allan deviations ~ 3x10-15 at 1000 s), the unmodeled time-dependent motion of the large (34 m) tracking antennas emerges as the leading noise contributor since other contributions to the noise budget can be calibrated. The antenna mechanical noise can be reduced by combining two-way Doppler tracking data from the large antenna with receive-only tracking data from a smaller, more stable antenna to produce up to an order-of-magnitude improvement in data quality after all other calibrations (Figure 1) [1].

Approach

Our team collaborated with Yebes Observatory in Spain to acquire receive-only (three-way mode) tracking data of BepiColombo from the 13.2 m antenna of Santa Maria at both X- and Ka- bands in November 2020 [2]. Overlapping tracks from ESA's 35 m Malargüe station were provided via ongoing collaboration between ESA and JPL.

Two separate receive-only tracks with the 13.2 m station were scheduled based on expected two-way passes of BepiColombo by the 35 m station: DOY329 for 57 minutes and DOY331 for 125 minutes. Due to instrumental errors and unavailable uplink, only ~36.5 minutes of overlap data from DOY331 was found to be useable.

Each dataset provides data for three links: X-band up/X-band down, X-band up/Ka-band down, and Ka-band up/Ka-band down. The phase of the BepiColombo signal carrier is extracted for each link to produce sky frequencies which are then coherently combined to calibrate the noise of solar plasma and ionosphere to generate plasma-free observables [4, 5]. This data is then processed to remove modeled Doppler shifts accounting for relative spacecraft motion leaving Doppler residuals (Figure 2). The calibrated Doppler residuals contain several noise contributions including, but not limited to, antenna mechanical noise, tropospheric noise, and noise from the station reference clocks. The TDMC method can be used to transfer the local noise of the three-way antenna to the two-way signal [1]. If the antenna mechanical noise and tropospheric noise of the three-way station is lower than those of the two-way station, this TDMC technique can result in a significant reduction in the noise of the observed Doppler data.

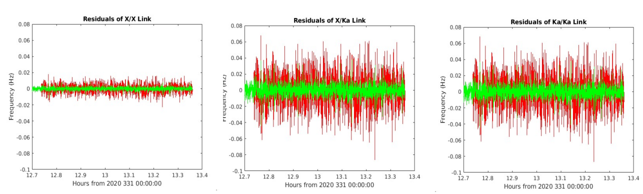

Figure 2. Doppler residuals of two-way and three-way data after plasma calibration for the X/X, X/Ka, and Ka/Ka links. We see the three-way residuals are larger than the two-way residual for this dataset, thus not adequate for the full demonstration of the TDMC technique.

Results

The noise fluctuations of the data are characterized in the time domain using the Allan deviation metric (Figure 3). Our analysis found the small amount of available three-way data did not have lower noise than the overlapping two-way data and thus the application of the TDMC method did not produce a lower noise when applied to these datasets. While it is likely the smaller 13.2 m antenna was more mechanically stable than the 35 m antenna, the local noise at the Santa Maria site, located on an island off the coast of Portugal, is likely affected by excessive tropospheric noise due to suboptimal atmospheric conditions. For future TDMC experiments, a site with favorable atmospheric conditions or with a water vapor radiometer to calibrate the tropospheric noise should be selected [6, 7].

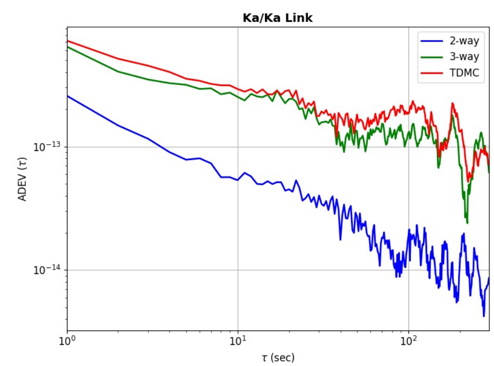

Figure 3. Allan Deviation gives a metric of the noise fluctuation in the time domain. In this figure is a comparison of two-way data (blue), three-way data (green), and application after TDMC (red). In this case, the three-way data contains more noise than the two-way data and so application of the TDMC does not improve the noise.

Significance/Benefits to JPL and NASA

Though our analysis found this dataset was not adequate for the full demonstration of the TDMC technique, the task resulted in the development of a pipeline and tools for converting datasets from a VLBI station to a JPL-standard data format, allowing application of spacecraft dynamics and plasma noise calibration, and application of the TDMC technique. These tools can be leveraged in future TDMC experiments carried out by JPL for streamlined analysis and can be used by the broader JPL radio science community.

References

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Clearance Number:
RPC/JPL Task Number: R21250

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