A Demonstration of the Time-Delay Mechanical Noise Cancellation (TDMC) Technique with Cassini Doppler Data

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Abstract

Radio science experiments for planetary geodesy or tests or relativistic gravity involve precise measurements of the spacecraft range rate enabled by two-way microwave links. Since the uncertainty on the estimated parameters depend almost linearly on the noise in the radio link, finding ways to reduce disturbances is essential for best scientific results. Tropospheric and antenna mechanical noises, among the leading noise sources in two-way Ka-band radio links, could be reduced using a suitable combination of Doppler data collected at the two-way antenna and at an additional, smaller and stiffer, three-way antenna [1]. The Time-Delay Noise Cancellation technique (TDMC) can provide significant reduction of the measurement noise if the listen-only antenna is located in a site with particularly favorable tropospheric conditions. This noise-reducing technique has only been tested by artificially producing a large mechanical noise event at the two-way antenna and using a similar three-way antenna to cancel the disturbance. We report on a practical demonstration of the capabilities of the TDMC technique applied to Doppler data from Cassini spanning 2004 through the last Titan gravity flyby in 2016. The tracking configuration in those passes was not tailored for the use of the TDMC, therefore the technique proves to be effective only with favorable noise conditions. Nonetheless, for those passes where tropospheric or antenna mechanical noises were relevant, we find substantial noise reduction. For example, Doppler data from the Titan-122 gravity flyby processed with the TDMC show about a factor-of-three noise reduction (at 60-s integration time) with respect to the two-way link. These results suggest that the choice of the three-way antenna and the scheduling of the tracking passes are crucial parameters that should be considered to fully exploit the improvement in accuracy provided by the TDMC technique. [1] Armstrong, J. W. et al., Radio Science 43 RS3010 (2008)

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1 Noise in Doppler links

Doppler tracking of deep space probes is used for navigation and radio science experiments. An accurate measurement of the spacecraft's radial velocity is obtained through microwave links sent by an Earth station and coherently retransmitted to the same station (two-way link) or to a different station (three-way link). Orbit determination methods are then used to solve for the central body's gravity field and rotational state. The noise in the Doppler link drives the accuracy of the estimated parameters (Figure 1). Ground antenna mechanical noise and tropospheric noise are dominant disturbances in precision radio science experiments with Ka-band links (Asmar *et al.*, 2005).

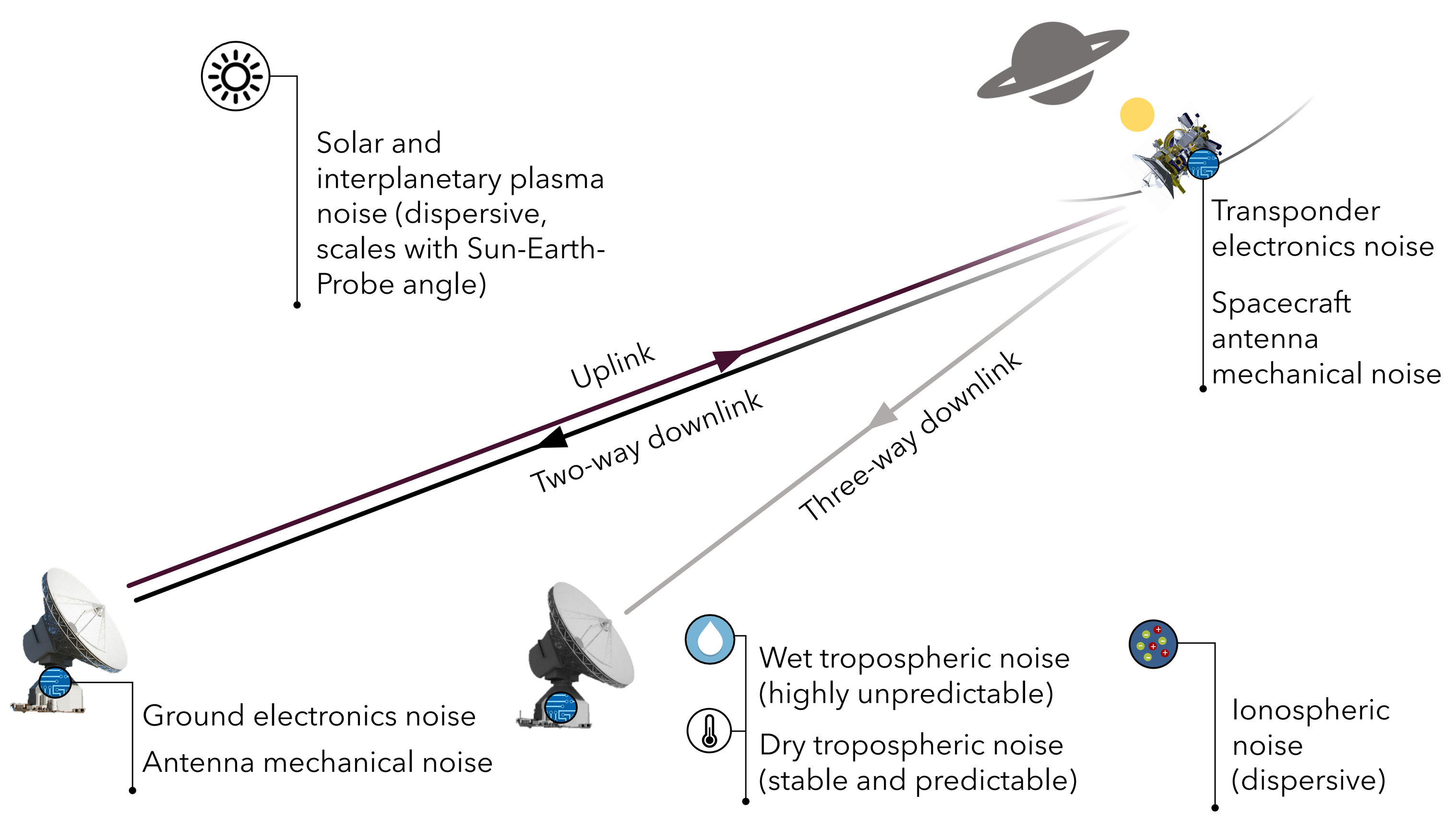
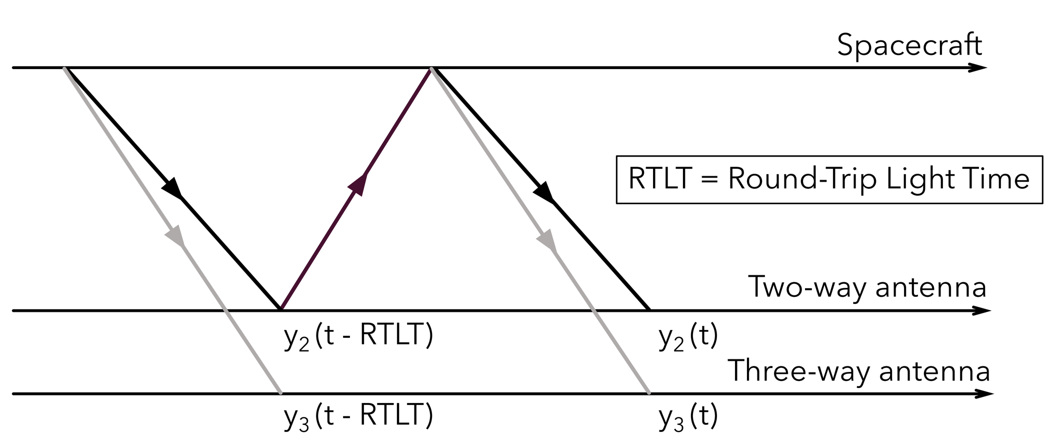


Figure 1: Main noise sources in a two-way (or three-way) Doppler link.

2 Time-Delay Mechanical Noise Cancellation (TDMC)

The linear combination E (t) of Doppler observables contains both uplink and downlink local noises at the three-way antenna, but with the two-way link's signal content (Figure 2). If the listen-only antenna is small (thus, stiff) and is located in a site with favorable tropospheric conditions, the Time-Delay Mechanical Noise Cancellation (TDMC) technique provides substantial noise reduction (Armstrong *et al.*, 2008).



$$E(t) = y_3(t) + y_3(t - RTLT) - y_2(t - RTLT)$$

Figure 2: Principle behind TDMC. $y_2(t)$ ($y_3(t)$) are the time series of two-way (three-way) Doppler observables ($y = \Delta f / f_0$ is the fractional frequency fluctuation).

3 TDMC with Cassini Doppler data

We applied the TDMC to Doppler data from the Cassini spacecraft collected during several tracking passages spanning the arrival at Saturn in 2004 through the last Titan gravity flyby in 2016. Since the Cassini tracking configuration was not tailored for the use of TDMC, we considered only those passages where the two-way/three-way data overlap was at least longer than one RTLT and where the Sun-Earth-Probe (SEP) angle was larger than 90°, so that plasma noise at X-band was not the dominant disturbance.

For each passage, we integrated Cassini's trajectory including all the main perturbative effects (e.g., planetary and satellite gravitational accelerations, solar radiation pressure, the acceleration due to the on-board RTGs). We then fitted the Doppler observables with an estimation filter and solved Cassini's state plus a suitable set of global parameters. Finally, we computed the linear combination E (t), the Allan deviation and the autocorrelation function of the residuals.

4 Results

Table 1 lists three Cassini tracking passages where the TDMC leads to non-negligible noise reduction wrt the two-way and three-way Doppler links. For those passages, the two-way link was dominated by a noise source which is correlated at the RTLT, as shown by the peak in the autocorrelation function (Figure 3). The dominant noise, which can be local troposphere or antenna mechanical noise, or a combination of the two, is successfully canceled by the TDMC (see the Allan deviation curves in Figure 4).

Table 1: Cassini tracking passages where TDMC grants noise reduction. DSA-1 is ESA's ESTRACK 35-m Deep Space Antenna 1 in New Norcia. During the Cassini mission, the RTLT ranges from 2 to about 3 hours.

Flyby	Pericenter epoch (altitude)	Two-way antenna (diameter)	Three-way antenna (diameter)	Data overlap	TDMC duration
Titan 033 (1932 km)	29-JUN-2007	DSS 25 (34 m)	DSS 14 (70 m)	3.4 hrs	0.7 hrs
Titan 074 (3651 km)	18-FEB-2011	DSS 43 (70 m)	DSS 34 (34 m)	6.4 hrs	3.9 hrs
Titan 122 (1698 km)	10-AUG-2016	DSS 35 (34 m)	DSA-1 (35 m)	3.2 hrs	0.5 hrs

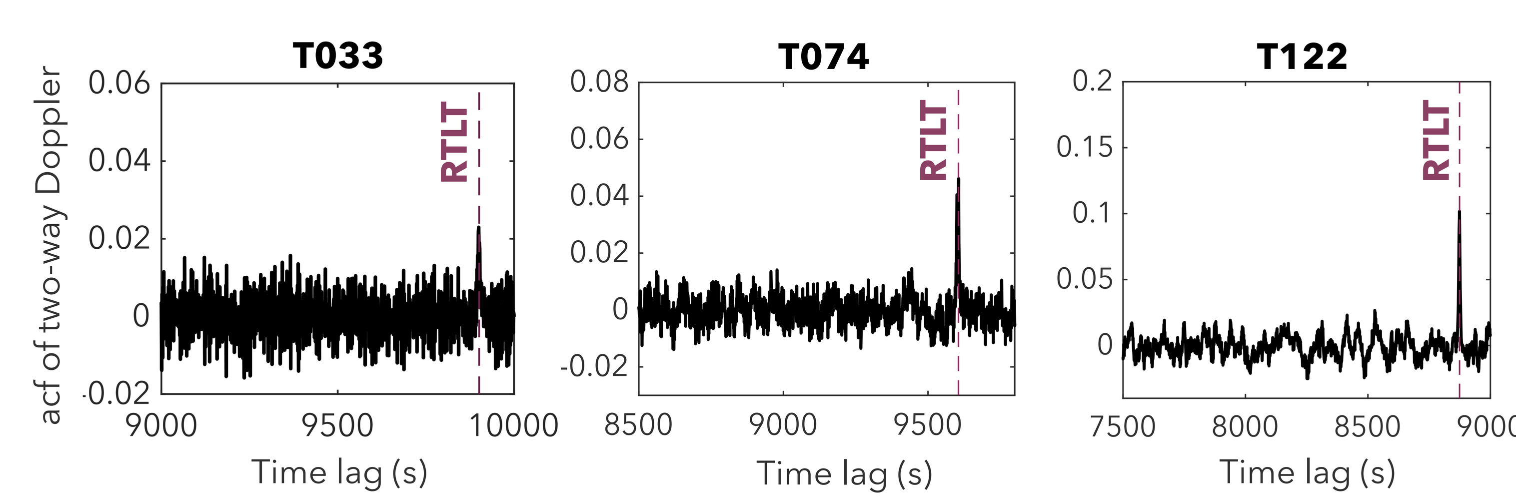
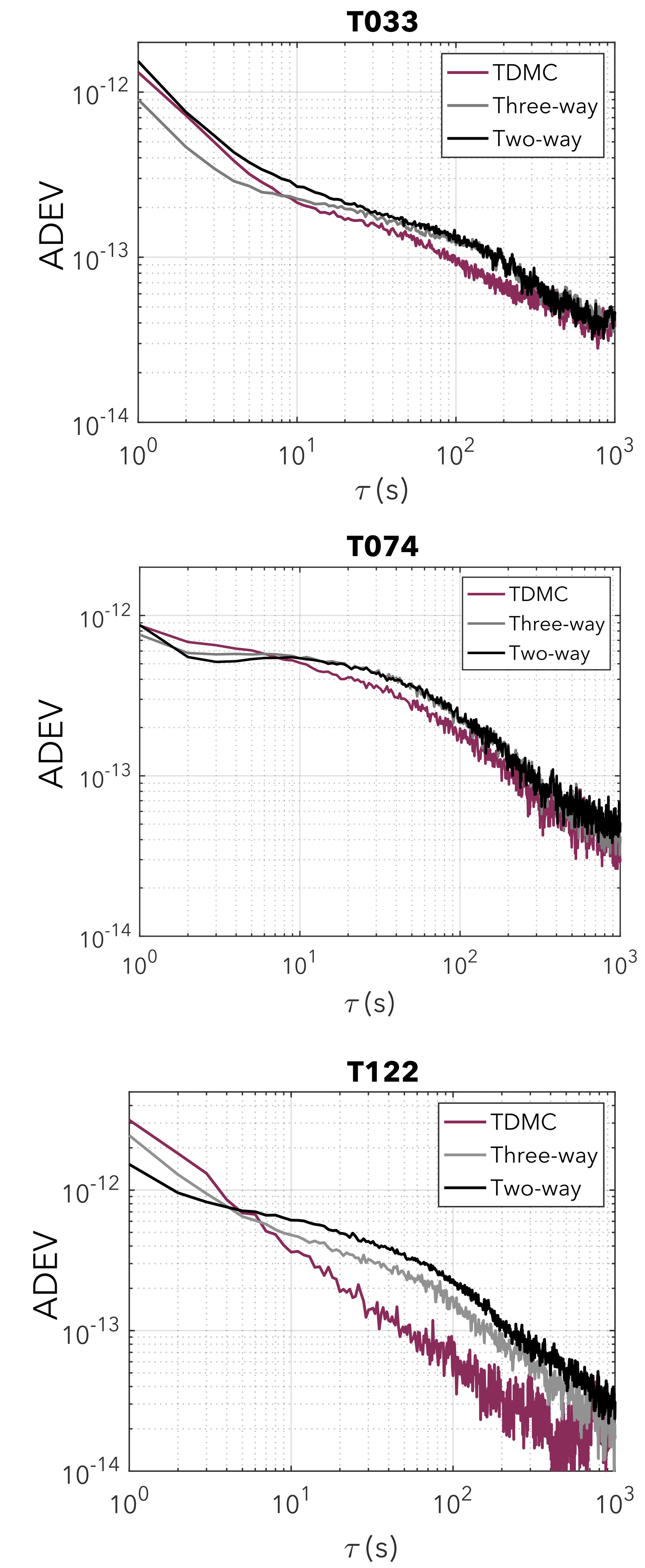


Figure 3: Autocorrelation function of two-way Doppler residuals for T122, T074 and T033. Vertical dashed lines mark the round-trip light time.



- **T033:** the TDMC reduces two-way noise for 10 s < τ < 200 s. At those time scales, the noise is likely to be dominated by troposphere and/or a large antenna mechanical noise event.
- **T074:** the TDMC cancels two-way antenna mechanical noise, while tropospheric noise is essentially unchanged as the two antennas belong to the same complex.
- **T122:** the use of the TDMC for this passage grants a factor-of-three noise reduction with respect to the two-way link at 60-s integration time. The TDMC here cancels tropospheric noise, which dominates the two-way link (the antennas are from different complexes). The noise left in the TDMC link is a combination of secondary uncorrelated noises.

Figure 4: Allan deviation of two-way, three-way and TDMC links for T033, T074 and T122.

5 Conclusions

- We showed the first example of the application of the TDMC to Cassini Doppler data. Although the tracking configuration was not tailored for the use of TDMC, we found substantial noise reduction (a factor-of-three for T122).
- The TDMC, coupled with the choice of an appropriate three-way antenna, can be used to largely improve the science return of future planetary science missions, such as BepiColombo or Juice, as shown by numerical simulations (Notaro *et al.*, 2018; Mariani *et al.*, 2018).

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Cassini Doppler and ancillary data can be found on NASA's Planetary Data System.