Improvement of BepiColombo's Radio Science Experiment Through an Innovative Doppler Noise Reduction Technique

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Abstract: The Mercury Orbiter Radio science Experiment (MORE), onboard the ESA/JAXA BepiColombo mission to Mercury, is designed to estimate Mercury's gravity field, its rotational state, and to perform tests of relativistic gravity. The state-of-the-art onboard and ground instrumentations involved in the MORE experiment will enable to establish simultaneous X/X, X/Ka and Ka/Ka-band links, providing a range rate accuracy of 3 μm/s (at 1 000 s integration time) and a range accuracy of 20 cm. The purpose of this work is to show the improvement achieved on MORE's performance by means of the Time-Delay Mechanical Noise Cancellation (TDMC) technique. The TDMC consists in a combination of Doppler measurements collected (at different times) at the two-way antenna and at an additional, smaller and stiffer, receive-only antenna located in a site with favorable tropospheric conditions. This configuration could reduce the leading noises in a Ka-band two-way link, such as those caused by troposphere and ground antenna mechanical vibrations. The results of end-to-end simulations and estimation of Mercury's gravity field and rotational state considering the TDMC technique are presented. The results for a two-way link from NASA's DSS-25 (in Goldstone, CA) or from ESA's DSA-3 (in Malargue, Argentina) are compared, while the APEX is assumed as the receive-only antenna. It shows that in best-case noise conditions, the TDMC technique allows to obtain a factor-of-two accuracy gain on both global and local parameters, considering DSA-3 as a two-way antenna. Such improvement in the scientific objectives of MORE is of geophysical interest as it could provide a constraint on the interior structure of Mercury.

Key words: Mercury; BepiColombo; Mercury Orbiter Radio science Experiment; Doppler; Time-Delay Mechanical Noise Cancellation

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0 Introduction

Radio science investigations for planetary geodesy and for tests of general relativity are based on precision radio tracking by means of range and range rate measurements, which are used to reconstruct the spacecraft orbit and the geophysical parameters of interest. Over the years, these measurements have become more and more demanding in order to allow estimating larger sets of parameters with increasingly high accuracy. In this sense, the upcoming BepiColombo mission to Mercury, jointly developed by the European Space Agency (ESA) and the Japanese Space Exploration Agency (JAXA), will set a new standard. The dual-spacecraft BepiColombo mission is scheduled for launch in October 2018, and will arrive in Mercury in December 2025. One of the two spacecraft, the Mercury Planetary Orbiter (MPO), will be devoted to the study of the internal structure of Mercury and its surface geology and, amongst other instruments, it will host the Mercury Orbiter Radio science Experiment (MORE). The MPO orbit will be nearly polar with pericenter at 480 km and apocenter at 1 500 km.

MORE consists of a ground- and space-based radio tracking system that exploits highly-stable, multi-

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frequency radio links in X and Ka bands. The key onboard element is represented by the Ka-band Translator (KaT) that, along with the onboard Deep Space Transponder (DST) and the sophisticated ground equipment, enables simultaneous two-way links in X/X (7.2 GHz uplink/8.4 GHz downlink), X/Ka (7.2/32.5 GHz) and Ka/Ka band (34/32.5 GHz), providing plasma-free range rate accuracies of 3 μm/s (at 1 000 s integration time) at nearly all elongation angles[1-2]. Range observables, accurate to 20 cm (two-way), will be attained using a novel, wideband (24 Mcps) ranging system, based on a pseudo-noise modulation scheme. The quite large non-gravitational accelerations at Mercury, about 10^{-6} m/s^2, will be removed to a large extent using the accelerometer data provided by the Italian Spring Accelerometer (ISA)[3]. The state-of-the-art technologies employed in the experiment make MORE the most advanced radio system ever flown in space.

MORE is designed to estimate the gravity field and the tidal deformation of Mercury, its rotational state, and to perform a wide set of relativistic gravity tests[4-5]. The experiment performance depends on the noise in the Doppler and ranging measurements, thus on the noise level on the radio link. Although the technological progress in the last decade has allowed to reduce noise, a strong limitation in the Doppler performance comes from the ground antenna mechanical noise and from the tropospheric noise. Antenna mechanical noise refers to unmodeled motions of the parabolic dish and its supporting structure caused by gravitational loads, differential thermal expansion and wind gusts. These large disturbances are due to the limited mechanical stability of the large, moving structures used for deep-space tracking. Tropospheric noise is caused by fluctuations of the water vapor content along the propagation path of the signal in the lower layers of the atmosphere. Calibration systems have been implemented for this disturbance, however they successfully operate only at Doppler integration times longer than 100 seconds, much longer than those required by MORE to sample Mercury's high-order gravity field.

A novel tracking technique, called Time-Delay Mechanical Noise Cancellation (TDMC), has been proposed by Armstrong et al.[6], with the aim of reducing leading noise sources in precision Doppler measurements. The technique relies on the use of simultaneous two-way and three-way Doppler data, combined to form a new observable. Armstrong et al.[6] showed that if the three-way antenna is small and stiff and it is located in a site with favorable tropospheric conditions, the TDMC can reduce mechanical and tropospheric noises in the two-way link.

The technique has been successfully demonstrated using two similar antennas. Furthermore, Notaro et al.[7] simulated Doppler noise for the BepiColombo mission profile considering a suitable three-way antenna and showed that the TDMC is most effective for reducing noise at short Doppler integration times (< 100 s), where tropospheric noise cannot be calibrated.

In this paper, we aim to start from the noise models in Ref. [7] for a full measurement simulation and parameter estimation analysis. Then, we evaluate the performance of the TDMC on the accuracy of the estimated parameters by comparing the results with the reference two-way link. The work is organized as follows：Section 1 characterizes the main disturbances in two-way Doppler links and provides the mathematical treatment for the Time-Delay Mechanical Noise Cancellation technique. Section 2 introduces the orbit determination method and summarizes the simulation scenario. The results of the simulations are presented and discussed in Section 3, followed by the conclusions in Section 4.

1 Time-Delay Mechanical Noise Cancellation(TDMC)

Path delays arising when the signal propagates through dispersive media such as Earth ionosphere and interplanetary plasma, among the leading noise sources in two-way Doppler links, can be suppressed by increasing the carrier frequency and the Sun-Earth-Probe (SEP) angle or by using multi-frequency links[8-9]. Tropospheric noise, instead, is caused by refractive index variations as the signal travels through Earth's troposphere. The tropospheric path delay h_T can be defined by integrating the refractive index n along the line of sight of the antenna up to the maximum height of the troposphere h^*[10-11]

$$h_T = \int_0^{h^*} (n-1)\,\mathrm{d}h \tag{1}$$

A main portion of the total path delay (about 90%) comes from dry gases in the atmosphere; however, this delay depends only on the atmospheric pressure at the antenna and thus can be estimated and calibrated down to

1 mm accuracy[11]. Although water vapor fluctuations in the line-of-sight of the antenna account for only 10% of the total path delay, they are the most important cause of tropospheric noise due to their unpredictability. However, this wet path delay can be partially calibrated using water vapor radiometers.

Prior to BepiColombo, multi-frequency links (X/X, X/Ka and Ka/Ka) and water vapor radiometers were used for the first time in order to delete plasma noise and reduce tropospheric noise on Doppler measurements collected with the Cassini spacecraft during the gravitational wave experiment[12]. The Allan deviation (a common measure of link frequency stability) of the two-way link's Doppler residuals was about 3×10^{-15} at 1 000 s, corresponding to less than 1 μm/s accuracy in the spacecraft radial velocity[9]. Cassini's Doppler accuracy was limited by ground antenna mechanical noise and residual tropospheric noise, both difficult to decrease because of the large moving antenna structures involved in the Doppler measurement and due to the intrinsic unpredictability of water vapor fluctuations. Reducing those noises becomes particularly cumbersome at short integration times (< 100 s), where water vapor radiometers cannot work efficiently due to thermal noise.

Following these considerations, Armstrong et al.[6] introduced an innovative Doppler tracking technique, the TDMC, which involves the use of simultaneous two-way and three-way Doppler links. In a two-way Doppler link, local noises at the two-way antenna (for example mechanical M_2 and tropospheric T_2 noises) are correlated at the Round-Trip Light Time (RTLT) T so that the two-way link's time series is (see the schematic in Fig. 1).

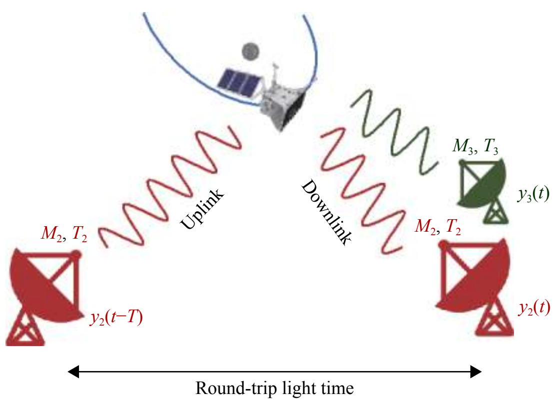

Fig. 1　Simplified schematic of two-way and three-way links for BepiColombo. Two-way antenna and two-way link signals are represented in red, while three-way antenna and three-way downlink are drawn in green. Only antenna mechanical noise M and tropospheric noise T are represented for simplicity.

$$y_2(t) = M_2(t) + M_2(t-T) + T_2(t) + T_2(t-T) + y_s(t) \quad (2)$$

In a three-way Doppler link, instead, the uplink and downlink legs are uncorrelated

$$y_3(t) = M_3(t) + M_2(t-T) + T_3(t) + T_2(t-T) + y_s(t) \quad (3)$$

In Equations (2) and (3), $M(t)$, $T(t)$ are the mechanical and tropospheric noise time series of fractional frequency fluctuations ($y = \Delta f/f_0$), whilst $y_s(t)$ is the Doppler signal corrected for antenna location and Earth motion. It can be shown that the TDMC observable, defined as follows[6]

$$y_{\mathrm{TDMC}}(t) = y_3(t) + y_3(t-T) - y_2(t-T) \quad (4)$$

Equation (4) contains the uplink and downlink mechanical and tropospheric noise contributions at the three-way antenna, as well as the two-way link's signal content. Consequently, if the three-way antenna is stiff and it is located in a dry site (where water vapor fluctuations account for only a small fraction of the total tropospheric noise) this operation could lead to order-of-magnitude reductions in Doppler noise, while still maintaining an adequate level of SNR (granted by the larger two-way antenna).

The choice of the three-way antenna is fundamental for achieving best results. In addition to the abovementioned characteristics, the optimal listen-only antenna should include at least a cryogenic Ka-band receiver and a high-stability frequency standard to minimize secondary noises, that are slightly increased as a result of Equation (4). The most suitable candidate is the 12-m Atacama Pathfinder Experiment (APEX) radio-astronomy antenna in Chajnantor (Chile). Previous studies show that the mechanical and tropospheric noises at APEX are about one order of magnitude lower than the ones at the reference NASA two-way antenna DSS-25[7].

2　End-To-End Simulation

We simulated two-way and three-way Doppler data over the MPO 1-year nominal mission around Mercury considering, as two-way antennas, either NASA DSS-25 or ESA DSA-3 (currently the only ESA station with Ka-band uplink capability), and APEX as three-way antenna. We accounted for station visibility and operational constraints due to the pointing of the moveable onboard High Gain Antenna (HGA). We also simulated and included ISA acceleration measurements that allow to recover the MPO orbit[4-5]. Since the accelerometer error is composed by a random noise and systematic errors, we included the accelerometer calibration parameters in the solve-for parameters in order to evaluate a realistic achievable accuracy through the Orbit Determination (OD) process. The main accelerometer systematic errors can be calibrated by estimating a daily bias and bias-rate, and the amplitude of the periodic error at MPO orbital period.

The data were processed in 24 h long batches using the JPL MONTE code and an in-house developed software to integrate the trajectory and carry out the orbital fit. The mathematical formulation is based on Ref. [13]. The a priori Mercury's gravity field and tidal Love number k_2 were taken by the HgM005 solution derived from MESSENGER radio data[14]. The assumed Mercury's orientation parameters are based on Margot's recommended model, which includes the librations in longitude[15]. The parameters of interest were estimated applying a multi-arc method by means of square root information, weighted, least-squares filter[16]. The global solve-for parameters are the gravity field in spherical harmonic coefficients to degree and order 30, the pole orientation, the amplitude of the libration in longitude and the amplitude of ISA periodic error at MPO orbital period. The local solve-for parameters are the spacecraft position, the velocity, the ISA bias and its drift.

We generated non-white noise from the Power Spectral Density (PSD) of the single noise sources composing the two-way and three-way links. We reconstructed the frequency-domain signal using uniformly distributed random phases, and then we retrieved the noise time series through a Fast Fourier Transform (FFT) algorithm[7, 17]. Finally, we computed the total two-way and three-way noise using Equations (2) and (3), with T provided by the light time solution.

For what concerns ground segment noises, we included tropospheric noise, antenna mechanical noise, frequency standard and receiver thermal noises for each of the three antennas. Since tropospheric noise is extremely variable depending on season and observation time, we only accounted for best- and worst-case winter and summer day and night conditions, using models and statistical data in literatures[18-20]. In addition, we used radiometer data from APEX's weather station website to estimate the tropospheric wet path delay through Equation (1).

We did not consider any wet tropospheric calibration at either of the antennas, since we evaluated the results at short Doppler integration time (10 s). Furthermore, we assumed the same frequency behavior for the mechanical noise model of DSS-25, DSA-3 and APEX, although for the latter we scaled the model amplitude according to the lower mechanical noise of the stiffer antenna[21]. Lastly, for what concerns the frequency reference, we considered a Cryo-cooled Sapphire Oscillator (CSO) at DSS-25, and a Hydrogen maser at both DSA-3 and APEX[22-23].

The MORE experiment on BepiColombo will involve the use of the multi-frequency link technique to suppress plasma and ionospheric noises. Thus, we included the Deep Space Transponder (DST) (X/X, X/Ka links) and the Ka-band Translator (KaT) (Ka/Ka link) on the spacecraft noise model. We computed the plasma-free, non-dispersive correlated Doppler observable as a linear combination of the three radio links[8].

$$y_{PF}(t) = y_{KK}(t) + \frac{1}{13} y_{XX}(t) + \frac{1}{35} y_{XK}(t) \tag{5}$$

We assumed the other noises as uncorrelated over the three links. The multi-frequency link allowed us to neglect plasma and ionospheric noises in this study. We also included the Radio-Frequency Distribution Assembly (RFDA) and HGA disturbances in the spacecraft noise model. In particular, the HGA mechanical noise, caused by large thermal dilations during the orbit, is a dominant player in the end-to-end error budget of the experiment. Notaro et al.[7] has shown that since disturbances coming from the onboard HGA are uncorrelated, they are actually a limit to the accuracy gain attainable with the TDMC technique on the MORE experiment. The worst-case HGA disturbance is 1.32×10^{-14} (at 1 000 s integration time). Since HGA noise is not easily predictable, we used three different noise levels：100% (corresponding to the worst case), 50% and 25%.

3 Results and Discussion

Since the aim of this work is to assess how the TDMC can improve the experiment performance, we report the results in terms of covariance analysis. The results are summarized in Table 1 for the two alternative tracking configurations (DSS-25/APEX and DSA-3/APEX). The table shows the accuracy improvement in terms of the gain factor $\sigma_{2way}/\sigma_{TDMC}$, where σ_{2way} is the

Table 1　Formal uncertainty and gain factor for selected global parameters considering the nominal two-way tracking configuration（DSS-25 or DSA-3）and the TDMC link, the results are shown assuming 100%，50% or 25% HGA noise level.

Goldstone（Two-way：DSS-25，Three-way：DSS-25/APEX）				
HGA Noise level	Parameter	Gain Factor（$\sigma_{2way}/\sigma_{TDMC}$）	Formal Unc.（Two-way）	Formal Unc.（TDMC）
Global parameters				
100%		1.30	3.28×10^{-4}	2.56×10^{-4}
50%	*GM*/（km³·s⁻²）	1.37	3.02×10^{-4}	2.21×10^{-4}
25%		1.42	2.96×10^{-4}	2.08×10^{-4}
100%		1.31	8.39×10^{-11}	6.42×10^{-11}
50%	J_2	1.49	7.61×10^{-11}	5.11×10^{-11}
25%		1.60	7.37×10^{-11}	4.62×10^{-11}
100%		1.40	5.86×10^{-4}	4.19×10^{-4}
50%	k_2	1.60	5.37×10^{-4}	3.36×10^{-4}
25%		1.70	5.22×10^{-4}	3.06×10^{-4}
100%		1.46	0.66	0.46
50%	*RA* [arcsec]	1.70	0.61	0.36
25%		1.83	0.59	0.32
100%		1.37	0.22	0.16
50%	*DEC* [arcsec]	1.57	0.20	0.13
25%		1.67	0.19	0.11
100%		1.31	0.37	0.28
50%	*LIB* [arcsec]	1.43	0.34	0.23
25%		1.51	0.32	0.22
Malargüe（Two-way：DSA-3，Three-way：DSA-3/APEX）				
Global parameters				
100%		1.43	3.50×10^{-4}	2.45×10^{-4}
50%	*GM*/（km³·s⁻²）	1.59	3.27×10^{-4}	2.05×10^{-4}
25%		1.65	3.20×10^{-4}	1.94×10^{-4}
100%		1.49	8.13×10^{-11}	5.46×10^{-11}
50%	J_2	1.74	7.43×10^{-11}	4.28×10^{-11}
25%		1.88	7.22×10^{-11}	3.84×10^{-11}
100%		1.47	5.70×10^{-4}	3.87×10^{-4}
50%	k_2	1.71	5.21×10^{-4}	3.04×10^{-4}
25%		1.84	5.05×10^{-4}	2.74×10^{-4}
100%		1.48	0.58	0.39
50%	*RA* [arcsec]	1.78	0.53	0.29
25%		1.96	0.51	0.26
100%		1.47	0.20	0.14
50%	*DEC* [arcsec]	1.73	0.18	0.11
25%		1.87	0.18	0.10
100%		1.52	0.38	0.25
50%	*LIB* [arcsec]	1.75	0.35	0.20
25%		1.88	0.34	0.18

formal uncertainty considering only the two-way link and σ_{TDMC} refers to the case where the TDMC technique is applied. The results are shown for each of the three assumed HGA noise levels. In the table, we only show results for selected global parameters：Mercury's GM, J_2, the Love number k_2, the pole Right Ascension (RA) and Declination (DEC), and the 88-day amplitude of Mercury's libration in longitude (LIB).

In the worst-case scenario, corresponding to 100% HGA noise level, the gain factor attainable with TDMC for the DSS-25/APEX combination is 1.3, 1.4 and 1.4, respectively, on Mercury's GM, J_2 and k_2. For the DSA-3/APEX combination, the gain factor on the global parameters is slightly higher, ranging from 1.43 for the GM to 1.49 for the J_2. When the HGA noise level is calibrated to 25%, instead, the gain factors on the global parameters increase to 1.42 for the GM, 1.6 for the J_2 and 1.7 for the k_2 for the DSS-25/APEX combination. In these best-case noise conditions, the DSA-3/APEX antennas allow to achieve a gain factor as high as 1.88 on J_2. Large improvements for the DSA-3/APEX combination in best-case HGA noise conditions are also achieved in the estimation of Mercury's rotational state, with gain factors of about 2 on RA, DEC and LIB.

Figure 2 shows the power spectrum of the simulated gravity field (HgM005) defined by

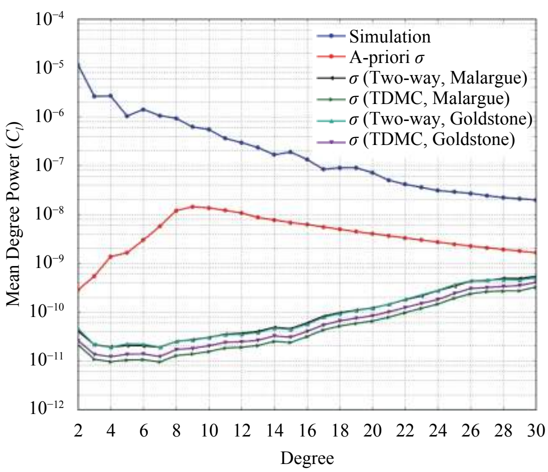

Fig. 2　RMS power of gravity of the simulated HgM005 gravity field (blue), its a priori uncertainty (red), and the associated formal uncertainties obtained through the OD process for the reference two-way link from DSS-25 (Goldstone, cyan) and DSA-3 (Malargüe, black). Green and magenta curves refer respectively to the DSA-3/APEX and DSS-25/APEX TDMC combinations.

$$C_l = \sqrt{\frac{1}{2l+1}\sum_m \left(C_{lm}^2 + S_{lm}^2\right)} \tag{6}$$

where l is the degree and m is the order of the spherical harmonic expansion. The figure also shows the gravity field a priori uncertainty and the formal uncertainties obtained through the OD process for the reference two-way link and for the TDMC configuration, considering either DSS-25 or DSA-3 as two-way antennas and assuming the best-case HGA noise level (25%). As shown in Fig. 2, the TDMC gain factor is almost constant for each degree of Mercury's gravity field; the value is higher for the DSA-3/APEX combination with respect to DSS-25/APEX.

The gain achievable with TDMC on the local parameters is reported in Figure 3 and Figure 4, which show the formal uncertainty on the MPO position expressed in the Mercury-centered Radial-Transverse-Normal (RTN) frame in best-case conditions, assuming HGA noise calibration to 25%. More precisely, Figure 3 compares results for the reference DSS-25 two-way link (orange) with the TDMC link from DSS-25/APEX (cyan), while Figure 4 refers to the DSA-3 and APEX antennas. Both plots report the gain factor obtained after applying the TDMC technique (green curves).

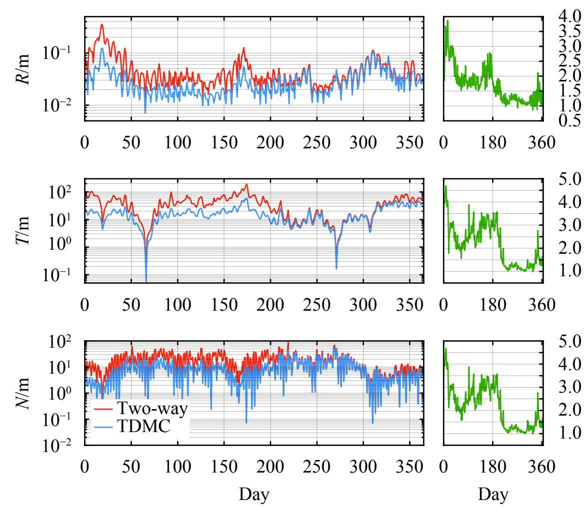

Fig. 3　Left: formal uncertainties for MPO position in Mercury-centered RTN frame considering two-way link from DSS-25 (orange) and DSS-25/APEX TDMC configuration (cyan). Right: gain factor. HGA mechanical noise is calibrated to 25%. For both figures: the radial component is reported at the top, the transversal component in the middle, and the normal component at the bottom.

Since local parameters are pertinent to each arc, their formal uncertainty is most affected by the simulated tropospheric noise at the ground stations, that accounts for both diurnal and seasonal variability. This effect is particularly visible in Figure 3. DSS-25 and APEX are located, respectively, in the northern and southern hemispheres; thus, when tropospheric noise is highest at DSS-25 (during the summer months), it is correspondingly lowest at APEX, and vice versa. Consequently, the gain factor on the RTN components is higher than 2 in the first 180 days (that span from March to October 2026); when tropospheric noise reaches seasonal lows at DSS-25, the gain factor decreases sharply to about 1-1.2 (see rightmost part of the green plots). Conversely, DSA-3 and APEX are located in the same hemisphere; therefore, the gain factor on the RTN components for the DSA-3/APEX combination oscillates around a mean of ～1.8 over the course of the 1-year mission (see green plots in Fig. 4).

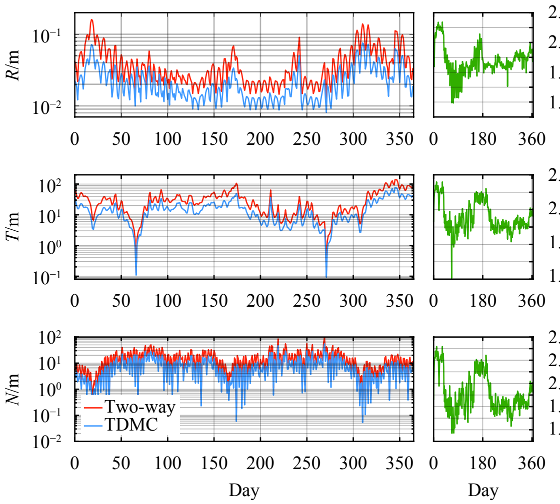

Fig. 4　Left: formal uncertainties for MPO position in Mercury-centered RTN frame considering two-way link from DSA-3 (orange) and DSA-3/APEX TDMC configuration (cyan). Right: gain factor. HGA mechanical noise is calibrated to 25%. For both figures: the radial component is reported at the top, the transversal component in the middle, and the normal component at the bottom.

In the worst-case scenario(corresponding to 100% HGA noise level), the gain factors on the spacecraft RTN position reach maximum values of about 1.3 and 1.4, respectively, for the DSS-25/APEX and DSA-3/APEX combinations.

The differences between the best- and worst-case gain factors (for both the two-way antennas) are driven by HGA noise, a dominant player in BepiColombo's simulated noise, that cannot be canceled by the TDMC technique. Thus, as reported in Table 1, a reduction in HGA noise improves the accuracy gain attainable with TDMC.

Table 1 also indicates that the gain factors on the global parameters are higher for the DSA-3/APEX configuration with respect to DSS-25/APEX. This is related to differences in common visibility times of the two-way/three-way antenna configurations. The small longitudinal separation between DSA-3 and APEX (～2°, as opposed to ～49° for DSS-25/APEX) allows more Doppler data to be used for the TDMC technique. In particular, about 98% of the total Doppler data are used for the TDMC on a typical passage, against 64% for the DSS-25/APEX configuration.

The results in this paper agree with a previous study aimed at evaluating the TDMC accuracy gain using Doppler noise simulations[7]. Notaro et al.[7] found that the gain factor for the DSS-25/APEX configuration is about 2, in accordance with the right plots in Figure 3.

4　Conclusions

In this paper, we presented the results of numerical simulations for the BepiColombo radio science experiment carried out exploiting the TDMC technique. The adopted noise models include the tropospheric scintillation at the interested sites, G/S antenna mechanical noise, frequency standard and receiver thermal noises plus the noises coming from the onboard HGA, RFDA and KaT. We also considered calibration of dispersive noise through the multi-frequency link.

The results show that the biggest limitation in the application of TDMC to BepiColombo is the uncorrelated noise coming from the HGA, which can not be canceled by the proposed technique.

However, we found that if the HGA noise is calibrated to 25%, the TDMC provides a gain factor of about 2 on the formal uncertainty of the global parameters in the case of DSA-3 as reference two-way antenna. The same gain can be obtained with the two-year extended mission.

TDMC could provide a significant accuracy enhancement over the nominal two-way tracking configuration when the main noises in the radio link are the two-way antenna's tropospheric and mechanical noises. These precision Doppler tracking conditions can be achieved using multi-frequency links to cancel plasma noise and calibrating secondary disturbances such as the one coming from the onboard HGA. This technique is especially effective at short integration times (< 100 s), where water vapor radiometers cannot calibrate tropospheric noise.

Another result is that the TDMC gain is maximized if the three-way antenna is close in longitude to the two-way one. Since ESA DSA-3 is longitudinally closer to APEX, we obtained a higher TDMC gain using the DSA-3/APEX combination with respect to NASA DSS-25.

Thanks to Ka-band and multilink radio tracking of BepiColombo, complemented by measurements of the ISA accelerometer, BepiColombo will provide a global determination of Mercury's gravity field exceeding the science requirements of the mission. The use of the TDMC technique will allow to achieve a factor-of-two accuracy gain on the determination of Mercury's gravity field and rotational state. With the TDMC, MORE can reach an accuracy of 0.2 arcsec on the amplitude of the 88-day libration in longitude and about 3×10^{-4} on the Love number k_2, thus the experiment can provide an independent constraint to further discriminate among models of the interior of Mercury.

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一种新型多普勒噪声抑制技术对BepiColombo任务无线电科学实验的性能提升

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摘　要： 在欧洲空间局和日本宇宙开发机构联合开展的BepiColombo水星任务中，将开展水星轨道器无线电科学实验，包括估计水星的引力场及其旋转状态，并对广义相对论进行验证。目前地面系统和星上设备的主流配置可以在无线电科学实验中建立X/X、X/Ka和Ka/Ka多个频段的链路，测速精度可达3 um/s（1 000 s积分），测距精度为20 cm。提出了基于时延机械噪声对消技术提高无线电科学实验性能的方案。时延机械噪声对消技术需要处理在两个测站不同时刻的测量数据，一个测站实施双向多普勒测距，对另一个单收测站的要求较为严格，该测站需要具有较好的对流层条件。这种方法能够显著降低Ka频段双向链路的主要测量噪声，包括由对流层和天线机械系统震动引起的噪声。我们给出了端到端的仿真性能，并估计了在使用时延机械噪声对消技术前提下的水星引力场和旋转状态。考虑使用NASA位于美国本土戈尔德斯敦的DSS-25天线或欧空局位于阿根廷马拉圭的DSA-3天线作为双程测量站，并考虑使用位于智力的APEX天文观测天线作为单收站。分析结果表明在最好的噪声条件下，使用DSA-3天线作为双程测量站时，时延机械噪声对消技术可将待估计的全局和局部参数的估计精度提升一倍。对于无线电科学实验的目标，这一可能的性能提升对行星地质物理学很有意义，它将有益于研究水星内部的结构。

关键词： 水星；BepiColombo；水星轨道器无线电科学实验；多普勒；时延机械噪声对消技术

High lights：

- Time-Delay Mechanical Noise Cancellation (TDMC) technique is proposed to improve the tracking performance in Mercury Orbiter Radio science Experiment (MORE), onboard the ESA/JAXA BepiColombo mission to Mercury.
- The results of end-to-end simulations and estimation of Mercury's gravity field and rotational state considering the TDMC technique are fully presented.
- TDMC provides a gain factor of about 2 on the formal uncertainty of the global parameters in the case of DSA-3 as reference two-way antenna, if the noise from high gain antenna (HGA) onboard the spacecraft is calibrated to 25%.

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