Report on first inflight data of BepiColombo's Mercury Orbiter Radio-science Experiment

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BepiColombo's Mercury Orbiter Radio-science Experiment (MORE) was conceived to enable extremely accurate radio tracking measurements of the Mercury Planetary Orbiter to precisely determine the gravity field and rotational state of Mercury, and to test theories of gravitation (*e. g.* Einstein's Theory of General Relativity). The design accuracy of the radio tracking data was 0.004 mm/sec (at 1000 s integration time) for range-rate measurements and 20 cm for range (at a few seconds of integration time). These accuracies are attained due to a combination of simultaneous two-way microwave links at X (7.2-8.4 GHz) and Ka-band (32-34 GHz) to calibrate the dispersive plasma noise component. In this letter, we present the first analysis of range and range-rate data collected by ESA's deep space antenna (DSA) during the initial cruise phase of BepiColombo. The novel 24 Mcps pseudo-noise (PN) modulation of the Ka-band carrier, enabled by MORE's Ka-band Transponder (KaT), built by Thales Alenia Space Italy, provided two-way range measurements to centimeter-level accuracy, with an integration time of 4.2 s at 0.29 astronomical units. In tracking passes with favorable weather conditions, range-rate measurements attained an average accuracy of 0.01 mm/s at 60 s integration time. Data from 20 to 24 May 2019 were combined in a multi-pass analysis to test the link stability on a longer timescale. The results confirm the noise level observed with the single-pass analysis and provide a preliminary indication that the MORE PN ranging system at 24 Mcps is compatible with the realization of an absolute measurement, where the need to introduce range biases in the orbital fit is much more limited than in the past. We show that in the initial cruise test the BepiColombo radio link provided range measurements of unprecedented accuracy for a planetary mission, and that, in general, all target accuracies for radio-metric measurements were exceeded.

I. INTRODUCTION

The BepiColombo mission was launched on an Ariane 5 rocket on 20 October 2018 from the Kourou European spaceport in French Guyana. It is currently in route to Mercury, where it will start its 1-year planetary orbital phase on 15 March 2026. The Mercury Composite Spacecraft (MCS) is the result of an international effort: the Mercury Planetary Orbiter (MPO) and the Mercury Transfer Module (MTM) are provided by ESA, while the Mercury Magnetospheric Orbiter (MMO), was developed by JAXA [1]. The MTM hosts the electric propulsion system that is used for BepiColombo's low-thrust interplanetary trajectory to Mercury. The MPO and MMO will be placed in two different orbits around Mercury to conduct comprehensive multidisciplinary investigations of the innermost planet of the Solar System.

The Mercury Orbiter Radio-science Experiment (MORE) is one of the eleven scientific investigations onboard the MPO. MORE will use Doppler and range measurements from ESA's European Space Tracking (ESTRACK) and NASA's Deep Space Network (DSN) ground stations to determine the gravity field, rotational state and tidal response of Mercury, and to perform a test of theories of gravitation [2]. The latter will begin during the cruise phase by exploiting the peculiar geometry of superior solar conjunctions, starting in March 2021 [3]. The core of the MORE experiment is the KaT, the onboard transponder dedicated to science which allows us to establish a two-way coherent radio link at Ka-band between a ground station and the spacecraft. The instrument's frequency stability has a specified Allan deviation (ADEV) of 10^{-15} at 1000-s integration time and was tested on the ground at $4 \cdot 10^{-16}$ [4]. The KaT will operate in synergy with the Deep Space Transponder (DST), also onboard MPO, which enables two-way coherent radio links at X/X and X/Ka bands (one uplink at X-band coherent with two downlinks at X- and Ka-band). The multifrequency link will be used during solar conjunctions to calibrate path delay fluctuations induced on the signal's phase by solar plasma, especially at low values of Sun-Probe-Earth (SPE) angle [5]. The pre-launch expected accuracy of range-rate measurements with the multifrequency link was 0.004 mm/s at 1000-s integration time. The KaT enables also range measurements with a 24 Mcps pseudo-noise modulation of the Ka-band [6]. This technology constitutes the real novelty of the MORE radio tracking system and was expected to attain an accuracy of 20 cm after a few seconds of integration time in the Hermean phase. The higher chip rate (therefore the higher frequency of the clock component of the code) strongly reduces multipath effects and the ensuing biases in ranging measurements.

We report on the analysis of the first MORE's inflight data collected during a test campaign executed in May 2019. First,

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we performed a single-pass fit to assess the performance of the link. Subsequently, we performed a multi-pass analysis to assess the stability of the tracking system on a 5-day timescale.

II. TEST CAMPAIGN

The MORE test campaign in May 2019 includes thirteen two-way radio tracking passes from the ESA's ESTRACK DSA-3 station located in Malargüe, Argentina, and four from NASA's DSN DSS-25, located in Goldstone, California, USA. DSS-25 also performed eight listen-only passes (3-way, i. e. uplink from DSA-3 and downlink to DSS-25) during the overlapping visibility time with DSA-3. Another test campaign, with uplink from DSS-25, was performed in August 2019 and demonstrated NASA's capability to establish simultaneous links at X/X and Ka/Ka band with the spacecraft (DSN results will be presented in a future report).

Here, we will report on the results of the May test campaign for DSA-3 only. The test was executed without imposing constraints on the scheduled operations. The average Earth-BepiColombo distance was ~ 0.29 AU and the Sun-BepiColombo distance was ~ 1.15 AU. The spacecraft was approaching solar opposition, which occurred in July 2019.

III. DATA ANALYSIS SETUP

The data analysis is based on a precise orbit determination (OD) process [7], implemented in the JPL's MONTE code [8]. A dynamical model of BepiColombo's trajectory is used to propagate its motion and compute the radio-tracking observations, which are then fitted with a least-squares filter to estimate selected model parameters. For the purpose of a multi-pass analysis, the dynamical model must accurately describe the spacecraft motion for the entire timespan of the data included in the solution. The main non-gravitational acceleration acting on the spacecraft during interplanetary cruise is the solar radiation pressure. Furthermore, the spacecraft is rotated around the axis that points to the Sun approximately every 12 hours in order to reduce the number of wheel off-loading (WOL) maneuvers. The unbalanced thrusters induce uncompensated ΔVs with poorly known magnitudes and directions. Therefore, these parameters are estimated in our orbit determination solutions. During this test campaign, a total of 26 WOL were executed, 18 of which concentrated from 12 to 19 of May 2019. The spacecraft composite shape was simplified to a bus with a cross sectional area of 18 m^2 covered in Multi-Layer Insulation (MLI), plus the MTM solar panels with a total area of 42 m^2. The thermo-optical properties of the MLI and of the MTM solar panels are initialized with the reference values measured on ground and adjusted as part of fitting process. Other surfaces, e.g. magnetometer boom and onboard antenna, are neglected in this analysis, since they have a marginal contribution to the overall solar radiation acceleration. The MPO solar panel was also not accounted for in our analysis since it was kept edge-on to the Sun. The spacecraft attitude and first-guess trajectory are based on the official mission kernels [9].

The list of estimated parameters for both the single-pass and multi-pass analysis includes:

- the spacecraft state (position and velocity) with respect to the Sun,
- the thermo-optical properties of the solar panels and the bus,
- a range bias, accounting for errors in the calibration of the station and of the transponder delay,
- the three components of residual ΔV due to WOL maneuvers (when needed).

We first carried out a fit of Doppler and PN range data with the Ka/Ka link for each individual pass presented in Table 1. After the fit, the root-mean-square (RMS) value of the Doppler and range residuals (observed minus computed) is indicative of the noise in the link. We validated the observed noise level by merging data from the 20-24 May period in a multi-pass fit (see Section IV). We used only Ka/Ka Doppler and range data, i. e. the multi-frequency noise reduction technique was not applied, since the spacecraft was close to solar opposition that is characterized by negligible solar plasma effects [10]. We calibrated the tropospheric path delay using the Global Navigation Satellite System (GNSS) seasonal and daily calibrations. Ionospheric calibrations were unavailable.

The expected accuracy on the Doppler at 60 s integration time is 0.017 mm/s [2]. A detailed error budget for the novel PN ranging at 24 Mcps, based on the Consultative Committee for Space Data Systems (CCSDS) guidelines [11], provides an expected accuracy on ranging at the centimeter level:

$$\sigma_{CL\_sine\_sine} = \frac{c}{4\pi \cdot f_{RC}} \sqrt{B_{l\_G/S} \cdot \left(\frac{N_{0\_KaT}}{P_{RC\_KaT}} + \frac{N_{0\_G/S}}{P_{RC\_G/S}} \right)} \quad (1)$$

Where c is the speed of light, f_{RC} is the ranging clock (RC) frequency, $B_{l\_G/S}$ is the one-sided bandwidth of the ground receiver, $\frac{P_{RC\_KaT}}{N_{0\_KaT}}$ and $\frac{P_{RC\_G/S}}{N_{0\_G/S}}$ are the RC component signal to noise spectral density in the KaT and in the ground station (G/S) receiver, respectively. This formula derived for thermal noise, does not account for other effects, such as time-varying range biases, which were included at conservative levels in the pre-launch error budget.

The total two-way range bias between BepiColombo and DSA-3 is ~ 525 m. This value can be split in different contributions: the station delay, the delay due to the Radio Frequency Distribution Assembly (RFDA) onboard the spacecraft, the

TABLE I
MEASUREMENT ACCURACY OF MORE RADIO LINK IN KA-BAND. DOPPLER RESIDUALS ARE AT 60 S INTEGRATION TIME, RANGE RESIDUAL AT 4 S.

Date 2019 May	Doppler RMS (@60 s)	PN Range 24 Mcps RMS (@4 s)
2	0.048 mm/s	25.4 mm
8	0.040 mm/s	8.0 mm
14	0.006 mm/s	8.0 mm
15	0.007 mm/s	N. A.
16	0.016 mm/s	8 mm
17	0.030 mm/s	9 mm
20	0.038 mm/s	12.9 mm
21	0.008 mm/s	20.0 mm
22	0.005 mm/s	N. A.
23	0.007 mm/s	7.5 mm
24	0.014 mm/s	7.8 mm
29	0.016 mm/s	7.7 mm

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KaT and the physical path. The station delay from the ground transmitter to the antenna aperture and back is approximately 1 μs. It is measured through an internal loop before every tracking pass and is included in the orbital fit. The onboard RFDA, measured from ground tests, contributes for ∼ 20 ns. During the test this value, although only approximately known, could be assumed as constant. The KaT internal delay is ∼ 728 ns, obtained thanks to the internal self-calibration loop of the instrument. The KaT delay was measured before and after every pass. A total of 21 measurements were collected, resulting in a stable KaT internal delay of 719.32 ns with a standard deviation of 0.013 ns. We used the value of ∼ 728 ns because tests on the ground showed a constant offset of ∼ 9 ns between the self-calibration loop and the test equipment measurements.

IV. RESULTS

The analysis of the single tracking passes provided an average performance on the Doppler measurements in good agreement with the predictions for most passes (see Table 1). Regarding the novel PN range at 24 Mcps, the accuracy reached the unprecedented level of ~1 cm in most of the cases. Both Doppler and range residuals exhibited a higher noise in some passes. This excess noise could be traced to unfavorable weather conditions at the station (especially high winds, leading to a larger antenna mechanical noise). In terms of ADEV, eight out of the twelve passes were below the required performance of $1.4\ 10^{-14}$ at 1000 s, while four were above this threshold. Fig. 1 collects the Allan deviations for each of the aforementioned passes. Remarkably, such low Allan deviations were obtained without the accurate water vapor calibrations used in the Cassini and Juno Ka band radio science experiments [10], not yet available at the DSA-3 station.

Most curves show a clear feature in correspondence of the round-trip light time (RTLT ∼ 270-330 s). The feature of the ADEV at the RTLT corresponds to a $\cos^2$ frequency modulation of the signal's spectrum which is due to local noises affecting both uplink and downlink signals. This is an indication that a correlated noise was dominant at the two-way antenna, likely a combination of path delay variations due to turbulence in the Earth's troposphere, or due to wind-induced buffeting of the antenna dish [12]. Indeed, as expected, the autocorrelation function of the residuals shows a marked peak at a RTLT, as reported in Fig 2.

A multi-pass analysis was performed to verify if the novel ranging technique can provide an absolute measurement.

The dataset from 20 to 24 May 2019 was selected since it contains 5 adjacent passes for Doppler and 4 for PN range. On 22 May, ranging measurements in Ka-band were not collected. This dataset was selected because during this period the spacecraft performed only two wheel off-loading maneuvers. WOL1 occurred on 22 May 2019 at 01:47:56 UTC and WOL2 on 23 May 2019 at 03:04:45 UTC.

Only one range bias was estimated for the 5-day fit (Fig. 3). This orbital solution is compatible with the realization of an absolute time of flight measurement, which has never been obtained with radio tracking techniques routinely used before BepiColombo or other planetary spacecrafts. With previous ranging technologies, such as sequential ranging at X-band, orbital fits including range measurements were always obtained by estimating a different range bias at every pass, with a scatter of tens of centimeters due to errors in the station calibration and multi-path effect on the X-band carrier [13]. We obtained similar results for the orbital fit of BepiColombo multi-pass case by processing X-band data only. The estimation of a single range measurement bias over the 5-days arc is not well-suited to adequately fit BepiColombo's range data collected with the X/X link only.

Fig. 3 shows Doppler (left) and range (right) residuals of the Ka/Ka radio link. The RMS of the Doppler residuals at 60 s integration time is perfectly in line with the single-pass analysis (see Table 1) and the expected performance. The RMS value of range residuals also confirms the single-pass results, with an unprecedented accuracy at interplanetary distances of 1.5 cm over 4 passes at an integration time of 4.2 s. The pass on 20 May was affected for half of the time by strong winds, and during the pass on 21 May snow was detected at the station. Hence, this already noteworthy achievement could be improved in more favorable weather conditions. We highlight that these results are based on a limited dataset, and thus have to be considered as a preliminary indication. Further analysis on a longer timescale (possibly without the presence of maneuvers) is necessary to convincingly demonstrate that the use of range biases in the OD process can be drastically reduced.

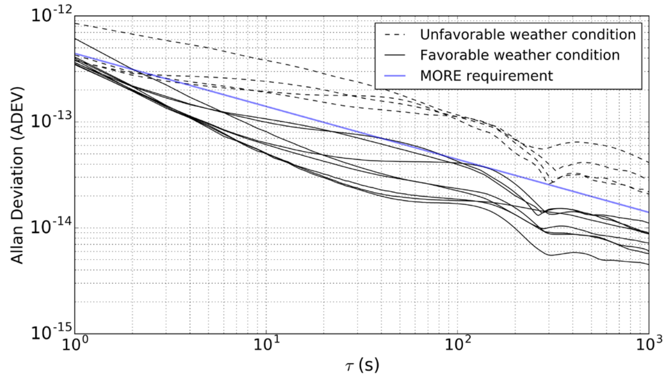

Fig. 1. ADEV of MORE's Ka-band residuals of the radio tracking passes established between ESTRACK DSA-3 and BepiColombo. In black are reported the passes with favorable weather conditions which satisfied the MORE requirement, represented by the blue line. The black dashed lines represent the passes under unfavorable weather conditions, above the experiment requirement.

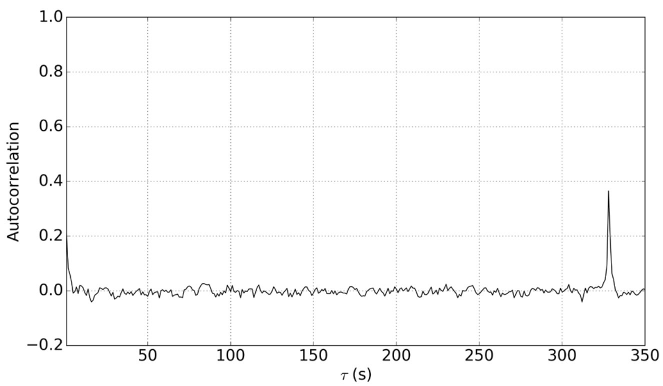

Fig. 2. Autocorrelation function of range-rate residual of the first pass of the test campaign, 2 May 2019. The peak at the RTLT is an indication that correlated noise was dominant. This was an unfortunate case and many other passes do not show any peak at RTLT.

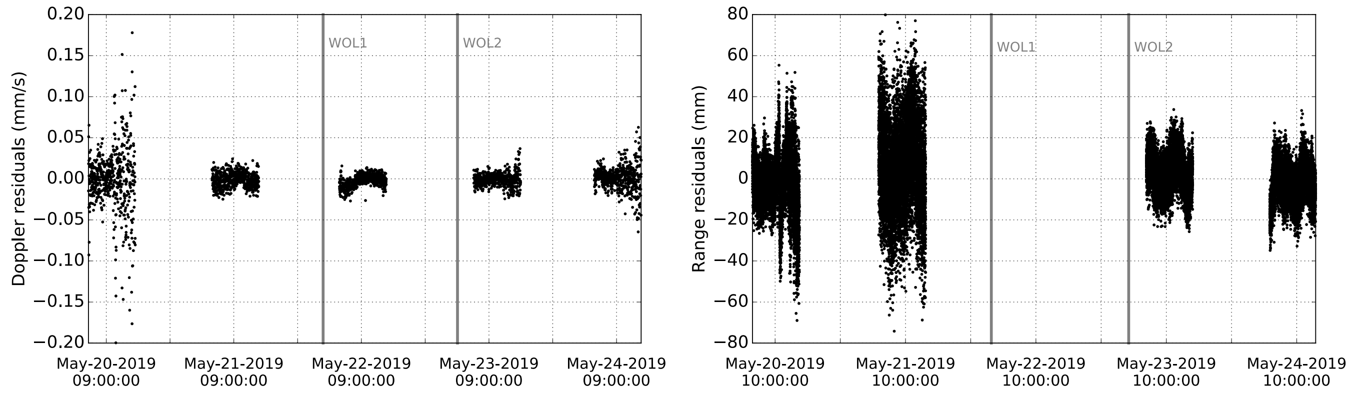

Fig. 3. BepiColombo Ka-band residuals of the passes from 20th to 24th May 2019, established between the ESA ESTRACK DSA-3 station and MORE's KaT. The two gray vertical lines represent the time of the two wheel off-loading maneuvers. Left panel shows Doppler residuals at 60 s, right panel shows residuals at 4 s of the novel PN ranging at 24 Mcps. A single range bias per station is estimated in the orbit determination process. The Doppler RMS of the 5 passes is 0.02 mm/s, but it is dominated by the first noisy pass; the average RMS of the last four Doppler passes is 0.01 mm/s, while the first one presents an RMS of 0.04 mm/s. The overall RMS of the PN ranging data is 15 mm, for the last two it is only 9 mm.

In our fit, the estimation of residual ΔV from wheel off-loading maneuvers makes the solution less robust due to some aliasing with the spacecraft's initial position and range bias.

V. Conclusion

This analysis reported the preliminary in-flight performances of the Ka-band two-way coherent radio tracking link of BepiColombo. Key elements in this demo were the MORE's KaT and ESA ESTRACK DSA-3. Thirteen passes executed in May 2019 have been independently analyzed. The accuracy obtained on the Doppler data is in good agreement with the predictions made in the design phase of the radio science experiment (0.017 mm/s @ 60 s). The accuracy of the PN ranging at 24 Mcps exceeded the expected performance, considering the actual Earth-spacecraft distance. Range measurements were established with an accuracy at centimeter level at a count time of 4.2 s. A multi-day analysis was then conducted to retrieve the performance of the radio tracking system on longer timescales. The orbital fit is compatible with the estimation of a single range bias over 5 days, suggesting that the BepiColombo radio system may enable the use of range measurements in OD without the need of estimating multiple range biases. Although the dynamical coherence of the orbit was interrupted by two wheel off-loading maneuvers, the performance of the KaT are shown to be consistent with expectations. A dedicated end-to-end test, starting in September 2020, has the objective of characterizing the MORE experiment setup in controlled dynamical conditions, providing the opportunity to confirm that the MORE PN ranging at 24 Mcps is a realization of an absolute time-of-flight measurement. This result would be crucial to understand the performance of the upcoming tests of General Relativity with BepiColombo, planned for the cruise and the Hermean phase.

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