Accurate characterization of the noise sources affecting BepiColombo's radio tracking observables

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Abstract. The ESA mission BepiColombo, nowadays, represents a milestone for the precision levels that can be obtained in the determination of the orbit of a spacecraft. The high accuracy provided by the embedded radio system, together with modern techniques used for the calibration of tropospheric noise, such as the usage of a microwave radiometer, allows to estimate the state of the spacecraft with a very small uncertainty. Doppler measurements collected during the first two Solar Conjunction Experiments performed by BepiColombo have been analyzed in order to understand which are the main sources of residual noise still affecting the data after the calibration process, with the aim of improving the overall calibration procedure itself. The study showed that, even though the usage of radiometers led to a strong reduction of the noise due to the troposphere, the main error source can still be identified in some un-calibrated tropospheric effects. This indicates that the improvement of the overall calibration process strongly relies on the refinement of the method used for tropospheric noise removal.

Introduction

The latest advances in the technology of the radio systems used for deep space navigation led to a great improvement in terms of precision and accuracy in the deep space orbit determination. The strong reliability offered by the present-day radio systems necessarily requires very high and demanding standards in terms of calibration procedures, in order to maximize the precision levels that can be obtained.

BepiColombo spacecraft is equipped with one of the most precise radio systems ever flown in space, composed by two different transponders, the Deep Space Transponder (DST), enabling X-band/X-band and X-band/Ka-band radio links, and the Ka Transponder (KaT), enabling Ka/Ka radio link, both for ranging and Doppler. The two transponders, used simultaneously, allow the establishment of the so called multifrequency link, which plays a crucial role in the calibration process. It has been shown, in fact, that, through the linear combination of triple-link observables, it is possible to remove from the measurements the noise introduced by dispersive media such as solar plasma and Earth's ionosphere [1,2], which usually represent the dominant source of noise affecting the signal.

The radio system described before represents the key instrument of the Mercury Orbiter Radio science Experiment (MORE) which, during the entire duration of the mission, will be performing different investigations in terms of gravity, geodesy and fundamental physics [3]. During cruise the main radio science experiments performed are the Solar Conjunction Experiments (SCE), which are mainly focused on the estimation of the Parametrized Post-Newtonian (PPN) parameters [4].

This work presents an analysis performed on the BepiColombo tracking data collected during the first two solar conjunction experiment (SCE1 in March 2021 and SCE2 in January/February 2022), which have been used as a testbed to verify the effectiveness of different calibration

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techniques. The data analyzed have been collected at the ESA's Deep Space Antenna in Malargue (DSA3) and comprise a set of Doppler and Range measurements in X- and Ka- bands for both uplink and downlink, registered during a total of 31 tracking passes (17 related to SCE1 and 14 related to SCE2).

Tropospheric delay calibration

Once removed the errors introduced in radiometric observables by the dispersive media through the linear combination of the triple-link measurements, the main noise source affecting the signal is represented by Earth's troposphere. The water vapor layer present in the troposphere introduces a time-variable delay which affects doppler and, to a lesser extent, range observables. The standard procedure used to remove tropospheric effects from the measurements is based on data obtained from the Global Navigation Satellite System (GNSS). However, a new calibration system based on a water vapor radiometer, called Tropospheric Delay Calibration System (TDCS), has been recently installed at the Malargue ground station in order to improve the calibration of the tropospheric effects. A detailed description of the TDCS and the results of a first validation test, performed with the Gaia spacecraft, are given in [5,6].

In the context of the MORE experiment, the first two solar conjunction experiments represented a great opportunity to further validate the TDCS performances, also in correspondence of a solar conjunction. A recent work has been carried out in which the TDCS and the GNSS calibrations have been compared performing an orbit determination analysis on the data collected during SCE1 and SCE2. The main point of the study was the analysis of the noise in the residuals, which are defined as the difference between the observables measured at the ground station and the observables generated by a mathematical model of the spacecraft's dynamics. As described in detail in [7], the TDCS calibrations led to an average reduction of doppler observables noise up to 51% with respect the noise level reachable with GNSS calibration. Concerning range observables, the TDCS didn't show an improvement as strong as the one brought into doppler ones but still a better performance than GNSS. In general, we can say that, nowadays, the TDCS represents the best option for the calibration of tropospheric effects.

At the current state of the art, the calibration procedures performed on the BepiColombo data comprise the removal of the errors introduced by the ground station and spacecraft's electronics (ranging only), the errors introduced by the dispersive media (solar plasma and ionosphere) through the multifrequency link and the errors introduced by the troposphere through the TDCS calibrations. In order to further improve this calibration process, a preliminary analysis, described in the following section, has been conducted on the post-calibration residuals relative to SCE1 and SCE2, with the aim of understanding which are the main residual noise sources still affecting the measurements. Identifying the main sources of un-calibrated noise is the first step to improve the overall calibration process. In order to reach this goal, the Doppler residuals obtained from the analysis of SCE1 and SCE2 data have been studied in terms of Allan standard deviation (ASD) and autocorrelation, relating these functions to two quantities that are suspected of being indicators of possible residual noise sources: the wind speed and the Sun Earth Probe (SEP) angle.

Doppler residuals analysis: SCE1

Starting from SCE1 residuals, the first step of the study concerned the visualization of the ASD and autocorrelation in relation with the wind speed registered at the Malargue station during the different tracking passes. Figure 1 shows the outcome of the analysis.

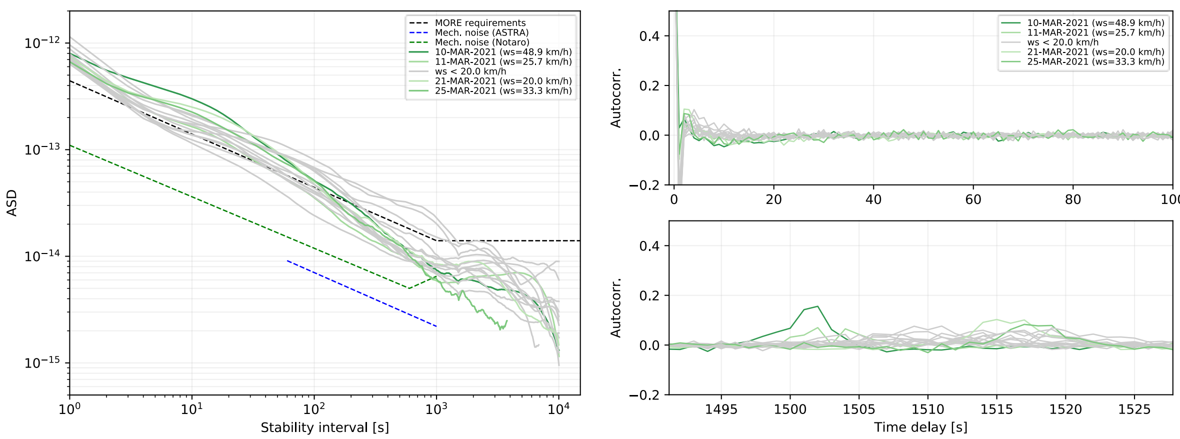

Figure 1: Allan standard deviation (left) and autocorrelation function (right) of SCE1 Doppler residuals related to the wind speed.

The graph on the left is showing the residuals' Allan standard deviation relative to each tracking passes. The curves are presented in shades of green in which a darker green represents an higher wind speed registered during that tracking passes. The grey curves, instead, represent passes in which the wind speed registered was below 20 km/h. The same concept applies for the autocorrelation graph. What can be observed from the ASD curves is that the 4 passes in which a moderate/high wind speed was recorded are, for low values of integration time (τ), all well above the MORE's stability requirement for two-way Doppler residuals (represented by the black dashed line) while, at high values of τ, the requirement is fulfilled. This indicates that, in terms of calibration, the residual noise still strongly affects the instrument stability at low values of integration time so a further noise removal is still required. About this point, the autocorrelation curves on the right are showing high autocorrelation peaks around the Round Trip Light Time (RTLT) giving us a strong hint about the nature of the main residual noise source. A peak at the RTLT, in fact, indicates that the noise affecting the residuals recurs at the location of the ground station. Moreover, it is clearly visible that the highest autocorrelation peak is related to the pass in which the highest wind speed value (48.9 km/h) was record, suggesting that the noise sources could be strongly related to the wind at the station. This consideration leads to the assumption that this main noise sources could be residual un-calibrated tropospheric effects or antenna mechanical noise (AMN). Concerning the latter, the ASD graph has been completed with two colored dashed line representing some literature models of antenna mechanical noise: the green one has been extracted from [8] while the blue one is extracted from the noise budget drafted in the frame of the ASTRA studies [9,10]. The comparison between these dashed lines and the residuals Allan deviation curves shows that at values of τ around 1000s the AMN may become the predominant noise sources while for smallest values the biggest noise contribution is given by another source which, as what discussed before, is very likely to be un-calibrated troposphere.

The second step of the study concerned a similar analysis to the one already described but, this time in relation of the Sun Earth Probe angle. The SEP is a parameter of interest for this analysis because, in condition of superior solar conjunction (SEP < 3°), the TDCS radiometer enters the *sun-avoidance mode* which is aimed to avoid the direct intrusion of the Sun into the observation beam of the instrument. This task is accomplished by creating a pointing offset between the pointing direction of the radiometer and the actual position of the spacecraft. However, even if this technique avoids an undesired presence of the Sun into the radiometer's observations it also implies that the observed troposphere portion, used for the calibration, is different from the actual troposphere which interferes with the ground station/spacecraft link.

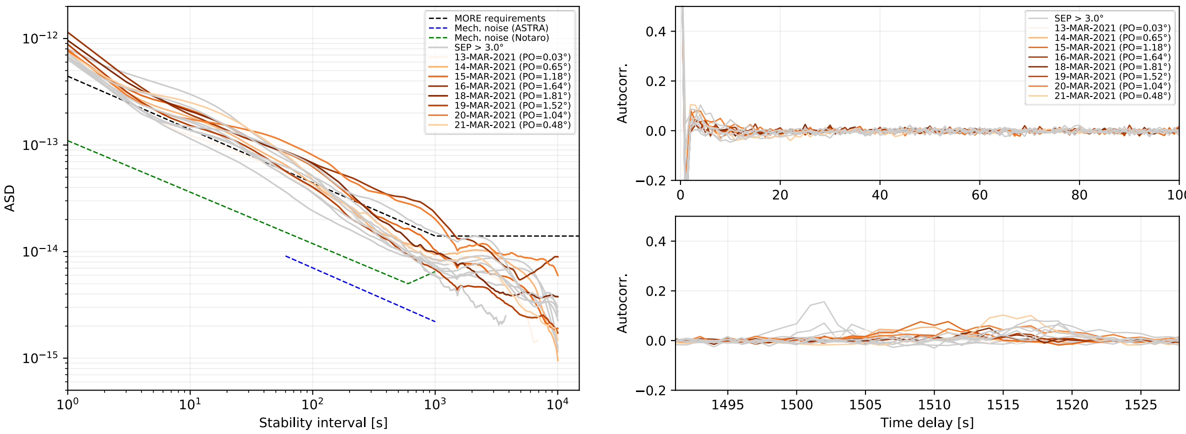

Figure 2: Allan standard deviation (left) and autocorrelation function (right) of SCE1 Doppler residuals related to the SEP.

Figure 2 shows the outcome of the analysis of the residuals in relation with the Sun Earth Probe angle. Similarly to what discussed before, the curves are presented in shades of orange in which a darker orange represents an higher value of radiometer pointing offset. The highest value of pointing offset angle registered during SCE1 is about 1.81°. The grey curves represents all the passes in which the SEP was above 3°. The first difference we can notice between the ASD curves of the two different analysis is that, while the passes with strong wind showed a good behaviour for high values of the stability interval, in this case we can clearly see that the passes which are above the black dashed line at high τ values are characterized by the radiometer working in Sun-avoidance mode, suggesting that the main reason of this divergence from the stability requirement can be found in un-calibrated troposphere due to the reasons explained before. This observation is somehow confirmed by the autocorrelation curves showing the typical feature around the RTLT. However it has to be underlined how these autocorrelation peaks in this case are lower with respect to the one of the pass characterized by high wind speed. Another consideration to be done is that, among the two curves which are consistently above the requirement it is not comprised the pass in which the highest value of pointing offset was registered. This could be due to the fact that during the two critical passes some more unfavorable conditions added to the radiometer working in Sun avoidance. Some more aspects to be discussed concerning the Allan deviation curves are that, as shown in the wind speed analysis, when the curves are under the requirement at 1000s, the antenna mechanical noise becomes the predominant noise source while at low values of τ the two dashed line are still far from the residuals' curves, underlining how the un-calibrated troposphere has to be pointed out as the main source of noise still to be calibrated.

Doppler residuals analysis: SCE2

The same analysis performed for SCE1 was replicated with SCE2 data.

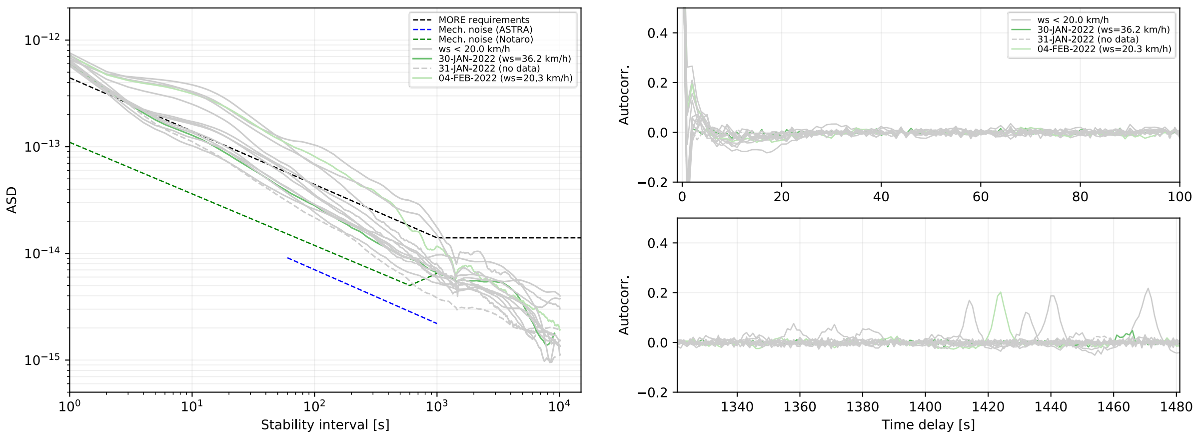

Figure 3: Allan standard deviation (left) and autocorrelation function (right) of SCE2 Doppler residuals related to the wind speed.

Unfortunately, as shown in Figure 3, during the second solar conjunction experiments only a couple of passes where characterized by a moderate wind speed so, concerning the wind analysis, no much more consideration to what discussed for SCE1 can be done. We can notice how one of the two passes in question presents an high autocorrelation peak around the RTLT.

Much more interesting, instead, the outcome of the analysis performed in terms of SEP angle.

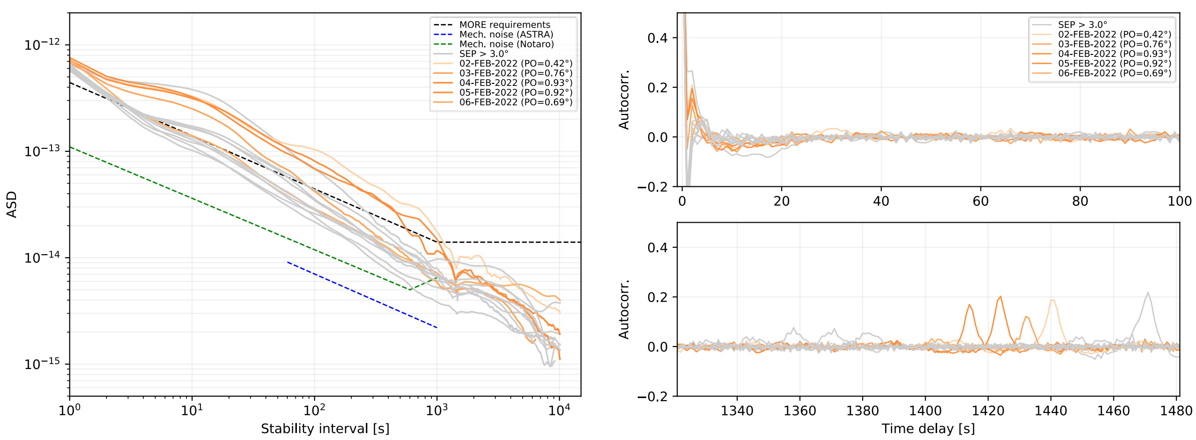

Figure 4: Allan standard deviation (left) and autocorrelation function (right) of SCE2 Doppler residuals related to the SEP.

Observing the left graph in Figure 4, we can see that before the stability interval point $\tau = 1000s$, almost all the curves related to passes characterized by the radiometer working in Sun-avoidance mode are well above the requirement curve. On the contrary, a good amount of passes in which the SEP was above 3° reach the stability requirement at low values of integration time. This is a strong indication of how the mismatch between the troposphere observed by the radiometer and the actual troposphere present along the antenna's line of sight is a relevant source of error. Also in this case, the autocorrelation function shows the typical peaks around the round trip light time, reinforcing the idea that the main noise sources can be found close to the antenna location. An aspect that is particularly interesting to notice is the fact that, during SCE2, the pointing offset registered are much smaller than those occurred during SCE1, however the autocorrelation peaks of the former are much higher than those showed by SCE1 data. This could be due to the fact that SCE2 was performed during the period between January and February which in Malargue

(Argentina) is comprised in the summer time. The highest temperature during the summer could lead to a stronger turbulence in the atmosphere thus the highest autocorrelation peaks may be a consequence of this particular condition.

Summary

The presented work had been performed in the frame of the first two BepiColombo's solar conjunction experiments with the aim of extracting information about the noise sources that are mainly affecting the residuals after the full calibration process. The high-precision radio system embedded in BepiColombo's probe requires a very accurate calibration of the measurements in order to maximize the accuracy of the spacecraft's state estimation and the identification of the main noise is a crucial first step for the improvement of the calibration process. For this purpose a study on the calibrated data from SCE1 and SCE2 had been conducted by analyzing the behaviour of Doppler residuals' Allan standard deviation and autocorrelation in function of the wind speed and Sun Earth Probe angle.

Conclusions and future work

The study conducted showed that, in all the different cases analyzed, a common behaviour of the residuals were to present a peak of autocorrelation function around the round trip light time. This particular peaks are due to the fact that there is a recurrent noise that enters into the observables at a location close to the ground station, indicating that some residual un-calibrated tropospheric effects and the antenna mechanical noise due to the vibration of the antenna structure induced by the wind are probably the main sources of error in the calibrated data. The fact that both of this noise sources can be located at the antenna location, thus both contributing to the autocorrelation peaks at RTLT, makes the separation of their effects a difficult task to accomplish. However, the analysis of the residuals' Allan standard deviation gives us a strong hint of the fact that between the two, the main component of the overall noise is the un-calibrated troposphere. The comparison, in fact, between the different ASD curves and the literature model of the antenna mechanical noise shows that the former are, especially for low values of integration time, quite far from the AMN models demonstrating that the residual troposphere represents a bigger source of error with respect the mechanical noise. However, at high values of integration time ($\tau > 1000$s) the residuals' Allan deviation match with one of the two AMN literature model, indicating that, once removed the residual troposphere, the antenna mechanical noise may represent the new biggest noise source.

In conclusion, this work had been very useful to individuate the trail to enter in the next future in order to improve the calibration process. It was discussed how the very precise BepiColombo's radio system allows, thanks to the multifrequency link, the cancellation of dispersive media-induced noise and how the recently installed TDCS improves strongly the calibration of the tropospheric effects. However it has been showed how this latter system can still be improved in order to reduce the residual un-calibrated troposphere. Different techniques, aimed to the minimization of the un-calibrated troposphere and described in literature, such as the so called *beam-crossing technique* described in [11], will be the attention of future works and analysis in order to obtain the desired improvement in the noise removal process. Other parallel works will concern the analysis of the antenna mechanical noise which, after the minimization of the residual troposphere, will represent the biggest challenge in the calibration process.

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