Deep space orbit determination via Delta-DOR using VLBI antennas

This is the final peer-reviewed author’s accepted manuscript (postprint) of the following publication:

Published Version:
Deep space orbit determination via Delta-DOR using VLBI antennas / Fiori F.; Tortora P.; Zannoni M.; Ardito A.; Menapace M.; Bellei G.; Budnik F.; Morley T.; Mercolino M.; Orosei R.. - In: CEAS SPACE JOURNAL. - ISSN 1868-2502. - ELETTRONICO. - 14:2(2022), pp. 421-430. [10.1007/s12567-022-00424-5]

Availability:
This version is available at: https://hdl.handle.net/11585/891649 since: 2022-10-21

Published:
DOI: http://doi.org/10.1007/s12567-022-00424-5

Fiori, F., Tortora, P., Zannoni, M., Ardito, A., Menapace, M., Bellei, G., Budnik, F., Morley, T., Mercolino, M., Orosei, R., 2022. Deep space orbit determination via Delta-DOR using VLBI antennas. CEAS Sp. J. 14, 421–430.

Deep Space Orbit Determination via Delta-DOR using VLBI Antennas

Francesco Fiori,[1] Paolo Tortora[2], and Marco Zannoni[3]
Alma Mater Studiorum - Università di Bologna, Via Fontanelle, 40 - 47121 Forlì FC, Italy

Alessandro Ardito[4]
Arpsoft Srl, Via della Stazione di S. Pietro, 65 - 00165 Roma RM, Italy

Marco Menapace[5]
Serco Services GmbH. Lise-Meitner-Strasse, 10 - 64293 Darmstadt, Germany

Gabriele Bellei[6]
Deimos Space, Ronda de Poniente, 19 - 28760 Tres Cantos, Madrid, Spain

Frank Budnik[7], Trevor Morley[8]
European Space Agency, Robert-Bosch-Straße, 5 - 64293 Darmstadt, Germany

Mattia Mercolino[9]
European Space Agency, Keplerlaan, 1 - 2201 AZ Noordwijk, The Netherlands

and
Roberto Orosei[10]
Istituto Nazionale di Astrofisica, Via Piero Gobetti, 101 - 40129 Bologna BO, Italy

Nomenclature

B = baseline, the vector joining two receiving ground station antennas [m]

θ = angular position in the sky of the target spacecraft, with respect to the baseline B [rad]

τ = geometric time delay between two receiving stations in the direction of the spacecraft [s]

ρ = distance between two receiving stations in the direction of the spacecraft [m]

c = speed of light [m/s]

t_1, t_2 = time of arrival of a radio wave for each ground station [s]

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[1] PhD student, Dipartimento di Ingegneria Industriale.
[2] Full Professor, Dipartimento di Ingegneria Industriale, Interdepartmental Center for Industrial Research in Aerospace.
[3] Assistant Professor, Dipartimento di Ingegneria Industriale, Interdepartmental Center for Industrial Research in Aerospace.
[4] CEO.
[5] Ground Station Systems Engineer, European Space Operations Centre.
[6] Flight Dynamics Engineer, European Space Operations Centre.
[7] Flight Dynamics Engineer, European Space Operations Centre.
[8] Flight Dynamics Engineer, European Space Operations Centre.
[9] ExoMars Principal System Engineer, European Space Technology and Research Centre.
[10] Senior Researcher, Istituto di Radioastronomia.

I. Introduction

Deep space missions have usually stringent requirements in terms of orbit determination and, in specific phases, such as flybys and orbit insertion, an accurate knowledge of the spacecraft position and velocity is critical to mission success. Information about the spacecraft (S/C) dynamical state is reconstructed via an Orbit Determination (OD) process where radio tracking and, in some cases, optical measurements (or "observables") are fitted in a least-square iterative process which makes use of an accurate dynamical model of the S/C and the environment [1], [2]. With the commencement of the Deep Space Antenna (DSA) network in 2005, the European Space Agency (ESA) has been able to improve and refine orbital solutions obtained by conventional tracking methods. Ranging (measured by the round-trip light time of a ranging signal generated at one ground antenna) and Doppler (obtained by measuring the frequency shift of a microwave carrier sent to the spacecraft from a ground antenna and coherently retransmitted back by the spacecraft) measurements were complemented by the Delta-DOR (Delta-Differential One-way Ranging) measurements capable of providing a very accurate angular position of the spacecraft in the plane-of-sky [3].

The ESA DSA network consists of three 35 meter diameter dish deep space antennas located in Cebreros (Spain), New Norcia (Australia) and Malargüe (Argentina), thus widely separated in longitude. The DSAs belong to ESA's tracking station network (ESTRACK), a global system of ground stations linking satellites in orbit and ESOC, the European Space Operations Centre, Darmstadt, Germany. However, DSAs are meant to be shared among all current deep space missions in flight, significantly constraining the tracking schedule. During a typical radio tracking session, ranging and Doppler observables are acquired for long tracking passes (typically 4 to 8 hours) in a two-way configuration (so they only require a single ground antenna, which acts both as transmitter and receiver). Conversely, Delta DOR observations have the drawback of requiring at least two antennas (and no more than two can be available simultaneously, because of their longitude separation), but the advantage of requiring them to work in one-way mode (they are only used as receivers) and to be used for about two hours, at most.

The baseline between the two receiving antennas should be kept as large as possible to increase its inherent geometric accuracy, with typical values on the order of 10^4 km. However, constraining the minimum length of the baseline has the effect of reducing the time windows in which Delta DOR observations are feasible to a few hours due to the visibility of the target from the receiving antennas. Moreover, the S/C and quasar are seen rising at a station and setting at the other one, so the signals' recordings are performed at relatively low elevation. This leaves little room for adaptation of the tracking schedules of these antennas and brings about the need for possible alternatives for the receiving stations. These alternatives would have to satisfy the same data collection requirements for computing Delta DOR observables and should have the following capabilities:

1. acquire the S/C and quasar signals in the necessary frequency range (with specific requirements for the minimum sampling frequency and bit resolution) in an open-loop mode;
2. the gain-to-noise-temperature (G/T) should be sufficiently large for receiving the faint signals involved, which translates into large dish diameters with cryogenic cooled receivers;
3. they require a quite high clock stability on ground (requiring H-masers) and each station clock needs to synchronise to UTC (at least to a certain extent).

Despite the challenging constraints to be fulfilled, the type of transmission involved in the Delta DOR allows for a simple and stand-alone open loop recording. Since the spacecraft is transmitting pure sinusoidal waves at different frequencies, the recording of the spacecraft's DOR tones can start at any moment without affecting the final results (apart from the total recording time) and it may last for an arbitrary amount of time. This is valid since there is no beacon telling us that the DOR transmission is started: therefore, there is no particular need for precise synchronization of the recorders with the S/C transmission time, and the signal may be recorded at any time after the real start of the DOR transmission.

The antennas belonging to the Very Long Baseline Interferometry (VLBI) network worldwide perfectly meet the hardware requirement to record and deliver data useful for Delta DOR observations. Similarly to the DSAs, they are equipped with receivers at X band which can reach the values of 2MHz recording bandwidth and a 2-bits quantization value, and are provided with high stability clocks. This is why there have already been a number of experimental activities where VLBI antennas were used in support to Deep Space Probes navigation activities in Australia [4], Europe [5], Japan [6] and China [7], [8], [9].

Another recent study [10] proved that exploiting the antennas of the European VLBI network (EVN) to form Delta-DOR measurements using a VLBI antenna and a DSA offers reliable results. This work involved successfully translating the acquired data using a software translator for VLBI data, to enable their successive analysis by ESA’s software correlator. As a natural extension of this work, we show here how real data acquired by tracking ESA’s mission GAIA [11], which transmits at the typical X-band frequencies allocated to Deep Space communication (~8.4GHz), could be gathered and processed by ESA's Delta DOR software correlator [12] using a mixed DSA-VLBI architecture. Our OD solution is fully compatible with the one obtained using a conventional baseline formed by two DSAs.

II. Working Principle

Delta-DOR is an interferometric technique which measures the angular position of an interplanetary S/C along a projected terrestrial baseline on the celestial sphere (see [3], [13] and [14] for more details). The simplest Delta-DOR measurement setup requires two receiving high gain antennas equipped with proper hardware, capable of recording in a specific range of frequencies. Recordings of the S/C signals are processed by means of a software correlator to form the S/C differential one-way ranging (DOR). However, as this measurement is affected by several error sources (media crossed by the radio wave, station clock instabilities and other instrumental effects), it is possible to calibrate it by carrying out alternate DOR observations of the S/C and a nearby (in terms of angular position) quasar. The quasar will act as a calibrator, as its direction is typically known to better than 1 nrad, and a Delta-DOR measurement can be formed by subtracting the quasar DOR from the S/C DOR.

Considering a generic signal emitted from the S/C, it will reach the two receiving antennas at different instants of time, t_1 and t_2 (Fig. 1).

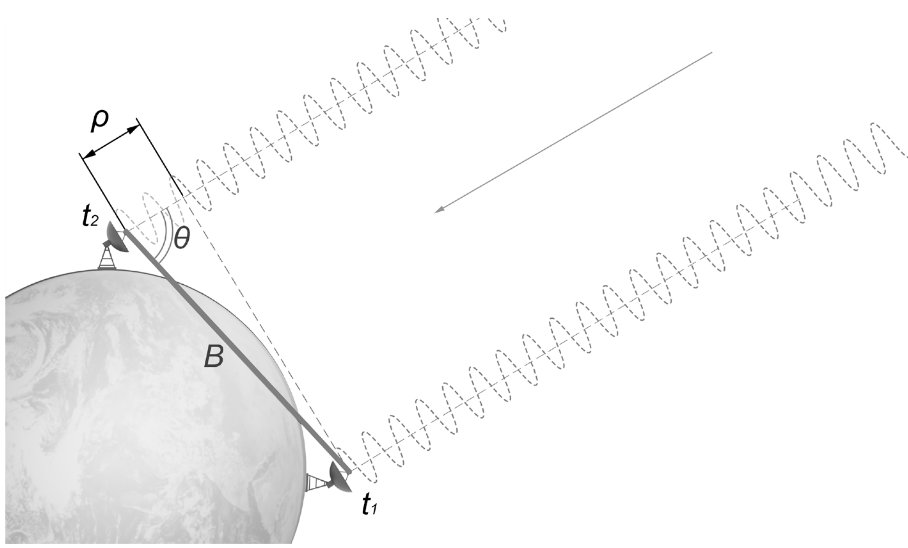

Fig. 1 Geometry of a Delta-DOR setup.

The time difference between t_1 and t_2, the delay τ, can also be seen as a spatial difference ρ, once multiplied by the speed of light c: this is valid under the approximating assumption that the incoming wavefront is planar, which always holds true in case of interplanetary S/C. The knowledge of the time delay, τ, is used to obtain a measurement of the angle formed by the incoming signal and the baseline, by solving a simple trigonometric problem (Equation 1).

$$\rho = c\tau = Bcos(\theta) \tag{1}$$

Where B is the baseline and θ is the angle describing the geometric misalignment between the baseline and the direction of the incoming signal. It is possible to highlight the sensitivity of the angle θ with respect to the time delay τ by differentiating Equation 1 [13]:

$$\frac{d\theta}{d\tau} = -\frac{c}{B \sin \theta} \tag{2}$$

The baseline B appears at the denominator showing that a large value translates into a low sensitivity of θ with respect to errors in the measured τ.

As previously mentioned, standalone S/C DOR measurements are not accurate enough for the purposes of Deep Space OD, thus DOR measurements from a quasar, with a small angular distance in the sky, are used as a calibration source. Extracting the DOR observable, i.e. the time delay, requires a very different methodology, depending on what is being observed, the quasar or the S/C. In the following, we provide details on the two distinct processing techniques, which are however described in greater details in [14].

II.a Quasar signal processing

In case of quasar DOR measurements, the received signal is in form of white noise. In order to obtain a time delay from the recordings at two different receiving stations, a cross correlation process is needed, which can be defined as:

$$\mathcal{R}_{f,g}(\tau) \stackrel{\text{def}}{=} \int_{-\infty}^{+\infty} f(t) * g^*(t-\tau)dt \tag{3}$$

where $f(t)$ and $g(t)$ are the two waveforms of the recordings, and g^* is the complex conjugate of g. Since the signals are sampled, the formula translates in the analogous for discrete time:

$$\mathcal{R}_{f,g}(\tau) \stackrel{\text{def}}{=} \sum_{t=-\infty}^{+\infty} f(t) * g^*(t-\tau) \tag{4}$$

The quasar recordings include two main types of noise mixed together: the thermal noise at the receiver and the quasar noise. The quasar noise is common to both recordings while of course the thermal noise is local to each ground antenna. By applying the cross-correlation function described in Eq. (4) it is possible to extract a peak when the value of delay τ (discrete or continuous) is exactly equal to time delay between the recordings (τ), as shown in Fig. 2. Each digital sample of the quasar signal gives a positive contribution, leading the function to have a maximum value.

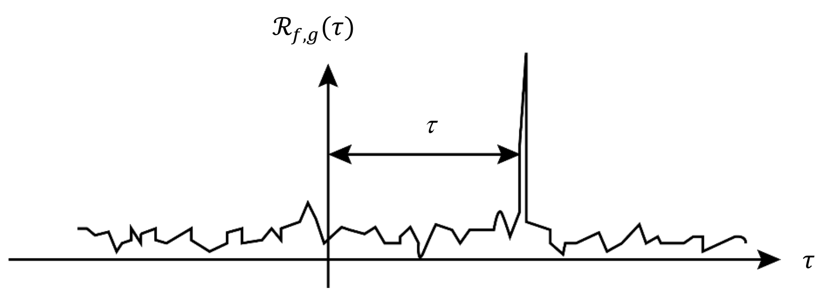

Fig. 2 Example of the output of cross correlation of the functions *f* and *g*.

The peak may be located at positive or negative values of τ, depending on which signal is delayed with respect to the other (and on the definition of the variable related to the delay in the cross correlation itself).

In the real case of a quasar DOR measurement, a simple cross correlation of the recorded signal will not lead to a solution, since the quasar has different relative velocities with respect to each ground station (mainly due to the Earth's rotation, as the quasar may be considered fixed). This gives rise to two different values of the Doppler shift of the received signal, so that a recording cannot be considered just a delayed copy of the other, but it is also characterized by a certain amount of Doppler stretch. This effect is taken in consideration in ESA's software correlator [12], which takes as an a-priori model the differential delay between the two stations, that is the delay in the arrival time of the same signal to the stations. Such delay is used at one of the two data streams for alignment in time and rotation in phase to the data stream of the other station. This way it is possible to compute a properly Doppler corrected correlation and to extract the quasar DOR.

II.b S/C signal processing

Theoretically speaking, the S/C signal processing could be faced as the quasar's one. The delay could be extracted by means of a simple correlation process, as described in Section II.a, but in practice it is done in a very different way. In fact, the S/C should transmit a wideband pseudo-noise signal (similar to the one of a quasar) in order to perform a classical correlation. However, this would be extremely inefficient (if not impossible) in terms of required transmission power, so another smarter solution had to be found, consisting in the transmission of a certain number of the so-called DOR tones, simple sinusoidal signals at given frequency values within the allocated S/C downlink frequency band.

The S/C correlator takes advantage of an a-priori model (provided for every station as range and range-rate between the S/C and the ground antenna), that is used first to derive the on-board transmitted frequency, and later on in the process to stop the phasor of the signal at every station separately. The stopped phasors are then filtered and cross-correlated to determine the differential phase [1], which represent, however, an ambiguous solution. In fact, every shift of the incoming signal by an integer multiple of its sinusoidal period will lead to a peak of correlation. This situation is represented in Fig. 3, which highlights that comparing the recordings of the same DOR tone at two receiving stations, it is only possible to extract a differential phase ($\Delta\phi$), which corresponds to the misalignment in time between the sinusoid received at a station with respect to the other one. For the first DOR tone at frequency f_1, the differential phase measured is 2π ambiguous (for every integer value of k_1) and it is strictly related to the time delay τ that the two recordings experience:

$$\Delta\phi_1 + 2k_1\pi = 2\pi f_1 \tau \tag{5}$$

The same can be done for the other two transmitted DORs at frequencies f_2 and f_3: they will have the same time delay τ but obviously different measured differential phases:

$$\begin{aligned} \Delta\phi_2 + 2k_2\pi &= 2\pi f_2 \tau \\ \Delta\phi_3 + 2k_3\pi &= 2\pi f_3 \tau \end{aligned} \tag{6}$$

If we plot these values on a phase/frequency plane, the situation is the one shown in Fig. 4.

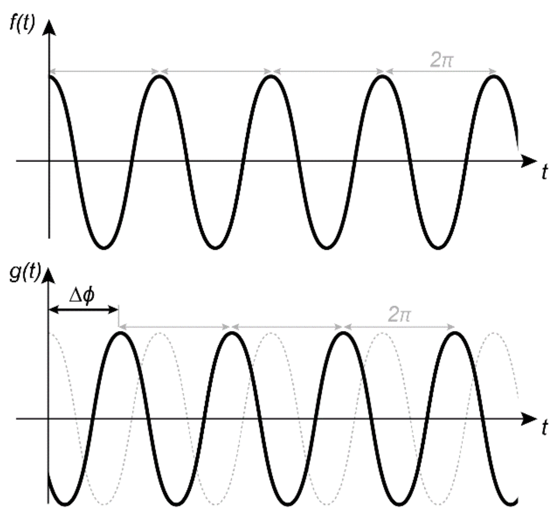

Fig. 3 Differential phase $\Delta\phi$ of a given DOR tone between two stations, one recording the signal $f(t)$ and the other one the signal $g(t)$.

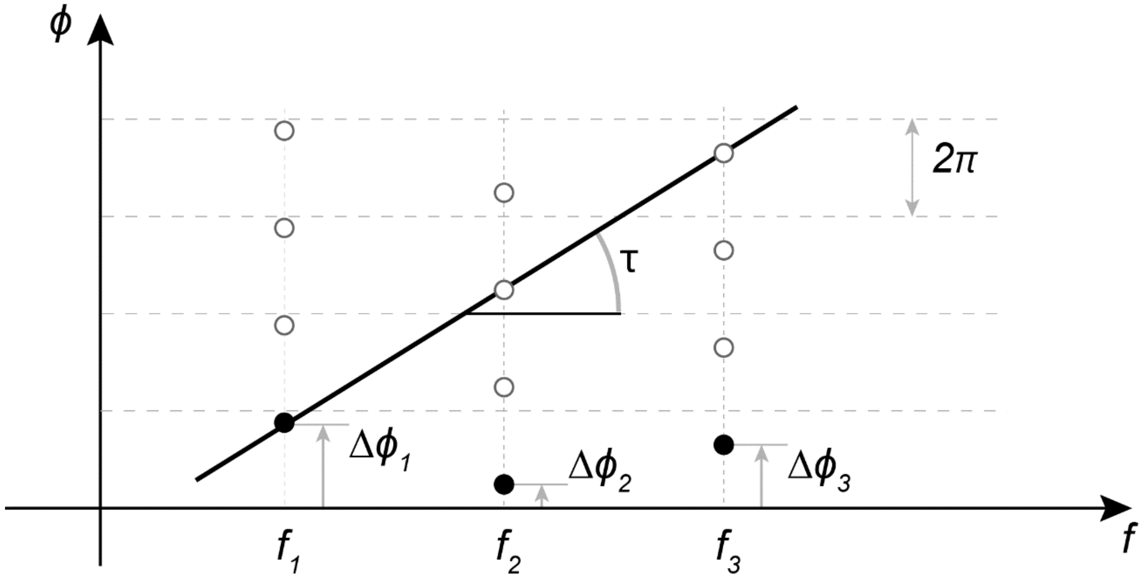

Fig. 4 Method used for solving the integer ambiguities in case of 3 DOR tones.

The black dots correspond to the measured differential phases, and the problem becomes the one of searching for the best integers k_i which, multiplied by 2π and added to the three $\Delta\phi_i$, yield the best least square fit to a straight line. Once the line which best fits the three dots is found, the solution (the time delay τ) can be computed, as it is simply the slope of the line itself. Lastly, it had been shown in [12] that for large delays in the S/C DOR observation (mainly due to station clock offsets up to 6 μs) the best fit algorithm represented in Fig. 4 would fail and find wrong values for the integers k_i. This tell us immediately that a *blind* search of the right set of integers is simply not feasible. The algorithm has to take advantage of the information of *where* the right delay is expected (at least, roughly), in order to perform a focused search. To this aim, the quasar DOR measurement (which, apart from a small contribution due to the Earth troposphere, is usually considered as the clock offset between the two ground station involved in the Delta-DOR observation) could be easily used as an *a-priori* information to drive properly the S/C Integer Ambiguity resolution, and finally get to the computation of the calibrated time delay [14].

As a final step, the computed time delay (the Delta-DOR observable) becomes the input for the OD process, where it is compared to a mathematical model (also called the "computed observable") which makes use of the S/C orbit propagation and dynamical model [15]. The difference between the observed and computed Delta-DOR observable (the so-called "residual") is minimized in a least-square sense within the OD code and generates the correction to be applied to the S/C dynamical state.

III. Data collection and preprocessing

Delta-DOR data useful for OD require recordings of both S/C DOR tones and quasar (Q) noise. An ideal setup would allow the correction provided by the quasar to be obtained simultaneously to the S/C signal acquisition. However, this is not usually possible since both sources have an angular separation in the sky which, even if kept to a minimum, are sufficiently far apart such that either the S/C or the quasar is outside one of the antenna beamwidths. To compensate for this, Delta-DOR measurements consist of a series of alternating recordings of both sources to obtain sequences of S/C-Q-S/C, usually in a time span of one hour. The result of each data processing carried out using two receiving antennas is a DOR observable, and the S/C DOR is interpolated at the time of the quasar recordings.

The recording setup is configured according to a consolidated procedure used at ESTRACK's DSA stations, which requires a modification if antennas from the VLBI network are used. This is due to the different hardware mounted at VLBI antennas, which are equipped with recorders capable of providing output in VLBI Data Interchange Format (VDIF) [16] or Mark5B [17] formats, whereas ESA's backend for DSAs provides data in the Raw Data Exchange Format (RDEF) [18]. Even if the recording output is different in terms of the binary file structure, VLBI antennas can provide recordings with characteristics similar to those required by ESA's Delta-

DOR software correlator. The VLBI recordings may then be converted to the RDEF format, which can be handled by ESA's correlator to finally compute the Delta-DOR observable.

For this study, ESA's Deep Space Antenna of New Norcia, has been used in an unconventional baseline together with the VLBI antenna of the Italian National Institute of Astrophysics (INAF) located at Medicina (Italy), which is part of the European VLBI network. The target probe of this experimental Delta-DOR observation was ESA's GAIA S/C [11] and a nearby quasar. The S/C was transmitting three DOR tones at X-band (each one separated by 5 MHz from the other) which were scheduled to be collected at ESA's DSA baseline formed by New Norcia and Cebreros on November 25th, 2018, between 19:00 and 21:00 UTC.

It was decided to perform a shadow pass from the Medicina VLBI antenna during the regular New Norcia – Cebreros Delta-DOR pass supported by ESA ground stations, so there would not be a need for any modification to the standard ESA Delta-DOR tracking pass setup. In addition, the tracking geometries are very similar and the New Norcia – Medicina baseline (~11.085 km) is only shorter than the New Norcia – Cebreros baseline (~11.600 km) by ~515 km. The outputs of the shadow pass at the Medicina VLBI antenna were three series of S/C-Q-S/C recordings, stored in VDIF file format, with the same timings (and the same target objects: GAIA and quasar 0400+258 (B1950)/CTD26) as for the New Norcia - Cebreros tracking schedule, see Table 1 for details.

	VLBI	**DSA**
S/C Sampling bandwidth	2MHz	50kHz
S/C quantization	2 bit	8 bit
Quasar Sampling bandwidth	2 MHz	2MHz
Quasar quantization	2 bit	2 bit
Representation	Real	Complex
File format	VLBI Data Interchange Format (VDIF) [16]	Raw Data Exchange Format (RDEF) [18]

Table. 1 Summary of the recording modes at the VLBI and DSA ground stations

The recordings carried out at Medicina required software data translation [10]. Firstly, all channels needed to be extracted to different files, converting the binary structure into the RDEF data type. The hardware limits at the VLBI antennas were 2 MHz of recordable bandwidth at 2 bit/sample for both the S/C and quasar recording. The real valued recordings were spanning a baseband down-converted signal of 0-2 MHz, so that the target DOR tone was located in the middle of the channel (at about 1 MHz). Thus, after conversion from real-to-complex samples by means of a Hilbert filter, an additional frequency shift of 1 MHz was required, to bring back the DOR tone to about 0 Hz frequency and to obtain a signal spanning from -1 to 1 MHz, as in the DSA recording. These processing steps were applied to both the S/C and quasar signals. Finally, the S/C signals required an additional pre-processing to narrow the recording bandwidth to 50 kHz and to increase the resolution to 8 bit/sample. This additional filtering was not required for the quasar signals.

In principle, the different recording mode for the S/C DOR signals at the VLBI station (with respect to the one carried out at the DSA station) should cause differences in the Carrier to Noise Density Ratio (C/N_0) because we have a larger recording bandwidth (2 MHz instead of 50 kHz, which should add about 16 dB) but a lower bit quantization (2 bit/sample, instead of 8 bit/sample, which should subtract about 36 dB). Overall, we would expect to lose 20 dB Hz in the C/N_0 at the VLBI station with respect to the same S/C signals acquired at the DSA.

In order to test these hypotheses, we show a sample recording of the GAIA signals in Fig. 5. The upper left panel depicts the real-valued signal of one of the DOR tones at 2 MHz bandwidth, 2 bit quantization (VDIF format) at Medicina (only a crop of 50 kHz around the middle channel is shown). The lower left panel depicts the conversion to complex 50 kHz, 8 bit signal (RDEF format) of the same recording shown in the first row. For direct comparison, the lower right panel depicts the complex signal at 50 kHz, 8 bit directly acquired in RDEF format at New Norcia.

First, we compare the plot and the C/N_0 value between the MED 2 MHz-2 bit and the MED 50 kHz-8 bit (upper and lower plots in the left column) and can state the following: (i) the transformation from 2 MHz to 50 kHz does not introduce any loss of C/N_0 because we apply a low pass FFT filter to remove the noise power out of the band of interest, before down-sampling the signals from a 2 MHz bandwidth to a 50kHz bandwidth; (ii) the re-quantization from 2 bit to 8 bit does not imply a gain in the C/N_0 because the thermal noise in the DDOR signals is much higher than the quantization noise; thus, thermal noise dominates and the re-quantization does not affect the C/N_0 value; (iii) the low-pass FFT necessary to step (i) described above implies a very slight (~0.6 dB Hz) decrease of the C/N_0 because of the non-ideality of the filter at the cut-off frequency.

Thus, we can fully explain the almost identical values of the C/N_0 of the upper left figure (41.9 dB Hz) and the lower left figure (41.3 dB Hz), which differ indeed only by about 0.6 dB Hz, see step (iii) above.

Subsequently, we looked into the C/N_0 values between the MED 2 MHz-2 bit and the NNO 50 kHz-8 bit (upper left and lower right panels). Given what demonstrated above, about the lack of effect of both the different bandwidth and quantization, we would expect the C/N_0 values to be almost identical. However they are different by ~8.3 dB Hz (MED = 41.9 dB Hz, while NNO = 50.2 dB Hz) and this can be ascribed to: (i) MED has a diameter of 32 meters while NNO has a diameter of 35 meters, and this causes MED to have a smaller gain with respect to NNO, quantifiable in -0.78 dB; (ii) MED is a Cassegrain antenna, with the X-band received in the primary focus, while NNO is a beam waveguide antenna with the X-band receiver in the pedestal room, and this causes a higher system noise temperature at MED, with respect to NNO; (iii) in addition, NNO has up-to-date frontend electronics which yields a lower noise floor at NNO. Lastly, as these data are affected by random noise, in principle we should analyze a very large data set (namely infinite) for our results to become statistically significant, while we are analyzing a single interval covering 1s, only.

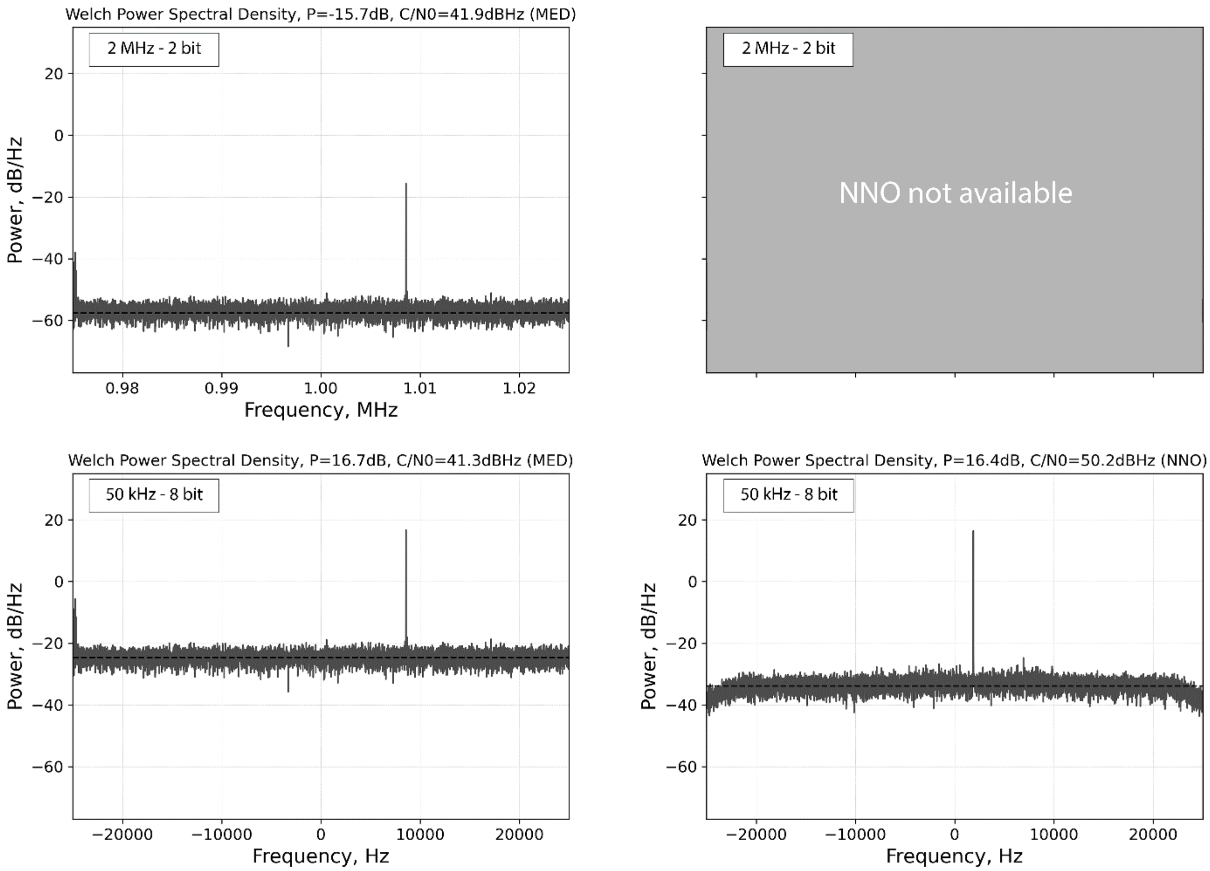

Fig. 5 Comparison of 1s of recording of the GAIA signals at Medicina (MED), left panel, and New Norcia (NNO), right panel, before (upper panel) and after (lower panel) conversion from the VDIF format to the RDEF format. Periodogram using Welch method, segments of 0.25s with a 50% overlap, see text for details.

Summarizing, the final output of this preprocessing phase was a series of alternating S/C and quasar DOR data sets. For the S/C, we had three simultaneous recordings (the same number of the transmitted DOR tones) spanning 50 kHz once converted to baseband. For the quasar, there were again three simultaneous recordings at the same frequency values of the DOR tones, spanning 2 MHz.

IV. OD analysis of recorded data

After preprocessing, the data acquired at the VLBI antenna at Medicina were stored in the RDEF binary format, identical to the recordings carried out at the New Norcia DSA, so that both data sets could be processed together in ESA's software correlator. The data sets acquired at both stations are comprised of three sequences of S/C-Q-S/C recordings of different lengths (S/C data analysis requires shorter tracking than the quasar, mainly because of the larger signal-to-noise ratio - SNR).

For the quasar, the recordings acquired at the Medicina and New Norcia ground stations were symmetrically split into several fragments. The three quasar scans included 8, 5 and then 2 fragments, respectively, each of them intended to be correlated with its corresponding one at the other site, in order to output the main observable, the time delay (or DOR). The final quasar DOR was obtained by averaging all the fragments to have a statistically stable result. In our case, each fragment included 64 seconds of recording, the minimum integration time needed to obtain a successful signal correlation.

For the S/C, the signal processing followed a similar path: the data set was again split in several fragments of 10 seconds each. Since the S/C signal is a sine wave, with a much stronger SNR than the quasar, it is usually easier for the software to extract the observable (i.e. the differential phase), allowing for shorter recordings and nonetheless precise results. Each 10 seconds fragment is compared to its corresponding one at the other ground station to extract the residual phase. This is affected by an unknown error of 2π in the phase, so a process of ambiguity solving is performed before computing the final DOR observable. Then all the S/C DORs are averaged, interpolated, and subtracted to the quasar DOR, in order to obtain the "a-priori Delta-DOR".

The Delta-DOR output of the software correlator was passed on to ESA/ESOC Flight Dynamics (FD) team, to check if the GAIA angular observables computed using the mixed ESTRACK DSA-

VLBI baseline were indeed correct. In addition to the Delta-DOR observables, GPS-based tropospheric corrections for the Medicina VLBI antenna were provided to the FD team. These are based on zenith delay estimates computed by the International GNSS Service (IGS) and are required to correct for the relevant errors due to the low elevations involved in the Delta-DOR passes. Since the dry and wet elevation mapping functions show a dominant contribution of the dry component at very low elevation [1], the calibration file considered only the dry component of the troposphere, leading to errors on the order of a few centimeters for each DOR observable (thus fully negligible within Delta-DOR observations).

The first step in the OD process was the estimation of GAIA orbital solution using only standard Doppler and ranging data. Then, the classical Delta-DOR observable from the New Norcia-Cebreros baseline was added to the setup, but not used to update the orbital solution (this is usually referred to as a "passthrough"). The black dots in Fig. 6 represent the residuals between the observed and the computed Delta-DOR observable along the New Norcia-Cebreros baseline, together with their 1-σ formal accuracy (in the form of an error bar overlapped to each residual). The formal accuracy for each Delta-DOR observable, displayed in Table 2, is an output of ESA's DDOR S/W correlator and is computed according to the error budget described in [14].

	Baseline	
	New Norcia – Cebreros	**New Norcia – Medicina**
DDOR1 error [ns]	0.29	0.41
DDOR2 error [ns]	0.32	0.53
DDOR3 error [ns]	0.36	1.42

Table. 2 Formal accuracy of each Delta-DOR observable

The offset from zero of the three black residuals (which are clearly not minimized in a least square sense) indicates that the Delta-DOR observable would yield additional information into the OD setup and allow a small correction to the GAIA orbital solution. Lastly, the FD team also added the Delta-DOR observable computed using the New Norcia-Medicina baseline to the same OD setup. The light grey dots in Fig. 6 represent the residuals between the observed and the computed Delta-DOR observable along the New Norcia-Medicina baseline, together with their 1-σ formal accuracy.

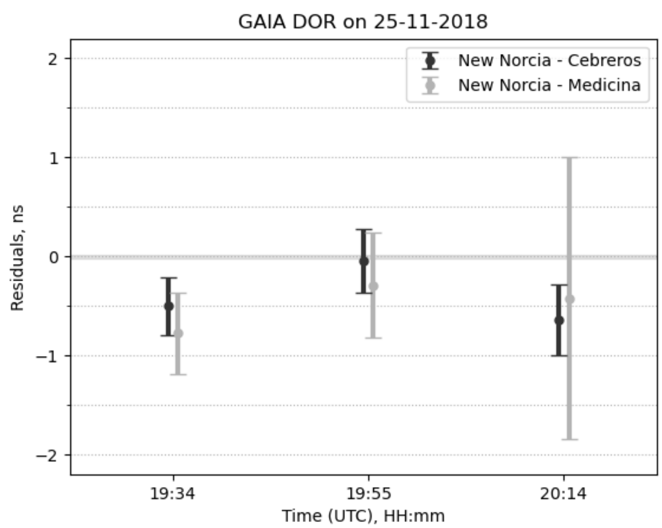

Fig. 6 Residuals of orbit determination using a classical baseline and a mixed DSA-VLBI baseline with the Medicina VLBI antenna.

We can see from Fig. 6 that all Delta-DOR residuals (from both baselines) are negative valued. This is probably due to the limitation in the tropospheric modelling for the New Norcia receiving station common to both baselines, which viewed the S/C and quasar at a very low elevation angle for the entire tracking pass (with the lowest elevation angle of about 7° corresponding to the third residual, marked as Q3 in the right panel of Fig. 7).

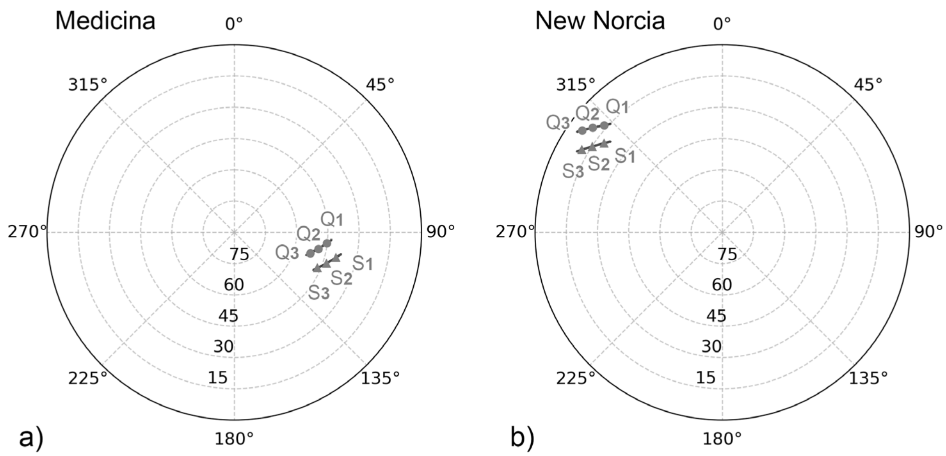

Fig. 7 Polar plots of the azimuth and elevation angles (the latter in the radial direction) of S/C and quasar recordings for (a) Medicina and (b) New Norcia.

The first residual of the New Norcia-Medicina baseline shown in Fig. 6 considered 512 seconds of quasar recordings, the second one 320 seconds and the third only 128 seconds. This is reflected in their uncertainty, with the latter having a much larger error bar than all the other cases.

Most important is that all the residuals obtained with the New Norcia-Medicina baseline are fully compatible (within 1-σ) to the residuals of the classical New Norcia-Cebreros baseline. This compatibility provides reliable proof of the robustness of a mixed DSA-VLBI antenna baseline for data acquisition. These results are positive for future analysis of a VLBI based Delta-DOR, which could increase schedule flexibility in the DSA booking process and potential richer observational geometry (given the different baseline orientation one may get observing from different VLBI antennas), while preserving high accuracy in deep space probe navigation.

V. Conclusions

In this note we presented the experimental results obtained by tracking ESA's GAIA S/C using an unconventional configuration where a mixed ESTRACK-VLBI baseline (involving the antennas of New Norcia and Medicina, in Australia and Italy, respectively) was used to form Delta-DOR observables. The S/C and quasar recordings needed to compute the uncalibrated S/C DOR and quasar DOR were carried out on November 25, 2018, in a time span of about 2 hours between 19:00 and 21:00 UTC, as a shadow pass of a classical Delta-DOR pass between New Norcia and Cebreros (Spain) antennas. The data preprocessing needed to convert the VLBI-based observables to a format compatible with ESA's software correlator proved successful, as both the S/C and quasar independent correlations offered excellent results. Once the Delta-DOR observables were formed, they were processed by ESA/ESOC Flight Dynamics team in their OD code, in order to carry out a consistency check between the angular measurements obtained via the experimental procedure and the ones obtained via a standard process. The Delta-DOR residuals, computed as a difference between the computed and observed observables are slightly offset with respect to the GAIA OD solution obtained using only Doppler and ranging data. However, we found that the Delta-DOR residuals obtained with the New Norcia-Medicina baseline are fully compatible (within 1- σ) to those of the classical New Norcia-Cebreros baseline.

In conclusion, it has been shown that VLBI antennas offer the capability of being exploited in future missions with Delta-DOR requirements, increasing the number of possible baselines and observation time windows.

Future research will focus on obtaining Delta-DOR observables using a full-VLBI baseline. We expect the effort to be mainly focused on the data pre-processing phase, but this may require additional developments if telemetry harmonics are to be used as substitutes of DOR tones. This missing step would prove the capability of the VLBI network of providing S/C OD observables in a standalone configuration, thus without subtracting observation time from classical deep space antenna networks.

Acknowledgments

The VLBI observations were carried out at the Italian Medicina radio telescope, managed by INAF - National Institute for Astrophysics. We acknowledge the valuable support provided to the experiments by the local staff, in particular Giuseppe Maccaferri, Simona Righini, Monia Negusini, Roberto Ricci and Roberto Ambrosini. Finally, special thanks to Marco Lanucara and his team at ESA/ESOC for the fundamental support provided in operating ESA's S/W Delta-DOR Correlator. The authors would like to thank Rukiah Shenai Mitri for her comments, insightful suggestions and careful reading of the manuscript, and Andrea Togni and Edoardo Gramigna for the valuable discussions on signal processing techniques and performance.

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