Delta-DOR Observations using VLBI Antennas

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Delta-DOR is a technique which addresses the problem of orbit determination of a target deep space spacecraft, in particular by determining its angular position in the sky. This can be achieved by means of analyzing both quasar signals, using this radio source as a calibrator, and a proper signal transmitted by the target spacecraft. These signals should be received by two or more stations, possibly set at a large distance from each other. Nowadays, ESA can count only on a few stations, more precisely the largest ones, since large SNRs are required to acquire the faint transmissions involved. This study has the aim to exploit a different set of stations, the ones belonging to the VLBI network, to perform Delta-DOR measurements. VLBI antennas have in general the right hardware requirements but lack a proper recording output, therefore a software translation of the recorded signal is required. As a proof of concept of the proposed technique, a shadow pass, involving an Italian VLBI station, of a standard ESA Delta-DOR session has been scheduled. The recorded data were successfully translated and analyzed by means of the ESA's software correlator, showing the feasibility of this innovative procedure.

I. Nomenclature

α	=	angle between spacecraft and quasar as seen from a receiving station
B	=	baseline, the straight line which connects two receiving stations
c	=	speed of light
f_j	=	frequency of the j-th DOR tone
$f(t), g(t)$	=	generic recorded signals
k_j	=	non-dimensional integer value for the j-th DOR tone
$\Delta\phi$	=	differential phase
$\Delta\rho$	=	differential ranging
$\rho, \dot{\rho}$	=	range and range rate of the spacecraft with respect to a receiving station
$\mathcal{R}_{f,g}$	=	discrete cross correlation between functions $f(t)$ and $g(t)$
τ	=	time delay between the arrival of the same signal at the receiving stations
θ	=	angular position in the sky of the spacecraft with respect to the baseline
t_i	=	time of arrival of a signal at a generic i-th station

II. Introduction

Spacecraft's orbit determination is a topic of fundamental importance in the space field, since a given mission's success or failure depends on it. Information about the position and velocity of the spacecraft are required to predict the future states of the spacecraft by means of trajectory propagation. Some missions require a very accurate and precise knowledge of the state of the spacecraft which is not a straightforward task in case of deep space probes.

To assess the problem of collecting information about the deep space probe's ephemeris, different techniques are used: ranging, Doppler and Delta-DOR (Differential One-way Ranging) [1]. Each of these techniques can be exploited to measure a different type of information regarding the spacecraft's state.

Ranging is a technique which is capable of providing information about the distance between the spacecraft and the receiving station; this is achieved by computing the time a particular signal takes to travel the distance between spacecraft and receiver. Doppler is used to measure the relative speed between the spacecraft and the receiving station, which can be done by measuring the difference in frequency of a sinusoidal signal in the receiving side with respect to the transmitted frequency. Delta-DOR provides the last piece of information, which is the angular position in the sky of the spacecraft, obtained by measuring the time difference a signal is received at two or more receiving stations.

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Despite being a very powerful technique, Delta-DOR has the main disadvantage in terms of number of stations involved to perform the analysis: in fact, it requires at least two simultaneously recording receiving stations in order to collect information about the transmission angle in a single plane and at least three antennas to have a complete knowledge of the angular position.

The purpose of this work is to exploit VLBI (Very Long Baseline Interferometry) antennas in order to perform Delta-DOR observations. ESA (European Space Agency) collects Delta-DOR measurements thanks to their Deep Space Antennas, part of the ESTRACK network, located in Australia, Spain and Argentina. Since their number is limited, involving two antennas to perform Delta-DOR is an expensive requirement; therefore, finding other candidate parabolic dishes has the advantage to widen the possible number of antennas which can be used to perform Delta-DOR. This would allow obtaining measurements even when ESA's antennas are used for other scopes and/or increase the angular resolution by adding baselines not available to date.

The characteristics of ESA stations is that they reach very large values of SNR, allowing them to acquire very faint transmissions: this is a fundamental requirement due to the extremely low power levels of the signals received at the ground stations. Therefore, these antennas are equipped with very large diameter dishes, together with cryogenic receivers. The VLBI antennas are similar to the classical ESA ones, in particular for what concerns the SNR performance, so that their use in the context of Delta-DOR measurements seems quite straightforward. However, their recording output is the VDIF (VLBI Data Interchange Format) file type and is natively not supported by ESA's Delta-DOR numerical code, a software correlator [2] which requires as input recordings in the RDEF (Raw Data Exchange Format) file type [3].

A software translator, converting VDIF files to the RDEF format, had to be designed and implemented, so that the recordings of an Italian VLBI antenna could be used as input to ESA's software correlator, together with the output of one of the classical ESA's stations. The experimental results obtained using data from an observation campaign carried out in November 2018 are presented, showing that the Italian VLBI antenna could be successfully used to perform Delta-DOR measurements.

III. Delta-DOR – Basic Principles

Delta-DOR is a radiometric technique which is used to measure the angular position in the sky of a target deep space spacecraft [4]. The term *Differential One-way Ranging* refers to the fact that a signal travels only one-way from the spacecraft to the receiving stations and what is measured is the differential ranging, seen as the difference between the times of arrival of the same signal at the receiving stations. The term *Delta*, instead, refers to the use of a quasar signal for calibration purposes, since the position of the quasar is very well known, thanks to large efforts spent in their mapping, a task that is performed by the VLBI community. The quasar should be a small angular distance from the spacecraft, so that the path traveled by the signal is approximately the same, and most of the path-related errors can be cancelled out.

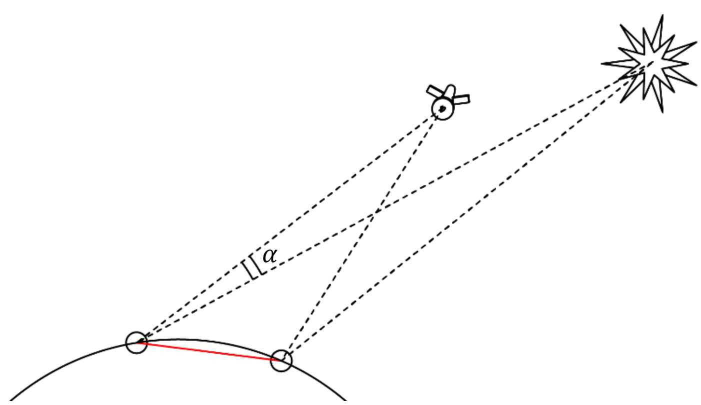

Fig. 1 Simplified scheme of a baseline consisting of two receiving stations.

Considering a baseline of two receiving stations as in Fig. 1, where the spacecraft and the quasar are separated by a small angle α, the solution of the Delta-DOR technique is the angle θ in the plane containing the receivers and the spacecraft. Figure 2 depicts a simple geometric description of how the problem is solved.

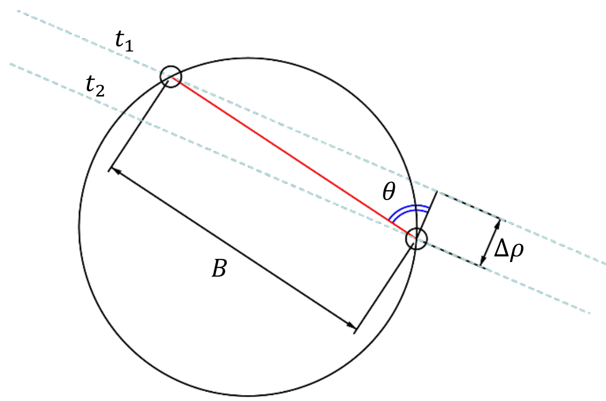

Fig. 2 Geometric setup used to determine the differential ranging.

The wave front of the signal (this is valid for both the quasar and the spacecraft) reaches the first station at time t_1, then the second one at time t_2, after a given time delay τ. This time delay can be converted into a distance, the differential ranging, by multiplying it by the speed of propagation of the wave (the speed of light *c*):

$$\Delta\rho = c\,\tau = c\,(t_2 - t_1) \tag{1}$$

This is valid under the assumption of incoming planar wave front, which is always the case for deep space probes. In this simple geometric setup, the differential ranging can also be seen as the projection of the baseline B into the direction of the incoming signal:

$$\Delta\rho = B\,cos(\theta) \tag{2}$$

Finally, combining Eq. (1) and Eq. (2) and solving for the incoming angle θ, the angular position in the sky of the spacecraft, the solution is provided.

$$\theta = \cos^{-1}(c\,\tau/B) \tag{3}$$

Differentiating and rearranging Eq. (3), the accuracy of the solution can be seen in terms of the other terms:

$$d\theta/d\tau = -\,c/(B\sin(\theta)) \tag{4}$$

Since the baseline B is at the denominator, it is immediate to conclude that large values provide higher accuracies. This is why Delta-DOR is typically performed using stations which are very far from each other, with baseline values in the order of 10^4 km.

The observable quantity is the time delay τ, which can be extracted by properly analyzing the received signals at both receiving stations. The ESA correlator deals differently with the quasar and spacecraft transmissions, since they have two different natures: one is basically white noise and the other is in the form of unmodulated tones. Since the antenna cannot point simultaneously both at the spacecraft and the quasar, the recording setup includes alternating scans of the quasar and the spacecraft. This introduces an inherent error, since the calibration given by the quasar should be interpolated for the time of the spacecraft's recordings.

A. Quasar's signal processing

The quasar signal is in the form of white noise. In order to extract the time delay between times of arrival at the receiving stations, a discrete cross correlation between the recorded signals is computed:

$$\mathcal{R}_{f,g}(\tau) \overset{\text{def}}{=} \sum_{t=-\infty}^{+\infty} f(t)\,g^*(t-\tau) \tag{5}$$

Where g^* is the complex conjugate of g. Since f and g are recordings containing the same quasar noise, shifted in time, to which an inherent non-correlated instrumental noise is embedded (different for each station), the output of the computation is a function with a peak corresponding exactly to the time delay τ. It should be noted that to achieve a solution, the recordings have to be properly Doppler compensated for the relative motions of the receiving stations (since the quasar may be considered fixed in space, as it is extremely far from Earth). This contribution is mainly due to the Earth's rotation and it is accounted for within the correlator by providing flight dynamics' team generated input files, those containing information related to the position of every element considered in the analysis.

ESA's correlator requires as input as many channels of noise as the DOR tones transmitted, each channel spanning 2 MHz in the frequency domain with a quantization value of 2 bits [5].

The result of the correlation is used for calibration purposes: indeed, the position of the quasar is known with high accuracy and what is measured is the error in the expected time delay τ. This value contains all contributions to the error related to the light path, the clock offset between the recorders, the delay in the transmission of the electronic side; if not properly accounted for, the error would be so large that it would make the spacecraft's DOR observable useless.

B. Spacecraft's signal processing

Since the spacecraft has the capability of transmitting arbitrary signals, for power efficiency purposes the choice of a noise type transmission has been discarded in favor of a collection of pure sine waves at different frequencies: these can be the so-called DOR tones or eventually the telemetry harmonics, due to the signal modulation while transmitting data to the ground. The spacecraft's transmission consists of at least three DOR tones (with a typical setup of four) at properly selected frequency values. The telemetry harmonics can also be used, but they have the main disadvantage of a lower transmitted power with respect to the dedicated DOR tones.

However, for both cases a cross correlation in the classical sense would lead to an ambiguous solution since the signal is a continuous repetition of itself. Therefore, a different approach is used to extract the observable, and this is done by means of a software PLL (Phase Locked Loop).

A single DOR tone is recorded in a channel which spans 50 kHz at 8 bits quantization level [5] and then compared with the same DOR tone received at the other station (the signals $f(t)$ and $g(t)$, as shown in Fig. 3).

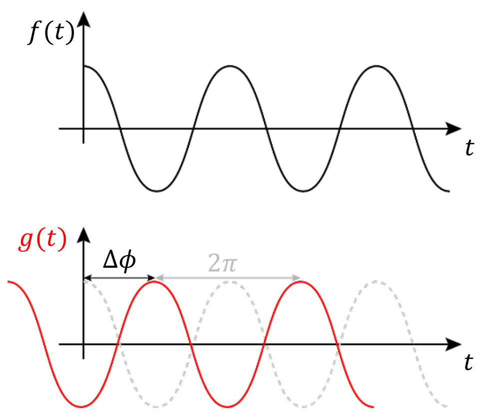

Fig. 3 Differential phase $\Delta\phi$ between $f(t)$ and $g(t)$ recordings.

The ESA correlator can extract the differential phase $\Delta\phi$ value, to which an unknown integer number of 2π "cycles" has to be added to find the real solution. In order to solve the ambiguity, a differential phase is found for each j-th tone; we know that the total phase is an integer amount of 2π to which the differential phase is added, and it depends on the time delay and the specific DOR tone's frequency:

$$\Delta\phi_j + 2k_j\pi = 2\pi f_j\tau \tag{6}$$

By making a system of many Eqs. (6), one can find all the unknowns, the k_j values and the time delay τ. This requires an *a priori* knowledge of the possible expected value of τ since there is still an ambiguity, and it is extracted from the same flight dynamics' input file, which was previously provided for the quasar Doppler correction.

IV. The planning of the Delta-DOR recordings

Information about transmitted times, frequency, polarization of the DOR tones, together with the positions of the target spacecraft and quasar in the J2000 reference frame, are required to plan the recording session. These data are used to setup a recording plan at the VLBI stations. Once all the required pieces of information about the spacecraft's transmission have been collected, a Doppler correction is computed for the received DOR tones. Finally, the schedule[2] needed at the VLBI facilities for controlling the antenna and the recorders can be written and the recording session may start. The outcome of the observations will then be ready to be processed by ESA's software correlator once the data have been properly translated.

Information about quasars are collected in catalogs, where their strength and coordinates are listed. It is possible to obtain the ephemeris of the considered spacecraft by exploiting some publicly available web tools, such as NASA's *JPL Horizons*[3]; from this information, it is possible to check the spacecraft's visibility during the desired recording session.

Recalling the setup of the ephemeris, it should be noted that in the J2000 reference frame it is a static value for the quasar but not for the spacecraft. A static value may also be chosen for the spacecraft, but it is important to check that the target will always be visible by the receiving antenna during the whole recording session, since the antenna beam width is limited, and the spacecraft may go out-of- sight.

Another important parameter that can be extracted from *JPL Horizons* web tool is the distance spacecraft/ground station (the so-called range, ρ). The range-rate ($\dot{\rho}$) is used to compute a correction for the Doppler in the received frequency as in Eq. (7), where the frequency f_t of the transmitted DOR signals (or the telemetry harmonics) should be known in advance.

$$f_r = f_t \, (1 - \dot{\rho}/c) \tag{7}$$

Where f_r is the received Doppler-corrected frequency of the originally transmitted tone f_t. In the setup of the schedule for the VLBI recording session, since the recording channels' frequencies have to be properly centered, f_r must be used as value for the center of the channel. In fact, depending on the value of the range-rate, f_t may be too off so that the DOR tone would not be recorded inside the considered channel.

V. Data Translation

The recording performed at VLBI stations have some major differences with respect to the classical inputs used for ESA's correlator (the RDEF format, whereas the VLBI recordings are in the legacy Mark5B or in the new standard VDIF), i.e. the different ways in which the recorded samples are stored and the information contained in the header alongside the samples.

Another difference is that the RDEF format contains complex-valued samples (*I* and *Q*), while the values recorded at the VLBI facilities are only real, so the imaginary part has to be provided artificially in the translation phase through a Hilbert filter.

Due to hardware limitations of the backend, the spacecraft's channels cannot span 50 KHz at 8 bits quantization as required by the ESA correlator, but are limited to the same value used for the quasar, 2 MHz at 2 bits quantization. Therefore, these spacecraft's recordings should also be resampled and requantized.

Owing to the above-mentioned limitations, a software translator had to be written which should be capable of:

1) Rearranging the side information stored in the header parts of the Mark5B and/or VDIF recorded files into the structure of the RDEF;
2) Extracting the samples and creating their missing imaginary part (starting from the only real-valued samples recorded in the Mark5B or VDIF);
3) Resampling and requantizing the extracted samples accordingly to the input required by ESA's software correlator.

VI. Experimental Tests

After the planning session, data suitable for Delta-DOR were collected in different recording sessions. The first attempts of the Delta-DOR analysis was with transmissions of the spacecraft Cassini, but for instrumental problems

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[2] Information about the schedule standards may be depicted from the *SCHED User Manual*, available at the following web page, http://www.aoc.nrao.edu/software/sched/index.html

[3] See the official *JPL Horizons* web page, https://ssd.jpl.nasa.gov/horizons.cgi

those recordings did not lead to a solution of Delta-DOR observable. Afterwards, some recordings were planned considering the spacecraft GAIA, which finally could bring to a proper correlation solution.

A. Early Attempts and Instrumental Issues

In the beginning of this study, a first attempt of Delta-DOR has been performed using the Cassini spacecraft before its Grand Finale in September 2017. In this case, two Italian receiving stations were involved, the VLBI stations of Medicina and Noto, located in Emilia-Romagna and Sicily, respectively. They form a baseline which is too short for the required accuracy, as described in Eq. (4), therefore the analysis has been planned for demonstration purposes only.

For this first analysis, information about Cassini's transmission had to be collected: the spacecraft was planned to transmit telemetry with harmonics, which could be used for the Delta-DOR analysis. The first step was to compute the Doppler on those transmitted values; in this particular case, the harmonics experienced a shift in frequency of about 1 MHz, which is far from being negligible. The code used to compute the Doppler Effect (exploiting ephemeris data from *JPL Horizons*) has been validated during one of the transmission sessions of Cassini with a real time spectrum analyzer, where the computed Doppler shift could be crosschecked with the real-time transmissions. The data were recorded in the Mark5B file type, so that they had to be translated into the RDEF format for processing.

However, the telemetry harmonics were completely embedded in the noise and no solution from ESA's correlator could be found; by integrating many seconds, it was possible to see a faint signal only in the station of Medicina; Noto was experiencing much higher and non-nominal thermal noise levels, so that nothing could be seen. Even the correlation of the signal of the quasar led to no solution, so it was clear that the excessive noise had invalidated the recordings.

Problems related to a possible non-nominal behaviour of the translator could be excluded only after the analysis of a very strong quasar, whose signal could be correlated even in presence of the excessive thermal noise of Noto's back-end. In this case, in one of the two stations a double simultaneous Mark5B-VDIF recording was possible (since the standard switched towards the VDIF file type), so that the station of Medicina was recording VDIF whereas Noto both Mark5B and VDIF. Data were translated into RDEF from Mark5B for Noto and from VDIF for Medicina; since they provided a good correlation result (Fig. 4), we were able to confirm that both translators were working properly.

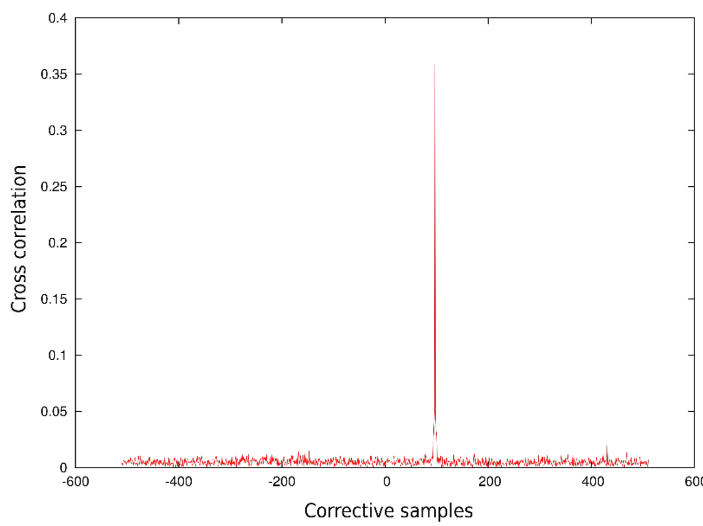

Fig. 4 Quasar correlation with Medicina-Noto baseline, 64s of integration.

In this case, the outcome related to the correlation of one channel containing quasar's noise is 97 samples, which corresponds to a delay τ of 48.5 µs (remembering that the recording is at 2 MHz sampling rate). It should be noted that, before the correlation, the correlator automatically shifts in time the recordings, taking into account the expected geometric delay; the computed τ value contains all the errors not already considered, comprising a possible clock offset between the receiving stations.

B. Final Successful GAIA Tracking session

In order to avoid the problems of noise encountered in the case with the Cassini spacecraft, a shadow track of a dedicated Delta-DOR session with the GAIA spacecraft has been scheduled, so that also an ESA receiver could be used for the analysis. The differences with the Cassini case is in the transmitted power, which is much larger in the dedicated DOR tones with respect to the telemetry harmonics, and the introduction of a classical ESA receiving station as a replacement of the Italian station which experienced excessive thermal noise.

The recording was performed in November 2018, when GAIA was transmitting three DOR tones (located at 8460, 8465, and 8470 MHz) which were received at the stations of Cebreros (Spain) and New Norcia (Australia). Considering the Doppler Effect, the expected received tone frequencies would have to be corrected by a value lower than 10 kHz for the station of Medicina, which can be considered negligible in the setup of the VLBI schedule. The ephemeris of the spacecraft in the J2000 reference frame were sufficiently steady that a fixed value was allowed during each scan without running into the risk of losing visibility from the antenna. For convention reasons, the transmitted right circular polarization had to be set to left circular polarization in the schedule, otherwise the VLBI receiver would record a different signal than ESA's station, leading to no correlation solution. This has been proven by recording both polarizations at Medicina and using the provided recordings of New Norcia for the correlation: a solution was obtained only in case of left circular polarization setup in the VLBI schedule.

The recordings were in the new VDIF format, since in the meantime the Mark5B became obsolete. In Fig. 5 the FFT (Fast Fourier Transform) of the first second of recordings is shown.

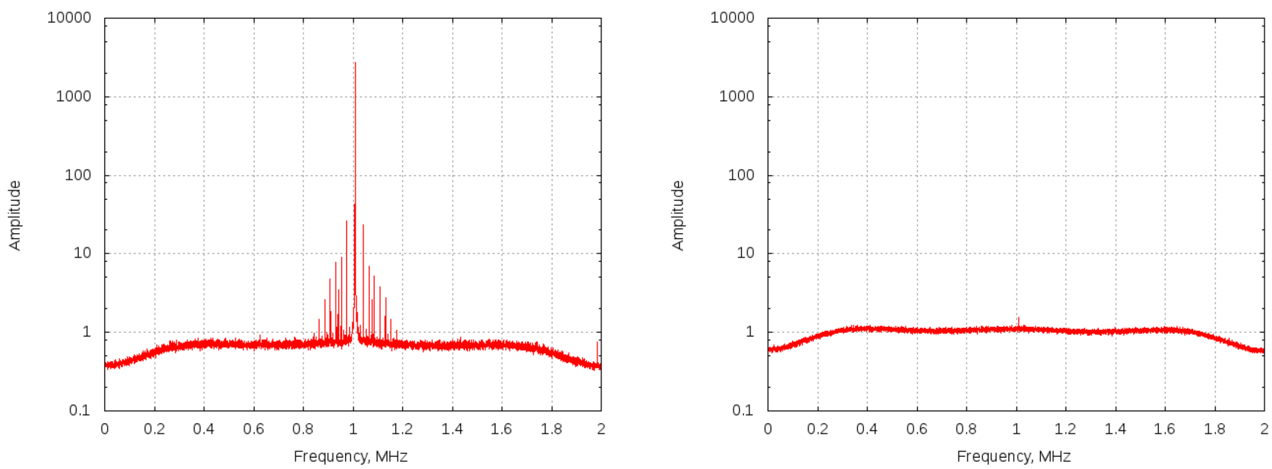

Fig. 5 Spectrum of the recordings in VDIF format for Medicina station, 1 s of integration. On the left, one of the DOR tones (located at 8465 MHz) of the GAIA spacecraft; on the right, the same channel containing quasar's noise.

The channels containing the other two tones are similar (they differ in intensity of the signal), so they are not shown here; the channels with quasar noise have always a spectrum which is similar, so they are not show too. The fact that there are side tones in the spacecraft's recording is due to the non-conventional way in which GAIA was transmitting DOR tones, since it experienced a failure in the DOR-dedicated tone transponder and a backup solution was used.

The following step was to translate the recordings into the standard Delta-DOR input file, the RDEF. In this case, the spacecraft transmission needed to be resampled at a lower sampling rate, going from 2 MHz to 50 kHz, as described above and this is depicted in Fig. 6.

We can see a shift in the frequency of the DOR tone (it is not perfectly in the middle of the channel), and this is due to the rounding of the frequency value set in the VLBI schedule; ESA's software correlator automatically handles this frequency shift thanks to the Doppler predictions allowed by the provided flight dynamics' input files.

In Fig. 7 the power spectral density of the recordings performed at ESA's station are shown, which can be used as a first reference to assess how a good recording should look like.

The following steps entailed the analysis of these data using ESA's software correlator. The first outcome (Fig. 8) is related to the correlation of one channel containing quasar's noise.

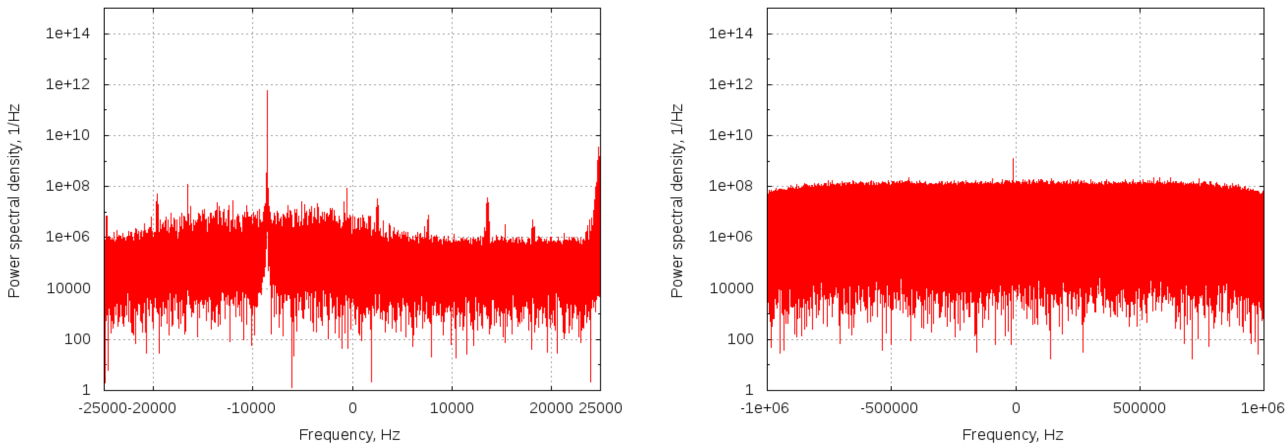

Fig. 6 On the left, the power spectral density of the resampled channel, translated into RDEF, containing the transmitted DOR tone of the GAIA spacecraft in the station of Medicina, 1 s of integration; on the right, the channel containing quasar's noise.

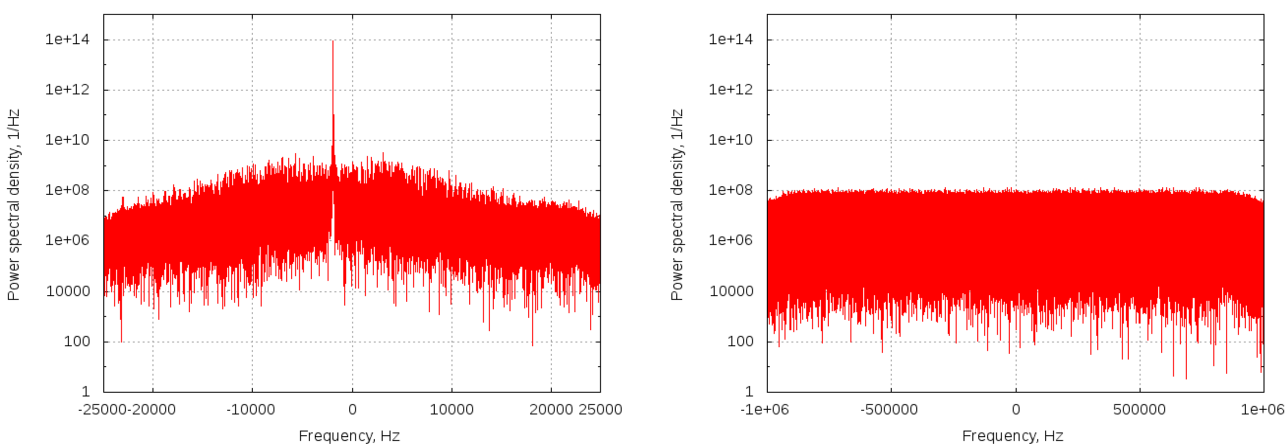

Fig. 7 On the left, the channel recorded into RDEF, containing the transmitted DOR tone of the GAIA spacecraft in the station of New Norcia, 1 s of integration; on the right, the channel containing quasar's noise.

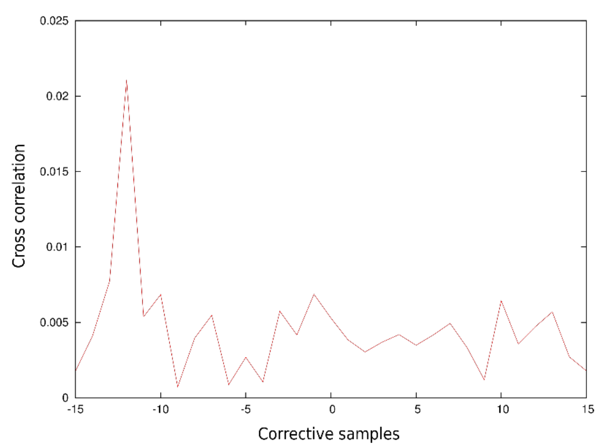

Fig. 8 Quasar correlation with Medicina-New Norcia baseline, 16s of integration.

The output is 12 samples, which corresponds to 6 µs (then the result is furtherly improved to subsample accuracy within the ESA correlator). This time delay is computed for many time intervals, in order to have a statistically significant output. This output is used as a correction for the spacecraft observable. However, before finding the final solution, the spacecraft recordings should also be analyzed.

The first computation is the Doppler correction, which is performed using the data contained in the flight dynamics' side file. The correlator gives as output the recordings properly frequency shifted, so that the DOR tones are now located in the middle of the channel, as shown in Fig. 9.

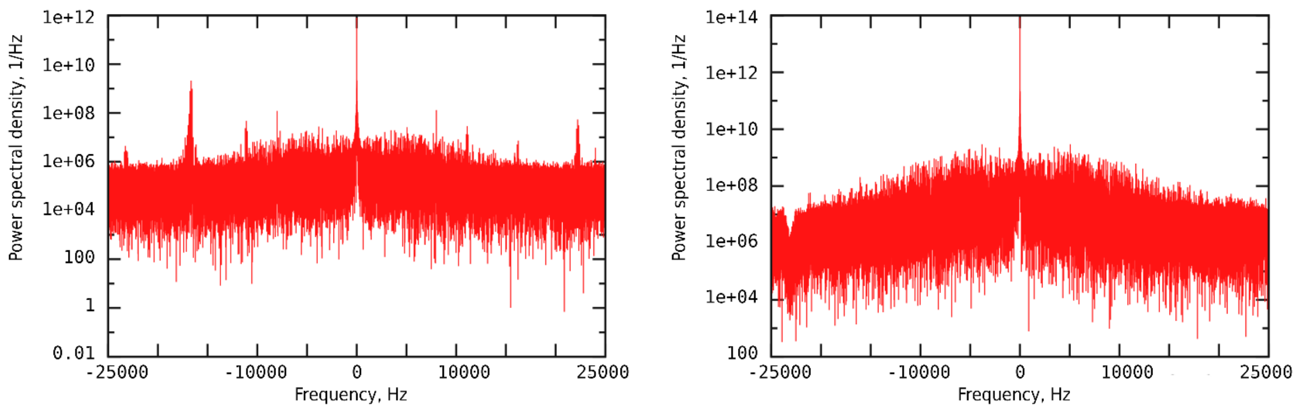

Fig. 9 Power spectral density of a DOR tone after Doppler correction, 1 s of integration; on the left, the recording of Medicina; on the right, New Norcia.

The Doppler corrected data of Medicina is then multiplied by the New Norcia's one, so that the residual frequency difference can be extracted (to check if the phasors have been properly stopped). The result is depicted in Fig. 10.

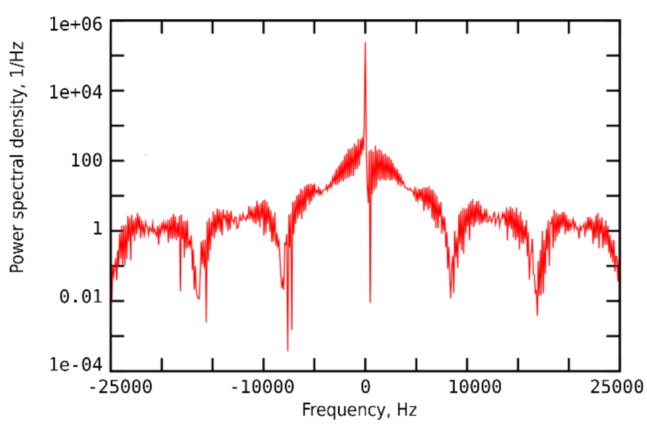

Fig. 10 Power spectral density of the stopped phasor.

The positive results indicate that the entire data acquisition, pre-processing, translation and correlation procedure was carried out correctly. This is the very first time that a VLBI station was used in conjunction with a standard Deep Space tracking antenna to carry out Delta-DOR measurements. Therefore, our initial goal of exploiting VLBI antennas for Delta-DOR analysis has been reached and an experimental proof-of-concept was successfully executed.

VII. Conclusion

The aim of this study was to show the feasibility of the Delta-DOR technique with non-classical receiving ESA stations, such as the stations belonging to the VLBI network. With this objective in mind, a first attempt using transmissions from the Cassini spacecraft was planned and data were recorded from two Italian VLBI stations; however, this led to no solution due to technical malfunctions and noise-related problems. However, the same VLBI baseline which did not succeed in finding Cassini's signals correlation was successful in correlating a very strong quasar, showing some initial good results of the proposed technique.

Therefore, in order to obtain a properly working correlation comprising the spacecraft part, a shadow pass with an Italian VLBI antenna during a standard Delta-DOR session was planned. In this case, it has been decided to have a mixed ESA-VLBI baseline to avoid the noise problems encountered in the first attempts. After some initial data gathering about the transmission timing and characteristics, such as polarization of the transmitted DOR tones and frequency with Doppler correction, the transmissions had been recorded with the receiving station of Medicina and furtherly collected for analysis in the ESA correlator.

The following step was to translate the recordings from the VLBI file types into the Delta-DOR standard, the RDEF. Therefore, the recordings could be processed together with data collected at the station of New Norcia: this analysis led to good correlation results, both for the quasar and for the spacecraft transmissions. This first experimental proof-of-concept shows that the use of VLBI stations for Delta-DOR measurements is possible, and that the missing building blocks in the software processing chain were successfully designed, implemented and tested.

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