A Common Receiver Architecture for ESA Radio Science and Delta-DOR Support

Firmware modifications have allowed the European multi-mission radio receiver to provide the navigation support needed for missions to Mars and Venus.

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ABSTRACT | The need to support radio science experiments and enhance navigation accuracy for the currently flying deep-space missions of the European Space Agency (ESA) has triggered the development of suitable tools in the agency's deep-space stations. This paper describes the modifications implemented in the ESA standard receiver, the Intermediate Frequency and Modem System (IFMS), for the above goals. These modifications were possible due to the highly flexible architecture of the IFMS. Results obtained in the area of radio science research and delta differential one-way ranging tracking are also presented.

KEYWORDS | Delta-DOR; radio science; receivers; scintillation

I. INTRODUCTION

With the launch of the Mars Express, Rosetta, and Venus Express deep-space missions, the European Space Agency (ESA) faced new requirements coming from the radio science community and from the need to provide very precise navigation support.

Radio science [1] experiments had to be supported, for the first time, from ESA deep-space stations. Furthermore, complementary means to validate and refine the orbital solutions obtained with the use of standard techniques (as integrated Doppler and ranging), such as delta differential one-way ranging (delta-DOR) [2], became mandatory for accurate orbit determination prior to critical maneuvers like planetary flybys or orbit insertions.

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Radio science experiments imply the open-loop recording of the received downlink signal (open loop means in this context that the signal tracking loops are not closed). The collected data help the space research in several areas, going from study on solar plasma effects on the radio link during solar conjunctions to the evaluation of the physical properties of atmospheres surrounding planets.

Delta-DOR is a deep-space navigation technique making use of at least two largely separated ground stations, receiving simultaneously the signal transmitted from a deep-space probe and, for calibration purposes, from a radio source (e.g., a quasar). This technique also requires at each site the capability to acquire in open loop the spacecraft and quasar received signals, the availability of a very stable frequency reference, and a sufficient antenna gain over system temperature ratio (G/T). The latter is needed to detect, with a reasonably small integration time, noise-like quasar signals after cross-correlation of the two data streams [3]. A suitable communication network is needed to transfer the large amount of open-loop recorded data to a central processing facility. Furthermore, a machine correlating the open-loop data streams is required to provide the observable parameters to the orbit determination team [4].

Requirements coming from these two areas drove the modifications of the ESA existing multimission receiver, the Intermediate Frequency and Modem System (IFMS) [5], to adapt it to support the downlink data recordings in various configurations as requested by the radio scientists and needed for delta-DOR measurements.

The main goal of this paper is to describe the firmware modifications implemented in the IFMS to adapt it for open-loop data reception. These modifications were possible due to the highly flexible architecture of the

IFMS, based on the extensive use of field-programmable gate arrays (FPGAs). The open-loop receiver, which currently supports both radio science experiments and delta-DOR measurements, is a fully digital and flexible machine, able to cover multiple channel reception with accurate synchronization among different channels, several sampling rates, quantization levels, and modes of operation.

In this paper, we also present some results obtained in the area of radio science research and delta-DOR tracking with the new features of the IFMS.

Results of the delta-DOR measurements with Mars Express (MEX), Venus Express (VEX), and Rosetta operational campaigns are presented, focusing on the achieved performances.

Results for the scintillation index [6], phase noise, and Allan deviation at S- and X-band downlinks, recorded during the Mars Express and Rosetta superior solar conjunctions, are presented as function of the Sun-Earth-probe (SEP) angle, together with a comparison with existing models available from literature.

II. OVERALL SYSTEM ARCHITECTURE

The ESA radio science and delta-DOR systems are largely based on the same hardware. Both rely on open-loop data recordings, need highly stable frequency references, and require an external unit to store the high amount of data produced. For delta-DOR, a correlator (placed in a central location) is needed in order to generate delta-DOR tracking products.

Fig. 1 shows the delta-DOR system architecture [4].

ESA deep-space ground stations are equipped with hydrogen masers (two in each station for redundancy) in order to fulfill the tracking performance requirements for deep-space missions. Careful thermal regulation means and the use of phase stable cables ensure that the excellent frequency stability of the masers is available to all subsystems with no degradation. The achieved performances allow support to delta-DOR and radio science without any modification to the baseline system.

The IFMS was modified for simultaneous multiple signal reception as well as for raw data precise time tagging, essential in the frame of delta-DOR measurements. It was upgraded to receive in open-loop mode up to eight channels, located in different portions of the downlink spectrum, with time-tag synchronization accuracy among the channels better than 1 ns.

The receiver modifications are detailed in Section III.

Two external storage units (ESUs), each consisting of an off-the-shelf server, were deployed in every station to offload the receiver from storage burden. The use of this solution also permits fast formatting and long-term storage of the data.

Once the data are stored in the ESU, they have to be transferred from the ground stations to a central location for further processing. The amount of data to be transferred can be quite substantial, especially in the case of delta-DOR observations (up to 11 Gbyte per observation). Data transfer has to be completed in less than 12 h in order to have DOR tracking products delivered to ESA Flight Dynamics within 24 h from data acquisition. To cope with this requirement, an ad-hoc data transfer approach using already existing resources was defined [7].

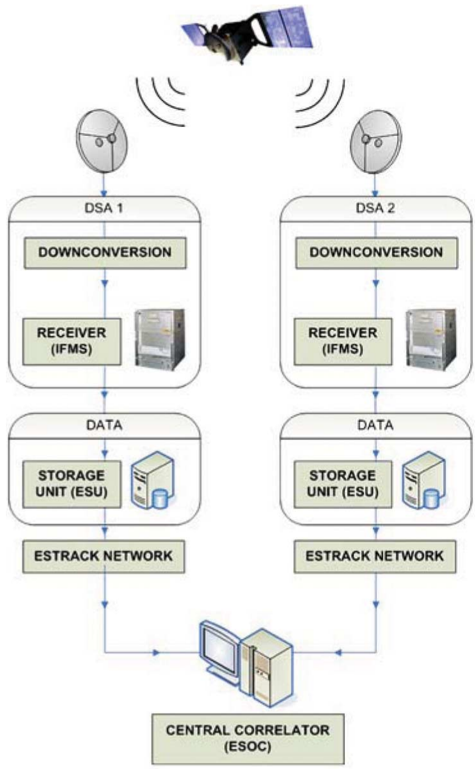

Fig. 1. *Block diagram of the delta-DOR system. For radio science experiments, only one leg is required.*

While radio science data are delivered to the scientists, delta-DOR data are processed by a correlator machine located at the European Space Operations Centre. A software correlator approach was selected, to exploit software flexibility, keeping the design simple and containing costs. The correlator is capable of processing both the spacecraft signal and the quasar's noise-like signal [8].

III. IFMS RECEIVER DESIGN

A. Signal Processing

The IFMS is implemented using signal-processing algorithms on a generic digital signal processor (GDSP) platform. To support radio science and delta-DOR, the IFMS firmware was upgraded to implement a new receiver mode called enhanced open loop (EOLP) [9]. In this mode, the IFMS can process blocks of the intermediate-frequency (IF) spectrum. Up to eight subchannels at selected offset

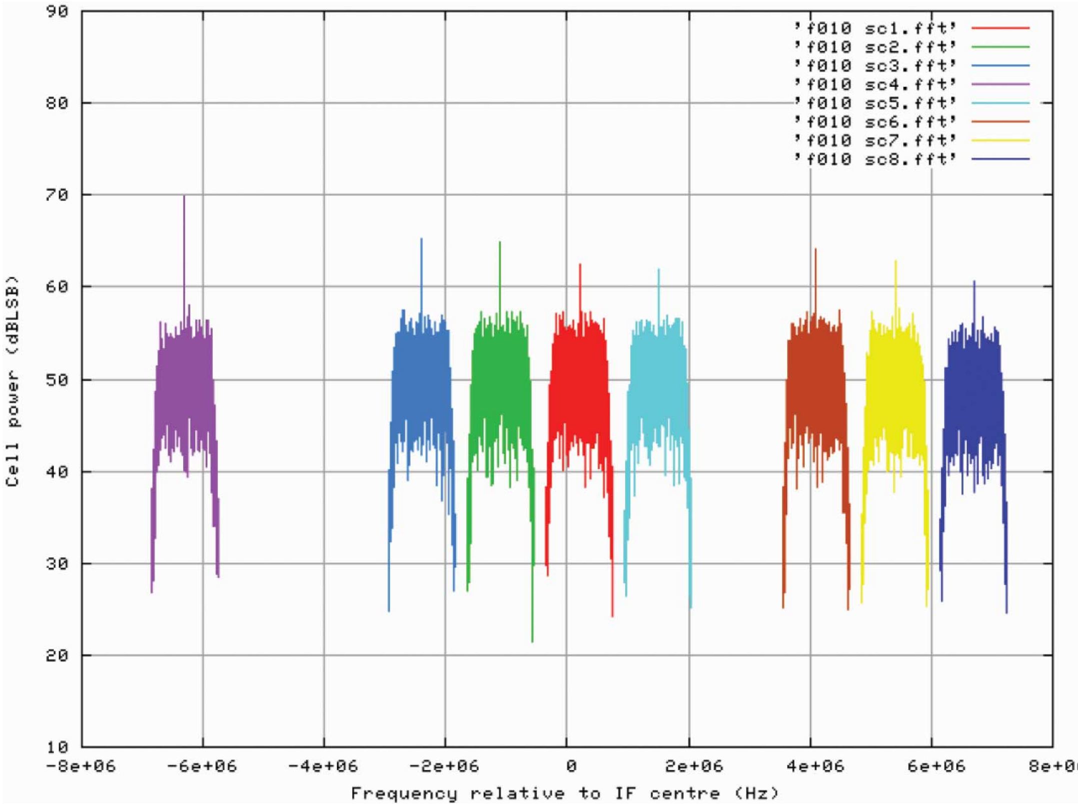

Fig. 2. ***Fast Fourier transform of eight subchannels of 1-MHz bandwidth, at different frequencies around 70 MHz.***

frequencies can be captured with bandwidths from 1 kHz to 2 MHz, as shown in Fig. 2.

Samples in each of the subchannels are synchronized and time-tagged so that the correlator can extract the DOR tracking products. The EOLP receiver makes use of two of the existing IFMS signal-processing modules, called GDSP.

The front-end sampler is called the high-speed common front end (HS-CFE). This consists of a low-pass antialias filter with a 3-dB cutoff frequency around 110 MHz followed by a wide-band automatic gain controller (AGC), as shown in Fig. 3. The AGC prevents the saturation of the analog-to-digital converter (ADC). The

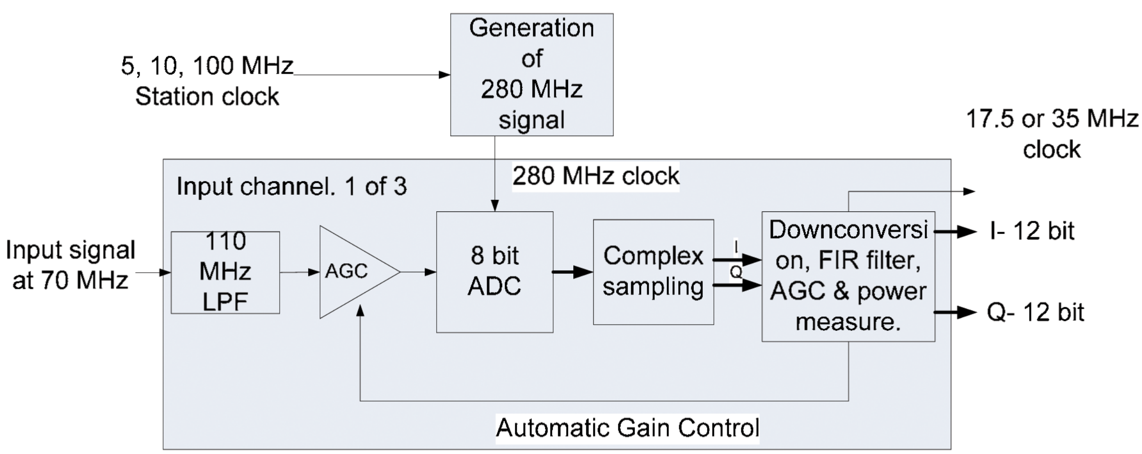

Fig. 3. ***High-speed common front end block diagram.***

sampling clock for the ADC is derived from the station reference and is set to exactly four times the IF center frequency (70 MHz). The 8-bit ADC produces samples at 280 MHz, which are then preprocessed using complex direct sampling by multiplying the signal by the 70-MHz sine (0, +1, 0, −1...) and cosine (+1, 0, −1, 0...) samples. This complex baseband signal is then processed by a high-speed digital processor which bandlimits, downconverts, and downsamples the signal to a 12 bit per component complex output stream sampled at either 17.5 or 35 MHz depending on the configuration.

All eight subchannels are aligned to better than 1 ns, as required for delta-DOR (see Section IV). Since the IFMS processes the entire IF signal digitally, there is no skew between time tags on individual subchannels. Receiver signal-processing tasks in the IFMS are allocated to the GDSP modules. All GDSPs can read IF sample streams from any signal bus. A block diagram of the EOLP receiver is shown in Fig. 4.

Up to three distinct signals centered at 70 MHz are sampled by the HS-CFE with up to 24-MHz bandwidth, downconverted to zero IF, and distributed as baseband complex streams to the GDSPs.

Each GDSP implements four independent subchannels and the captured data are time-tagged, formatted, and sent as user datagram protocol/Internet protocol (UDP/IP) packets over a 100-Mbit/s local-area network (LAN) to the ESU. Each GDSP synchronizes its internal clock to UTC (Coordinated Universal Time) using the station interrange instrumentation group timecode standard time reference. In fact, time-tagging coherency between the subchannels inside the GDSP is based on counting clock cycles. This is exact over an arbitrary period because it uses the same frequency reference. Up to two EOLP GDSPs can be present, giving a total of eight subchannels.

The subchannel processor block consists of a phase rotator that turns the incoming complex samples at rates of 17.5 or 35 MHz. The samples are then filtered and decimated to reduce the sample rate to the required value. Furthermore, they are formatted and transmitted out of the block on a serial interface.

The complex phase rotation is controlled by a numeric controlled oscillator (NCO) clocked at 35 MHz. The subchannel's center frequency is defined by the NCO frequency plus a dynamic Doppler offset, which is derived from the supplied Doppler predicts.

B. Formatting

Formatted captured data for all four subchannels are sent to the ESU using fixed-length records. Each record consists of a header section and a data section. The number of samples stored in the data section depends on the selected quantization scheme. Generally, the narrow-band spacecraft signal recordings for delta-DOR are performed using 50-kHz channels with 8-bit resolution, whereas the wide-band quasar recordings are performed using 2-MHz channels with 2-bit resolution. For radio science acquisitions, usually a 4- or 100-kHz sampling rate and a 16-bit resolution are used.

The header includes a timestamp that represents the time of arrival of the first sample in the record corrected back to the input interface of the GDSP. This can be used along with the known sample rate to determine the time of arrival of any of the samples in the record. The header also contains information on the gain of each subchannel and

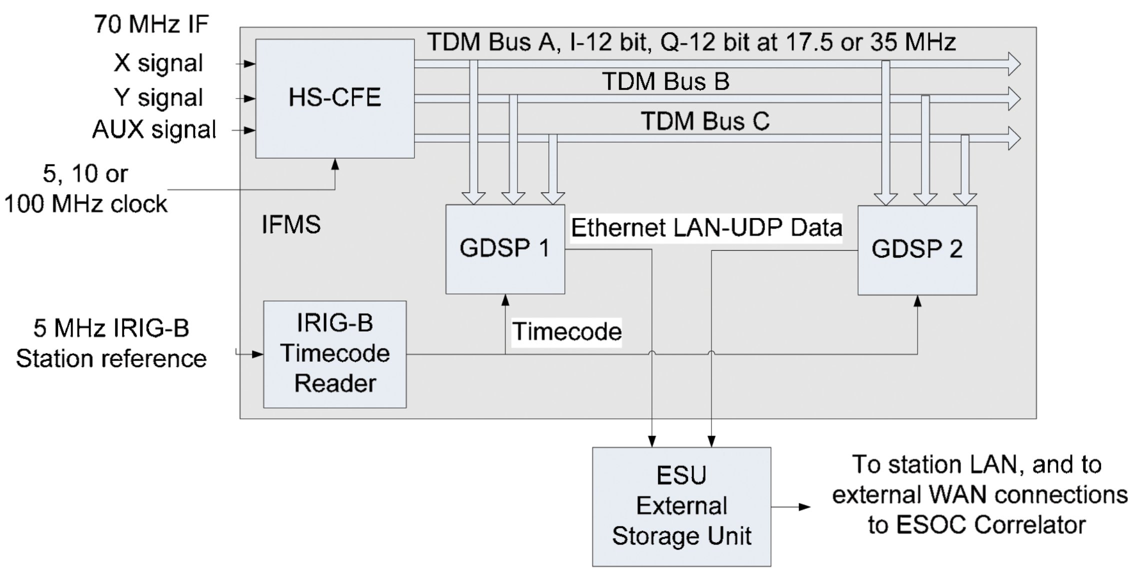

Fig. 4. *ELOP receiver block diagram.*

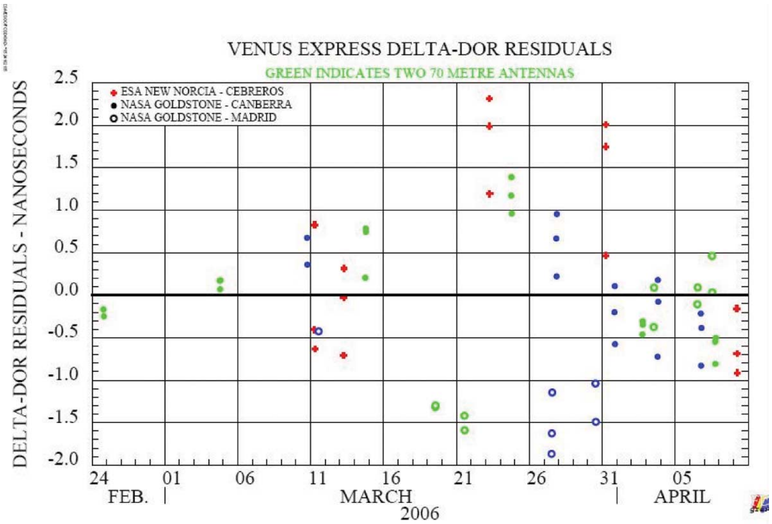

Fig. 5. *VEX delta-DOR residuals of ESA and JPL data points. Red points indicate ESA data, green points DSN data using 70-m antennas, and blue points DSN data acquired using 34-m antennas.*

parameters to allow reconstruction of the subchannel NCO phase at any time.

Data are sent to the ESU through a UDP LAN connection. The connection is unidirectional, and the correct establishment of the protocol between ESU and IFMS is controlled at a higher level, through a transmission control protocol/IP protocol.

IV. ΔDOR—RESULTS

A typical delta-DOR session consists of three acquisitions, 5–10 min long: spacecraft, quasar, and again the spacecraft signal. Since the currently flying ESA deep-space spacecrafts are not equipped with transponders capable of generating dedicated DOR tones, the acquisitions are made on the even harmonics of the telemetry subcarrier [3] using a narrow filter bandwidth of 50 kHz. Based on the fact that the quasar position is known down to better than 1 nrad, it can be used to minimize the difference delay between the two stations. With this calibration, the delays due to the media traversed by the radio wave (such as troposphere, ionosphere, and solar plasma), the time-tagging offsets, and other station instrumental effects can be adjusted for. Due to the noise-like signal structure of a quasar, a much wider recording bandwidth (2 MHz) has to be used in order to have enough correlated signal-to-noise ratio. The flight dynamics postprocessing, needed to calculate the spacecraft trajectory, is used to evaluate the accuracy of the results in terms of orbit residuals [1].

The key test in order to assess the system performance was the tracking of MEX, an ESA spacecraft currently orbiting around Mars. Since MEX is an orbiting spacecraft, its trajectory can be very accurately determined by means of standard navigation techniques only, such as Doppler and ranging. These measurements alone provide orbital solutions relative to the planet accurate down to 200 m. The ephemerides of Mars are also known with an error of the same order of magnitude. Therefore, MEX could be used as a reference object to evaluate the overall system accuracy.

Two series of measurements were performed in early 2006. Processing of the six sets of DOR data showed that all but one of the delta-DOR measurements were accurate to better than 0.5 ns, the root mean square (rms) value being 0.3 ns. Only one of the data points gave results above this value. This is likely due to the fact that the tracking conditions for this case were unfavorable, since the quasar was almost 15° away from the spacecraft while it should normally be less than 10°. Furthermore, the correlated spectral power flux density of the quasar was less than 0.1 Jy (1 Jy is $= 10^{-26}$ W/m^2/Hz), while for the other measurements only quasars with at least 0.7 Jy of correlated spectral power flux density and angularly close to the spacecraft were tracked.

Following these results, operational delta-DOR measurements were performed with VEX. Up to 15 data points derived from data acquired on five separate occasions in March and early April 2006 augmented a total of 45 NASA delta-DOR measurements obtained in the same time frame. Results of the ESA and Jet Propulsion Laboratory (JPL) delta-DOR data taken on VEX are summarized in Fig. 5.

Analysis shows that the quality of the ESA delta-DOR measurements is comparable to that obtained by the NASA Deep Space Network (DSN) with rms residual values of about 1.3 ns for ESA delta-DOR points and of 0.8 ns for JPL [4]. This difference in accuracy can be explained by the concurrence of several causes: the availability, on the JPL side, of 70-m antennas (ESA: 35-m antennas), the larger channel bandwidth used for quasar recording (4 MHz), and better tropospheric corrections.

After the VEX operational campaign, data were also taken from Smart-1 spacecraft, while it was still orbiting around the Moon. The goal in this case was to test the system capability to correctly record and postprocess dedicated DOR tones, generated in the Smart-1 onboard transponder, instead of high-order telemetry harmonics.

It has to be remarked that in this case, data residuals were not used in the orbit determination process of the spacecraft. However, also in this case, the magnitudes of the DOR and delta-DOR residuals were fully consistent with the uncertainties in the Smart-1 orbit determination. The stability of the solution (versus the integration time) was much better than in the case of VEX or MEX, due to the use of DOR tones implying much higher signal-to-noise ratios.

Since early 2007, ESA has also performed delta-DOR measurements with the Rosetta spacecraft, prior to the critical flyby of Mars, which occurred on February 25, 2007. A total of 31 ESA and 55 JPL delta-DOR data points were taken on this occasion. Results in terms of residuals are shown in Fig. 6. In this case, ESA data were much better than the required performance of 1 ns, having an rms of 0.53 ns, while JPL data showed an rms of 0.16 ns. This difference in accuracy can also be explained as for the VEX case. It is also to be noticed that on two occasions, ESA data were acquired with the Rosetta transponder in sustained lock, which produced extremely degraded signal characteristics.

V. RADIO SCIENCE—RESULTS

The EOLP receiver mode is also used for radio science applications, i.e., for scientific experiments that make use of the radio-frequency (RF) telecommunication link established between a ground station and a deep-space probe. Open-loop data have been routinely recorded since 2006 in the scope of the VEX mission during slots dedicated to radio science experiments, and delivered to groups responsible for postprocessing and interpretation of the data. The open-loop data sets are complemented with closed-loop products recorded during the same slots, consisting of integrated Doppler and ranging measurements on a dual frequency link (2- and 7/8-GHz bands). The whole VEX radio science experiment has the objective of investigating the physics of the Venus surface, neutral atmosphere and ionosphere, the Venus gravity field, and the interplanetary medium [10].

In this section, we present some results obtained from measurement campaigns organized by the authors during superior solar conjunctions, i.e., during specific phases of deep-space missions when the geometrical configuration of the system Sun-Earth-probe is such that the Earth–spacecraft telecommunication link passes through the solar plasma, within few solar radii from the Sun. Under such circumstances, the solar charged particles induce various degradation effects on the RF signal, like amplitude fluctuations, increase of phase noise, and spectral broadening. A large quantity of data was recorded on the IFMS during three campaigns: the superior solar conjunctions of Ulysses and MEX in 2004 (during August 2004 and September 2004 respectively), and of Rosetta in April 2006. In this paper, we show summaries of the

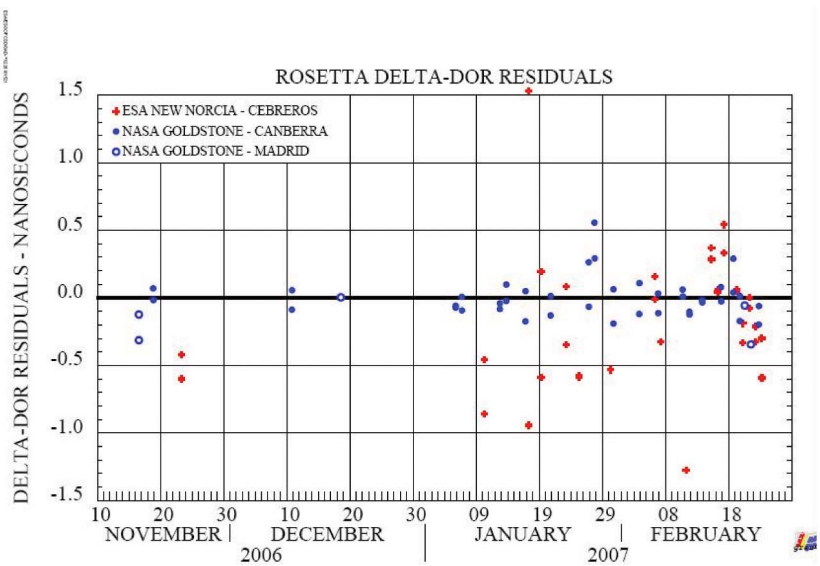

Fig. 6. ***Rosetta delta-DOR residuals of ESA and JPL. Red points indicate ESA data and blue points DSN data acquired using both 34- and 70-m antennas.***

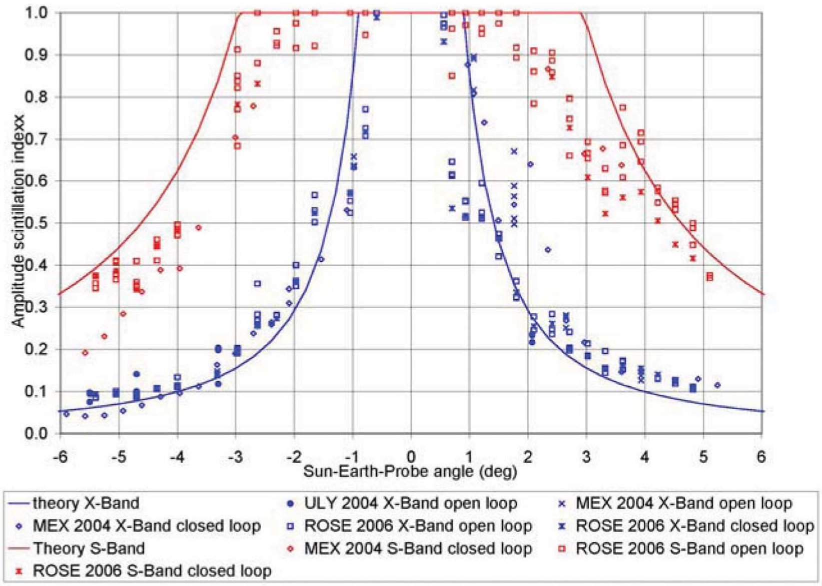

Fig. 7. ***Measurements of the amplitude scintillation index in the 2- and 8-GHz bands during three solar conjunctions: in August 2004 (Ulysses), September 2004 (Mars Express), and April 2006 (Rosetta). The measurements are based on open- and closed-loop data. The phase-locked loop used for tracking the remnant carrier was 100 Hz (2BL) at 8 GHz and 30 Hz (2BL) at 2 GHz, for the Mars Express and Rosetta campaigns. The theoretical predictions (solid line) are based on [11], related to the case of quiet solar activity. The agreement between theory and observations is excellent in the 8-GHz band and not very good in the 2-GHz band, where the scintillation effect is overestimated by the theoretical model.***

amplitude scintillation index and the solar phase noise measurements during these conjunctions.

As far as the amplitude scintillation index (m) is concerned, this is defined as the ratio between the standard deviation of the received signal power fluctuations (say, σ_P) and the average power $\overline{P}$

$$m = \sigma_p/\overline{P}.$$

The amplitude scintillation index is of interest because it is easily measurable and can be put in direct relation with solar plasma related physical quantities [6], [11]. During the above-mentioned measurement campaigns, the scintillation index was calculated based on the acquired open-loop data. The instantaneous signal power is obtained with the square module of the complex phasor of the residual carrier, derived from the I&Q components stored in the open-loop data sets. It is also computed with closed-loop data, using the estimation of the time-varying power level of the residual carrier as reported by the coherent AGC. Fig. 7 shows a summary of all measurements made during the three campaigns, in the 8- and 2-GHz bands, together with the theoretical predictions based on scintillation models reported in [12]. The agreement between theory and measurements is excellent in the 8-GHz band, whereas the theoretical model overestimates the scintillation effect in the 2-GHz band.

Phase noise $L(f)$ and the one-sided spectral density of phase deviations $S_\Phi(f)$ [13] can also be calculated from IFMS closed- and open-loop recordings. Prior to the calculation of these quantities, phase residuals are extracted from the recorded data by means of either some polynomial fit applied directly to the data or fitting the recorded data with orbital data provided by the ESA Flight Dynamics group.

In the case of closed-loop data, phase information is already available from Doppler measurements at a

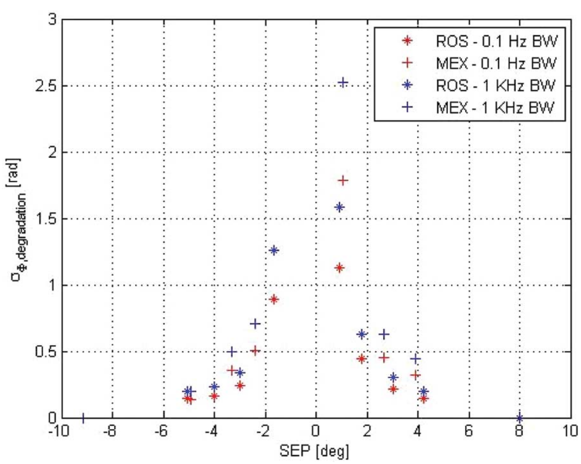

Fig. 8. ***Phase jitter X/X-band links during the solar conjunctions of Mars Express (September 2004) and Rosetta (April 2006).***

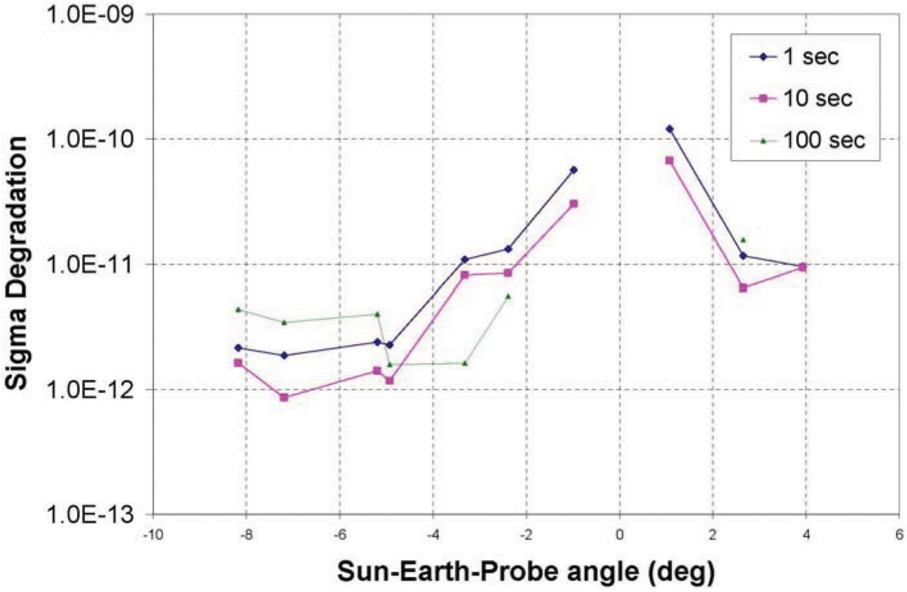

Fig. 9. *Degradation of the Allan deviation versus SEP angles during the solar conjunctions of Mars Express (September 2004, X/X band). DOY231 (SEP -9.15° used as reference.)*

maximum output rate of 10 Hz, which limits the measurement of phase deviations to 5-Hz offsets. Open-loop data recordings with the IFMS allow measurements far from the carrier, since the sampling frequency in open-loop mode can go as high as 2 MHz. The major difficulty in this case lies in the unambiguous extraction of phase residuals, which is particularly difficult in the case of noisy signals. So far, two different methods have been used with IFMS recordings. The first one unwraps the phase by adding multiples of $\pm 2\pi$ when jumps above a default tolerance are present. This approach is very likely to fail when noisy signals are to be processed. A second approach is therefore used, which employs a software phase-locked loop (PLL) to lock the phase and quadrature samples available from open-loop recordings in order to extract the phase information unambiguously.

The characterization of phase instability information during solar conjunction phases is relevant not only for radio science research but also for dimensioning the PLL bandwidths for future mission phases in which low SEP angles will be reached. Fig. 8 shows the Phase jitter, calculated as

$$\sigma_\phi = \sqrt{\int_0^{BW} S_\phi(f)df}.$$

Phase residuals can also be processed in order to yield valuable Allan deviation results, which is the standard characterization of phase instability in time scales above seconds [13]. In this case, phase residuals are extracted, fitting the data with orbital data provided by ESA Flight Dynamics.

Fig. 9 presents the degradation of Allan deviation as a function of the SEP angle during the solar conjunction of MEX, also computed from data acquired with the open-loop receiver.

VI. CONCLUSIONS

In this paper, we have presented the implementation of a delta-DOR and radio science receiver for deep-space applications, which was developed in a record time of ten months. This was possible because the ESA deep-space stations were designed to meet the stringent requirements that are also essential for delta-DOR tracking and for accurate radio science measurements.

The existing receiver platform (IFMS) allowed the implementation of the EOLP function with no hardware changes and with the single addition of an external unit for data storage. The data captured by this enhanced receiver allowed producing valuable delta-DOR tracking products, which were used to support the navigation of the ESA deep-space spacecrafts VEX and Rosetta during critical mission phases. ESA delta-DOR results show accuracies in the orbit residuals values below 1-ns rms, which correspond to an angular uncertainty of 30 nrad or, equivalently, to an uncertainty of 4.5 km at a distance of one astronomical unit.

The achieved performances of the enhanced IFMS are fully compatible with the requirements of the ESA orbit determination team and with the needs of the radio science community for currently flying as well as for future ESA deep-space missions. ■

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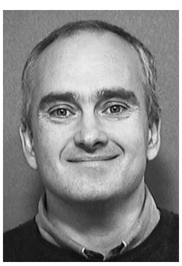

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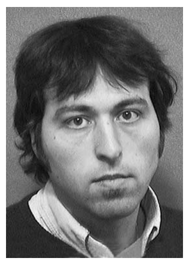

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