VENUS EXPRESS SPACECRAFT OBSERVATIONS WITH EVN RADIO TELESCOPES

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ABSTRACT

The ESA Venus Express spacecraft was observed at X-band with several European radio telescopes during a 2008-2010 observational campaign in a framework of the assessment study of the possible contribution of the European VLBI Network (EVN) to the upcoming ESA deep space missions. The first goal of these observations was to develop and test the scheduling, data capture, transfer, processing and analysis pipeline. Observed data recorded in a VLBI-compatible mode were transferred from the radio telescopes to Metsähovi Radio Observatory (MRO) where they were processed with an ultra-high spectral resolution software spectrometer-correlator and then analysed at Joint Institute for VLBI in Europe (JIVE). The high dynamic range of the detections allowed us to achieve a milli-Hertz level of spectral resolution accuracy and to extract the phase of the spacecraft signal carrier line. Several physical parameters can be retrieved from these observations.

Here we report the technology aspects of our research and preliminary scientific results obtained during several multi-station VLBI phase referencing observations of the Venus Express.

1. INTRODUCTION

Planetary and other science mission spacecraft (S/C) as targets of radio astronomy observations offer a new tool for studying a broad variety of physical processes ranging from dynamics of extraterrestrial atmospheres to geodynamical diagnostics of planetary interiors to fundamental physics effects of spacecraft motion. Many of these applications require an extremely high angular resolution achievable only with VLBI, coupled with very high spectral resolution. This technique has been demonstrated in the highly successful experiments of VEGA, Huygens [1, 2] and Smart-1 [3] with VLBI Tracking Experiment. Its further development called Planetary Radio Interferometry and Doppler Experiment (PRIDE) is adopted by a number of prospective planetary science missions as a part of their scientific suite [4]. These include the Phobos-Mars mission (launch in 2011), the BepiColombo/MMO mission to Mercury (launch in 2014), ExoMars mission (launch in 2018) and prospective studies of the Europa Jupiter System Mission (EJSM) and Titan Saturn System Mission (TSSM) (launches in 2020 and later). The ESA Venus Express spacecraft (VEX S/C) radio transmission signals are an interesting target for exercising this new science support method, usable in prospective ESA planetary probe and deep space missions. In 2008 a campaign including a number of European VLBI Network telescopes (see Fig. 1) started with trial observations of VEX in a framework of the PRIDE based on spacecraft observations, S/C signal detection, data processing and analysis. This paper describes the analysis methods, introduces the software developed for handling the analysis flow, and presents the most recent detections we achieved during the single-dish. The VEX observations were performed with the participating antennae, Metsähovi (Aalto University, Finland), Wettzell (BKG, Germany), Yebes (OAN-IGN, Spain), Medicina (INAF-RA, Italy), Matera (ASI, Italy), Noto (INAF-IRA, Italy) and Puschino (ASC-LPI, Russia) in coordination with ESA Space

Fig 1: European VLBI Network radio telescopes and partners. These antennae can be used for our purpose of VLBI spacecraft tracking.

Astronomy Centre (ESAC), and ESTRACK station Cebreros, Spain. The high dynamic range of our phase detections allow to extract and analyze the phase of the S/C carrier line from many different physical perspectives, among which the S/C orbitography and propagation effects are the first in the line. The typical SNR achieved in the observations is of several thousands in 1 Hz accuracy or several millions in 1 mHz. We demonstrate how the phase-time of the S/C signals was applied to detect interplanetary plasma scintillation on a novel frequency band (X-band) and present the results of this two-year work.

	dish	*Elevation*	*SEFD*
Metsähovi	14-m	75.6 m	3200
Wettzell	20-m	67.2 m	750
Yebes	40-m	543.4 m	200
Medicina	32-m	143.2 m	320
Matera	20-m	669.1 m	3000
Noto	32-m	998.9 m	770
Puschino	22-m	-	-

Table 1: summary of the basic parameters and characteristics of the European VLBI antennas used during the 2008/10 campaign.

2. THEORETICAL APPROACH

The VEX S/X-band transponder operates at up/downlink margins designed to maintain usable links out to the Venus apogee distance (1.7AU). This allows observations to cover narrow Solar elongations ß, the opening angle between Sun-Earth-S/C. Phase-time behaviour of the S/C signal along line-of-sight at various Solar elongations gives insights into the signal propagation through solar system plasma, as shown later below. Near-Earth and near-Venus troposphere and magnetosphere effects have not been taken into account, but may play a significant role in following observations when Venus is in a closer position respect to the Earth.

S/C signal phase-time behaviour is derived from observational data through ultra-narrowband phase locking onto the S/C carrier or ranging tones. High-resolution spectra from the individual telescope observation are used to generate an initial phase model. The model and residuals are refined in subsequent iterative processing steps. Phases are calibrated via the VLBI phase referencing technique (data correlated by JIVE). This allows compensating for the phase drift of Earth-based station H-maser clock references.

Phase noise of the VEX on-board VeRa Ultra-Stable Oscillator (USO) phase-locked to the Rx/Rs uplink carrier is cleaner (Allan deviation <3*10^{-13} @ 1-100s) than the phase noise of our observations. The uplink carrier is tied to a local atomic reference, such as H-masers. The USO is unlikely to cause significant additive phase noise in the transmission downlink and thus measurement artefacts [5].

With the method described above we can determine the apparent topocentric frequency of the S/C carrier line and accompanying ranging tones down to sub-mHz accuracy and can calibrate the phases on a per-baseline basis using the VLBI phase referencing technique.

2.1 S/C observations

Frequency and transmission schedule information was kindly provided by ESA. We observed the 8400-8450 MHz X-band downlink carrier and modulation tone signals in single-dish and multi-dish configurations with the participating EVN telescopes. Several data acquisition systems are used with a sampling bandwidth (BW) ≤ 16MHz, which is more than enough to capture the S/C signal. Due to the characteristics of VLBI observations and the recording equipment, each observation can imply the transfer and processing of over 10 TB of data. Data and first stage results is stored on Metsähovi disk systems with near 100 TB aggregate capacity. Final results and data copies for VLBI phase referencing are stored in JIVE.

2.2 First S/C detection using software spectrometer

The initial detection of the S/C carrier and tones is performed using the high-resolution spectrometer software (SWSpec) [6] developed at Metsähovi. A Python PyQt4 GUI allows fast reconfiguration for new processing jobs and easy selection of settings and parameters. Through the NRAO mark5access library (developed by NRAO), SWSpec supports several input file formats broadly used in the VLBI community such as Mark5A/B/C (developed by Haystack/MIT), PCEVN (developed by Metsähovi) and VDIF (standardized VLBI data exchange format). In addition SWSpec supports various other multi-channel multi-bit formats generated by iBOB 10GbE, Metsähovi VSIB and other data acquisition systems. An SWSpec pass extracts one selected raw data channel from the input data file. It performs accurate windowed-overlapped discrete Fourier transforms and spectrum time integration. All parameters are freely configurable. Time-integrated spectra are written to disk for the next step of fitting a phase-stopping polynomial to select tones in the spectrum.

SWSpec can additionally extract the phase of the Phase Calibration frequency comb injected into the analogue receiver chain at the telescope to determine instrumental phase drift. It is useful as a problem checking utility, since some of the old baseband receiver hardware are getting unreliable (VLBA rack BBC/VC units). However, it has no direct application in S/C processing.

For our VEX spacecraft spectrum analysis usually is used 3.2M DFT points and Cosine-squared windowing for a spectral resolution of ≤ 5 Hz and had 5-20 second time integration for coarse phase detection.

2.3 Phase-stopping polynomial fit

The output spectra of SWSpec are processed using MathCAD and Matlab scripts developed at JIVE. They extract the moving phase of S/C tone frequencies (tones detected by visual inspection) from the series of integrated spectra. An M-order (M=4-7) phase stopping polynomial, see Eq. 1, is fitted into the S/C carrier line frequency detections *f* through the series of spectra of all time-integration steps *t* using a Weighted Least Mean Square (WLMS/WLS) method with weights w_{SNR} depending on detection SNR and nearby radio interference (RFI) considerations, see Eq. 2:

$$P(f) = \hat{C}_{pp}(0)f^{0} + \ldots + \hat{C}_{pp}(M-1)f^{M-1} \qquad (1)$$

$$\left(T^{T} W_{SNR} T\right)\hat{C}_{pp} = T^{T} W_{SNR} F \qquad (2)$$

Resulting polynomial coefficients C_{pp} are used as input to the next processing steps – phase stopping and narrow band tone filtering and extraction.

2.4 Tone tracking, filtering and phase detection

Spacecraft tone tracking software (SCTracker) [6], developed by Metsähovi, accepts the raw telescope input data, a list of S/C tone frequencies (relative to carrier), and the M-order phase stopping polynomial coefficients from the LMS fit. Double-precision polynomial evaluation is applied to the baseband sample sequence x[n] to stop the carrier tone phase. Eq. 3 shows the mathematical idea that SCTracker bases its calculations.

$$\tilde{x}[n] = x[n]\cdot\exp\left(\pm i \sum_{k=2}^{M-1} C_{pp}(k)\cdot(Tn)^{k}\right) \qquad (3)$$

Time-integrated windowed-overlapped spectra of the stopped baseband signal are written to disk. They are useful for checking the quality of the phase stop. Narrow bands (typically with 1:4000 decimation ratios) are extracted from the stopped baseband signal around each specified tone frequency. The current implementation of software allows a practically unlimited number of narrow bands to be filtered and down-converted, with arbitrary distribution of them in the input band. The extracted bands (with the tones in the centre) are filtered out into continuous complex time-domain signals with ≤ 4 kHz bandwidth using a 2^{nd} order Window-Overlap-Add (WOLA) DFT-based algorithm of the Hilbert transform approximation. The extracted signals are written to complex floating-point output files for further post-processing.

This is performed with the digital Phase-Lock-Loop (PLL) software at JIVE. The software runs high precision reiterations of the steps of Eq. 1 to 3 on the filtered low-rate signals. The residual phase in a stopped band is determined with respect to a set of subsequent frequency/phase polynomials initially applied for the phase stopping.

Depending on the SNR of the carrier line and individual tones, the final bandwidth of phase detections after secondary PLL can range from several kHz down to several mHz. In case of the VEX carrier line this bandwidth is in the range of 10-100 Hz. Fig. 2 illustrate residual phase variation of the carrier line residual after Doppler correction.

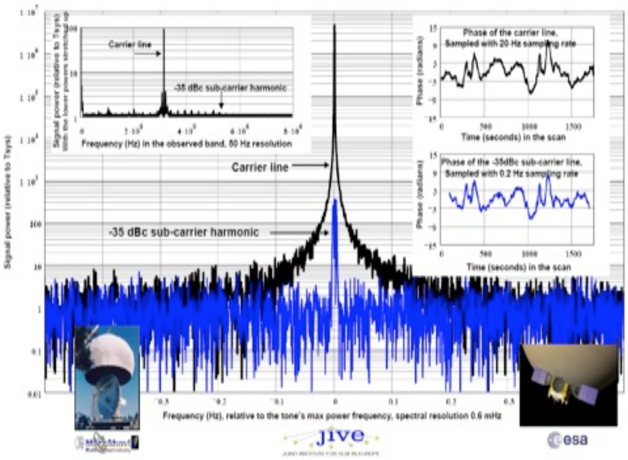

Fig 2: summary plot for VEX observations with Metsähovi telescope. Top left corner preview spectrum of 50 Hz resolution over 8 MHz video band, dynamic range > 40 dB. Top right, detected phases of the carrier line and sub-carrier with 0.6 mHz resolution.

3. METHODOLOGY

3.1 VEX observations

The ESA VEX spacecraft was selected as a "test-bench" target for our research. Several radio telescopes from the European VLBI Network have run observations of the VEX spacecraft on X-band, covering a range of Solar elongations from ~1.5 degrees (the closest elongation allowed by the two-way link) up to 45 degrees (at quadrature). Table 2 shows a summary of the observations done so far.

	# obs.	*# hours*	*# samples*
Metsähovi	11	25	55
Wettzell	9	18	41
Yebes	6	14	30
Medicina	4	7	21
Matera	2	4	11
Noto	1	2	6
Puschino	2	3	2
Total	35	73	166

Table 2: summary of the number of observations, hours and scans observed during the 2008/10 campaign with EVN radio telescopes.

The data communications link from VEX to the ground station antenna operates daily for 6 to 8 hours. Due to the limited observation time, the epoch sessions usually last 2 or 3 hours per session. In each session are recorded six to nine scans with duration of 19 minutes each. Multi-epoch observations are ideally scheduled twice per week. Unfortunately, we cannot run as many continuous observations as desired due to the high demand of antenna time for other astronomy purposes.

Data is recorded using the standard VLBI MkIV or VLBA data acquisition rack systems with 4 or 8 frequency channels with a configurable bandwidth of 8 or 16 MHz and 2-bit Nyquist sampling mode. Total aggregate recording data rate varies from 128 Mbps to 512 Mbps generating over a hundred of gigabytes each session. The data is transferred electronically from the antenna to the processing centre either in real-time or after the experiment. Using FPGA-based devices for data filtering and sampling has been developed as an alternative for the current VLBI equipments. The firmware prototypes have been designed with the FPGA board called iBOB designed at the Centre for Astronomy Signal Processing and Electronics Research (CASPER) laboratory of University of California, Berkeley [7], and it enables us to record same frequency bandwidth at 8-bit sampling. Alternatively, observations with the Puschino telescope were carried out using video bands of 4 MHz and K-5, the Japanese VLBI recording system.

The MkIV formatted data is recorded with Mark5A or PCEVN disk systems. Both units are recording systems specially designed for astronomic and geodetic VLBI observations. Files are electronically transferred either simultaneously or after the experiment through the Internet with Tsunami UDP [8] to Metsähovi for data processing. Data are processed with the ultra-high spectral resolution spectrometer-correlator software previously described. Processing tasks run in two iterative loops using MRO and JIVE software. With our current facilities the full processing cycle takes 5-10 times longer than the observation time, but is constantly being improved. Fig. 3, shows the latency for the data processing and final post-analysis of the observed scan.

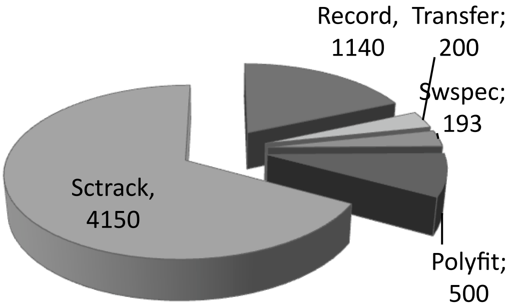

Fig 3: The summary chart of the data processing latency. Usually, it takes up to 3 hours to process a single scan.

3.2 Physical implications of S/C phase analysis: Interplanetary Plasma

Interplanetary Plasma Scintillation (IPS) originates from the diffraction of radio waves by fluctuations within the solar wind. Measurements of IPS have been conducted for many years to probe the solar wind throughout the inner heliosphere. The phase variations caused by the density fluctuations scatter the signal and cause the fluctuation in received power and phase. [Density variations and turbulence in the plasma scatter the S/C signal and cause fluctuations in received power and phase.]

Large variations (>> 1 radian) introduced across the wave front are known as "strong" scattering. When the variations are small (<< 1 radian) the scattered waves add constructively to generate much larger fluctuations in the signal received, known as "weak" scattering. The standard measurement of the level of IPS is *m*, the scintillation index. This is the ratio of the RMS variation in the strength of the source signal due to IPS to the average strength of the signal [9, 10]. Especially at higher frequencies, the scintillation index depends on the source angular size and structure.

In this sense, the spacecraft signal is an almost ideal source point that allows a good opportunity for radio science studies. Although its emitting power is subject to internal power variations, which depend on the data transmitted, the phase of its carrier line is a stable quantity because it is locked to a high precision atomic clock at the communication station. We note that the phase variations in this case are the result of a two-way propagation: from the communication station to the spacecraft and back to the observing station.

Phase scintillation caused by propagation through the solar wind, ionosphere and troposphere introduces noise in spacecraft radio science experiments. Scintillation can be the dominant noise source in precision Doppler tracking observations. High-precision tracking data are necessary for a good interpretation of the satellite signal propagation and the solar wind effect.

4. RESULTS

4.1 S/C signal propagation analysis

The detected S/C signal is the observed two-way link (uplink and downlink data communications) between the ground station and the spacecraft. The phase of the signal is extracted with the local hydrogen maser as a reference. By using nearby quasars as a reference source and VLBI observations, we are able to determine the absolute phase values between all the participating stations. The level and quality of the observations are strongly dependent on weather conditions, system noise temperature of the receiver and the accuracy and resolution of the radio telescope. But IPS analysis does not highly dependent on them.

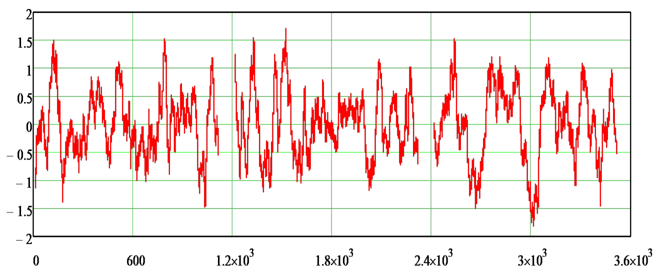

Fig 4: phase fluctuation from the 3 scans observed with the Wettzell radio telescope on 16/11/2009. X-axis is in seconds and Y-axis in radians.

As shown in the Fig. 4 the extracted S/C phase from 3 consecutive scans observed with the Wettzell telescope on 16/11/2009 show a high variation. The observations lasted for about an hour and they show a continuous fluctuation of the S/C phase in reference with the local H-maser of about -1.5 to 1.5 radians. Those values are in the level of our observations.

4.2 Interplanetary Plasma Scintillation analysis

The post-processing analysis of the spacecraft tracking data enables us to study several parameters of the S/C signal with mHz accuracy, among which the phase fluctuations of the S/C carrier line can be used for characterization of the interplanetary plasma density fluctuations along the signal propagation line at different spatial and temporal scales and at different Solar elongations.

These phase fluctuations caused by the solar wind are well represented by a near-Kolmogorov [11] spectrum. Multi-station observations can distinguish the up- and downlink plasma contributions, because they measure the S/C through different Fresnel channels. From our VEX measurements we derived such essential parameters as the phase scintillation index, bandwidth of scintillations and their dependence on the Solar elongation, distance to the target, position of the source in the Solar system, and the Solar activity index.

To model the detected phase variations in respect to the frequency we construct a polynomial function in the logarithmic scale to fit our data, see Eq. 4. Where x_0 and y_0 are fixed to 0.1 Hz to fit our observed data, α defines the slope, polynomial order, of the function.

$$y(x) = 1 + y_0 * \left(\frac{x}{x_0}\right)^{\alpha} \quad (4)$$

Fig. 5 shows the spectra of the phase variation due to the scintillations caused by interplanetary plasma along the signal propagation line for 4 different observations. The epochs displayed are spaced by approximately one month each and sorted by chronological order. The occultation of Venus for the Sun occurred at the beginning of the current year (02/01/2010). In the analysis for the observations with Medicina, Wettzell and Yebes we see that the scintillation band is predominant until 3 Hz. Instead in the observation performed on 18/01/2010 with the Metsähovi antenna we can observe that the scintillation band over pass the x-axis and goes over 10 Hz. In this particular case, for a correct analysis we had to modify our default scintillation and system noise bands to fit the high fluctuation of the phase. As default, scintillation band is set in the range from 3 mHz to 3.003 Hz and the noise band from 4 to 7 Hz. When the angle Sun-Observer-Target (SOT), is relatively small we need to

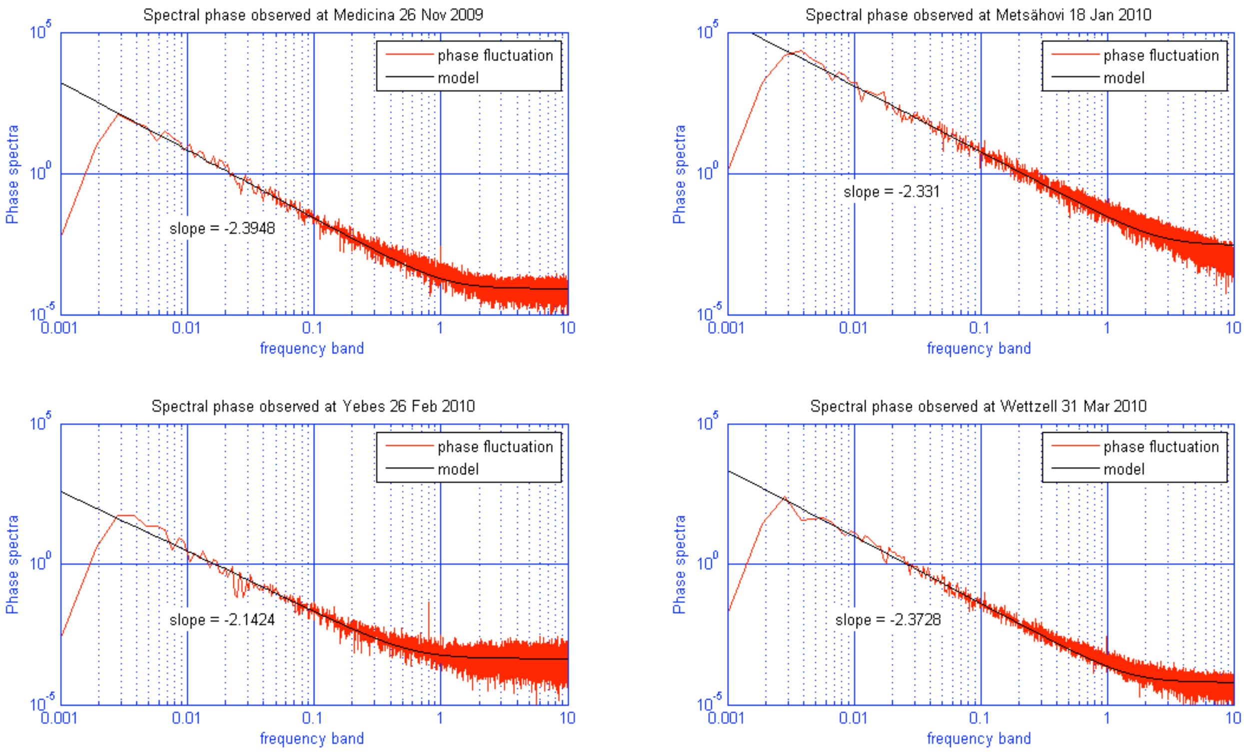

Fig 5: several phase fluctuation spectra sorted in chronological order. We can see the high effect on the phase scintillation from the data of Metsähovi 18/01/2010 caused by the Interplanetary Plasma. Venus elongation was only 6 degrees. As seen in data, the fitting model needs special considerations when the elongations are below 10 degrees.

redefine them according a visual inspection of the data. The system noise band was of the order from 40 Hz to 70 Hz and the scintillation from 0.003 Hz to 10 Hz.

Typical values of "alpha" derived from our measurements are in the range of 2.1-2.7 in a good agreement with Kolmogorov slope of 7/3. See Fig 5 with the computed scintillation index within the scintillation band from the phase fluctuations.

More observations will characterise the scintillation parameters for higher angle elongations of the SOT. This will reach its maximum of 45 degrees in mid-August. We are also very interested to study the troposphere effect on our data when Venus will be located between Earth and the Sun at the end of the year. By then, the contributions of the troposphere and the IP to the S/C signal will be similar and we hope will bring new important information to our research.

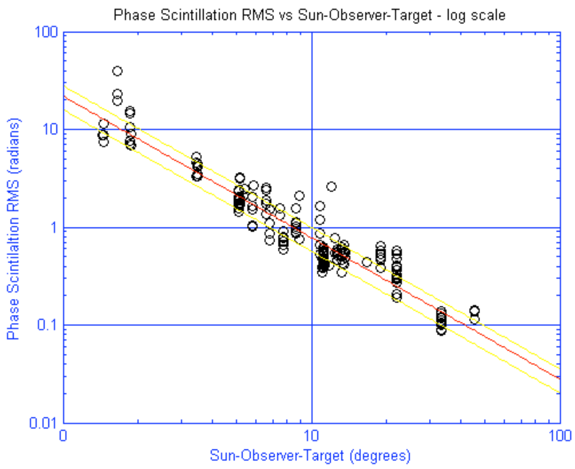

Fig 6: phase scintillation RMS caused by Interplanetary Plasma versus Solar elongation. Red line is the fitting model and yellow line is deviation.

Fig. 6 shows the phase scintillation RMS versus the SOT angle (in logarithmic scale). Our campaign of VEX observations started when the satellite was in a Solar elongation of 20 degrees. Venus was moving towards its occultation with the Sun. As mentioned, the occultation occurred at the beginning of the year. The observations done around those days showed very high phase fluctuations, the signal propagates through close regions to the sun and the effect of the solar wind to the S/C data is considerable. The phase scintillation took values up to 20-30 radians.

Currently, Venus is again located in the right hemisphere of the Sun-Earth plan with a SOT angle about 20-30 degrees.

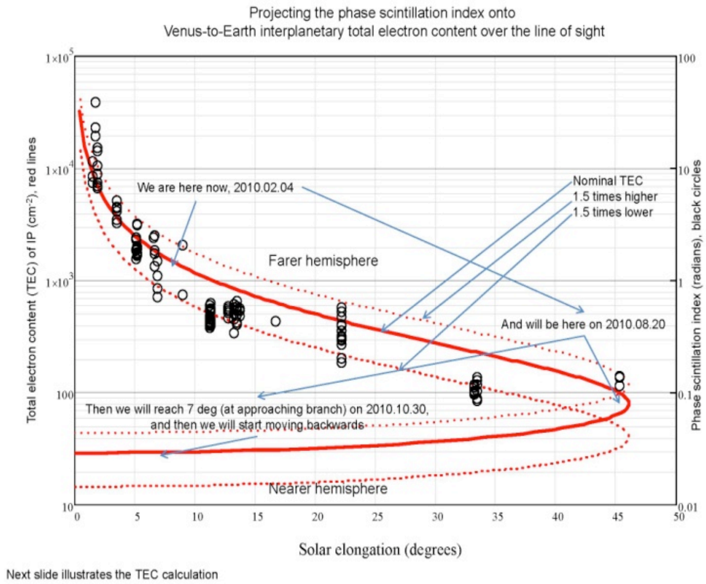

Fig 7: comparison between TEC simulation for the line of sight and the phase scintillation index extracted from analysis. They are in good agreement.

In Fig. 7 the RMS values of the phase scintillation are compared to Total Electron Content (TEC) for the line of sight. To simulate the values of TEC according to the position of the spacecraft as a function of Sun-Earth position, we assume that the electron density at certain point follows dependence to its distance towards the Sun of the potential of minus, Eq. 5.

$$Rho(y) = dl * y^{-2} \tag{5}$$

Where *Rho* is the electron density at a certain distance "*y*" from the Sun and *dl* is the normal electron density. In this case, we normalize the distances to 1 Astronomical Unit (AU). Therefore, the value of "*dl*" at 1 AU is 5 cm^{-3}. The theoretical TEC from the observer to the spacecraft can be calculated as the integral of the electron density through the propagation path, Eq. 5:

$$TEC = tecu^{-1} \int_{0}^{VEX} dl * sdp(y)^{-2} \partial y \tag{6}$$

Where "*tecu*" is defined as the total electron content per unit and is equal to 10^{16} m^{-2}. "*sdp*" is the distance of each point in the line of sight in respect to the sun.

The S/C carrier line phase scintillation measurements are complementary to the classical power scintillation measurements of signals from natural radio sources and are crucial for optimization of the design characteristics of PRIDE. Multi-epoch and multi-station observations let us study and compare at different temporal scales and with different stations simultaneously. A couple of attempts of VLBI sessions focussed on spacecraft tracking have been made, but they have not been too successful. The team expects to carry 4 e-VLBI sessions with most of the VLBI antennae participating. EVN-PC proposal committee has approved the sessions and we are looking forward to receive the allocated time.

5. CONCLUSIONS

Single- and multi-station observations of the spacecraft signal phase scintillations can assess the characterisation of the achievable accuracy of the phase-referencing VLBI tracking of the spacecraft during critical phases of the mission. Parameterisation of the phase scintillation dependence on the solar elongation and solar activity index will help to better determine the timing of entry events for planetary probes.

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6. ABBREVIATIONS AND ACRONYMS

BBC/VC Baseband Converters/Video Converters
DSN Deep Space Network
DFT Discrete Fourier Transform
EVN European VLBI Network
IP Interplanetary Plasma
JIVE Joint Institute for VLBI in Europe
MEX Mars Express
MRO Metsähovi Radio Observatory
NRAO National Radio Astronomy Observatory
PRIDE Planetary Radio Interferometry & Doppler Experiment
Rx Reception
SCTracker Spacecraft tracking software package
SOT Sun-Observer-Target
SWSpec Software Spectrometer software package
TEC Total Electron Content
Tx Transmission
USO Ultra-Stable Oscillator
VEX Venus Express
VLBI Very Long Baseline Interferometry

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