First Results of Venus Express Spacecraft Observations with Wettzell

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Abstract

The ESA Venus Express spacecraft was observed at X-band with the Wettzell radio telescope in October-December 2009 in the framework of an assessment study of the possible contribution of the European VLBI Network to the upcoming ESA deep space missions. A major goal of these observations was to develop and test the scheduling, data capture, transfer, processing, and analysis pipeline. Recorded data were transferred from Wettzell to Metsähovi for processing, and the processed data were sent from Metsähovi to JIVE for analysis. A turnover time of 24 hours from observations to analysis results was achieved. The high dynamic range of the detections allowed us to achieve a milliHz level of spectral resolution accuracy and to extract the phase of the spacecraft signal carrier line. Several physical parameters can be determined from these observational results with more observational data collected. Among other important results, the measured phase fluctuations of the carrier line at different time scales can be used to determine the influence of the solar wind plasma density fluctuations on the accuracy of the astrometric VLBI observations.

1. Introduction

The ESA Venus Express spacecraft (VEX S/C) radio transmission signals are an interesting target for exercising new science support methods usable in prospective ESA planetary probe and deep space missions. Spacecraft observations, detections, processing and analysis technology are based on the heritage of our team involved in the VLBI support of the VEGA and Huygens missions [1, 2, 3]. During a campaign in 2008-09, a number of European VLBI Network telescopes joined trial observations of VEX in the framework of the PRIDE (Planetary Radio Interferometry and Doppler Experiments). This paper describes the analysis methods, introduces the software developed for handling the analysis flow, and presents the most recent detections we achieved during a single-dish VEX observation performed at Wettzell. The high dynamic range of our phase detections—with a typical SNR of several thousands in 1 Hz or several millions in 1 mHz as achieved in observations with Metsähovi, Wettzell, Yebes, Medicina, Matera, and Noto stations in coordination with ESA Space Astronomy Centre (ESAC), and ESTRACK station Cebreros, Spain—allows 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 line. In particular we show 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 the 2009.11.6 Wettzell observation.

2. Theory

2.1. Spacecraft Detection

The technique employed in our observations enables us to obtain the spectra of the S/C radio signal, to determine the apparent topocentric frequency of the S/C signal carrier line and accompanying "ranging" tones with sub-mHz accuracy, and to determine the phases of these tones with respect to the phase of the Earth-based station's H-maser clock. Further on, the phases can be calibrated on a baseline basis using a VLBI multi-station phase referencing technique.

2.2. Interplanetary Plasma Effects

Interplanetary scintillation (IPS) originates from the diffraction of radio waves by fluctuations within the solar wind. Measurements of IPS have been conducted during many years to probe the solar wind throughout the inner heliosphere. The phase variations 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 the scintillation index m. This is the ratio of the rms variation in the strength of the source signal due to IPS and the average strength of the signal [4, 5]. It should be noted that, especially at higher frequencies, the scintillation index depends on the source angular size and structure. In this respect, the spacecraft, an almost ideal point source, provides a good opportunity. Although its emitting power is subject to internal power variations which depend on the transmitting data content, 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 results of a two-way propagation: from the communication station to the spacecraft and back to the observing station.

3. Methods: Data Processing and Analysis

The VEX observations at Wettzell started on 2009.11.16 using the standard VLBI Mark IV data acquisition rack with four 8 or 16 MHz channels and 2-bit Nyquist sampling for aggregate data rates of 128 or 256 Mbps. The Mark-IV-formatted data were recorded with Mark 5A and PCEVN disk systems. Immediately at the end of the observational run, files were electronically transferred through the Internet with Tsunami UDP to the Metsähovi Radio Observatory (MRO) for processing. Data were processed with the high-performance, ultra-high spectral resolution spectrometer-correlator software under development at MRO. Processing tasks ran in two iterations between MRO and JIVE, with the JIVE analysis software involved in the iterative loop.

With our current facilities the full processing cycle takes 5-10 times longer than the observational time, but we are constantly improving it.

3.1. Spacecraft Detection

Initial detection of tones was performed using the high-resolution spectrometer software developed at MRO (SWSpec). A Python PyQt4 GUI allows fast reconfiguration for new processing jobs. SWSpec supports several input file formats such as the (still common) VLBA and Mark IV magnetic tape formats on Mark 5A and PCEVN and the more modern Mark 5B and VDIF formats. In addition, it can handle various "raw" multi-channel, multi-bit formats. A SWSpec pass extracts one selected raw data channel and performs accurate windowed-overlapped discrete Fourier transforms and spectrum time integration. All parameters are fully adjustable. The S/C processing of 8 or 16 MHz baseband used 3.2M DFT points and cosine-squared windowing. Figure 1 shows the S/C Doppler detection with the Wettzell antenna, and Figure 2 the resulting spectrum (after Doppler model removed) with a spectral resolution of 0.9 mHz.
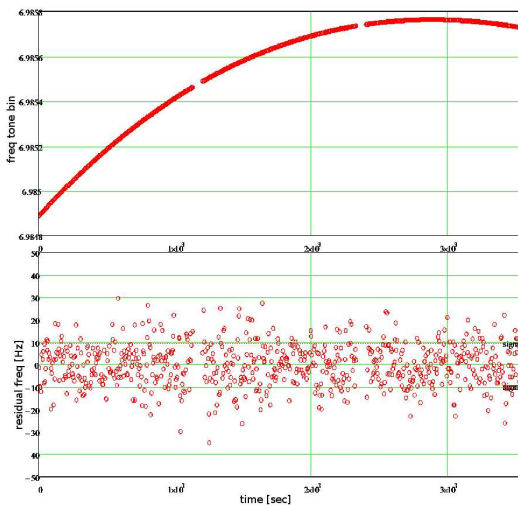

Figure 1. Top graph: Frequency detections of the VEX carrier signal at 8.412 GHz on 2009.11.16. Peak frequency spread is 8.7 kHz over 1 hour. Bottom graph: Post-fit stochastic residual exhibiting an RMS of only 9 mHz at 5s sampling.
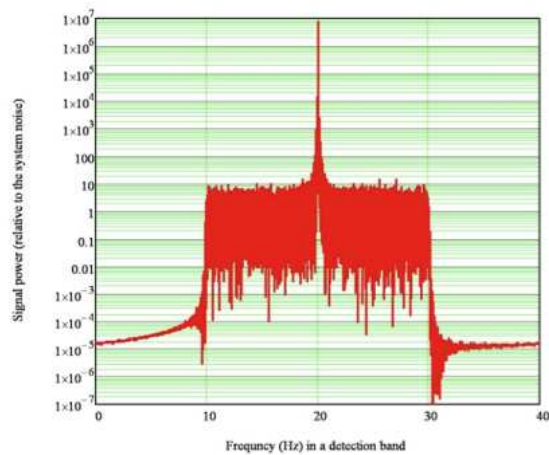

Figure 2. The resulting spectrum of the S/C carrier line in a zoom band after the Doppler correction. Spectral resolution at 0.9 mHz.

3.2. Tone Tracking, Filtering and Phase Detection

The output spectra of SWSpec are processed using MathCAD and Matlab scripts developed at JIVE. They extract S/C tone frequencies (detected by visual inspection) from the series of integrated spectra. A 4 to 7 order phase stopping polynomial is fitted to the S/C carrier line frequency detections using a weighted Least Mean Squares (LMS) method with weight coefficients depending on SNR and RFI considerations. The resulting polynomial coefficients are used as input to the next processing steps: narrow band adaptive filtering and Phase-Lock-Loop (PLL).

The spacecraft tone tracking software (SCTracker) developed at MRO accepts the original raw input data files, a list of S/C tone frequencies (relative to carrier), and the stopping polynomial coefficients for the carrier tone. A double-precision polynomial evaluation is applied for stopping tone phases. Adaptive filtering extracts and filters stopped tones down to a several kHz wide

bandwidth using a 2nd order WOLA (Window-Overlap-Add) DFT-based algorithm of the Hilbert transform approximation. The time-domain sample sequence of every extracted and filtered tone is written as an output data set for further post-processing using digital PLL software at JIVE. The residual phase in a stopped band is determined with respect to a set of subsequent frequency/phase polynomials applied for phase stopping. Depending on the SNR of the carrier line and individual tones, the final bandwidth of phase detections can range from several kHz to several mHz. In the case of VEX carrier line, this bandwidth is in the range of 10-100 Hz. Figure 3 illustrates the carrier line residual (after Doppler correction) phase variation.
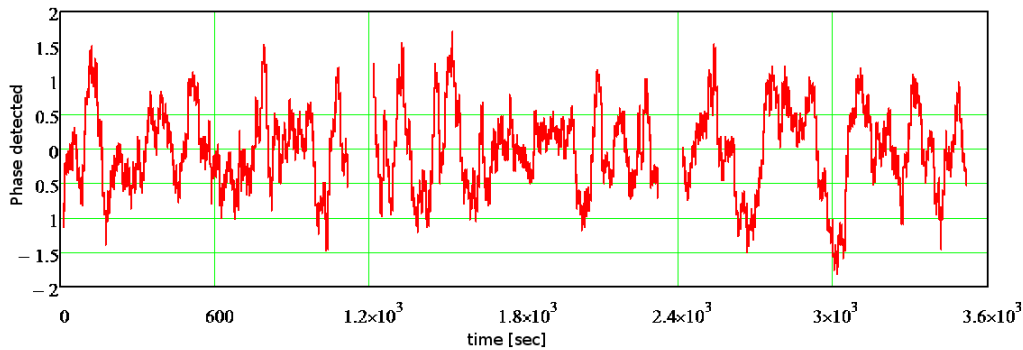

Figure 3. Narrow band phase detections after PLL tone tracking and band filtering of the S/C carrier line.

3.3. Scintillation Analysis

The post-processing analysis of the spacecraft tracking data enables us to study several parameters of the S/C signal with milliHz accuracy, among which the phase fluctuations of the S/C carrier line can be used for characterization of the Interplanetary Plasma (IP) density fluctuations along the signal propagation line at different spatial and temporal scales and at different solar elongations. These fluctuations are well represented by a near-Kolmogorov [6] spectrum. From our VEX measurements we retrieved such essential parameters as the phase scintillation index and 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. Multi-station observations can distinguish the up- and down-link plasma contributions, because they will observe the S/C through different Fresnel channels. Figure 4 shows the spectral power density of the slow fluctuation phase turbulence below 10 Hz. The S/C carrier line phase scintillations measurements are complementary to the classical power scintillation measurements of signals from the natural radio sources and are crucial for the optimization of the design characteristics of PRIDE.

4. Conclusion

The first results are encouraging, although more test and development observations are needed before obtaining physically significant results. The initial study focused more on the measurement techniques and data analysis. But the physical interpretation of the results is a task that we wish to continue in upcoming studies when more observational data is collected.
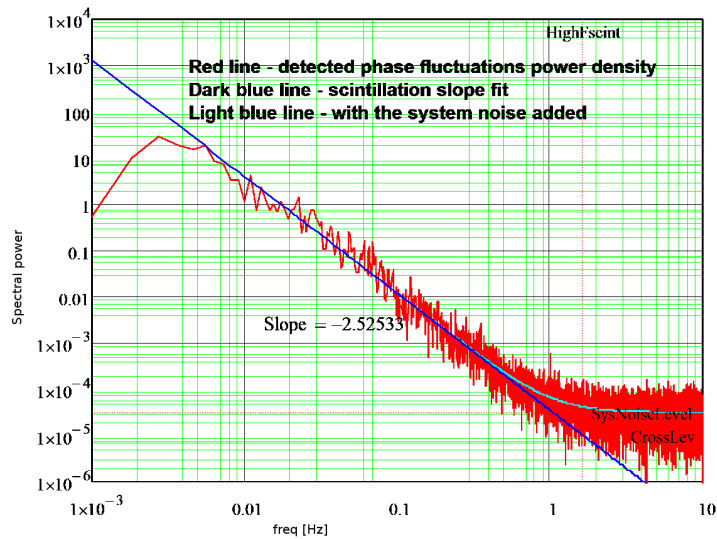
Figure 4. Spectral power density of slow fluctuation phase turbulence below 10 Hz. Note the high dynamic range of 10e06.

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