Venus and Mars Express Spacecraft Observations with Wettzell Radio Telescopes

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Abstract The ESA Venus, Mars Express, and Rosetta spacecraft were observed at X-band with the Wettzell radio telescopes Wn and Wz in the framework of an assessment study of the possible contribution of the European VLBI network to the upcoming ESA deep space missions and further projects. These observations were extended to regular weekly sessions to routinely run the processing and analysis pipeline. Recorded data were transferred from Wettzell to the JIVE cooperation partners for correlation and analysis. A high dynamic range of the detections allowed us to achieve a mHz level of the spectral resolution accuracy and extract the phase of the spacecraft signal carrier line. Several physical parameters can be determined from these observational results with more observational data collected. Apart from other results, the measured phase fluctuations of the carrier line at different time scales can be assessed to determine the influence of the Solar wind plasma density fluctuations on the accuracy of the astrometric VLBI observations.

Keywords VLBI, radio telescope, spacecraft signal, solar wind

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1 Introduction

The combination of Very Long Baseline Interferometry (VLBI) and Doppler spacecraft tracking has been successfully exploited in a number of space science missions, including VLBI tracking of the descent and landing of the Huygens Probe in the atmosphere of Titan [2] and VLBI observations of ESA's Venus Express and of the Mars Express Phobos flyby [7].

Based on the experience acquired in these projects, the Planetary Radio Interferometry and Doppler Experiment (PRIDE) concept has been developed. PRIDE is an international enterprise led by the Joint Institute for VLBI in Europe (JIVE). It focuses primarily on tracking planetary and space science missions through radio interferometric and Doppler measurements [3]. PRIDE provides precise estimations of the spacecraft state vectors based on Doppler and VLBI phase-referencing techniques [1]. These can be applied to a wide range of research fields.

Figure 1 shows the basic configuration for the PRIDE observations, where the observations of planetary spacecraft are combined with observations of natural radio sources.

Table 1 shows the main characteristics of the radio telescopes at the Wettzell observatory used for spacecraft observations. The 20-m Radio Telescope Wettzell (RTW) with station code Wz was finished in 1983 and is one of the main systems of the International VLBI Service for Geodesy and Astrometry (IVS). It is equipped with an S/X-receiving system. The antenna Wn with a 13.2-m dish is the northern telescope of the newly built TWIN Radio Telescope Wettzell (TTW), which was finished and inaugurated in 2013. TTW is a fast-slewing broadband telescope following the specifications of the VLBI Global Observing System

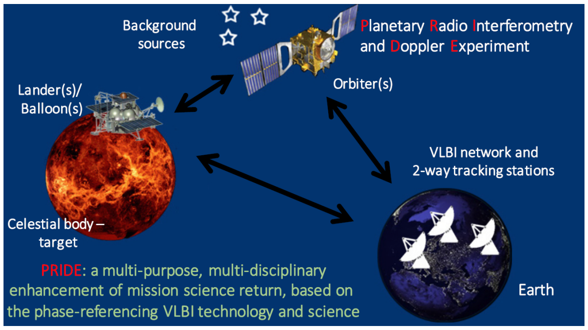

Fig. 1 Scheme of the Planetary Radio Interferometry and Doppler Experiments (PRIDE) observations.

(VGOS). The antenna Wn is currently equipped with a standard S/X-receiving system, which is extended with a Ka-band receiver.

Table 1 The radio telescopes at Wettzell used for the spacecraft observations.

Station	code	latitude	longitude	altitude (m)	dish (Jy)	SEFD-X
Wettzell	Wz	49°08'42.0"	12°52'37.9"	661.20	20.0	700
Wettzell	Wn	49°08'38.1"	12°52'39.7"	672.57	13.2	840

2 Observations

The PRIDE team initiated systematic observations of planetary spacecraft in 2009. ESA's VEX spacecraft was selected due to its high-quality signal, suitable transmission frequency, and possibility of being observed by European VLBI radio telescopes. The 20-m RTW (Wz) has participated since 2010 in 57 sessions involving VEX until the mission ended in 2014 and in 23 sessions involving MEX between 2014 and 2016. In 2015, the Wn was additionally included into the network of planetary spacecraft observations. A total number of 17 sessions were arranged since then with Wn. In our observations, the spacecraft signals are observed in X-band ($\lambda = 3.6\,\mathrm{cm}$, $f_o = 8.4\,\mathrm{GHz}$).

On 20 May 2015, we operated the first simultaneous observation of spacecraft using both Wn and Wz. After that, eight similar experiments were arranged. Figure 3 shows the relative power to noise ratio, the Doppler frequency residuals, and the difference between the telescopes' residuals detected on 26 October 2015.

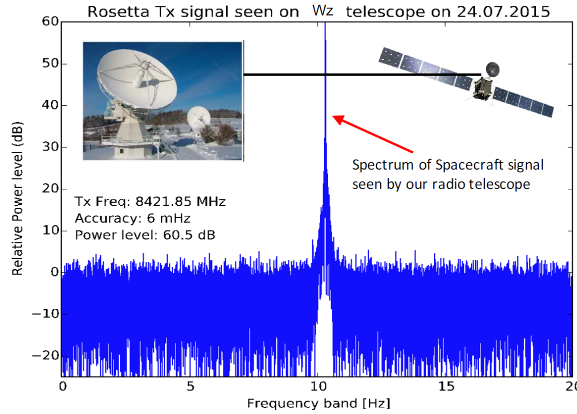

Fig. 2 Detection of the spacecraft signal transmitted by Rosetta by the Wettzell radio telescopes on 24 July 2015.

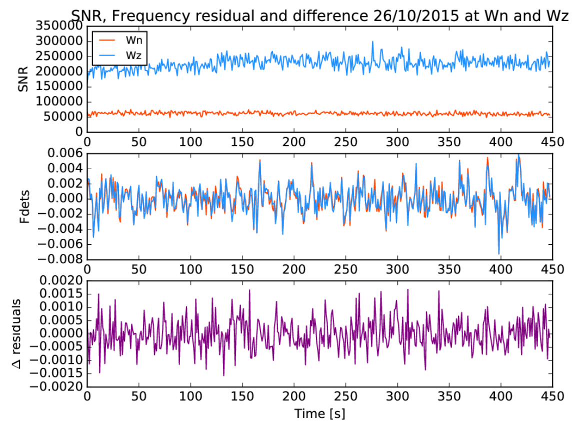

Fig. 3 Upper panel: relative power Wz (blue/upper line) and Wn (red/lower line). Middle panel: residual frequencies for same data. Lower panel: difference between both telescopes' residuals. The MEX data were observed at Wz and Wn on 26 October 2015. The standard deviations of the frequency detections are 1.78 mHz for Wn, 1.76 for Wz, and 0.5 mHz for the difference.

Spacecraft observations are research and development approaches to open new domains for geodetic VLBI. The geodetic benefit is the interrelation to other techniques to tie the different reference frames. VGOS supports spacecraft tracking, while mostly Earth orbiting satellites in the near field are in the focus [6]. But the IVS encourages developments which use VLBI on sources besides quasars (see different volumes of the past IVS General Meetings Proceedings). It opens doors to spacecraft navigation which is strongly related to the application of reference frames. Besides this, the observations of spacecraft are checks of the accuracy of the techniques at the location of the antennas and throughout the whole processing chain. Additionally, they are technical tests for possible future domains of VLBI, which are currently already possible. Another aspect is that one of the pillars of geodesy is gravity and the gravitational field [10]. In a wider sense, spacecraft observations with VLBI enable the determination of gravitational fields of planetary objects. From the point of view of a geodetic observatory the observations are quite valuable. Using two telescopes provides the possibility of more observations, because one telescope might be able to observe while the other is occupied by another session. It would also offer possibilities of new observation modes for differential VLBI, so that one telescope observes quasars close to the spacecraft while the other tracks the spacecraft itself. Current implementations do not take enough account of these possibilities.

3 Analysis

The data processing is conducted using the on-purpose software developed for multi-tone tracking of planetary spacecraft signals. The software is divided into three parts: the SWspec, the SCtracker, and the digital Phase-Locked-Loop. All three software packages were described in [7]. Figure 4 shows a block diagram of the spacecraft tracking software.

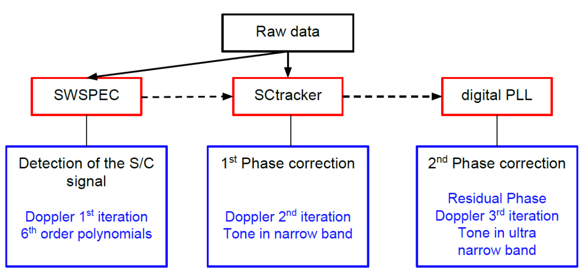

Fig. 4 Illustration of the data analysis steps and software modules used for spacecraft tracking purposes: SWspec, SCtracker, and digital PLL. The complete software is developed and maintained jointly by JIVE and Aalto University.

The three most important parameters out of our detections are Doppler noise, the Signal-to-Noise Ratio (SNR) of the carrier, and the phase scintillation indices. The output results for the first two parameters from a regular observation are shown in Figure 3. The results are utilized for a wide field of research:

- studies of the interplanetary scintillation caused by the solar wind at different solar elongations and positions with respect to the Sun [7].
- characterization of the properties of Coronal Mass Ejections (CME) and monitoring of similar events in almost real-time [8].
- determination of the speed of the solar wind using VLBI techniques.
- studies of the planetary atmosphere on Venus, using radio signal and aerobreaking techniques [9].
- determination of gravitational fields of planetary objects (moons, comets) by using fly-by techniques [5].
- radio occultation experiments to evaluate ingress and egress phenomena.
- orbit determination of the space missions, such as Radio Astron [3].
- enhancement and support of future planetary space missions: JUICE, ExoMars, Bepi-Colombo, etc.

4 Conclusions

Planetary spacecraft as targets for radio observations by ground-based radio telescopes provide a unique opportunity to investigate a wide range of scientific fields.

Tracking observations of spacecraft, ESA's MEX and Rosetta, will continue in order to improve detection measurements and the processing pipeline. Future space missions, such as ESA's Jupiter Icy Moon Explorer (JUICE), will benefit from such precise knowledge.

Radio science studies such as this one allow us to disentangle the contributions from the interplanetary plasma and the Earth's ionosphere. The research will continue with the goals of characterizing the atmospheric and ionospheric structure of planets and media, small body fly-by missions, atmospheric drag campaigns, radio occultations, detection of coronal mass ejections, or precise orbit determination of satellites. Besides the scientific output, the tests provide a technical feasibility study of the technical workflow from scheduling to analysis.

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