Near Field VLBI experiments with EVN radio telescopes

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The PRIDE – Planetary Radio Interferometry and Doppler Experiments – initiative of the European VLBI Network (EVN) focuses on a possible contribution and scientific return of the planned (ESA) planetary missions by enhancing the ground segment of the missions by a network of radio astronomical telescopes. PRIDE provides direct characterisation of the orbiter and surface elements signals by means of VLBI tracking and radial Doppler measurements; estimates of the spacecraft (S/C) state vectors (which can be used for: studying tidal deformations, seismology and tectonics of planetary bodies, planetary atmosphere dynamics and climatology; gravimetry; as an input to the fundamental physics packages; radio occultation observations); "Cruise" science plus mission diagnostics ("health check"), complementation to the DeltaDOR measurements and Direct-to-Earth (DtE) radio link for the delivery of critical data.

PRIDE is applicable to virtually any planetary mission: to Mercury (ESA-JAXA BepiColombo, 2014), Venus (VEX, CNES EVE and RSA Venera-D, ~2018?), Moon (ESA NEXT and Chinese Chang'E-2), Mars + Phobos (RSA Phobos-Grunt, 2011; ESA ExoMars, 2016?), Jupiter + Europa, Ganymede, Callisto (ESA-NASA Europa-Jupiter System Mission (EJSM), 2020), Saturn + Titan, Enceladus (ESA-NASA-JAXA Titan Saturn System Mission (TSSM), 2022?).

In VLBI-observations of spacecraft, the frequency or the phase of the signal detected at each station of the VLBI-network is measured. These topocentric detections from different stations are reduced to the common phase centre, usually – to the geocentre. For this reduction, the pre-calculated geocentric VLBI delays of the spacecraft signal are used:

$$\varphi_g = \varphi_s(t_s - \tau_s), \qquad f_g = \dot{\varphi}_g = \dot{\varphi}_s(t_s - \tau_s)\cdot(1-\dot{\tau}_s) = f_s(t_s - \tau_s)\cdot(1-\dot{\tau}_s);$$

where φ_s and f_s – are the measured phase/frequency, τ_s and $\dot{\tau}_s$ – geocentric delay for the station s and its derivative. The geometrical part of the delay is computed using the Sekido-Fukushima [1] model for a near-field radio source. In this model, a pseudo source vector is introduced in order to account for the effect of the curved wave front, and the variation of the baseline vector due to the difference of arrival time is taken into account up to the second-order by using Halley's method. The theoretical precision of the model is better than 1 ps for all radio sources above 100 km altitude from the Earth's surface in Earth-based VLBI observations. Apart from the geometrical part, contributions to the signal delay from troposphere, ionosphere, clock offsets/rates at the stations are taken into account as well. After this, the differential phases/frequencies ($\Delta\varphi$ or Δf) with respect to the reference station are calculated. These $\Delta\varphi$ or Δf are used as residuals in the least-squares estimation of the parameters in question, which could be, e.g., corrections to the station or the spacecraft coordinates.

Until now, several test VLBI-observations of spacecraft were carried out using EVN telescopes in the phase-referencing mode. Phase referencing observations with respect to the background radio sources are often used today for Deep Space navigation, see, e.g. [2], [3]. The basics of this method are that a reference source, usually a known quasar, is observed, then a target, a spacecraft in our case, at a few degree distance from the quasar is also observed. The apparent group delay and phase of the reference source are measured and compared with the predicted one according to the known model, corrections are derived and applied to the signal from the target.

Here we present some preliminary results of one of the most recent experiments, which took place on March 25, 2011. The ESA Venus-Express (VEX) spacecraft was observed at X-band (8.4 GHz, λ = 3.5 cm) using 4 radio telescopes: 20 m Onsala (Sweden), 14 m Metsähovi (Finland), 26 m HartRAO (South Africa) and 22 m Pushchino (Russia). Standard VLBI data acquisition system and disk-based Mark5A recording were used, and a bandwidth of 16 MHz. Cross-correlation of the signal from reference source, made with the software correlator SFX at the Joint Institute for VLBI in Europe (JIVE), allowed us to determine clock offsets and clock offset rates between the stations. The primary detection of the carrier frequencies of the spacecraft was conducted using the high-resolution software spectrometer SWSpec [4], developed at the Metsähovi Observatory, Finland and JIVE. For further processing, that is for phase stopping and narrow-band filtration of the carrier and its extraction, the spacecraft tone tracking software SCTracker [4] was used. The frequency detection noise is at a level of several mHz in 1 second and depends on the scintillations of the signal on the interplanetary plasma turbulence and telescope sensitivity and phase stability of its receiver. Results of the narrow-band signal processing were then analysed at JIVE using a specially developed software package according to the algorithm briefly described above.

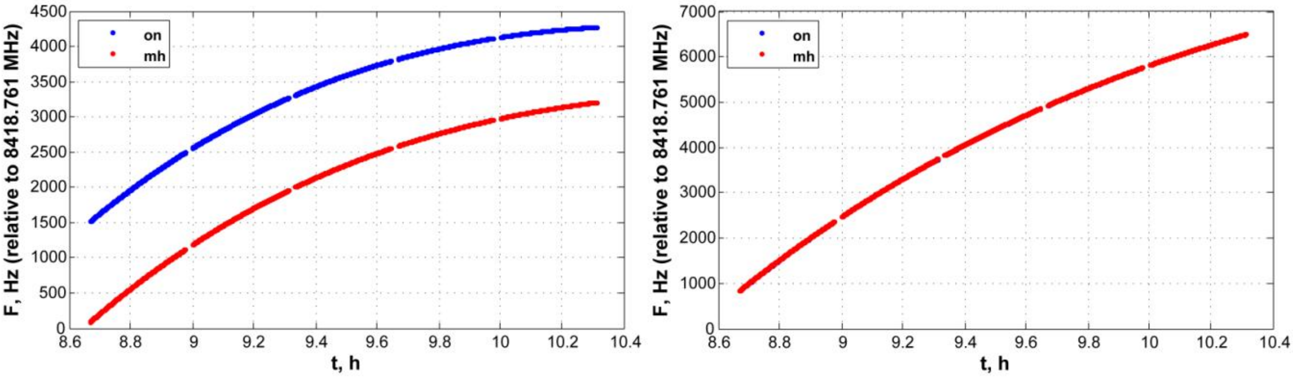

Fig. 1. Left – topocentric detections of the VEX carrier frequency at Onsala and Metsähovi, 25.03.2011; right – frequencies reduced to the geocentre.

Figure 1 depicts the topocentric detections of the VEX carrier frequency at Onsala and Metsähovi, and the corresponding frequency reduced to the geocentre. Figure 2 displays the differential frequency of the VEX spacecraft (baseline Onsala – Metsähovi). The fact that, statistically, it is very close to zero and reveals no slope, indicates the accuracy of the topocentric frequency detections reduction to the geocentre, which in its turn points to the quality and precision of the near-field delay calculation model.

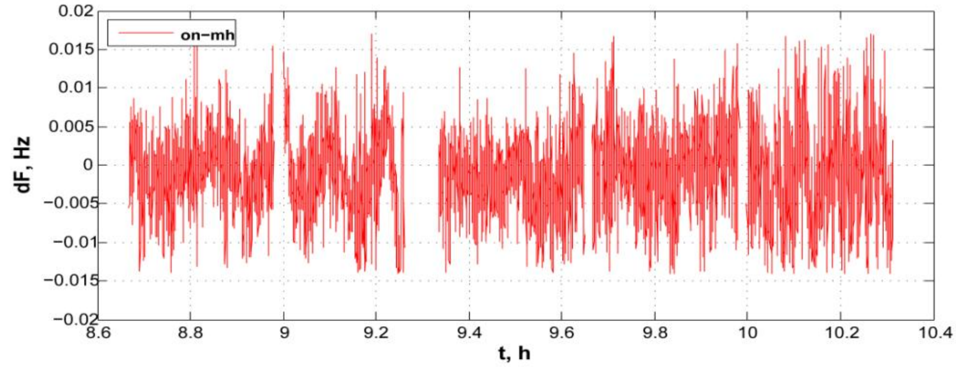

Fig. 2. Differential frequency of the VEX carrier on the baseline Onsala – Metsähovi, 25.03.2011.

We also conducted a test broadband processing of the spacecraft signal using the software correlator SFX at JIVE. Figure 3 represents the amplitude and phase of the cross-correlation function on the baseline Onsala-Metsähovi when using a near-field delay model. Note that in narrow band processing, a differential phase (used for all estimations as a residual) is calculated with an integration constant of 0. Broadband correlation of the spacecraft signal will help to reduce this initial phase ambiguity.

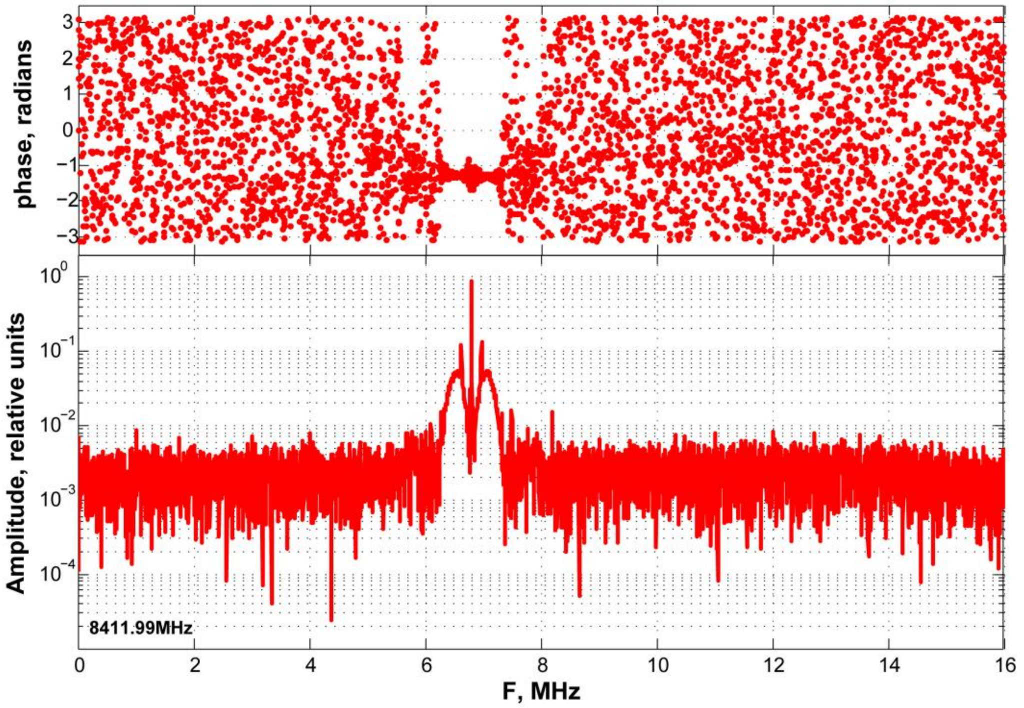

Fig. 3. Broadband correlation of the VEX signal on the baseline Onsala – Metsähovi, 25.03.2011 with the SFX correlator at JIVE: amplitude and phase of the cross-correlation function, averaging – 20 seconds. Most of the power of the spacecraft signal is concentrated within ~ 1 MHz wide band around the carrier line.

References

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