VLBI signals transmitted from Earth orbiting satellites

Ö. Karatekin, H. Sert, V. Dehant, B. Ritter, H. Vasseur, U. Hugentobler

Abstract Creating an absolute space-tie where all the geodetic methods are onboard is the key for an improved and stable terrestrial reference frame as well as with various scientific applications. Such satellite concepts have already been proposed to achieve an accurate and stable terrestrial reference frame. Next generation Galileo satellites can provide a single well-calibrated platform for the colocation of the space-based geodetic techniques establishing precise and stable ties between the key geodetic techniques. One of the most crucial and novel aspect of such concepts is the VLBI transmitter (VT) which will emit quasar-like signals from the space to be observed by the VLBI ground stations. VT can directly link the terrestrial and celestial reference frames and bring the unique features of VLBI technique to an Earth orbiting satellite. In the context of call for future Galileo payloads a novel VT has been under development. Here, we present the progress on ongoing ESA study for VT for Galileo as well as for other future missions.

Keywords VLBI, VLBI transmitter, space-tie

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1 Introduction

Global Navigation Satellite System (GNSS), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Satellite Laser ranging (SLR) and Very-long Baseline Interferometry (VLBI) are the main space-geodetic techniques to define accurate and stable International Terrestrial Reference Frame (ITRF). In addition, VLBI allows the realisation of International Celestial Reference Frame (ICRF) and Earth orientation parameters including the rotation angle (UT1 – UTC). Each geodetic technique is traditionally linked by so called 'local-ties'. Due to the scarcity of local-tie number as well as their accuracy (Altamimi et al. , 2016; Altamimi, Z. , 2008; Glaser et al. , 2015), combining the techniques onboard spacecraft is a promising candidate to create an accurate and continuous link between different geodetic techniques (Pollet et al. , 2023).

Galileo satellites allow already the use of GNSS and SLR methods and discussed in several studies (Thaller et al. , 2011, 2014; Zoulida et al. , 2016; Bury et al. , 2021). An additional VLBI transmitter onboard next generation Galileo satellites can offer an opportunity to benefit unique capabilities of VLBI technique to immediate referencing of the Galileo orbits to the ICRF through differential measurements with respect to quasars. VT would allow direct determination of the absolute orientation of the satellite constellation with respect to the ICRF and the improvement of the ITRF. It may also enable other scientific experiments such as improved relativity parameter determination, time-transfer experiments, ionospheric determination and modelling. Several mission concepts like GRASP (Nerem et al. , 2011) and E-GRASP (Biancale et al. , 2017) with VT have already been proposed to achieve an accurate and stable terrestrial reference frame. Recently, ESA FutureNAV programme included one component to implement the GENESIS mission, consisting of the collocation, for the first time ever, of the four space-based geodetic techniques (GNSS, VLBI, SLR and DORIS) onboard a single well-calibrated satellite establishing precise and stable ties between the key geodetic techniques. This aims to result in a unique dynamic space geodetic observatory combined with the measurements of geodetic collocation techniques stations on Earth, would contribute to improving ITRF.

Feasibility of VT onboard earth orbiting satellites including the compatibility with existing VLBI network, traditional VLBI processing and scheduling have been the subject of several recent studies; frame transformations between GNSS and VLBI (Plank et al. , 2017; Anderson et al. , 2018), performance of onboard Galileo VT for scheduling and estimation of the ascending node of the orbit (Wolf et al. , 2022), transferring UT1-UTC (Sert et al. , 2022) and technical feasibility (Jaradat et al. , 2021).

A VT, compatible with the accommodation constraints onboard a Galileo satellite, performance of the receiving stations as well as with the ITU regulations in all transmission frequency bands is currently under development for consideration of Galileo second generation satellites. The VT prototype for G2G has been developed within the frame of the Call for Ideas "H2020-ESA-038 GNSS Evolutions Experimental Payloads and Science Activities". The main objectives are:

- to improve the ties between different space geodetic techniques (GNSS, VLBI and SLR Retro-Reflectors.
- to contribute to the establishment of accurate and long-term stable reference frames (Inertial and Terrestrial) and to the absolute orientation of the Galileo constellation in inertial space, since VLBI is the only technique that has an access to International Celestial Reference Frame (ICRF).

In the next sections we provide the details of the VT mission concept, its design and technical specifications.

2 VT Mission Concept

The mission concept for the VT relies on the observations by the IVS (International VLBI Service) network stations. The IVS network currently consists of more than 30 stations with additional about 15 cooperating stations, mainly VLBA (Very Long Baseline Array) stations as well as DSS (Deep Space Station). The network is further extended in the framework of the VGOS (VLBI Global Observing System) project. The VGOS aims to extend IVS observation operations to 24 hours and 7 days per week in the future and to extend the observation bands from S and X to a band from 2 to 14 GHz to increase the accuracy of the products.

The Depth-of-Coverage (DoC) is shown in Figure 1. It displays the number of IVS stations that can be seen for a Galileo satellite located above a given geographical position for different networks. For all corresponding figures an elevation cutoff angle of 5° was used. The figures in the top are based on the CONT17 network of 14 stations (left) and on the typical R1 session with 9 stations (right). The bottom figures are based on all stations with more than 500,000 observations in the past 20 years (left): for a total of 27 stations, with cooperating VLBA stations included; (right): for only 17 IVS stations.

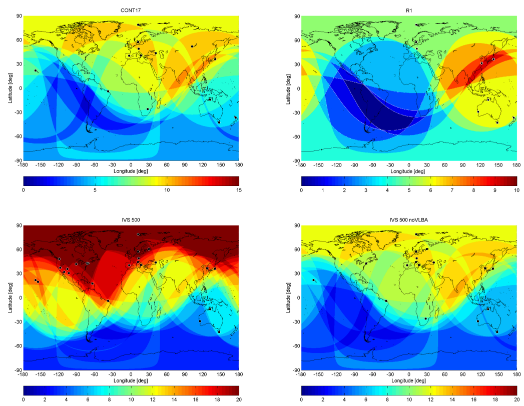

Fig. 1 (Top) Galileo Depth of Coverage (DoC) for different IVS networks: top left: CONT17, top right: typical R1 session, bottom left: all stations with more than 500,000 observations in 20 years, bottom right: same but without VLBA stations

it would be possible to schedule Galileo VT observations together with quasar observations in regular IVS sessions since all IVS telescopes are mechanically capable to track Galileo satellites that are moving at an angular speed below 1 arcmin/sec. In operational mode the VT transmitter can be permanently switched on and can be scheduled by IVS for observation with high flexibility for experimental measurement campaigns and for routine sessions. Alternatively, the VT can be on only during time periods for which observations are scheduled by the IVS network.

3 VT Design

The VT instrument is designed to be:

- Compatible with the VLBI Global Observation System (VGOS) as well as legacy VLBI stations, in terms of frequency, bandwidth, signal type and power spectral flux density at ground level.
- Compliant with ITU Radio Regulations.
- Maximizing the transmitted bandwidth for better measurement resolution.
- Simultaneous transmission in ≥ 2 frequency bands for ionospheric correction

The basic function of the VT equipment is to broadcast of low power spectral density wideband signals at different frequencies between 2 and 14 GHz. It includes two main aspects: the transmitted waveforms and the simultaneous transmission at multiple frequencies.

The VT is designed to transmit simultaneously up to four wideband signals with a power spectral flux density of less than few Jansky ($1Jy = 10^{-26}W/m2/Hz$) at the surface of the Earth which is compatible with VLBI ground stations and compliant with ITU regulations. The ITU Radio Regulations limit quite drastically the power flux density (PFD) that can be generated either at the surface of the Earth or at the geostationary satellite orbit, in the frequency ranges available for the VT application or in adjacent frequency ranges. The VT is designed so that from switch on until switch off, it is capable to transmit RF signals continuously, with a duty cycle of 100%.

Table 1 shows the signal characteristics of the VT compliant with ITU Radio Regulations. The transmitted signals is designed to be as wideband as possible, because the bandwidth directly impacts the resolution of the VLBI measurements. The transmitted waveforms therefore occupy as much as possible the complete bandwidth available in each frequency band.

Frequency band	Frequency range $[MHz]$	Center Frequency $[MHz]$	Occupied bandwidth $[MHz]$
S-	3100-3300	3200	200
C-	5250-570	5410	320
Low X	8200-8400	8300	200
High X	9200-9700	9450	500

Table 1 Signal characteristics of the VT

4 VT Technical Specifications

The VT is composed of two subsystems: the Electronic Box that generates the RF signals and the Antenna Subsystem that ensures the transmission of the RF signals to the VLBI ground stations. The two subsystems are connected by coaxial cables.

The Electronic Box ensures the generation of the two different types of waveforms: the white noise or deterministic pseudo-noise signal, intended for “standard” VLBI measurements as with quasars and the spread spectrum signal with a pseudo random sequence based on the Galileo master clock and aligned with the Galileo PPS, intended to provide an additional clock tie on one hand and to enable single-station VLBI measurements on the other hand. The generation of the latter waveform type requires external input signals (Galileo master clock and Galileo PPS). The former type of quasar-like signals will allow to be captured by VLBI ground stations and be conveniently implemented into the traditional pipeline of VLBI correlating and processing chain. The white noise is identical to thermal noise at a high temperature.

The pseudo-noise datastream is generated in an FPGA (Field-programmable gate array) for reasons of flexibility and re-programmability in course of the activity. The polarisation of the emitting antenna is Left Hand Circular Polarization (LHCP, IEEE specification). The spurious emissions (spurs, harmonics, intermodulation products, redundant spectral images, etc.) generated by the VT shall be at least 60 dB below the relevant signal power, for each operating band. As most of the VLBI bands sit right next to ITU protected bands, it is necessary to ensure band protection via filtering. VT relies on the analogue filters to ensure suppression of out-of-band spurious emissions since the separations between VLBI and ITU bands demand steep filters digital filters with arbitrary steepness are also considered.

At time of preliminary design, the transmit output filters were assessed, looking at technology, manufacturing and their performance in terms of insertion loss, in-band return loss and adjacent frequency band protection. The purpose of these output filters is indeed to reject out-of-band spurious and harmonics. Figure 2 shows the insertion loss measurements for S- and X bands respectively where y- axis is magnitude in dB. The preliminary filter parameters here varies from the signal properties in Table 1 updated later during the project. Based on the preliminary tests, it was possible to adopt and refine the filter specification for transmit filters to be integrated in the updated design. For all of four bandwidths manufacturing repeatability were concluded to be satisfying.

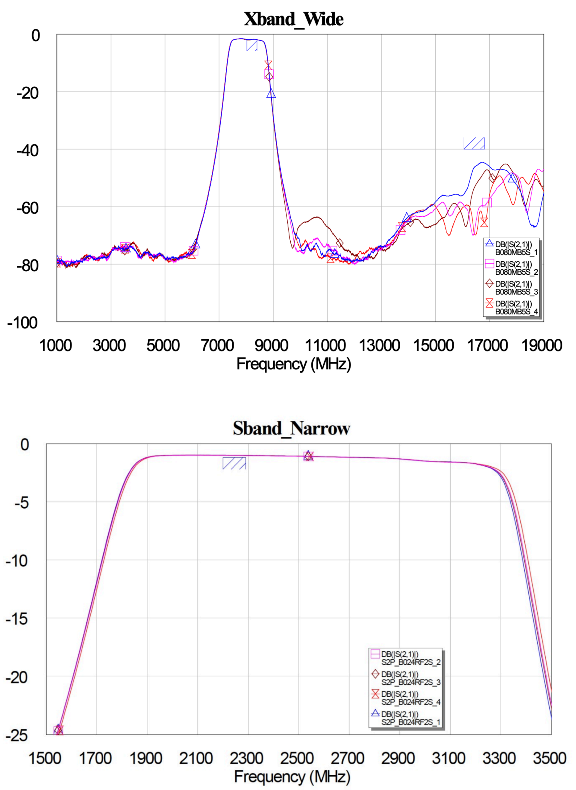

Fig. 2 (Top) X-band bandpass filter wideband insertion loss measurement of four different samples. Filter re-insertion will not attenuate third harmonic content, the amplifier is designed not to have gain higher than 15 GHz.(Bottom) S-band bandpass filter narrowband insertion loss measurement of four different samples.

The second waveform of VT is pseudo-random noise based on the onboard clock -master clock of Galileo satellite(s) in the context of the design- in addition to an internal clock. Having internal clock available, avoiding complete instrument incapability without an external clock dependency. Indeed, when an external clock signal is presented to the VT instrument, the internal clock source will automatically phase/frequency align to the master clock source and it can track the Galileo reference frequency with an Allan Deviation contribution better than 10^{-15} for $\tau = 1000s$. The pseudo-random noise generator is being implemented in an FPGA device. The pseudo-random sequence waveform consists of a spread-spectrum signal which mimics the autocorrelation property of white noise. Two types of waveforms are envisaged for this purpose: a BOC(40,20) signal or a Glonass signal.

The modulating waveform of the Glonass signal is a pseudo-random ranging code while BOC(m,n) is a binary offset carrier modulation. While the Glonass signal has most of its spectral energy concentrated around the carrier frequency (Top in Figure 3), the BOC-modulated signal has low energy around the carrier frequency and two main spectral lobes further away from the carrier, resulting in better flat spectrum characteristics (Bottom in Figure 3).

5 Summary and outlook

The development of an Elegant Breadboard prototype of the VT with its E-Box and its Antenna system has been ongoing within the framework of “H2020-ESA-038 GNSS Evolutions Experimental Payloads and Science Activities”. Technical specifications design and manufacturing of VT breadboard has been recently completed. The integrated tests are planned to verify the subsystem’s compliance to its technical requirements initially set in pursuit of Galileo enhancement and science objectives. An end-to-end ground subsystem demonstration to prove the compatibility of the VT with processing of its random noise and pseudo-noise at a VLBI Ground Station is foreseen in VLBI Ground station at the Geodetic Observatory of Wettzell. The VT designed for next generation Galileo satellites can be also tailored for other missions like ESA’s GENESIS mission consisting of the collocation, for

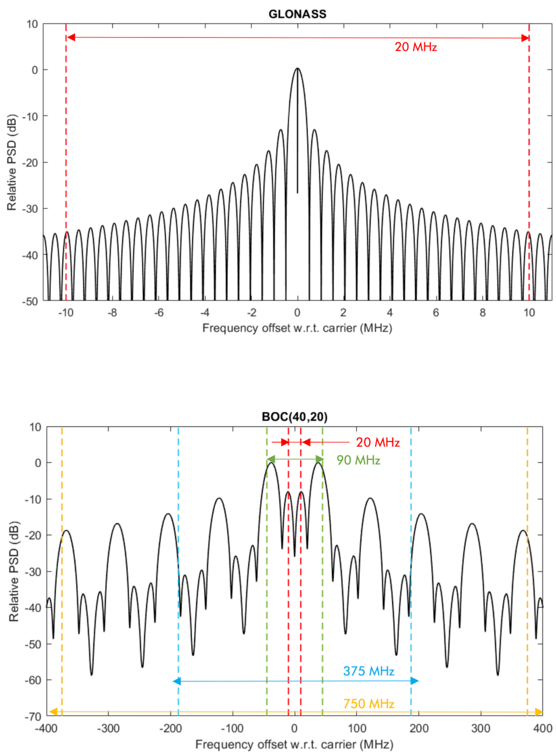

Fig. 3 (Top) Glonass spectrum.(Bottom) BOC(40,20) spectrum

the first time ever, of the four space-based geodetic techniques. It can also be positioned as an artificial radio source on the surface of the Moon to be tracked by VLBI antennas.

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