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Towards VLBI with ESA's Genesis satellite

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– on behalf of ESA GSET WG-3 (VLBI) –

Abstract We provide a short overview of the work done in Working Group-3 (WG-3) of the Genesis Science Exploitation Team (GSET) of the European Space Agency (ESA). ESA GSET WG-3 works on preparations for the future use of signals transmitted by the Genesis satellite to be used for geodetic Very Long Baseline Interferometry (VLBI) observations.

Keywords VLBI, Genesis, co-location in space, ITRF

1 Introduction

In 2022, ESA's Ministerial Council approved the Genesis mission as part of the ESA FutureNav programme. The goal of this mission is to contribute significantly to improving the International Terrestrial Reference frame (ITRF, Altamimi et al. 2023) in terms of accuracy and stability. Genesis is meant to be a co-location satellite that will link four space geodetic techniques on one platform orbiting the Earth Delva et al. (2023). These four techniques are Global Navigation Satellite Systems (GNSS), Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and Satellite Laser Ranging (SLR).

To link these four techniques in space, Genesis will be equipped with GNSS and DORIS receivers, SLR retroreflectors, and a transmitter that will send artificial VLBI signals that can be observed with VLBI Globsal Observing System (VGOS) of the International VLBI Service for Geodesy and Astrometry (IVS). Thus, Genesis will be a complement to the international network of ground-based co-location stations. The plan is to launch Genesis in 2028 and to operate it at least for 2 years.

In order to achieve a seamless interaction with the international geodetic services and geodetic science community as such, ESA created in early 2024 a Genesis Science Exploitation Team (GSET) with five working groups (WGs). One working group concentrates on the ITRF and techniques combinations using Genesis while the four other WGs focus on one space geodetic technique each. The task of the WGs is to advise ESA concerning the development of the Genesis payloads, to work towards a seamless cooperation and integration with the geodetic services, and to contribute to the scientific exploitation of the future Genesis data.

2 The Genesis orbit

Genesis is supposed to be launched into a circular orbit of 6000 km height with an inclination of 95^o. It will thus have an orbital period of about 3.8 h and move with an angular velocity of about 0.026^o/s. A horizon-to-horizon overpass at a VLBI ground station with a minimum elevation of 5^o will take 68 minutes at maximum. Fig. 1 depicts the to expected satellite ground track during 24 h and shows the instantaneous "visibility cap", i.e. the area where VLBI ground stations can see the satellite at an elevation $\geq 5^o$. From the satellite's point of view, the green area corresponds to an angle of 61.732^o. Within this green area, about 10 existing and future stations of the VLBI Global Observing System (VGOS) are located.

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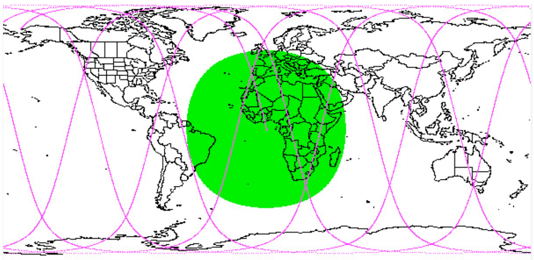

Fig. 1 Pink: Example of the to be expected Genesis ground track during 24 h. Green: Instantaneous "visibility cap", i.e. where the satellite is visible from VLBI ground stations $\geq 5^o$ elevation.

3 ESA GSET WG-3 (VLBI)

Working group 3 (WG-3) focuses on the VLBI aspects of Genesis. It has currently about 30 members and is lead by Rüdiger Haas, who is also the current chair of the IVS directing board. The WG members are experts in various aspects of VLBI and work at European and international institutions. WG-3 has online meeting every 4-6 weeks and discusses various aspects of future VLBI observations of Genesis signals.

The overall goal is to integrate future Genesis VLBI observations into the IVS operations in order to contribute strengthening the ITRF. This needs to be done without deteriorating any of the standard IVS products and should not harm other passive users of the radio frequency spectrum, such as users of radio astronomy. Thus, good compromises need to be found to achieve a "win-win-situation" that benefits the society and the science community.

The work of WG-3 is separated into seven work packages (WPs) that address slightly different aspects, but of course are all interlinked. These are WP-1 on frequencies and signals, WP-2 on ground station fidelity, WP-3 on delay resolution, correlation and fringe-fitting, WP-4 on scheduling, WP-5 on end-to-end simulations, WP-6 on test observations, and WP-7 on a potential Pseudo-Random-Noise (PRN) option.

4 WP-1: Frequencies and Signals

The idea is that Genesis will be observed with the modern VGOS network of the IVS. VGOS is a broadband system covering 2–14 GHz in two linear polarizations. Within this frequency range, there are four suitable frequency bands that the International Telecommunications Union (ITU) has allocated for space-to-earth transmission that ESA can use for the VLBI signal transmission from Genesis, see Table 1. While the occupied bandwidths are 200, 320, 400 and 500 MHz, due to necessary filtering the actual usuable bandwidths will be slightly smaller, i.e. 180, 310, 390, and 490 MHz.

Table 1 Genesis start and stop frequencies in MHz

Band-1	Band-2	Band-3	Band-4
3100–3300	5250–5570	8200–8400	9300–9800

In order to simplify VLBI processing and e.g. error search and calibration, ESA has been advised to use left-hand circular polarization for the transmission. Since the design of broad-band antennas with circular polarization is very challenging, it is expected to have several transmitting antennas on the satellite, each covering a smaller bandwidth. The relative location of these antennas and the antenna pattern have to be calibrated. This calibration information is essential for the VLBI fringe-fitting and post-processing. It is desirable that the final reference position w.r.t. the spacecraft center of mass is know with a comparable accuracy as the positions of the natural radio sources. The latter are at cosmological distances and have an root-mean-square position uncertainty of 30 μas, which relates to less than 1 mm at 6000 km distance. Thus, the transmit antenna calibration should be better than 1 mm.

The actual signal strength should not be too high so that other users of the radio frequency spectrum will not be disturbed. ESA has thus been advised to have a maximum spectral flux density on Earth surface in nadir direction of 20 jansky, which can be attenuated logarithmically in 15 steps by up to 20 dB. It is to be expected that extensive tests need to be done in the commissioning phase. Once the optimum attenuation level is found it probably can be fixed.

Since the satellite will be orbiting the Earth in just 6000 km orbital height, there will be differential attenuation effects purely due to the different free-space-loss for different ground station locations. For the Genesis frequencies the free-space-loss difference between an observing station directly below the satellite that sees the satellite at 90^o elevation and an observing station at the edge of the earth that sees the satellite at 5^o elevation, is on the order of 4.5 dB.

5 WP-2: Ground Station Fidelity

The VGOS ground station antennas have to be able to track the satellite and the VGOS backends have to be able to receive the transmitted signals.

The satellite moves with an angular velocity of about 0.026°/s. Modern VGOS radio telescopes have typically 12–13 m diameter and an half-power beamwidth (HPBW) at 10 GHz frequency of about 0.175°. Thus, the satellite will pass through the antenna beam within about 6 s. Therefore, continuous tracking capability is required. Several of the international VGOS stations are already capable of continuous satellite tracking by sending two-line elements (TLE) from the VLBI Field System (FS) to the antenna control units (ACUs). However, other stations still need to be updated during the coming years to allow satellite tracking directly from the VLBI FS.

The backends of the VGOS stations are prepared for broad-band observations. However, since the Genesis signals are different from the usually observed VGOS bands, some modifications will be necessary when changing between standard VGOS observations and Genesis observations. So far not all VGOS stations are able to smoothly and fast change frequency setup. However, work is ongoing to simplify this and allow easy and quick changes in frequency setup.

6 WP-3: Delay Resolution, Correlation and Fringe-fitting

Operational VGOS observations are performed since 2019 with a total number of 32 channels per polarization. Each channel has a bandwidth of 32 MHz. Groups of 8 channels are allocated and distributed in four different frequency ranges in order to cover 488 MHz with the so-called bandwidth synthesis technique. The total spanned and effective bandwidth are 7680 MHz and 2612 MHz, respectively, in each polarization.

Based on these VGOS operational standards, a potential frequency setup for Genesis observations was developed, see Table 2. Out of the eight channels in Band-1, only five (black and blue) will actually observe the signals transmitted by Genesis. The other three Genesis bands are wide enough to allocate eight channels each. The channels marked in blue are channels that also belong to today's frequency setup for operational VGOS. The total spanned and effective bandwidth are 6624 MHz and 2326 MHz, respectively.

The corresponding two-dimensional delay resolution function is presented in Figure 2. It has a higher level of ambiguities in both the group delay (tau) and differential ionosphere (TEC) dimensions than the currently used operational VGOS frequency setup. Nevertheless, it should be possible to make use of the proposed Genesis frequency setup.

Table 2 Start frequencies of a possible Genesis frequency setup with channels of 32 MHz bandwidth. The channels shown in red are outside the Genesis transmission band, i.e. will be dummy channels that will observed but cannot be used since there will be no Genesis signal. All channels shown in black and blue are inside the Genesis transmission bands. The channels shown in blue are overlapping with channels used for the current operational VGOS observations.

Band-1 f_{start}	Band-2 f_{start}	Band-3 f_{start}	Band-4 f_{start}
3096.4	5272.4	8024.4	9368.4
3128.4	5304.4	8056.4	9400.4
3160.4	5336.4	8184.4	9432.4
3192.4	5400.4	8216.4	9528.4
3224.4	5432.4	8248.4	9624.4
3256.4	5464.4	8280.4	9656.4
3288.4	5496.4	8312.4	9688.4
3320.4	5528.4	8344.4	9720.4

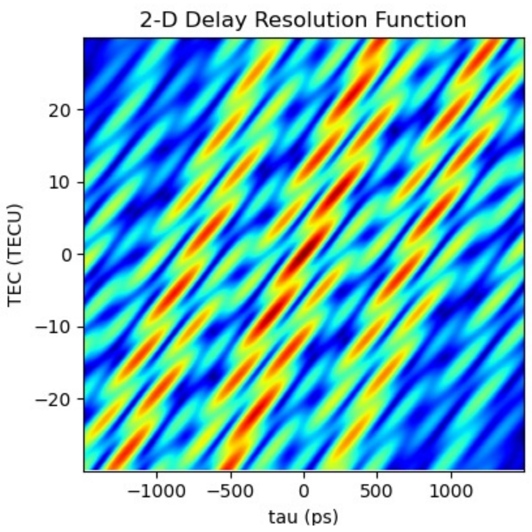

Fig. 2 The two-dimensional delay resolution function using the proposed Genesis frequency setup presented in Tab. 2.

7 WP-4: Scheduling

In VLBI, scheduling software is used to plan observations and to optimize the observing plan to be able to derive parameters of interest in the final data analysis. One prerequisite for successful VLBI observations is to achieve high enough signal-to-noise ratio (SNR) since it is an important parameter influencing the accuracy of the group delays. Usually, for VGOS observations, SNR of 20 per VGOS-band is the goal.

The spectral flux density for natural radio sources at cosmological distances is basically the same for all stations on earth. However, this is not true for signals transmitted by spacecraft orbiting earth. They differ due to the near-field geometry, including transmit antenna pattern and differences in free space loss. Thus, for satellite signals, the necessary observation time T to achieve a target SNR can be formulated as:

$$T = \frac{1}{2 \cdot B \cdot n} \cdot \left(\frac{\mathrm{SEFD}_1}{S_1} \cdot \frac{\mathrm{SEFD}_2}{S_2} \cdot \frac{\mathrm{SNR}}{\eta} \right)^2 \quad (1)$$

Here, B is the total observed bandwidth and n the number of sampled bits. The individual station sensitivities are expressed by the system equivalent flux densities (SEFD_i), and S_i are the individual spectral flux density values. SNR is the target signal-to-noise ratio, and η is a correlation efficiency factor.

The SEFD values in zenith direction for modern VGOS stations are usually on the order of 2000–3500 Jy for the frequency range 3–10 GHz. This includes average clear-sky atmospheric attenuation, which is station-dependent. Stations have higher SEFD values (i.e. less sensitivity) for observations at lower elevation angles, and this is usually expressed by station-dependent gain curves. Rain attenuation can only be modeled based on station-dependent statistical models, e.g. according to the recommendations of the International Telecommunications Union (ITU, ITU-R P.618-14, 2023).

We can do a simple "back-of-the-envelope" worst case calculation for clear sky conditions, assuming that two stations observe Genesis at an elevation of 5°. We assume that the Genesis signal flux density in nadir direction is 10 Jy and that the transmit antenna has 6 dB antenna gain pattern variation between boresight and edge of coverage. We assume that the two stations have a sensitivity of 4900 Jy for Band-1 at 5° elevation. For the smallest Genesis bandwidth (Band-1, 180 MHz), 2-bit sampling, and a SNR goal of 20, assuming correlation efficiency of $\eta = 0.75$, this means that the stations have to observe for $T = 30$ s.

Corresponding calculations and scheduling options have been included already in the scheduling software VieSched++ (Schartner and Böhm, 2019). Figure 3 depicts the common visibility of Genesis for the international VGOS network during 24 h. Several VGOS stations will be seeing Genesis simultaneously, thus allowing for scheduling many common observations.

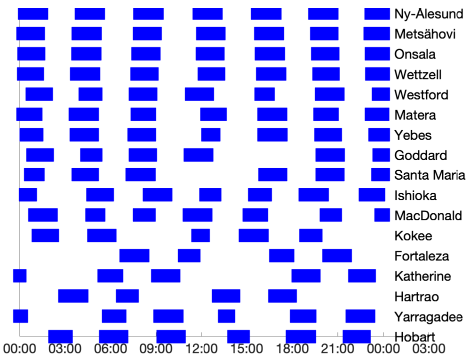

Fig. 3 Example of Genesis visibility during 24 h for the international VGOS network. Stations are ordered from North to South, and the first station on the southern hemisphere is Fortaleza.

8 WP-5: End-to-end Simulations

Simulations of satellite observations with the VGOS network were already done several years ago by Klopotek et al. (2020) using, e.g., the orbital parameters of the Lageos satellite, which also is in about 6000 km orbital height. At that time is was shown that VLBI observations of satellite signals opened up for orbit determination and geocenter determination, while determining the classical VLBI products without quality loss. Recent end-to-end simulations investigated e.g. the integration of satellite observations into standard operational VLBI observations (Schunck et al., 2024a), satellite visibility and orbit inclination (Schunck et al., 2024b), the necessary signal strength (Sert et al., 2025), and the impact of different orbit inclination on station position estimation (Wolf et al., 2025). More studies addressing further aspect of VGOS observations of Genesis are ongoing.

9 WP-6: Test Observations

The proposed Genesis frequency setup was tested first with the Onsala twin telescopes, observing natural radio sources. The observations were successful and the recorded data could be processed with the standard VGOS processing pipeline, resulting in fringes. Figure 4 presents as an example a corresponding fringe plot.

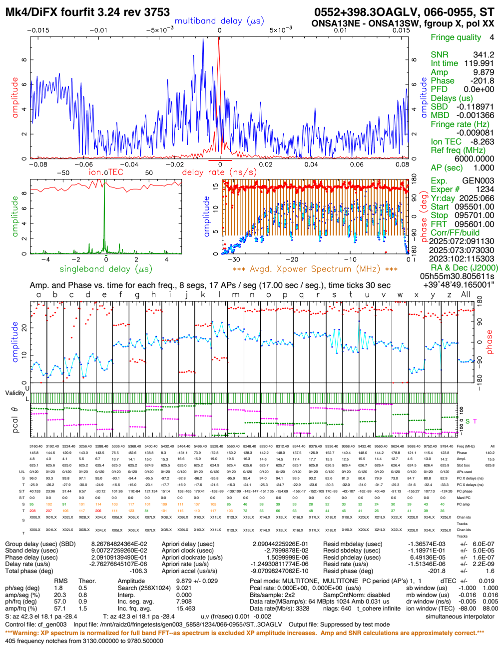

Fig. 4 Fringe plot using the proposed Genesis frequency setup with the Onsala twin telesopes observing a natural radio source.

10 WP-7: Pseudo-Random-Noise Option

Since Genesis will be sending in rather wide bandwidth, one idea was to also send a Pseudo-Random-Noise (PRN). This can be seen as an equivalent to GNSS code measurements, however with PRN codes that could cover more than 20 times wider bandwidth than, e.g., the Galileo E5a code. Thus, Genesis one-way ranging measurements could be 20 times more accurate than GNSS.

Provided that VGOS stations could be equipped with corresponding dedicated receivers, for example based on software defined radio (SDR), or that the corresponding data processing could be included directly in the standard geodetic processing pipeline, this could open up for useful one-way ranging measurements which could potentially be used for time and frequency transfer on intercontinental distances. However, there are a number of questions that still need to be studied and answered, including the calibration of the signal chains at the VGOS stations, as well as in how far the PRN signals would impact the pure interferometric measurements.

11 Conclusions and Outlook

ESA GSET WG-3 (VLBI) is active in preparing for future VLBI observations of signals transmitted by Genesis. Many important aspects have been addressed already and advise has been provided to ESA. However, there are still open questions to solve. We are looking forward to observing Genesis within a few years time.

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