

ESA Scout HydroGNSS Early Mission Results

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Abstract

The ESA Scout HydroGNSS mission demonstrates a new generation of GNSS reflectometry (GNSS-R) capabilities for hydrological climate monitoring from small satellites. HydroGNSS measures soil moisture, freeze–thaw state, inundation, wetlands and above-ground biomass by exploiting both traditional incoherent Delay Doppler Maps (DDMs) and several innovative signal types not previously available from spaceborne GNSS-R missions. Early in-orbit results confirm successful acquisition of signals from Galileo, dual-polarisation measurements, coherent complex channel data and reflections at the second GNSS frequency (L5/E5a). These enhanced measurements exhibit stronger-than-predicted performance and are expected to significantly improve retrievals of climate-relevant parameters while enabling new science opportunities. This paper summarises the mission architecture, instrument innovations and first results from early operations.

1 Introduction

HydroGNSS is rapid development small satellite mission is the first ESA Scout mission to be launched. The mission comprises two identical satellites that were launched into Low Earth Orbit on 28th November 2025. The mission will deliver science data under ESA's open and free data policy from mid-2026. The first mission results collected with the HydroGNSS payload have been captured and are presented following a brief summary of the mission.

2 HydroGNSS Mission

2.1 Overview

HydroGNSS is the first small satellite mission to be launched under the Scout programme as an element in ESA's FutureEO programme. ESA's Advisory Committee for Earth Observation (ACEO) selected the HydroGNSS through a competition based on several factors including the strength of the science case, novelty of the data and the scientific readiness of the mission. The two HydroGNSS satellites were produced within the required budget of <€30 million on a rapid schedule from Kick-Off in 2021 to launch in November 2025. The lifetime of the satellites in orbit is 3-5 years.

Water is a natural resource vital to climate, weather, and life on Earth, and unforeseen global variability in hydrology poses one of the greatest threats to the world's population. Global soil moisture measurements are valuable for accurate weather forecasting, flood warnings and agricultural irrigation, thus water management, as well as for climate modelling.

GNSS-Reflectometry is a type of bistatic radar utilising abundant GNSS signals as radar sources of opportunity (Figure 1), empowering small satellites to provide measurement quality associated with

larger satellites. HydroGNSS comprises two satellites using an innovative GNSS-Reflectometry instrument to collect parameters related to four Essential Climate Variables (ECVs) [1]:

- soil moisture,
- inundation,
- freeze/thaw,
- biomass,
- ocean wind speed (secondary objective)
- sea ice extent (secondary objective)

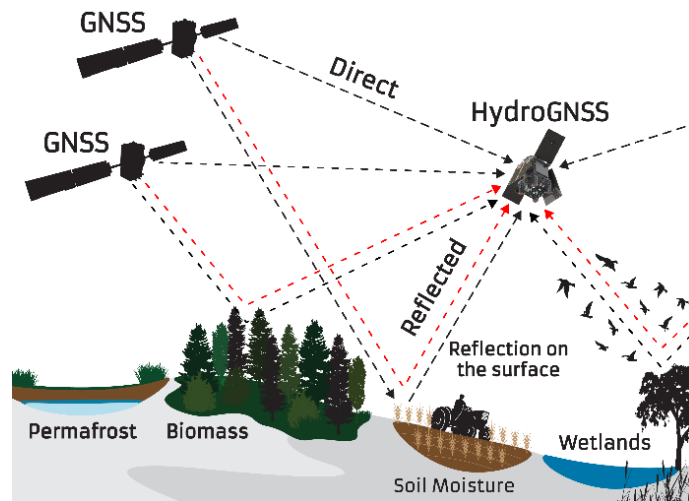


Figure 1. HydroGNSS uses a bistatic radar concept using dual frequency GNSS reflected signals for hydrological measurements related to Essential Climate Variables (ECVs)

The measurements from HydroGNSS complement and potentially fill gaps from other missions sensing soil moisture e.g. ESA’s SMOS and NASA’s SMAP missions, and complement ESA’s Biomass mission for forest biomass sensing, addressing coverage restrictions over northern regions. Two satellites provide global coverage (80% of land mass as specified in the Mission Requirement Document MRD) every 15 days with a mean revisit time at a location of less than 3 days, and it sets the framework for an expanded future constellation that could offering daily continuity in high spatial-temporal resolution observations of the Earth’s weather and climate.

The HydroGNSS instrument collects reflected GPS measurements processed on-board into Delay Doppler Maps as on its predecessors on UK TechDemoSat-1 and NASA CYGNSS missions. Beyond this, HydroGNSS introduces new measurements, exploiting Galileo signals (E1b+c), dual-polarisation, complex ‘coherent channel’ (amplitude/phase) and second frequency (L5/E5a) acquisitions. These measurements enable HydroGNSS to innovate the Level 2 products to access improved resolution on the ground, sensing inundated locations and separation of roughness and vegetation effects from soil moisture.

The industrial consortium is made up by Surrey Satellite Technology Ltd (SSTL) as the Prime Contractor and a team of Science Partners:

- Sapienza University of Rome, Italy
- Institut d’Estudis Espacials de Catalunya (IEEC) / Institute of Space Sciences (ICE-CSIC), Spain
- Finnish Meteorological Institute, FMI, Finland
- Università di Roma Tor Vergata, Italy
- Institute of Applied Physics, National Research Council – IFAC CNR, Italy
- National Oceanographic Centre, UK

- University of Nottingham, UK
- Technical University of Vienna (TUW)

2.2 Mission Elements and Phases

The mission is guided by the HydroGNSS Science Advisory Group (SAG), to address the aim of delivering science from an optimised small satellite to rapidly fulfil scientific aims. This group is chaired by one of the project science team members, includes ESA representatives, experts from the wider GNSS-R science community and is administered by SSTL (mission prime).

Scout is a rapid programme by institutional standards, and the compressed schedule helps to keep the development costs down and is on par with commercial missions. As opposed to most ESA missions the mission is operated by industry. The mission was procured as a Service Delivery Contract (SDC) under which science data will be delivered to users by SSTL, under ESA’s open and free data policy. SSTL delivers the science data to ESA as well as distributing it directly to end users. The data remains the property of ESA while SSTL having responsibility as the operator will be the owner of the two HydroGNSS satellites.

The mission architecture comprises the satellite payload, satellite platform, control and downlink ground segment, and the Payload Data Ground Segment, PDGS, including Level 1, Level 2 processors and data dissemination. The HydroGNSS satellite timeline is shown in Figure 2. Since launch the satellites have been undergoing commissioning using the Guildford and Svalbard ground stations, and orbit manoeuvring is being undertaken to raise the satellites to the operational height of 530 km where they are phased approximately 180 degrees apart. Following platform and payload commissioning, the payloads will be operated continuously for the 2.5-year lifetime with the potential of a 2 year life extension.

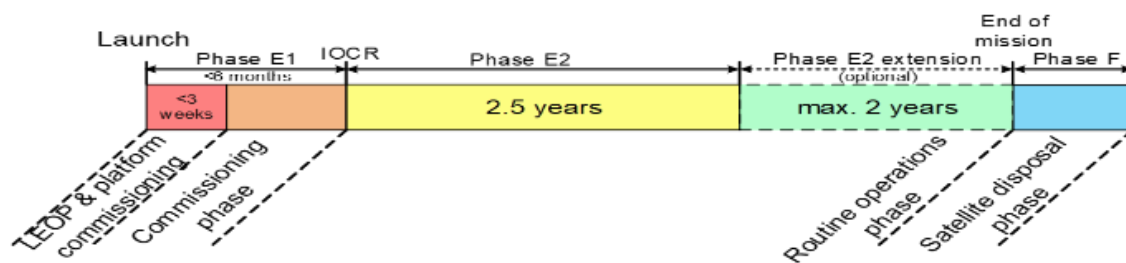


Figure 2. HydroGNSS satellite timeline post launch

2.3 The HydroGNSS Satellite

The HydroGNSS platform is the ‘SSTL-21’, it is a microsat, the smallest family member of the ‘SSTL-Micro’ platform series (see Figure 3). A microsat was chosen for the platform rather than a CubeSat, partly driven by the duty cycle for the payload which led to the sizing of the power system and associated spacecraft design. EEE part selection information and processes were also very well understood from extensive flight heritage on other missions.

To best support the mission aims and objectives over the globe, the selected platform offers the HydroGNSS mission near-continuous payload operation (100% duty cycle). The satellite also supports a large data store and a high data throughput to support the data volumes generated with these 24/7 payload operation. The satellite has precise attitude knowledge through the inclusion of star cameras, which allows accurate determination of the antenna gain towards the reflected signal specular point. The SSTL-Micro platform is based on scalable avionics, capable of accommodating a range of payload size, weight and power and a range of different payload applications. It

incorporates many features advantageous to a GNSS reflectometry mission and serving to provide high quality science data:

- Dual redundant SSTL core avionics to support mission lifetime availability and reliability.
- Mission configurability → software can be updated in-orbit, including on the Science Payload
- Deployable solar arrays → flexibility to support 100% Science Payload duty cycle at different orbit LTANs.
- An efficient battery regulated power bus running at 12V, suitable for a small satellite.
- High-rate Science Payload data downlink @ 200 Mbps
- On-board payload data storage of up to 500 GBytes
- Xenon propulsion system to support constellation phasing, altitude correction and collision avoidance firings.
- 3-axis stabilised AOCS subsystem
 - Capability to slew to a specific target of interest.
 - Capability to dynamically track the Ground Station during downlinks.
- 45 cm x 45 cm x 70 cm in size, and a mass of approximately 70 kg



Figure 3. HydroGNSS satellites after panels deployment

2.4 The Science Payload

The science instrument on-board the HydroGNSS spacecraft is a development of the SGR-ReSI flown on the UKSA TechDemoSat-1 and NASA CYGNSS missions. Compared to previous GNSS reflectometry missions has innovative capabilities and features capabilities and features of providing for every second 4 reflection measurements per each polarisation (RHCP and LHCP), each band (L1/E1, L5/E5a), and each processing mode (coherent and incoherent) for a total of 32 measurements per second, compared to only 4 on previous missions. The new measurements on HydroGNSS compared to TDS-1 and CYGNSS are shown in Figure 4 The top right of triangle shows extent of measurement from TDS-1 and CYGNSS, restricted to diffuse, unipolar measurements from GPS. Top left and bottom triangles are added with coherent channel polarisation at both GPS and Galileo, and in addition these are available at dual frequency.

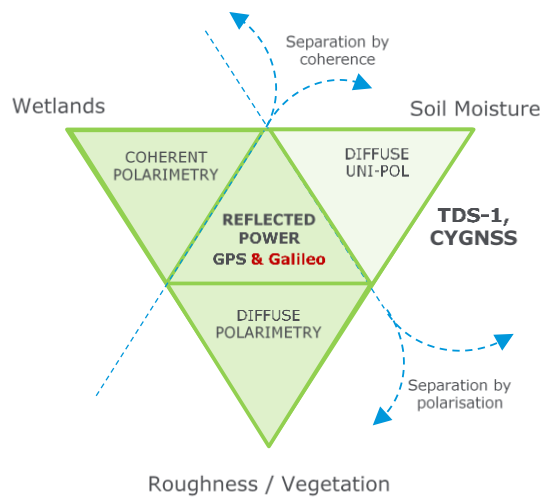


Figure 4. New Measurements on HydroGNSS compared to TDS-1 and CYGNSS.

These new measurements are aimed at improving the science of the mission, towards better determination of ECVs. Furthermore, the new features are expected to unlock additional products. For example, the coherent channel may be an enabler for precise altimetry over sea ice, inland water bodies and calm coastal waters [2,3].

The instrument nadir facet antenna uses 2 x 2 array of metal patches to implement an optimised dual frequency (L1/E1 and L5/E5) / dual polarisation receive antenna to facilitate these novel measurements. This antenna gives a peak gain of 11-12 dBi at L1/E1, with a good cross-polar performance at both frequencies and takes a physical area of about 32 cm x 32 cm on the spacecraft. The antenna is thus suited to GNSS reflectometry by providing a gain sufficient to target weak reflections, while still compatible with deployment on a small spacecraft. The low noise amplifier uses a similar approach to those on CYGNSS including a cavity filter, temperature sensor, load switch and test ports, while doubling up for the two frequencies and polarisations. The switches give access to black body loads for reference noise measurements.

The central science instrument unit, SGR-ReSI-Z, is a Delay Doppler Mapping Receiver tracking the direct GNSS signals through the Zenith Antenna and processing the reflected signals for the Nadir Antenna into Delay Doppler Maps. The Science Instrument signal processor uses open loop predictions to target position of the reflections at each specular point and collect forward scattered measurements in the form of Delay Doppler Maps (DDMs) where incoming signals are correlated with the on-board code replicas to give measurements from four simultaneous reflections. HydroGNSS uses a Digital Elevation Model (DEM) compatible with onboard resources to improve the targeting the specular point position over land [4]. The increased reflection prediction accuracy allows reduction for the DDM size needed to capture the specular point and thus reduce the power consumption and data downlink requirements.

2.5 Ground and User Segment

The mission architecture is illustrated in Figure 5. The Mission Operation Centre (MOC) and Payload Data Ground Segment (PDGS) are both based in Guildford, UK. Telemetry and Telecommand, and data download happen via Svalbard, with Guildford as backup. Once collected, the PDGS processes data from Level 0 to Level 1, Level 2 and Level 3, and makes use of operational processors provided by the Science Team, with support from Sapienza, IEEC/ICE-CSIC, Tor Vergata, FMI, IFAC, NOC, Nottingham, Vienna.

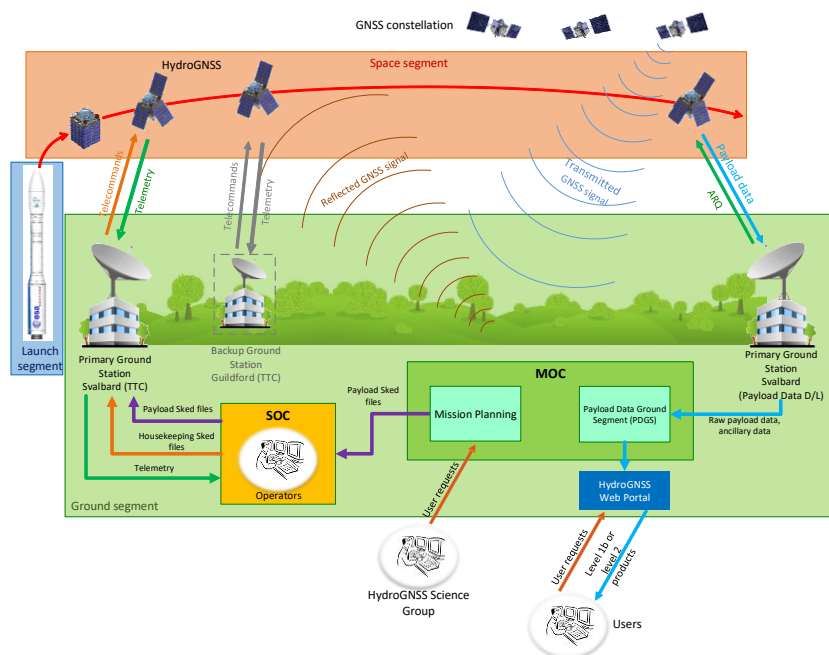


Figure 5 Top Level Mission Architecture

Figure 6 shows a schematic of the ground segment and data products. SSTL’s satellite planning tool is used to manage payload scheduling. The PDGS includes infrastructure derived from the MERRByS system used for TDS-1. Products are delivered using the industry standard NetCDF and made available at Level 1A and 1B, together with appropriate metadata, including calibration parameters. Level 1 calibration and Level 2 inversion algorithms may evolve and be refined during the mission as the scientific understanding of the new measurements improves.

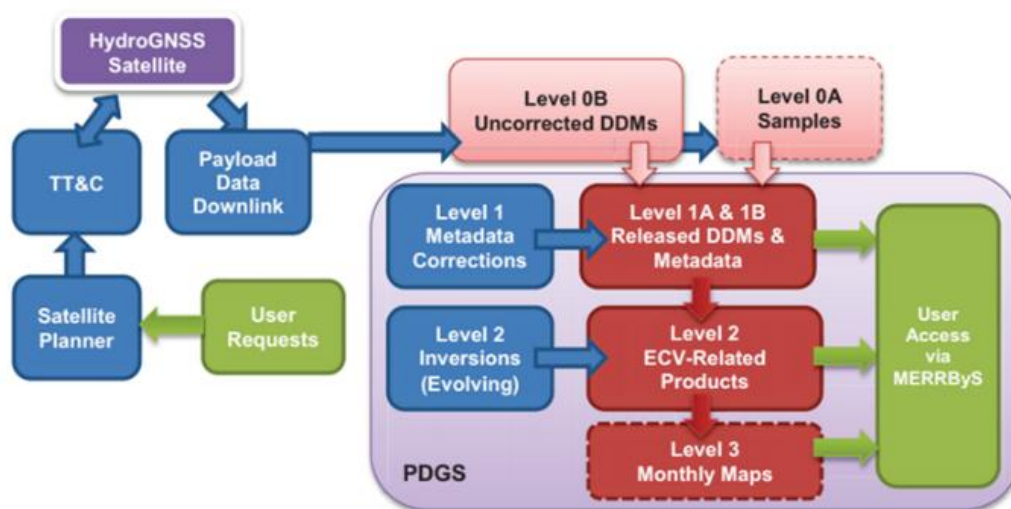


Figure 6 HydroGNSS Ground Segment & Products

3 Early Mission Results

3.1 Launch and First Payload Operations

Following several delays in the schedule, the two HydroGNSS satellites lifted off on 28th November at 10:44am local time from Vandenberg Space Force Base, California, on a SpaceX Falcon 9 as part of the Transporter-15 mission. Signals were acquired from both satellites within three hours of deployment, and both satellites were brought under control, and panels deployed a few hours later.



Figure 7 (left) Transporter 15 launch, (right) first HydroGNSS contact in Guildford ground station

Both payloads were operated within a week, and soon after, the first data was downloaded. An example of the Delay Doppler Maps (DDM) is shown in Figure 8. The left image is a reflection from E1 navigation signals generated by Galileo satellite PRN-E27, and the right is from GPS satellite PRN21. The strength of the peak of these reflections is related to a number of factors on the surface, including soil moisture, roughness and vegetation. The x-axis represents delay, while the y-axis represents Doppler, so the central point is where the specular point is on the surface. Any reflections at a distance from the specular point will have an increase delay, and will show further down the DDM. Depending on the alignment, the Doppler may also increase away from the central point.

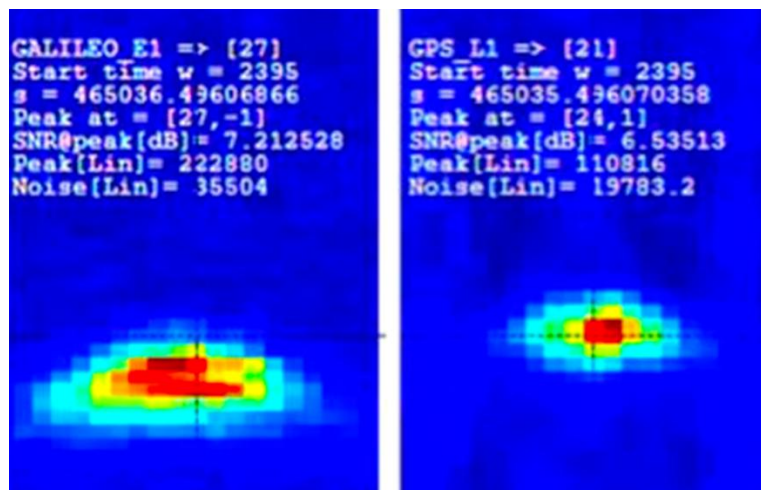


Figure 8 Two early Delay Doppler Maps of reflected GNSS signals captured by HydroGNSS-2 over Central Africa (left) Galileo signal (right) GPS signal

3.2 Reflection Tracks and Delay Doppler Maps

Following refinement and tuning of the instrument configuration, reflections have been gathered across the globe, testing the payloads in a near-continuous operational mode. The reflections have been visualised using a script that processes both DDMs and the accompanying metadata and allows an animation over a period of time. The reflected signal tracks received by the HydroGNSS comprise between one and four reflections from Galileo and GPS navigation satellites operating in MEO at any one time. Signals arrive at the HydroGNSS sensor from spaceborne GNSS signal reflections which appear in a quasi-random pattern.

Figure 9 shows an example of two reflections collected over the Mediterranean Sea. The DDMs in top right show Galileo E31 reflection strength at L1/E1 frequency in Left Hand Circular Polarisation

(LHCP) and Right Hand Circular Polarisation (RHCP) then in L5/E5a frequency in LHCP and RHCP. In the second row, the signals from the GPS PRN25 are shown, again L1 LHCP, RHCP and L5 LHCP, RHCP. The progression of the peak power of the L1/E1 LHCP for these two reflections is plotted on map on the left. The map also shows the antenna footprint of the payload in the red circle – when the specular point of a GNSS satellite enters the circle, measurements are taken. In this case, the tracks are passing over the sea, and so the scatter spreads the power in a parabolic shape, with the spread and peak signal strength having a dependence on the wind speed over the water. Reflections can be seen in both L1 and L5 frequency bands, although only in LHCP in this example.

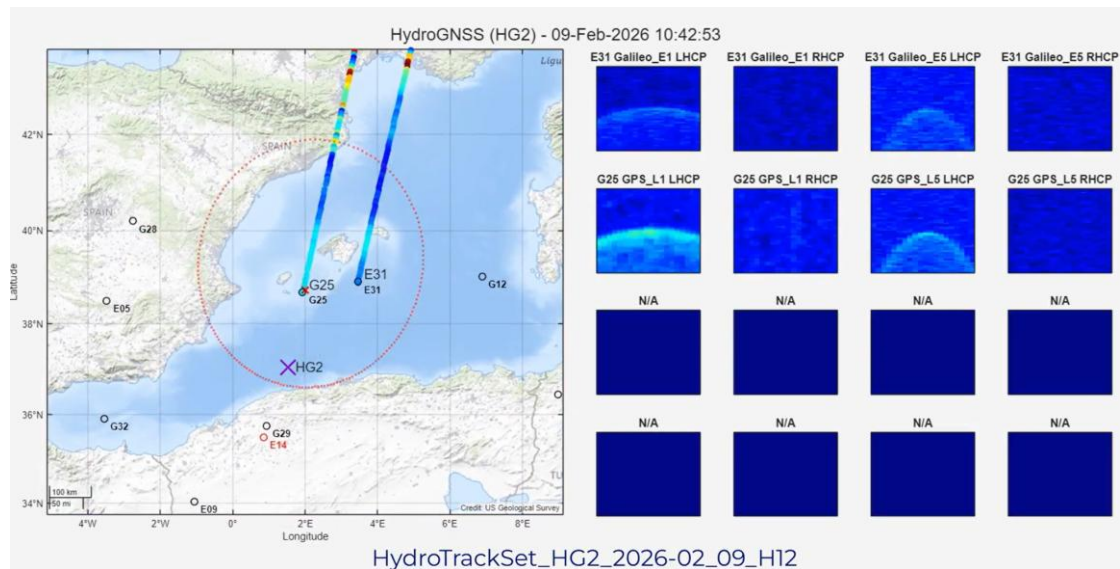


Figure 9 GNSS-R data captured over Mediterranean. (left) Map of signal tracks (right) Delay Doppler Maps for one Galileo reflection and one GPS reflection

In-orbit the satellite boresight is tilted backwards away from the direction of travel by 20 degrees. This gives access to slightly more reflections with higher incidence angles while still allowing collections of reflections nearer the nadir.

The strength of the reflection is visible in the tracks, as stronger reflections are shown in yellow and red. The strongest reflections come from very flat surfaces – over water this could indicate sheltered flat water, sea or lake ice. Over land, strong reflections could indicate inundation, or potentially very flat reflective land, that might be found for example where there is a salt lake. Other areas on the land show variations in signal strength as the water content increases, hence stronger signals give an indicator of higher soil moisture. Wet or frozen soil changes permittivity and hence reflectivity, and increased biomass attenuates the amplitude of the signal.

Figure 10 shows a period of collection in the region of Lake Superior on the US / Canada border. In this case, there are three Galileo signal reflections and one GPS reflection being collected. Signals can be seen in both L1/E1 and L5/E5a bands at LHCP, and some signal is observed in the RHCP DDMs for Galileo E4 at both frequencies. The GPS satellite G15 has no L5 as it is one of the older satellites (currently about 50% of GPS satellites broadcast in L5, though the number is increasing).

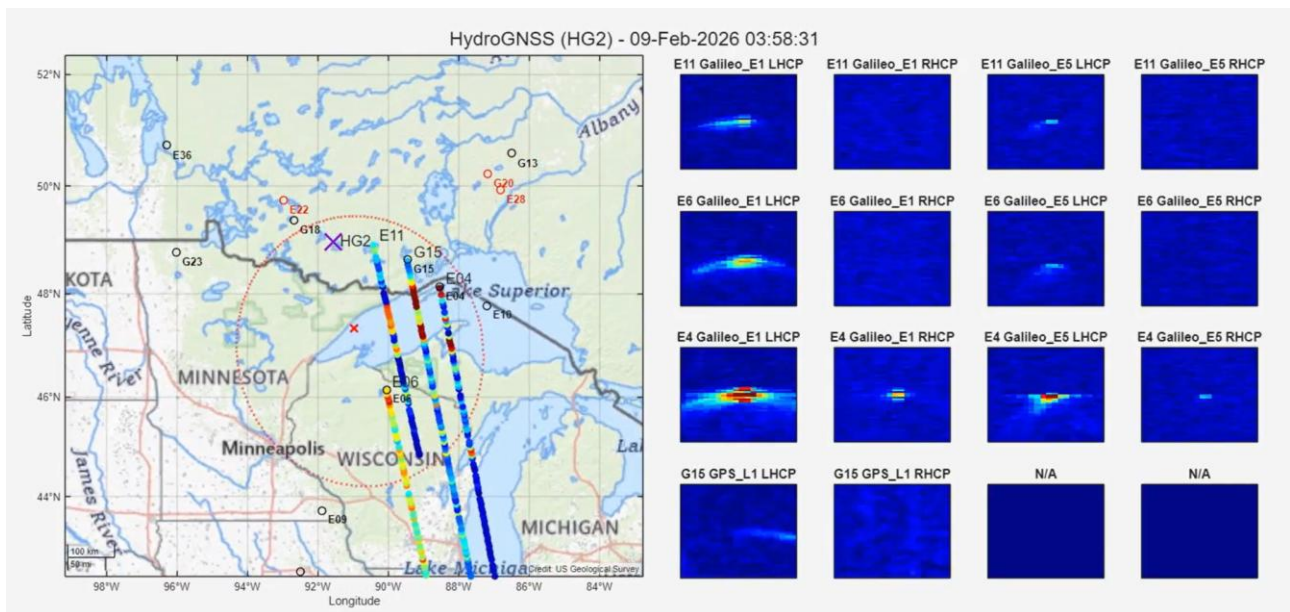


Figure 10 Left: GNSS-R data captured near Lake Superior. (left) Map of signal tracks (right) Delay Doppler Maps for three GPS reflections and one Galileo reflections

Signals from further away show as an increase on the delay axis of the delay doppler map. Strong signal peaks indicate reflection from smooth surfaces, while reflection from rough surfaces spread out the DDM pattern in delay and doppler showing as a wider parabola.

3.3 Review of Early Results

At the current stage of commissioning, full radiometric and geolocation calibration is still in progress; however, the initial analysis of the acquired data already provides a clear indication of the mission's technical performance and scientific potential.

One of the most significant findings is the measurable increase in the number of reflections available from the inclusion of Galileo signals. When both pilot and data components are exploited, Galileo returns exhibit power levels broadly comparable with GPS, with some systematic offsets likely attributable to differences in signal structure and modulation. The longer spreading codes of the Galileo system also appear to reduce cross-correlation noise, suggesting potential benefits for retrieval robustness, particularly in regions prone to radio-frequency interference.

A key outcome from the early payload characterisation is the strong detection of reflections at the second GNSS frequency, L5/E5a. Pre-launch simulation work had suggested that these signals would be detectable only under favourable conditions due to their lower transmitted power and higher susceptibility to attenuation. Instead, HydroGNSS has observed widespread L5/E5a reflections with strengths comparable to, and in some cases exceeding, those at L1/E1. The wider bandwidth of these signals is expected to yield finer surface resolution and opens the door to enhanced applications across both land and ocean domains.

The new RHCP cross-polarisation channel has been confirmed to operate as designed, although early data indicate that distinguishing true RHCP reflections from LHCP leakage will require careful calibration. Higher-incidence-angle reflections from forests and ice surfaces are expected to provide

clearer RHCP signatures as the mission progresses. Machine-learning-based retrieval methods, including neural networks trained on both co- and cross-polar data, are likely to be particularly effective in extracting additional geophysical information from these channels.

The coherent channel is also showing strong promise. Its high-rate complex measurements, available at approximately 300-m ground spacing, offer a dramatic improvement in along-track resolution when compared with standard DDMs. This capability is expected to contribute to sharper surface classification, improved identification of small-scale hydrological features and a potential pathway to phase-based altimetry over calm water and ice.

Overall, the early results demonstrate that the expanded measurement space provided by dual frequency, dual polarisation, coherent processing and full Galileo utilisation is functioning as intended and is already revealing capabilities beyond those originally anticipated. These findings lead naturally into an assessment of how HydroGNSS may contribute not only to its planned climate applications but also to new scientific and operational opportunities, as discussed in the conclusion.

4 Conclusion

The early performance of HydroGNSS confirms that its innovative GNSS-R measurement modes are delivering results beyond pre-launch expectations. Several findings stand out:

- Reflections from the second GNSS frequency band (L5/E5a) are significantly stronger than predicted. Given their wider bandwidth, these signals offer inherently finer spatial resolution and appear to provide valuable additional measurements across a broad range of surface types.
- Over the ocean, L5/E5a measurements have the potential to improve separation of wind-driven roughness effects from significant wave height, while also sharpening the mapping of sea-ice edges and small-scale ocean features.
- Over land, wider-band reflections may enhance the detection of inundation, improve retrieval of soil moisture and provide clearer mapping of freeze–thaw boundaries at higher spatial resolution.
- The availability of two frequencies positions GNSS-R as a candidate for future low-cost altimetry. Dual-frequency measurements allow estimation of ionospheric delay, a key requirement for precise range determination, opening a path towards small-satellite mapping of ocean currents, inland water bodies and ice freeboard.
- Additional innovations on HydroGNSS — coherent complex samples, full Galileo utilisation and dual-polarisation measurements — are performing well and are expected to significantly enhance future climate variable products. They also create opportunities for new remote-sensing applications, including land classification, biomass assessment and potential phase-based altimetry.
- In summary, HydroGNSS is not only meeting its mission objectives but is also revealing new possibilities for GNSS reflectometry as a versatile and low-cost technique for global environmental monitoring. These early results highlight the promise of future GNSS-R constellations to deliver high-resolution, high-frequency observations of Earth’s hydrological and cryospheric processes.

4.1 Next Steps

The mission goals are intended to be validated through calibration / validation activities with the Start of service planned for Summer 2026. The full results and validation of science products (Soil moisture, inundation, Freeze-thaw, Forest biomass) will be presented in a full paper at the end of

commissioning. A hybrid user workshop is planned for September 2026 to introduce the data that will become available online.

5 REFERENCES

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