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MINISTRY OF EDUCATION, YOUTH AND SPORTS

SWIGPOD: Evolution of the GNSS performance indicators aimed at end users' needs

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Focus of the new SWIGPOD

This fall started the ESA S2P-S1-SW-21 SWIGPOD project devoted to extensively upgrade the GNSS Performance Indicators, taking advantage of the newly introduced ESA SWESNET products.
Project is led by DLR, with NMA, ISS and IAP as subcontractors.
The aim is to provide simple to understand, but even more accurate nowcasting and partially forecasting services for various use cases and user communities. The range of interested GNSS users are invited to consultations of the planned service improvements which are ought to be well aimed to their users' perspective. But all GNSS services users are welcome to share their experience and challenges associated with degradation of GNSS services so that the products can be tailored also to their needs which will be also further configurable to specific ionospheric impact sensitivities.
Although focused at GNSS performance indications, SWIGPOD will provide also indicator for radioastronomy end-users like LOw Frequency ARray (LOFAR) telescope for suitable observing conditions.

Enhanced User Engagement
Configurable Thresholds
Advanced Event Analysis & Forecasting
Refined UI
Optimized API
Low-Latency Performance
High System Robustness
Comprehensive Observability
Reproducible Results
Scientifically Validated Approach
Support for proactive Alerting
Modern SSO Integration

2025 - 2027

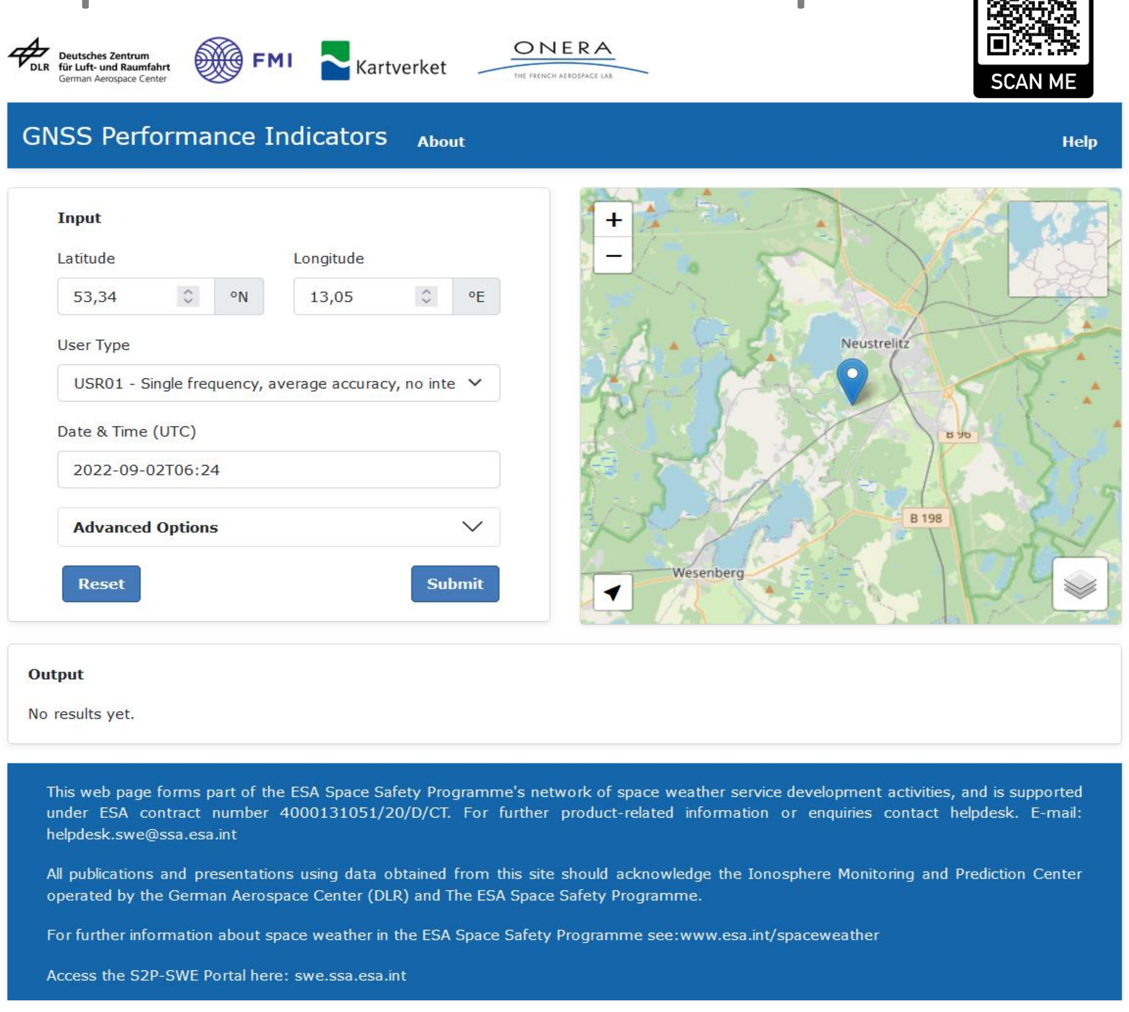
Space
Weather
Impact on
GNSS
Performance
Optimised for
Decision-Making

List of target User Groups and Subgroups

- **USR01**: Users of GNSS single frequency services, no integrity.
  - **USR01-A**: Users of GNSS Single frequency services with average accuracy (e.g. typical GNSS mass market user).
  - **USR01-B**: Users of GNSS Single frequency services with high accuracy by advanced post processing (e.g., transport and land surveying).
- **USR02**: Users of GNSS single frequency services with average accuracy, using integrity (e.g. EGNOS user).
- **USR03**: Users of multi-frequency GNSS systems with average multi-frequency accuracy, no integrity (commercial services, PRS).
- **USR04**: Users of multi-frequency GNSS systems with average accuracy, integrity (e.g. aeronautical multi-frequency, autonomous vehicles).
- **USR05**: Users or multi-frequency GNSS systems with very high accuracy (e.g. GNSS geodetic users, RTK).
- **USR06**: Users of satellite data communications with high availability / continuity.
  - **USR06-A**: Users of GNSS systems with high availability / continuity (e. g., Search-and-Rescue, Air Traffic Control/Management via Satellite, GNSS-R altimetry, high availability/continuity data networks such as Galileo Ground Segment Data Network).
  - **USR06-B**: Users of space-based services / products affected by the ionosphere and requiring (relying on) high availability / continuity GNSS services (e.g., UHF / C-band radars, UHF / low microwave radio-astronomy and deep space communications).

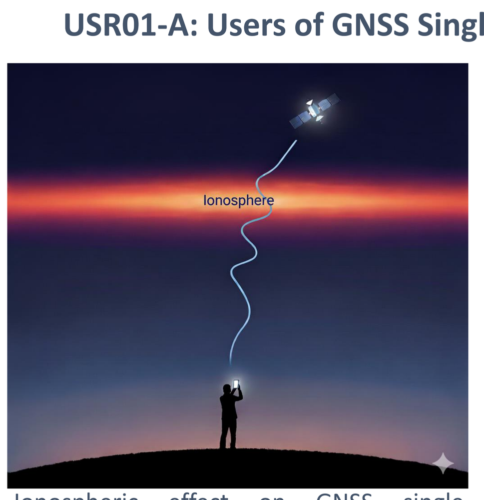
Operational service to improve

SCAN ME



Target User Groups and Subgroups

USR01-A: Users of GNSS Single frequency services with average accuracy



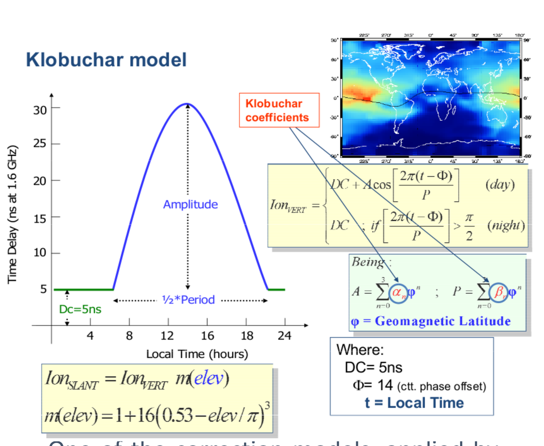
Ionospheric effect on GNSS single frequency users without integrity (generated by Gemini).

Under moderately disturbed conditions, large-scale traveling ionospheric disturbances LSTIDs can be responsible for TEC variations of up to 2 TECU in mid-latitude regions and as high as 3 to 4 TECU at low latitudes resulting in range errors of about **32 – 64 cm.** However, during severe and extreme magnetic storms, observations have recorded storm-time LSTIDs with amplitudes exceeding 13 TECU and, in extreme cases over 25 TECU, leading to a dramatical error increase **up to 4 meters.** Such uncorrected LSTID-induced error is one of the main sources of positioning degradation.

The impact of ionospheric gradients on single-frequency users manifests differently in the vertical and horizontal position components. During a strong solar radio burst event in December, 2006 positioning errors for single-frequency users have been reported to reach **20 meters** in the horizontal and **60 meters** in the vertical positioning.

Since users in USR01-A subgroup usually do not impose strict requirements on GNSS service accuracy and availability, the proposed product is expected to be especially useful for them during extreme events that cause significant degradation of single-frequency services.

USR01-B: Users of GNSS Single frequency services with high accuracy by advanced post processing

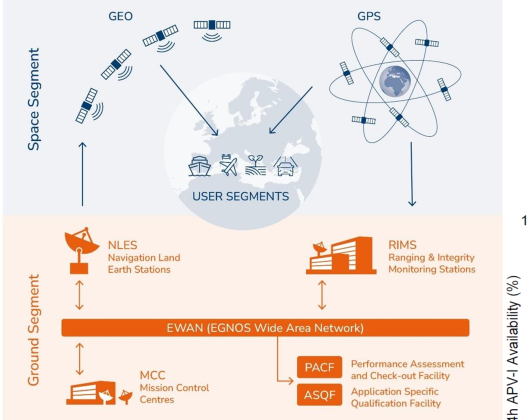


One of the correction models, applied by GNSS single frequency service users for position correction.

The scale of medium-scale traveling ionospheric disturbances (MSTIDs) is relatively small and they are highly dynamic. This means that they are not corrected for when using global ionospheric models such as Klobuchar or NeQuick, which are designed to represent only the background ionosphere with coarse spatial and temporal resolution.
When an LSTID passes through the signal path, the actual Total Electron Content (TEC) deviates significantly from the model's prediction. This discrepancy results in a large, uncorrected residual error that directly corrupts the positioning solution.
Some studies have shown that under disturbed conditions, applying a model like Klobuchar or NeQuick can unexpectedly degrade the horizontal positioning accuracy, in some cases increasing the horizontal error by **over 20%** compared to an uncorrected solution. This occurs because the model fails to represent the asymmetric TEC gradients associated with the disturbance, introducing a bias that is particularly detrimental to the north-south component of the position.

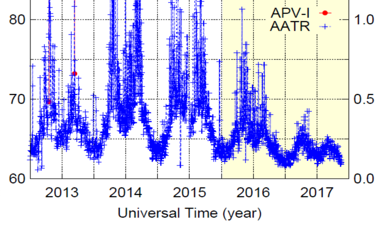
The USR01-B user subgroup is foreseen to get benefit from the proposed service by avoiding safety critical situations in navigation (e.g. transport) or high costs by useless expeditions (e.g. land surveying).

USR02: Users of GNSS single frequency services with average accuracy+integrity



European Geostationary Navigation Overlay Service (EGNOS).

The EGNOS produces an additional information data stream that is transmitted to airplanes via geostationary satellites. The transmitted data includes an estimate of ionospheric Vertical Total Electron Content (VTEC) and an error bound for that estimate (Grid Ionospheric Vertical Error (GIVE).



Maximum values of along arc TEC rate (AATR) values (blue pluses) and the daily EGNOS APV1 availability (red points) for a fault-free receiver,Canary Islands (MAS1) [Sanz et. al, 2014; Juan et al., 2018]

The proposed service for USR02 will deliver a performance indicator tailored to react to variations in VTEC that cause EGNOS problems.

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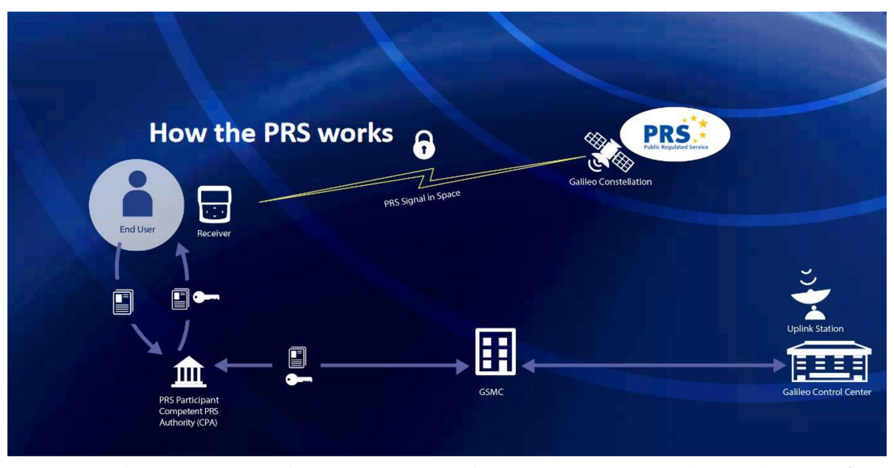
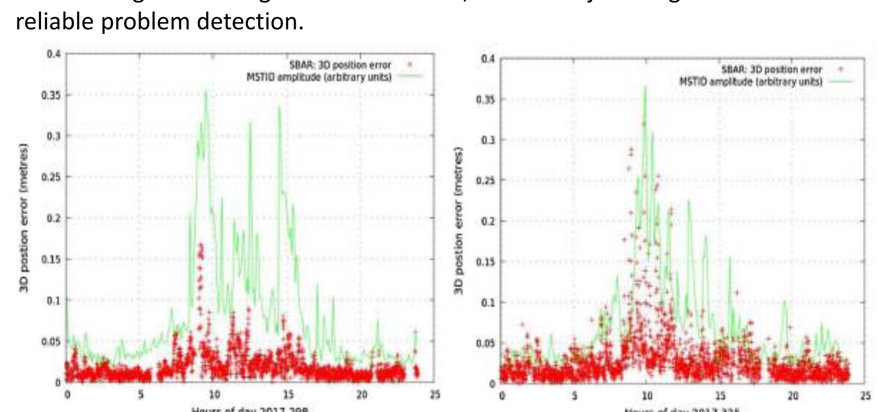
USR03: Users of multi-frequency GNSS systems with average multi-frequency accuracy, no integrity



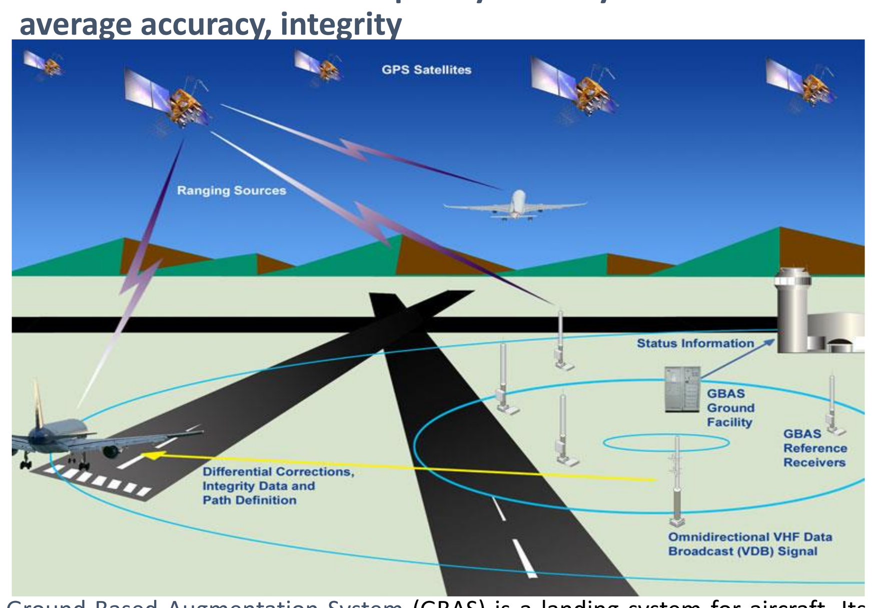
PRS provides position and timing restricted to government-authorised users, for sensitive applications which require a high level of service continuity. Examples of such strategic infrastructures are energy, telecommunications and finance. The PRS signal is designed to be robust, with anti-jamming mechanisms and reliable problem detection.



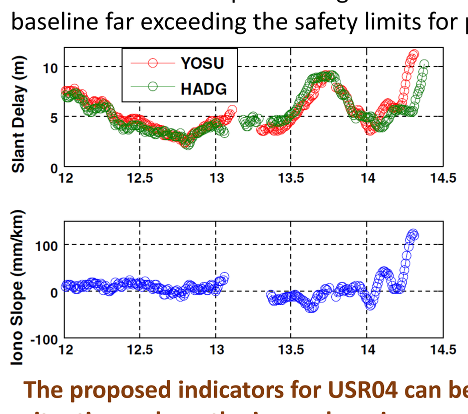
Relation between 3D position errors and maximum MSTIDs amplitudes on days 298 and 325 of 2017 [Timoté et al., 2020]

The proposed USR03 indicators will be a good asset to learn that the performance of GNSS based guidance can be occasionally deteriorated due to space weather (SWE) variations. For PRS users, who typically are aware about potential shortcomings in GNSS, it will be a handy tool for discriminating SWE based peculiarities in the service from anthropogenic error sources.

USR04: Users of multi-frequency GNSS systems with average accuracy, integrity



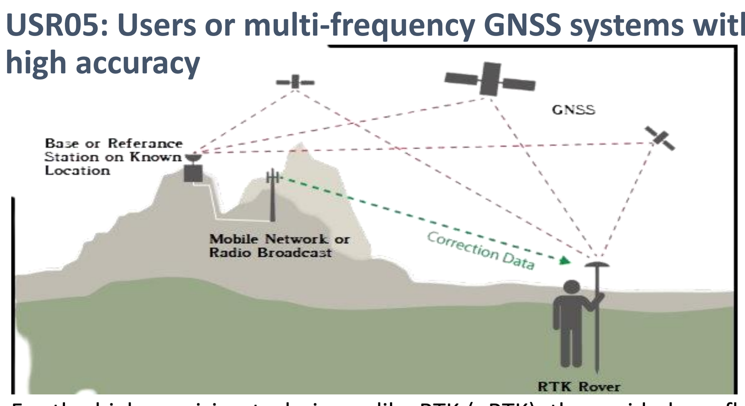
Ground-Based Augmentation System (GBAS) is a landing system for aircraft. Its core is a Differential GNSS (DGNSS) architecture, where a ground station is placed at the airport to which precision approach service is provided.
DGNSS architecture relies on the assumption that ionosphere is homogeneous in the distance between the ground-based reference station and the moving receiver. However, the ionosphere at times also shows irregularities that lead to a significant change of the experienced ionospheric delay over rather short distances. Some studies have shown that the anomalous ionospheric gradients can induce vertical positioning errors of **up to 10 meters** over a short 5 km baseline far exceeding the safety limits for precision approach.



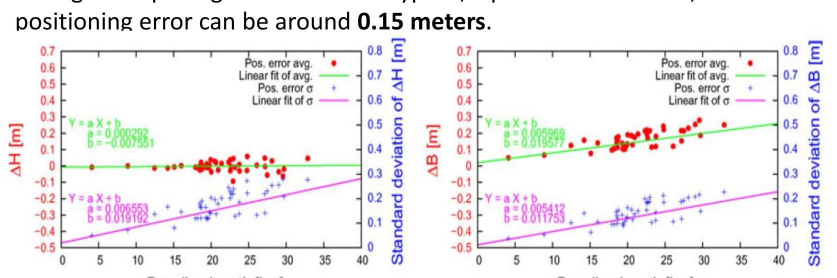
Maximum ionospheric gradient observed on Nov. 10, 2004: (top) – dual-frequency estimates of slant ionospheric delay; (bottom) – spatial gradient. Data versus UT hour for stations YOSU and HADG tracking PRN 31.
[Kim et al., 2015]

The proposed indicators for USR04 can be tuned to warn DGNSS users on the situations where the ionosphere is expected to be exceptionally turbulent.

USR05: Users or multi-frequency GNSS systems with very high accuracy



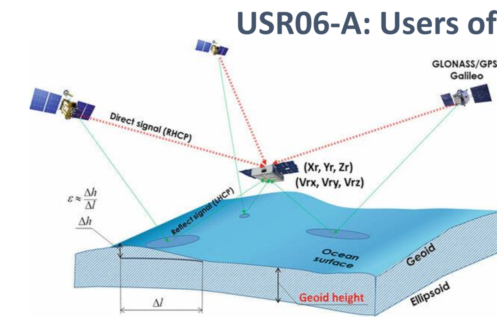
For the high-precision techniques like RTK (nRTK), the rapid phase fluctuations caused by TEC gradients can make it statistically impossible for the ambiguity resolution (AR) algorithm to correctly identify the true integers. During a severe geomagnetic storm of August 25 – 26, 2018, the AR success rate for an RTK system dropped by **27 – 37%** in Greenland, depending on the baseline length. For the same storm, the mean time required to achieve a reliable integer fix (Time-to-Fix) increased **by a factor of five.**
During geomagnetic storms that generate intense MSTIDs, studies have reported positioning errors of **more than 2 meters** for a 20 km baseline. Even during the passage of a more typical, quiet-time MSTIDs, the maximal positioning error can be around **0.15 meters**.



Positioning error as a function of baseline length for on November 20, 2003 (3-12PM). [Lejeune et al., 2012]

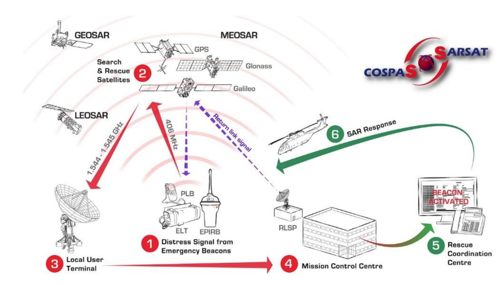
The proposed GNSS performance indicators for USR05 will be based on parameters linked to rapid fluctuations of GNSS signals. Similarly, as in the case of USR04 group, the service can warn the user on situations of enhanced ionospheric turbulence implying exceptionally long integration times for high precision results.

USR06-A: Users of GNSS systems with high availability / continuity



GNSS Reflectometry-Based (GNSS-R) altimetry

GNSS-R applications have traditionally been used for probing sea-surface height, winds and surface roughness. Nowadays, GNSS-R is used also for cryosphere, soil moisture and biosphere characterization. For all these applications, GNSS signal can be impacted by ionosphere variability in terms of strong gradient and in-homogeneities, creating scintillation of the transmitted signal and distortion of the Delay – Doppler Map (DDM). These distortions are critical for all GNSS-R applications, leading to errors or unavailability.



Search and Rescue Satellite Aided tracking (SARSAT) system

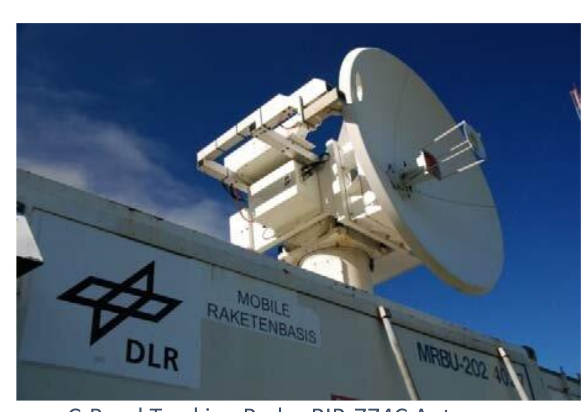
Search and Rescue, such as SARSAT system are defined to detect and locate mariners, aviators, and people in distress almost anywhere in the world at any time. TEC variability may impact the precise location of alerts. A critical issue is strong scintillation that may create loss of lock or loss of signal. The link between the beacon owner to be rescued and the Galileo Search and Rescue system utilizes signals in UHF- and L-bands, which both are prone to ionospheric disturbances.

The proposed GNSS performance indicators for USR06-A will warn on the ionospheric disturbances which are critical for DDM and can improve situational awareness in rescue operations during SWE variations.

USR06-B: Users of space-based services / products affected by the ionosphere and requiring high availability / continuity GNSS services

Low frequency array (LOFAR) radiotelescope core

LOFAR measurements are significantly impacted by ionospheric disturbances, which distort radio signals at LOFAR's observing frequencies. These distortions can cause radio sources to appear displaced and create intensity variations or fading (ionospheric scintillations). Ionospheric hindcasts for purposes of LOw Frequency ARray (LOFAR) telescope are applicable for selecting only suitable LOFAR core measurements for computationally very demanding processing. Relations of hourly ionoscore being used by LOFAR currently with their identification of ionospheric wave activity was compared with alternative products, e.g. the dTEC solution by Boyde et al. (2025),



C-Band Tracking Radar RIR-774C Antenna.

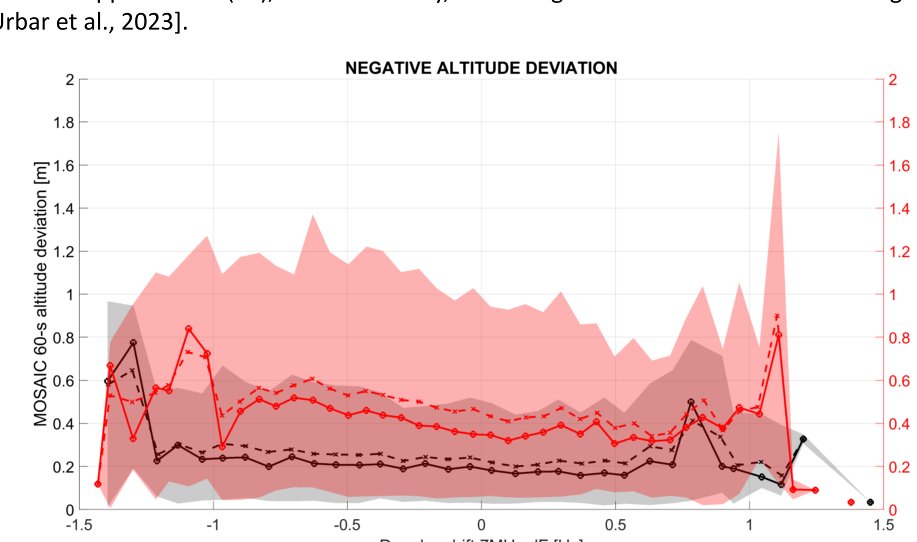
The performance of UHF – C-band space-based radar systems can be dramatically affected by two types of ionospheric effects: distortions due to the non-turbulent part of ionosphere layer, such as group delay, refraction, dispersion, Faraday rotation, and phase shift, and the effects due to ionospheric irregularities, such as phase perturbation, angle-of arrival and polarization variation, pulse broadening, amplitude and phase scintillation. These effects affect SAR imaging by causing range and azimuthal resolution degradation and range image shift.

The proposed GNSS performance indicators for USR06-B will detect the contaminating ionospheric disturbances, provide information on radio image distortions due to SWE.

USR0X-ALT: Users with additional needs to improve accuracy in altitude

Respective GNSS performance indicators can be combined from different inputs, one such example could be addition of another specific indicator of MSTID wave activity, the Continuous HF Doppler sounding (CDSS) indicators. CDSS is monitoring precisely specific levels of ionospheric F-layer. Currently SWESNET CDSS product is provided only for central Czechia, but actual monitoring is available from many tens of additional ionospheric reflection areas over Europe - already over Germany, Belgium and Slovakia with confirmed additions in Spain and northern Scandinavia during 2026. In areas for which the CDSS indicators of MSTID are available this input could be applicable e.g. for the aviation users (USR04) where the MSTID index cannot provide altitudinal accuracy degradation directly.

For the evaluation of the relation between the positioning accuracy degradations with CDSS, different types of GNSS receivers were set-up in Czechia along each other, often sharing an antenna, but representing a different GNSS user groups interests. There were performed longer-term measurements by geodetic receivers Trimble Alloy and Septentrio Mosaic-X5 with different corrections being used, also u-Blox F9P receivers were operated in parallel with and without SBAS corrections enabled. In addition, the u-Blox F9P-based positioning accuracy was provided from RTK solution. Significant ionospheric disturbance effects on EGNOS-supported GNSS positioning were found in all the configurations, notably also when using the advanced geodetic receivers. The positioning deviations were related with the MSTID activity where it was shown that the data show higher positive GNSS altitude deviations during positive CDSS Doppler shifts (dF), and conversely, more negative altitude deviations during negative dF, as shown below [Urbar et al., 2023].



Dependence of positioning deviations (restricted to only negative altitude deviations – as absolute value below the correct altitude) on the CDSS Doppler shift dF of the 7 MHz signal (daytime conditions). Septentrio PolarRxS and Mosaic 10th-90th percentile deviation ranges are denoted by pale red and grey areas, respectively. Deviations averages are shown as solid red and black lines, medians are dashed.