

Characterization of GNSS Interference in LEO over Europe

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ABSTRACT

This paper presents a multi-mission characterization of a persistent GNSS interference phenomenon observed in low Earth orbit over Europe using openly available measurements from the ESA Swarm constellation, Copernicus Sentinel satellites, and GNSS Radio Occultation missions. Multi-year datasets spanning 2021-2026 are analyzed to investigate the distribution, temporal evolution, affected GNSS signals, and likely source region of the interference. The results reveal persistent and geographically concentrated signal degradation over Europe, particularly in and around Eastern Europe, where multiple missions exhibit consistent reductions in carrier-to-noise-density levels, increased cycle-slips, and, in some cases, complete loss of GNSS observations. Similar patterns across diverse receiver types, orbits, and GNSS constellations and frequencies indicate a broad interference phenomenon likely originating from one or more high-power terrestrial interference sources in western Russia and/or eastern Ukraine. The analysis further shows that both the occurrence and physical extent of the interference have increased over time, with noticeable carrier-to-noise-density degradation becoming evident from 2024 onward. These findings demonstrate that terrestrial interference sources can produce measurable and operationally significant impacts on GNSS reception in LEO, contributing a space-based perspective to GNSS interference monitoring.

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) have many important uses in modern life. One of the more subtle but still important uses is Positioning, Navigation, and Timing (PNT) for space assets. GNSS PNT underpins many important aspects of operating and using spacecraft. For example GNSS is used extensively for Precise Orbit Determination (POD) and for the timing of satellite operations. The products and services delivered by spacecraft could be degraded or rendered unusable if GNSS signals are subject to interference or become unavailable. A lack of precise positioning could, for example, lead to incorrect pointing of payloads, and incorrect timing could disrupt operations where synchronization between spacecraft is necessary.

Interference of GNSS signals has become a prevalent issue over Europe during the last several years. The European Union Aviation Safety Agency (EASA) regularly documents GNSS outages affecting aviation users, while widespread disruptions have also been reported by maritime users [1, 2]. Space-borne GNSS receivers have increasingly been used as sensors for observing and characterizing GNSS interference. Multiple studies made with data from SPIRE satellites have demonstrated that measurements from LEO spacecraft can be used to geolocate terrestrial GNSS interference sources with high accuracy [3, 4]. Other sources have also considered spacecraft in LEO for detecting and geolocating interference sources [5, 6, 7, 8]. Other work has used GNSS Reflectometry (GNSS-R) payloads onboard the CYGNSS constellation to document and map radio-frequency interference over the Middle East [9]. GNSS Radio Occultation

(GNSS-RO) measurements have also proven useful for monitoring large-scale interference environments. Observations from COSMIC-1 and other RO missions have been used to estimate GPS interference power globally between 2006 and 2023, identifying persistent interference hotspots and documenting a substantial increase in interference over Europe following the start of the Russo-Ukrainian conflict[10]. More recently, the European Space Agency investigated the effects of terrestrial GNSS interference over Europe in early 2025 on POD and time synchronization products derived from the Swarm and Sentinel missions [11].

Whilst earlier work has demonstrated the ability to measure GNSS interference from LEO, the phenomenon remains insufficiently characterized. Previous studies have focused on geolocating interference sources, mapping interference using GNSS-R and GNSS-RO missions, or documenting effects on individual spacecraft and applications. What remains less well understood is the overall interference environment experienced by spacecraft over Europe, how it has developed over time, which GNSS constellations and frequencies are affected, and how different spacecraft experience the interference. The goal of this paper is therefore to characterize the interference using openly available GNSS observations from multiple spacecraft missions. By combining observations from different spacecraft, receiver types, altitudes, and mission profiles, we investigate the physical extent of the interference, its temporal development, the affected GNSS signals, and try to gauge its operational effects on space-borne GNSS receivers. The study works within the limits of the available data, but aims to provide a broader understanding of the interference environment in LEO over Europe and how it may affect current and future spacecraft missions.

2. DATA

The primary data for this analysis are openly available GNSS observation datasets from space-borne receivers at the lowest available processing level. These datasets are published by organizations such as ESA, EUMETSAT, NASA, and UCAR for three main purposes. (1) GNSS observation data used for deriving POD products to be used for geolocating earth observation data. (2) GNSS-RO data used for weather forecasting. (3) GNSS-R data for different remote sensing applications. The use of GNSS-R data has been left out of this study, which will instead focus on GNSS data collected for POD and RO. The datasets selected for this study and their characteristics are summarized in table 1. The observation periods used from each dataset, and the dataset sizes are summarized in table 2. Most of the selected missions share the same PODRIX receiver, which comes in two variants. The GPS only variant is named PODRIX, whilst the GPS+GALILEO variant is named PODRIX E. Some of the missions only carry GNSS-receivers for POD, whilst the Sentinel-6 and SPIRE spacecraft carry receivers for both POD and GNSS-RO. The key characteristics of the receivers are summarized in table 3. The bands + codes/channels are named according to the convention used by the RINEX data format¹. The band is the number, whilst the code/channel is the letter following the number. Besides, GNSS observations, processed POD data is used when available, mainly in SP3 format for easy locating of GNSS measurements. The only pre-processing made, is the reduction of measurements on the datasets with 1 Hz data-rates. These are sub-sampled to 0.1 Hz, to ease data processing.

Satellite	Avg. altitude	Inclination	Receiver	Receiver placement	Source(s)
SWARM A	450 km	87°	PDORIX	Zenith	[12, 13]
SWARM B	530 km	87°	PODRIX	Zenith	[12, 13]
Sentinel-1 A	693 km	98°	PODRIX	Zenith	[14, 15]
Sentinel-1 C	693 km	98°	PODRIX E	Zenith	[14, 15]
Sentinel-2 C	786 km	98°	PODRIX E	Zenith	[16, 16]
Sentinel-3 A	814 km	98°	PODRIX	Zenith	[17, 17]
Sentinel-6 A&B	1336 km	66°	PODRIX E, TriG (RO)	POD: Zenith 2x RO: fore & aft	[18, 19, 20]
SPIRE LEMUR-2*	400-600 km	Various	STRATOS (POD, RO)	POD: Zenith RO: side-mounted	[21, 22]

*Data available from multiple spacecraft.

Table 1: Summary of the selected missions and their key characteristics.

The main difference between the GNSS-POD and GNSS-RO data is, how it is gathered. GNSS-POD data is collected

¹<https://files.igs.org/pub/data/format/rinex.4.01.pdf>

continuously by tracking observable GNSS satellites and estimating the pseudo-range, carrier-phase, and carrier-to-noise-density ratios between the the individual transmitting GNSS satellite and the receiver. The GNSS-RO receivers sample the signal from an individual GNSS satellite at a high frequency. While a single RINEX file contains measurements taken from multiple GNSS satellites at multiple times, a NetCDF file contains measurements from a single GNSS satellite at a single point in time.

Satellite	Observation period	Data rate	Dataset size
SWARM A	2021-01-01 to 2026-05-31	1 Hz	185 GB
SWARM B	2026-01-01 to 2026-05-31	1 Hz	16 GB
Sentinel-1 A	2021-01-01 to 2026-05-31	0.1 Hz	19 GB
Sentinel-1 C	2026-01-01 to 2026-05-31	0.1 Hz	3.5 GB
Sentinel-2 C	2026-01-01 to 2026-05-31	0.1 Hz	3.5 GB
Sentinel-3 A	2026-01-01 to 2026-05-31	1 Hz	18 GB
Sentinel-6 A POD	2026-01-01 to 2026-05-31*	0.1 Hz & 1 Hz	37 GB
Sentinel-6 A & B RO	2026-05-01 to 2026-05-31	2000 soundings/day	97 GB
SPIRE LEMUR-2 POD	2026-01-01 to 2026-05-31	1 Hz	2.3 GB
SPIRE LEMUR-2 RO	2026-01-01 to 2026-05-31	3000 soundings/day	190 GB

*Auxiliary SP3 POD data only available until 2026-04-24 at time of writing.

Table 2: Summary of the dataset collected from selected missions.

Receiver	GNSS constellations + bands + code	Data format
PODRIX	G: [1C 1W 2W]	RINEX
PODRIX E	E: [1C 5Q], G: [1C -1W 2W 2L]	RINEX
STRATOS POD	G:[1C 2L]	RINEX
TriG	R:[1C 2C], G:[1C 2L 2W], E:[1C 5Q]	NetCDF
STRATOS RO	B:[1P 7D], E:[1C 7Q], R:[1C 2C], G:[1C 2L]	NetCDF

Table 3: Receiver characteristics.

G: GPS; E: GALILEO, R: GLONASS, B:BEIDU

3. OVERVIEW

Figure 1 shows accumulated GPS 1C carrier-to-noise-density (C/N_0) measurements collected by SWARM A during May 2026. The figure shows that an unusual signal environment exists over parts of Europe and Western Asia. After averaging over a large number of observations, geographical variations in mean C/N_0 are generally expected to be relatively small. The pronounced C/N_0 reduction observed over Europe therefore suggests the presence of an additional source of signal degradation. Understanding the origin, extent, and characteristics of this degradation is the primary objective of this paper.

To investigate this phenomenon, the analysis is divided into three parts. First, the geographical distribution of the interference is examined. Second, its temporal evolution is investigated using multi-year datasets. Finally, the interference itself is characterized in terms of signal degradation, affected GNSS constellations, frequency bands, and other inference properties such as cycle-slips and source power. Spoofing is not considered in this study.

A central question is whether the observed degradation arises in particular spacecraft, or receivers, or whether it reflects a true state of the GNSS signals. To address this question, observations from multiple missions are analyzed. The selected spacecraft operate with different receivers, orbits, and other particulars, allowing for a more generalized analysis. The working hypothesis throughout the study is that the observed degradation is caused by terrestrial interference sources whose emissions are sufficiently powerful to remain detectable at LEO altitudes.

The carrier-to-noise-density ratio (C/N_0) is used as the primary indicator of interference throughout this study. Increased interference power raises the effective noise floor at the receiver, resulting in a reduction of the measured C/N_0 . Interference is therefore identified as a reduction in C/N_0 , and throughout this work a decrease of 3 dBHz

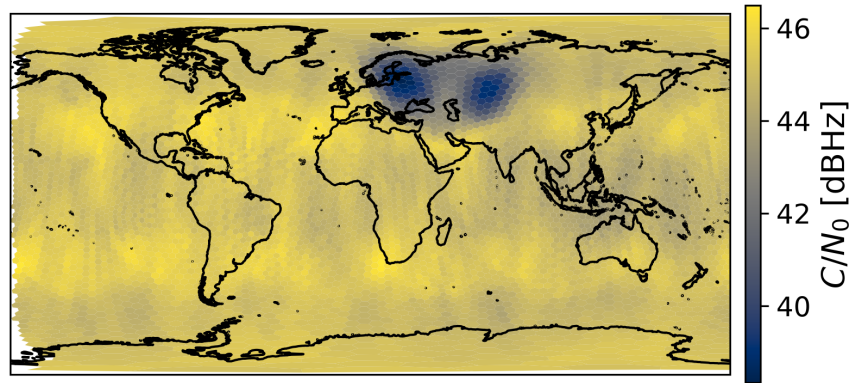


Fig. 1: Hexagon grid map of per-grid mean SWARM A GPS 1C C/N_0 measurements accumulated from 1 May to 31 May 2026.

relative to unaffected regions is used as a practical threshold for significant degradation. A reduction greater than 3 dBHz relative to the baseline unaffected regions are considered jammed for the purpose of this study.

Each measurement is associated with a geographic location and observation time. To enable visualization and comparison across missions, observations are aggregated into hexagonal grid cells and averaged within each cell. Just like in figure 1. Because absolute C/N_0 values differ between spacecraft and receiver types, the analysis will often focus on relative differences between affected and unaffected regions rather than absolute values alone.

4. INTERFERENCE ANALYSIS

This section investigates the GNSS interference phenomenon observed over Europe using the datasets introduced previously. The analysis examines the geographical distribution, temporal evolution, and signal-level characteristics of the observed degradation, with the aim of determining its extent, persistence, and impact on space-borne GNSS reception. Particular emphasis is placed on identifying patterns that are consistently observed across multiple missions and receiver types.

4.1 Location

Figure 1 gave a first indication of where the interference is located. Including measurements from multiple satellites can give a better understanding of how the interference is spread through space. Figure 2 shows jamming maps for different spacecraft at different altitudes. All the measurements are taken by PODRIX and PODRIX E receivers to make the maps as comparable as possible. The color shows how often a measurement taken within a cell is considered jammed (measurement 3 dB below global baseline). All the spacecraft except Sentinel-6 A show evidence of jamming at different amounts. The shape, size and persistence of the jammed areas are different for all the spacecraft. Equal for all spacecraft is that the jamming seems more significant over Western Europe, compared to Eastern Europe.

We find, that Sentinel-1 C has the highest number of jammed cells, and jammed measurements per cell, making it the satellite jammed the most over a larger area. Common for all spacecraft is, that the center of the jammed areas lies somewhere in Western Russia and/or Eastern Ukraine. This center lies approximately at 36° longitude and 51° latitude. In Figure 3 this center is mapped as a red star. The circle around the red star is the crossover point, where Sentinel-1 A crosses the interference sources horizon, meaning the spacecraft goes above a grazing angle of 0° as seen from the interference source assumed on ground. This horizon matches well with the boundary of the interference region. This horizon marks the Area of Interest (AOI) which is used in the future to delineate the interference region. The horizon, and thus the AOI, depends on the altitude of the spacecraft. The AOI is therefore unique to each spacecraft.

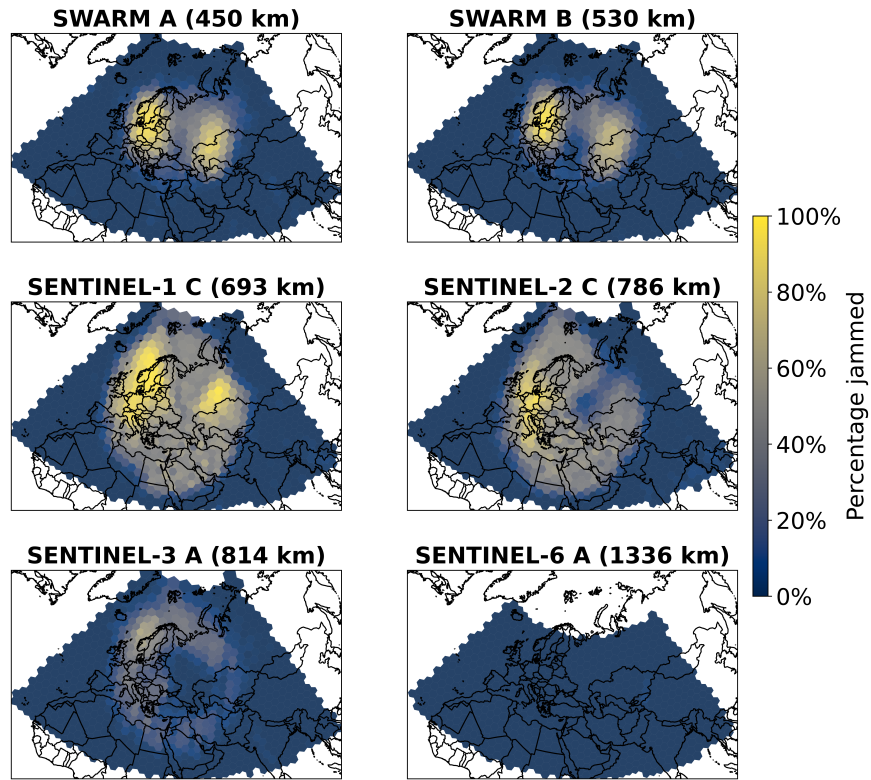


Fig. 2: Six maps for different spacecraft at different altitudes taken with PODRIX receivers. The colors indicate the avg. percentage of measurements in each cell marked as jammed. Data from 1 January to 31 May 2026.

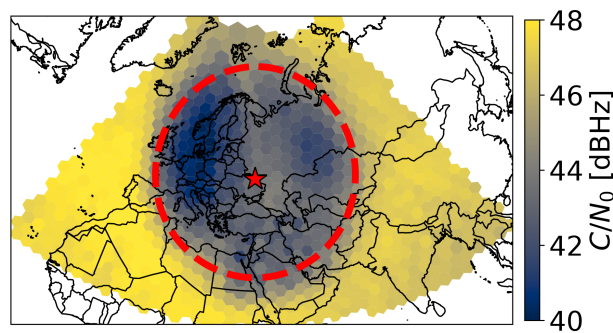


Fig. 3: The red star marks the center of the interference region. The red circle marks the horizon where Sentinel-1 crosses into the visibility of an observer on ground at the red star. Measurements are per cell averaged GPS 1C C/N_0 accumulated from 1 January to 31 May 2026.

4.2 Temporal Development

Figure 4a and 4b show the temporal development of the daily C/N_0 anomaly between the Europe AOI and the rest of the world. The anomaly is calculated as the daily C/N_0 mean inside the AOI subtracted by the daily C/N_0 mean outside the AOI. Three interesting observations can be made from these two graphs. First, there appears to be an early decline in anomaly magnitude, especially for the 2W code for both spacecraft. This decline accelerates significantly during 2024, where the 1C code anomaly also becomes more pronounced. The degradation of codes 1C and 2W stays persistent thereafter. Secondly, code 2W exhibits a larger C/N_0 anomaly than the 1C code, indicating a greater observed sensitivity to the interference. Third, that the ratio of interference between the 1C and 2W codes is different for the two spacecraft. Beyond the long-term increase in anomaly magnitude, only small periodic effects seems to be visible in the daily time series. A spectral analysis confirms that there may be a weakly half-year period to the anomaly, however this would need further study.

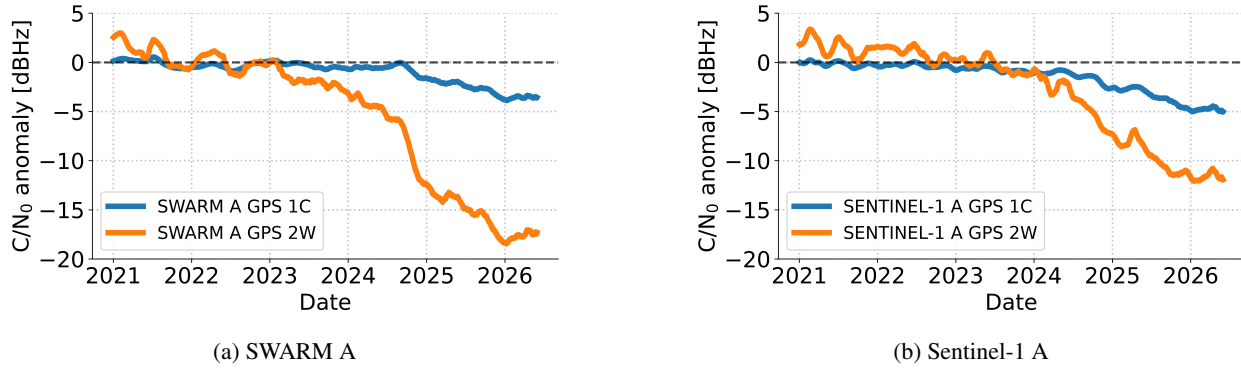


Fig. 4: Time series of the 30-day running average C/N_0 anomaly between measurements inside and outside the Europe AOI.

The temporal variation of the geographic location of the jamming is also analyzed. Figure 5 shows the measurements accumulated for the given year for SWARM A. It shows how weakly jammed areas begin to appear in 2024, with much more pronounced areas in 2025. From 2025 the two distinct jammed areas, which we have seen for both SWARM A and B can be seen to appear. The distinct areas do not seem to move, however they do increase in size and in their number of jammed cells. This suggests that the source region remains broadly unchanged while the severity and reach of the interference have increased.

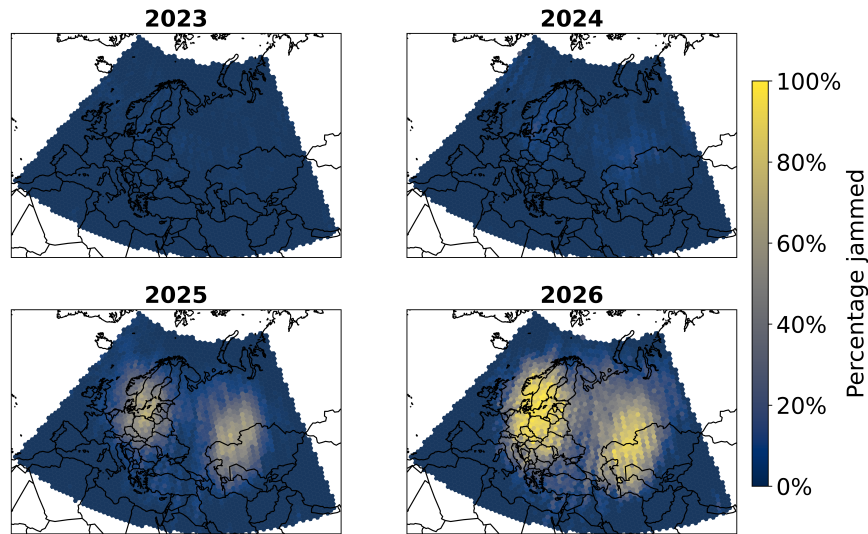


Fig. 5: Yearly accumulated jammed cells for SWARM A 1C. Measurements for 2026 are from 1 January to 31 May.

The temporal development of the interference can also be quantified by examining the number of affected grid cells and the accumulated jammed measurements per cell in figure 5. Between the 2023-2026 observation periods, the number of cells containing jammed measurements increased from 530 to 1779, indicating a more than three-fold increase in physical extent. The growth in the average number of jammed measurements per cell was even more pronounced, increasing from 10 to 663 over the same period. This suggests that the interference is not only expanding spatially, but is also becoming increasingly severe within the interference regions. The largest changes occur after 2024, which is consistent with the time series shown in figure 4.

Shorter-period variations are also studied. Figure 6 shows the hourly mean GPS 1C C/N_0 anomaly measured by SWARM A as a function of Local Solar Time (LST), calculated as $LST = UTC + \text{longitude}/15^\circ$. The results show little evidence of a systematic daily variation prior to 2026. In contrast, a pronounced 24-hour pattern becomes visible during 2026, with the nightly hours consistently exhibiting stronger signal degradation.

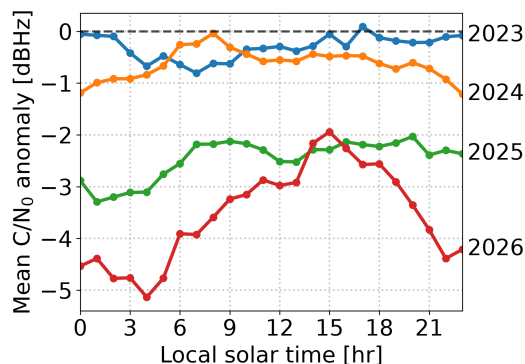


Fig. 6: SWARM A yearly accumulated mean hourly C/N_0 anomaly between AOI and outside AOI.

4.3 Interference effects

This section focuses on the nature of the interference and how the interference affects the GNSS receivers themselves. The effects are quantified by analyzing the overall C/N_0 signal degradation across different GNSS frequencies, the number of GNSS satellites from which signals can be tracked, the occurrence of carrier-phase cycle slips, and finally the interference power is calculated.

4.3.1 Signal degradation

Signal degradation is found by comparing C/N_0 measurements inside the AOI with those taken outside. The C/N_0 measurements are split into the source GNSS constellations, and the bands and codes/channels they are transmitted in. This reveals whether the interference is targeted against any specific GNSS constellations and/or bands. The signal degradations are shown as box plots in figures 7a to 7c and figure 8. One box shows the distribution of C/N_0 measurements inside the AOI, the other shows the measurements taken outside. The most noticeable degradations are those of the 1W and 2W codes for SWARM A in 7a. The W suffix indicates measurements obtained using codeless/semi-codeless techniques, of the encrypted P(Y) signal, allowing civilian receivers to use the L2 frequency without knowing the encryption key. This is a legacy solution from before the introduction of civilian L2 C signals. This legacy methodology of tracking the signal without the encryption key may explain the large C/N_0 degradation for 1W and 2W. The PODRIX E instrument is also able to track the 1W and 2W codes, but does so unreliably. These measurements are therefore left out in figure 7b. Other spacecraft tracking the same GPS L1 and L2 frequencies with different codes are less degraded inside the respective AOI's. The lower frequencies, namely GPS 2L (1227.60 MHz) and Galileo 5Q (1176.45 MHz) seem to be slightly more degraded than GPS 1C and Galileo 1C both on 1575.42 MHz. The TriG RO payload on Sentinel-6 is also able to receive GLONASS measurements. GLONASS transmits on far more frequencies than other constellations, and many of the frequencies are separate from the other constellations. However, Figure 8 shows that the degradation of GLONASS is similar to the degradation experienced by other constellations. TriG gives measurements in SNR and not C/N_0 .

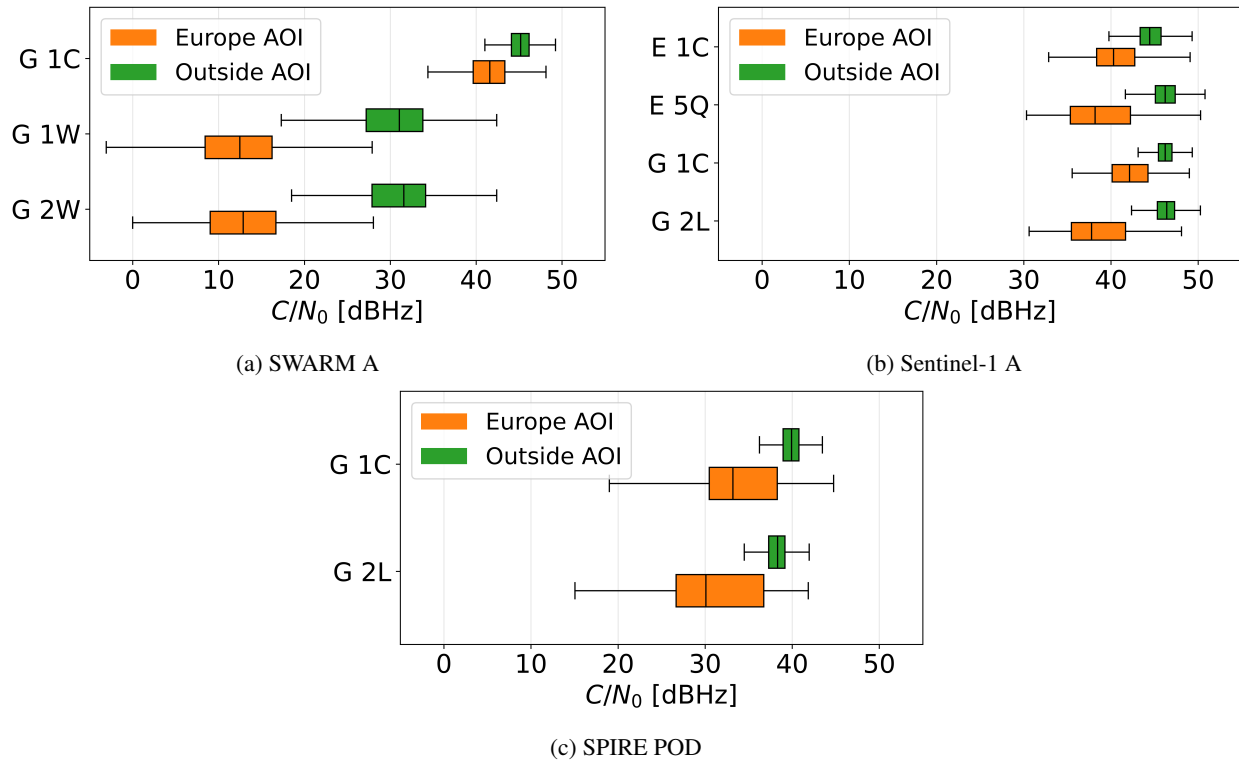


Fig. 7: Box-plots comparing C/N_0 measurements from inside and outside the AOI for the respective spacecraft, and constellations and bands/channels they track. Data from 1 May to 31 May 2026.

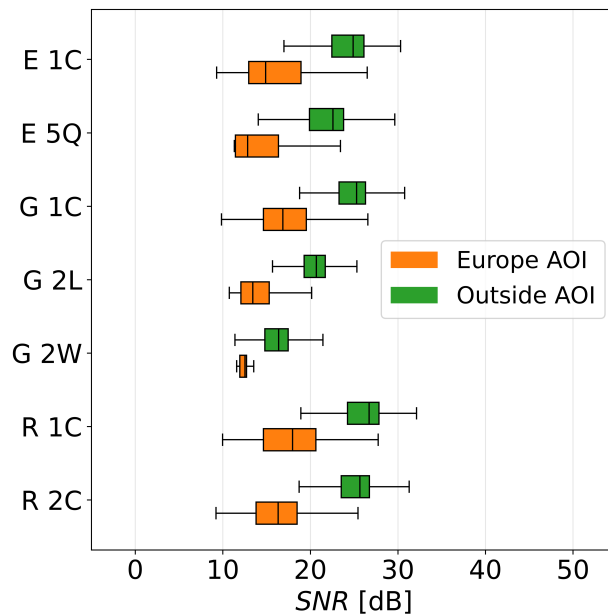


Fig. 8: Box-plot comparing Sentinel-6 A&B TriG RO signal SNR measurements from inside and outside the AOI for multiple tracked constellations and bands/channels. Data from 1 May to 31 May 2026.

4.3.2 Number of trackable satellites

Tracking a sufficient number of GNSS satellites simultaneously is essential for obtaining a reliable navigation solution. The distribution of tracked GNSS satellites for a selection of receiving satellites is shown in figures 9 and 10. Two interesting results are found. Firstly, the SPIRE satellites occasionally fall below tracking the four GNSS satellites needed to obtain a valid navigation solution, when inside the AOI. Secondly, the SWARM and Sentinel-3 satellites constantly track 8 satellites. This is likely due to a limitation in the GNSS receiver such that it cannot track more than that, and the number of trackable satellites does not fall below 8.

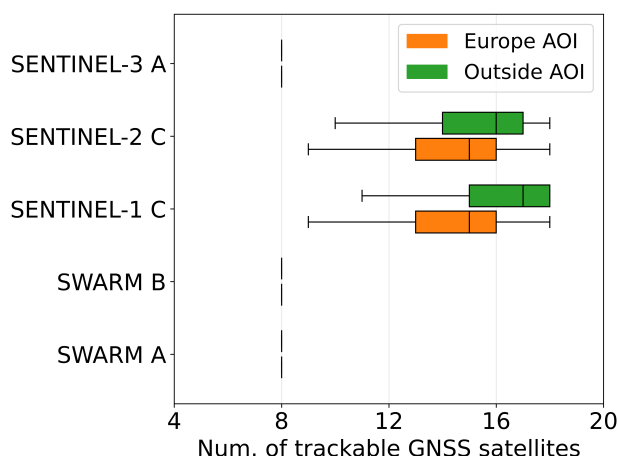


Fig. 9: Distribution of number of GNSS satellites tracked by selected satellites. Data from 1 May to 31 May 2026.

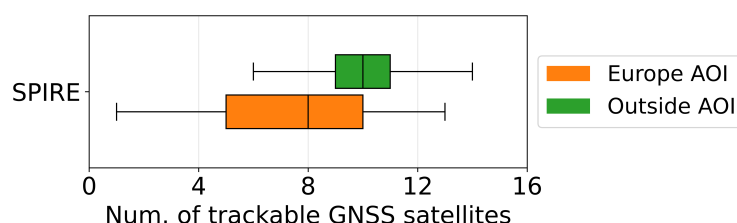


Fig. 10: Distribution of number of GNSS satellites tracked by SPIRE satellites. Data from 1 May to 31 May 2026.

4.3.3 SPIRE Radio Occultation

The RO measurements taken by the SPIRE constellation are especially affected by the presence of the GNSS interference over Europe. This results in a large area over Europe, where no Radio Occultation products are produced. However, the SPIRE STRATOS RO payload tracks more constellations and frequencies than the other GNSS receivers in this study. An estimate of how the constellations are affected can be found by finding ratio of successful measurements over Europe compared to similar latitudes elsewhere. These ratios are shown in table 4, and are calculated from data accumulated between 1st of January to 31st of May. The gap in measurements can be seen in figure 11.

	BEIDU	GALILEO	GLONASS	GPS
Availability	0.19	0.19	0.37	0.24

Table 4: Availability of different frequencies measured by SPIRE STRATOS RO payload.

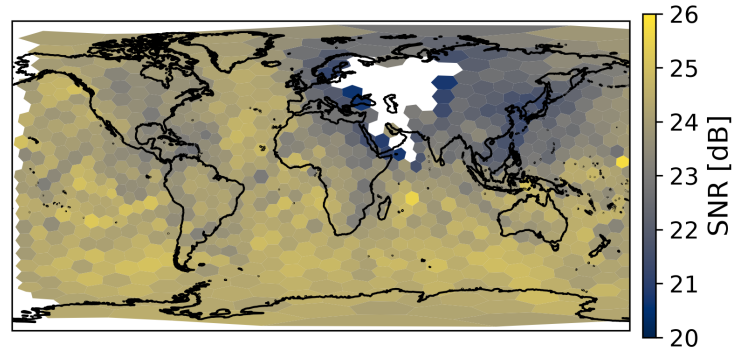


Fig. 11: SPIRE RO per-grid mean GPS 1C SNR from 1 May to 31 May 2026. No measurements in the white areas.

4.3.4 Cycle slips

Cycle slips are found using the Geometry Free (GF) combination of the GPS 1C and 2W phase measurements from SWARM A and Sentinel-1 A, and 1C and 2L phase measurements for Sentinel-1 C and SPIRE POD.

$$GF = (\lambda_1 \cdot \phi_1) - (\lambda_2 \cdot \phi_2) \quad (1)$$

A simple slip detector is applied based on a threshold value, which marks sudden jumps in the GF phase of more than a cycle between measurements. The total accumulated number of slips measured in the period of January 2026 to May 2026 is shown in table 5. The slips are measured inside the AOI and in an equivalently sized area outside the AOI. The equivalently sized area simply has a flipped latitude in the southern hemisphere. The results show that the number of slips and the ratio of slips varies a lot, also within the same receiver. Common for all the spacecraft is the marked increase in phase slips inside the AOI, against the outside. The location of the phase slips for Sentinel-1A is shown in figure 12. The number of phase slips from January to May 2026 for Sentinel-1 A is greater than all accumulated phase slips measured in 2025.

	Slips inside AOI	Slips outside AOI	Ratio
SWARM A	4355	2496	1.7
Sentinel-1 A	788	79	10.0
Sentinel-1 C	376	120	3.1
SPIRE	2320	1234	1.9

Table 5: Number of cycle slips detected for each spacecraft over equivalently sized areas both inside and outside their respective AOI's.

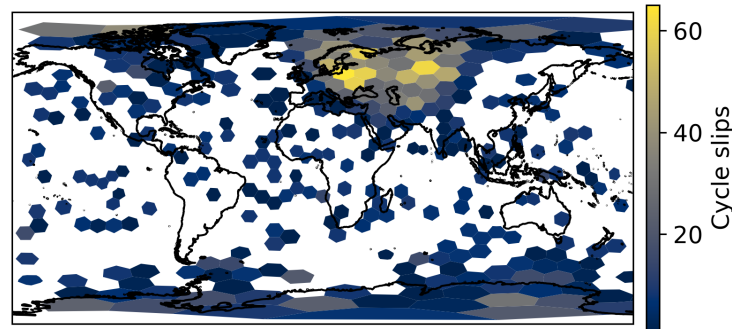


Fig. 12: Sentinel 1A cycle slips from January 1 to May 31 2026.

4.3.5 Interference Power Estimate

None of the satellites available for this analysis have payloads which can measure the interference power directly. The interference power estimate is therefore made using C/N_0 estimates. The C/N_0 is a measure of the power received from the carrier signal C against the background noise density N_0 . The carrier power at the receiver, sent from a GNSS satellite can be found using Friis transmission line formula, if the power and gain of the transmitter is known. Equation 2 shows Friis formula.

$$C = EIRP_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \quad (2)$$

Where $EIRP_t$ is the transmitter's Equivalent Isotropically Radiated Power, G_r is the receiver gain, λ is the wavelength, and d is the distance between transmitter and receiver. We assume no atmospheric losses, as both receiver and transmitter are in space. We assume the noise density to be constant, and thus it can be found using a C/N_0 measurement from outside the interference region as in equation 3.

$$N_0 = \frac{C}{(C/N_0)_{meas,outside}} \quad (3)$$

With the known noise density only the interference remains unknown for a measurement taken inside the interference regions, as shown in equation 4.

$$(C/N_0)_{meas,inside} = \frac{C}{N_0 + I_0} \rightarrow I_0 = \frac{C}{(C/N_0)_{meas,inside}} - N_0 \quad (4)$$

The EIRP of the interference source can then be estimated given an assumed bandwidth B of the signal being tracked.

$$EIRP_t = I_0 \frac{(4\pi d)^2}{G_r \lambda^2} B \quad (5)$$

The interference power is estimated using C/N_0 measurements from Sentinel-1. This platform is chosen because the GNSS receiver antenna gain pattern is documented in [23] as a function of the receivers zenith angle. For this analysis we will only consider GPS 1C C/N_0 measurements.

Based on the findings of [24], we assume a GPS satellite transmitting on L1 has an EIRP of 27 dBW. The mean distance between Sentinel-1 A and GPS satellites within 90 deg of its zenith is approx. 22700 km. The average zenith angle between the Sentinel-1 A spacecraft and the GPS satellites is approx. 61 deg. From [23] we find the equivalent PODRIX GNSS receiver antenna gain to be approximately -1 dBi. We can now estimate the carrier power from equation 2.

$$C = -127.5 \text{ dBm} \quad (6)$$

The Sentinel-1 A receiver measures an average C/N_0 of 42.7 dBHz inside its AOI and 47.4 dBHz outside its AOI. This information can now be used to derive the noise density N_0 and interference density I_0 using equations 3 and 4.

$$N_0 = -174.7 \text{ dBm/Hz}, \quad I_0 = -171.8 \text{ dBm/Hz}, \quad (7)$$

An average distance of 1872 km between spacecraft and interference source is used, together with an average zenith angle of 148°. The PODRIX receiver antenna gain at this angle is approx. -22 dBi. The GPS 1C bandwidth is 24 MHz. Combining this information with equation 5 gives:

$$EIRP_t = 383 \text{ kW} \quad (8)$$

5. DISCUSSION

This paper's findings show, that the interference phenomenon over Europe, which has gradually developed over a series of years, and still exist as of May 2026, can have real operational consequences for spacecraft. However, who gets affected and by how much is very much up to the individual circumstances of the spacecraft, and its GNSS setup. The severity of the interference is therefore relative. The spacecraft operators hardest hit, are likely already aware. Some of the severe degradations documented in this analysis, would be a good opportunity for anyone else, to review, if their on-orbit GNSS dependencies are robust enough, should the interference change or worsen. Future missions may need to consider GNSS interference as part of their mission design and operational risk assessments rather than as an exceptional event.

We estimated the location of the interference source(s) on Earth, somewhere around the border between Russia and Ukraine. We have based this estimate on it being the center location of the interference regions found across multiple spacecraft. Whilst a distributed network of interference transmitters may be able to give a similar interference patterns, we find it most likely to be a single transmitter or transmitters in a concentrated region. This is due to how multiple spacecraft show a reduction in interference when directly over the suggested interference source, where the spacecraft body is between jammer and receiver. This is further supported by the interference regions aligning with the horizon of the estimated jammer location. Additional evidence for a terrestrial origin is provided by the altitude dependence observed across the missions in figure 2. A general trend with increasing satellite altitude is, that the interference footprint increase but its magnitude decreases until it is no longer observed by Sentinel-6 POD.

We find that the interference has grown gradually over time, with a slight fall in C/N_0 already seen in 2022. The most significant increase and physical extent of the observed signal degradation happened after 2024. At the time of writing, there is little evidence that this trend has stabilized. If the current development continues, a growing number of spacecraft operating over Europe may experience degraded GNSS performance, particularly those relying on horizon-looking antennas or high-sensitivity GNSS measurements. The estimated source location and timeline of the interference places it within the Russia-Ukraine conflict. Whether the documented interference is a consequence of the conflict and/or a targeted attempt at disrupting spacecraft remains unknown. It may be prudent to assume that the interference is a wider part of the conflict, and may continue to worsen or change as the conflict continues.

The observed degradation does not appear to be limited to a single GNSS constellation or frequency band. GPS, Galileo, GLONASS, and BeiDou measurements all exhibit reduced signal strength within the affected regions. Although somewhat larger degradations are observed on lower-frequency bands, such as GALILEO 5Q, and GPS 2L, across multiple receivers. The legacy GPS 1W and 2W measurements are the most affected bands in terms of C/N_0 . This may suggest that older generation receivers are at the biggest risk of losing access to important dual-frequency combinations. This broad degradation suggest a wide-band interference source. The availability of SPIRE RO observations over Europe, does however suggest that GLONASS could be less affected. However this is not reflected in the measurements from the Sentinel-6 RO payload, which also tracks GLONASS. The exact reason why the SPIRE RO measurements are missing over Europe, remains unknown. It is therefore hard to conclude that GLONASS has better availability.

The observed increase in cycle-slip occurrence is noteworthy. While pseudo-range observables are typically accurate at the meter level, carrier-phase observations enable Precise Point Positioning (PPP) at the centimeter level when ambiguities are correctly resolved. Cycle slips introduce discontinuities in the carrier-phase time series that must be identified and repaired before PPP can be achieved. Consequently, the increased cycle-slip rates observed within the interference region suggest that the effects of the interference may extend beyond reductions in C/N_0 . The interference could directly impact the accuracy and reliability of navigation and orbit determination products relying on centimeter level precision, such as high-sensitivity Earth Observation products. The cycle-slip detection was based on a simple threshold detector, which would be insufficient in many other scenarios, however the speeds of the spacecraft makes the slips hard to miss, as the receiver has moved many integer phase values before the receiver is able to track the phase again.

The estimated jammer EIRP of approximately 383 kW should be interpreted as an order-of-magnitude estimate rather than a precise transmitter characterization. The calculation depends on assumptions regarding transmitter bandwidth, propagation geometry, GNSS satellite EIRP, receiver antenna gain, and the use of measured C/N_0 as a proxy for interference power. Nevertheless, the result demonstrates that exceptionally powerful terrestrial emissions are capable

of producing detectable degradation hundreds of kilometers above Earth and across a region spanning several thousand kilometers.

The selection of missions for the analysis was based on trying to get data from a variety of altitudes, spacecraft types, GNSS receivers, GNSS constellations, and receiver antenna orientations, within the limits of what is openly available. Some datasets are larger, spanning longer periods, some are shorter. Not every analysis has been made with every payload. We have found that although there are variations on how the interference is felt, it is the same interference felt by all the receivers. A key limitation of this study is that the analysis relies on processed observations rather than raw intermediate-frequency data. The main interference study is based on the C/N_0 estimates produced by the receivers. How exactly the individual receivers produce these estimates may vary, however it remains the most reliable and straightforward observable available across all considered datasets. It is therefore most meaningful to compare relative changes within a given receiver rather than absolute C/N_0 values between different missions. For this reason, much of the analysis is based on anomalies between measurements inside and outside the interference region. The consistent appearance of these anomalies across independent platforms and receiver architectures increases confidence that the observed effects are caused by the external signal environment rather than receiver-specific processing differences. Consequently, the deeper characteristics of the interference cannot be determined directly. The analysis therefore focuses on receiver-observable effects such as C/N_0 degradation, loss of tracking, and cycle slips. Despite this limitation, the agreement between multiple missions, receiver types, and orbits provides strong evidence that the observed behavior reflects a wider phenomenon rather than receiver-specific degradation.

The SWARM satellites in figure 2 show two distinct interference regions. This is likely due to the shape of the SWARM spacecraft, which are magnetometer missions carrying their primary payload on a boom in the anti-velocity direction. This elongated shape, combined with the near-polar orbit of the spacecraft, may explain the gap in the interference regions, as the spacecraft body blocks the interference when passing directly over the source region. Sentinel-1 being the most affected by interference relative to its altitude, could also be explained by the placement of its GNSS receivers. These are mounted on a separate platform from the spacecraft body, allowing them to point Zenith despite the spacecraft's look angle. The two radio occultation missions provide another example of how both receiver placement and antenna orientation affect the observed interference. Whilst the POD receiver on Sentinel-6 sensed little to no interference, the RO receivers, which point fore and aft towards the horizon, did see interference. A similar pattern is observed for the SPIRE Lemur-2 spacecraft, where the POD receiver experiences degradation, but the RO receiver is seemingly degraded beyond use inside the AOI. However, the lack of RO data from SPIRE over Europe does not necessarily mean that the RO payload is unable to take measurements. It may simply be unable to produce measurements of sufficient quality for radio occultation processing.

An important outcome of this work is the demonstration that routine GNSS observations collected by operational spacecraft can be used as a large-scale sensor network for monitoring interference. Unlike terrestrial monitoring systems, space-borne receivers provide a unique perspective on the spatial extent and evolution of GNSS interference, enabling characterization of events that span national borders and large geographic regions.

6. CONCLUSION

This paper investigated a persistent GNSS interference phenomenon observed in LEO over Europe using openly available measurements from multiple satellite missions. By combining observations from different spacecraft, receivers, orbits, and GNSS constellations, it was possible to make a generalized analysis of the physical extent, temporal development, and characteristics of the interference.

The analysis showed that the interference is concentrated over Europe and Western Asia, with a likely source region in Western Russia and Eastern Ukraine. The interference region has developed over time. It has expanded significantly between 2024 and 2026, while the magnitude of the observed C/N_0 degradation also increased, with no signs of the degradation stopping at the time of writing. Measurable reductions in C/N_0 were observed across multiple receivers, spacecraft, GNSS constellations and frequency bands, indicating that the interference affects a broad range of GNSS signals and receiver types. The results also showed that the effect of the interference depends heavily on the circumstance of the individual spacecraft. The interference has led to reduced satellite availability, elevated cycle-slip rates, and degraded radio occultation measurement availability, to the point that navigation solutions and radio occultation measurements have become unavailable in some cases.

The results demonstrate that high-power terrestrial interference sources can produce detectable and operationally sig-

nificant impacts on GNSS reception at LEO altitudes. While the severity of the effects depends strongly on the individual spacecraft, the observations show that large-scale terrestrial interference can affect space-borne GNSS receivers over regions spanning thousands of kilometers. Consequently, GNSS interference should be considered not only a terrestrial challenge but also a factor affecting spacecraft. Continued monitoring using space-borne GNSS receivers may therefore provide a valuable complement to terrestrial interference monitoring, contributing to improved GNSS resilience and space situational awareness.

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7. REFERENCES

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