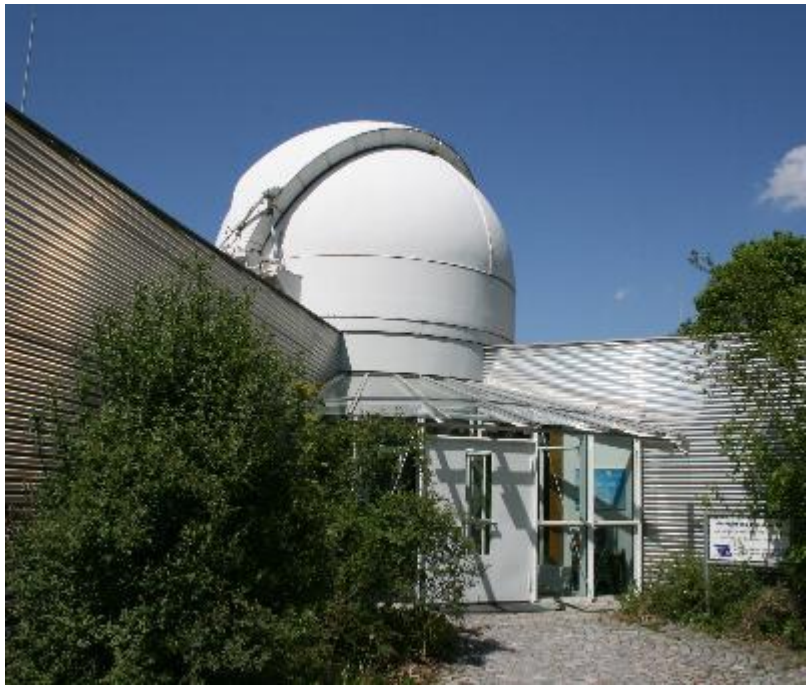
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GNSS spoofing-like emitter signal generation for validation of space-based GNSS RFI monitoring algorithms

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University of the Bundeswehr Munich

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GNSS vulnerabilities and radio frequency interference (RFI)

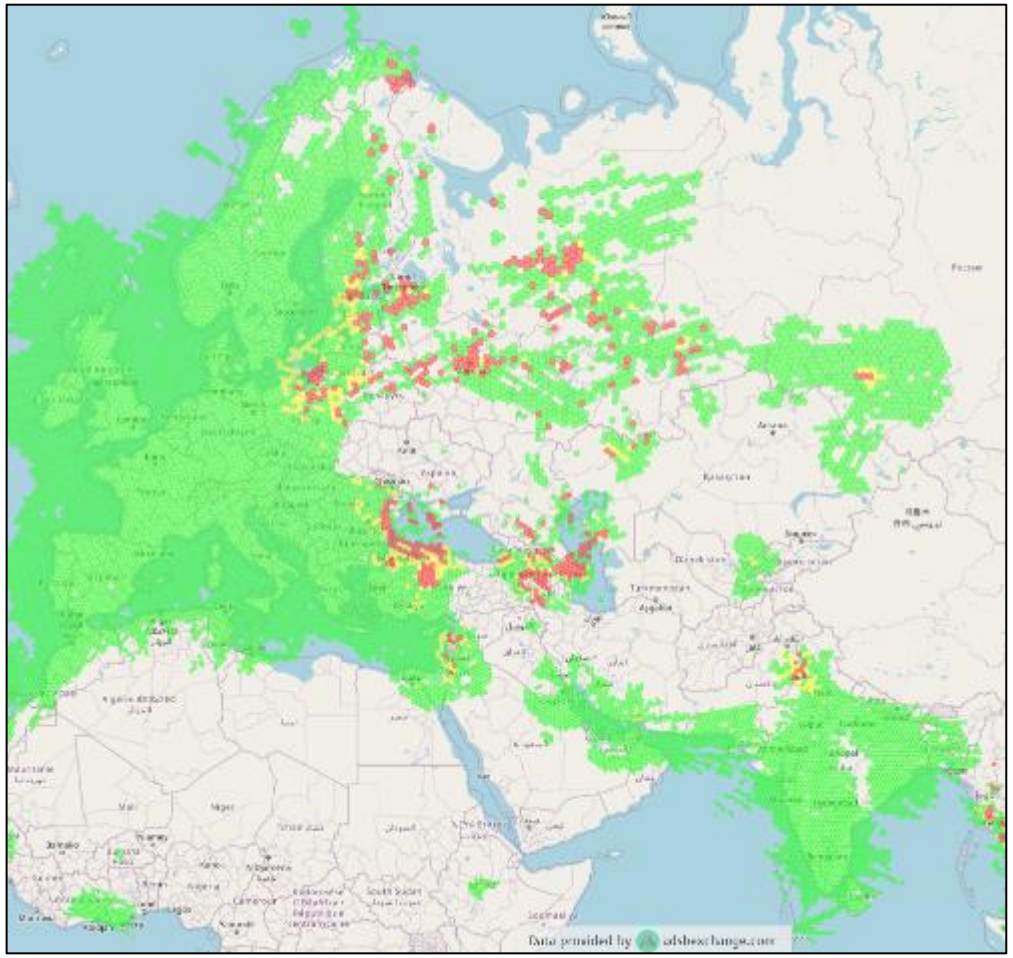


Figure 1: Global map showing jamming and spoofing events
Source: https://gpsjam.org

- Problem:
  - GNSS provides critical global PNT services with extremely weak received signal power.
  - Jamming and spoofing increasingly affect GNSS bands, even with wide-area impact.
- Limitation:
  - Terrestrial RFI monitoring is geographically sparse and locally constrained.
- Solution:
  - Signal observability from space enables large-scale and persistent coverage.
  - Unique Doppler and line-of-sight geometry enables RFI detection and localization.
  - A satellite payload can support RFI monitoring.

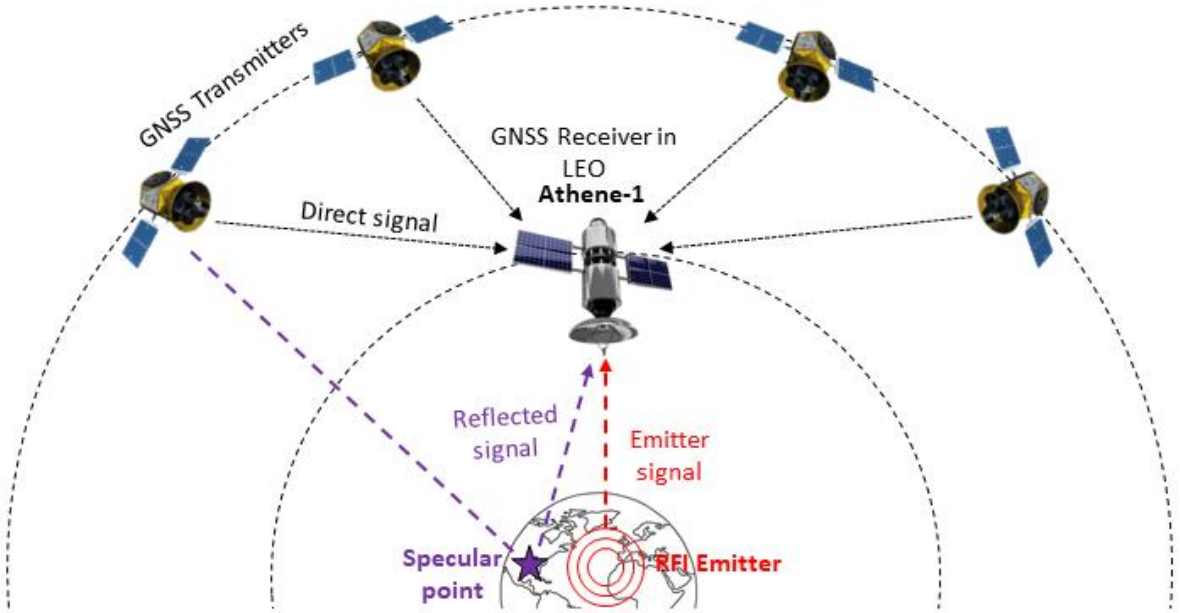


Figure 2: Overview of GNSS RFI and Reflectometry analysis

Orbit and Platform Parameters

- Multifunctional experimental lab in orbit
- Orbit – Sun-synchronous LEO
- Altitude ~500km
- Inclination – 97.4°
- Platform mass ~ 200kg
- Payload capacity ~ 75kg
- Experiments:
  - 5G networks, laser communication
  - GNSS RFI monitoring
  - GNSS Reflectometry
  - Sensor fusion, Artificial Intelligence
  - Automated data/image analysis
  - Structural health monitoring

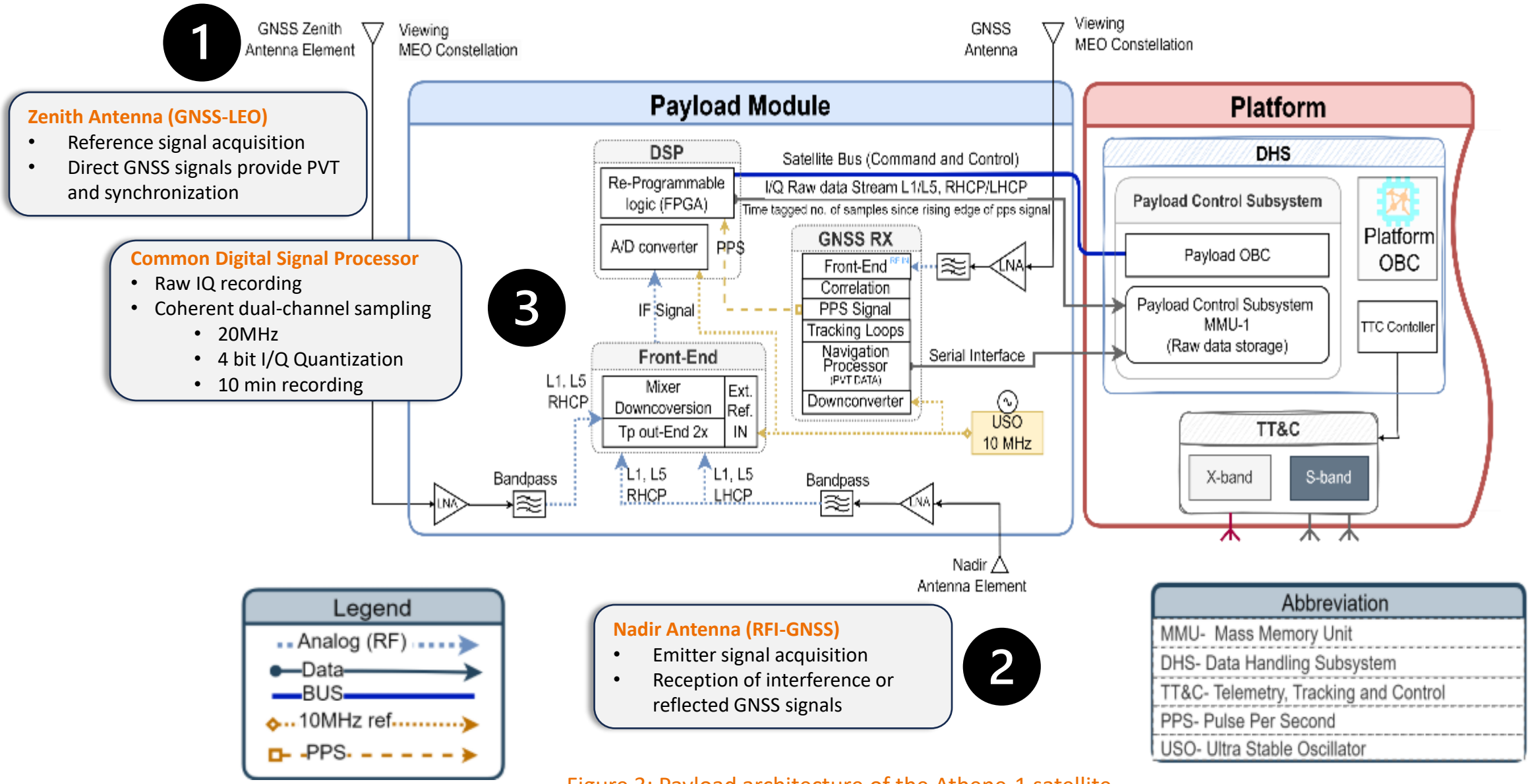


Figure 3: Payload architecture of the Athene-1 satellite

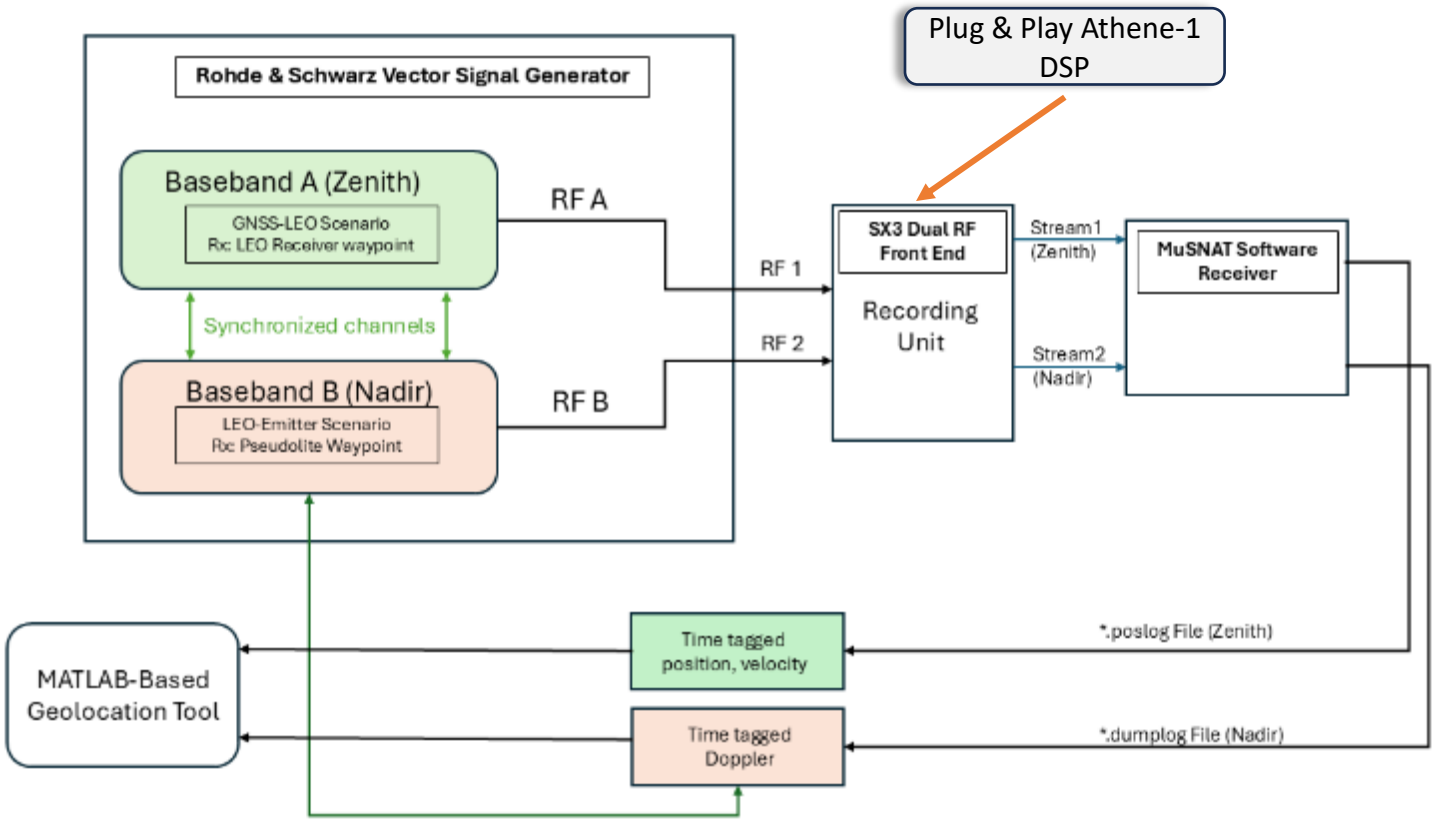


Figure 6: End-to-end laboratory testbed for time-synchronized validation of the GNSS RFI monitoring and GNSS reflectometry payload

Stage 1: Payload-only verification without satellite bus interfaces

- Purpose:
  - End-to-end replication of the spaceborne payload signal chain
  - Validation of time-synchronized dual-channel signal acquisition
  - Doppler-based single-LEO emitter geolocation under controlled conditions
- Testbed:
  - Dual-channel RF signal generation
  - Synchronized RF front-end and digitization
  - Software-based post-processing
- Outcome
  - Time-aligned raw IQ recordings
  - Doppler and geolocation observables for algorithm verification

Test case: controlled GNSS spoofing scenario

- Controlled spoofing scenario with known geometry and injected signal dynamics and parameters
- Simultaneous nominal GNSS reception and spoofing signal injection
- Reference case for evaluating observables, PVT consistency, and geolocation

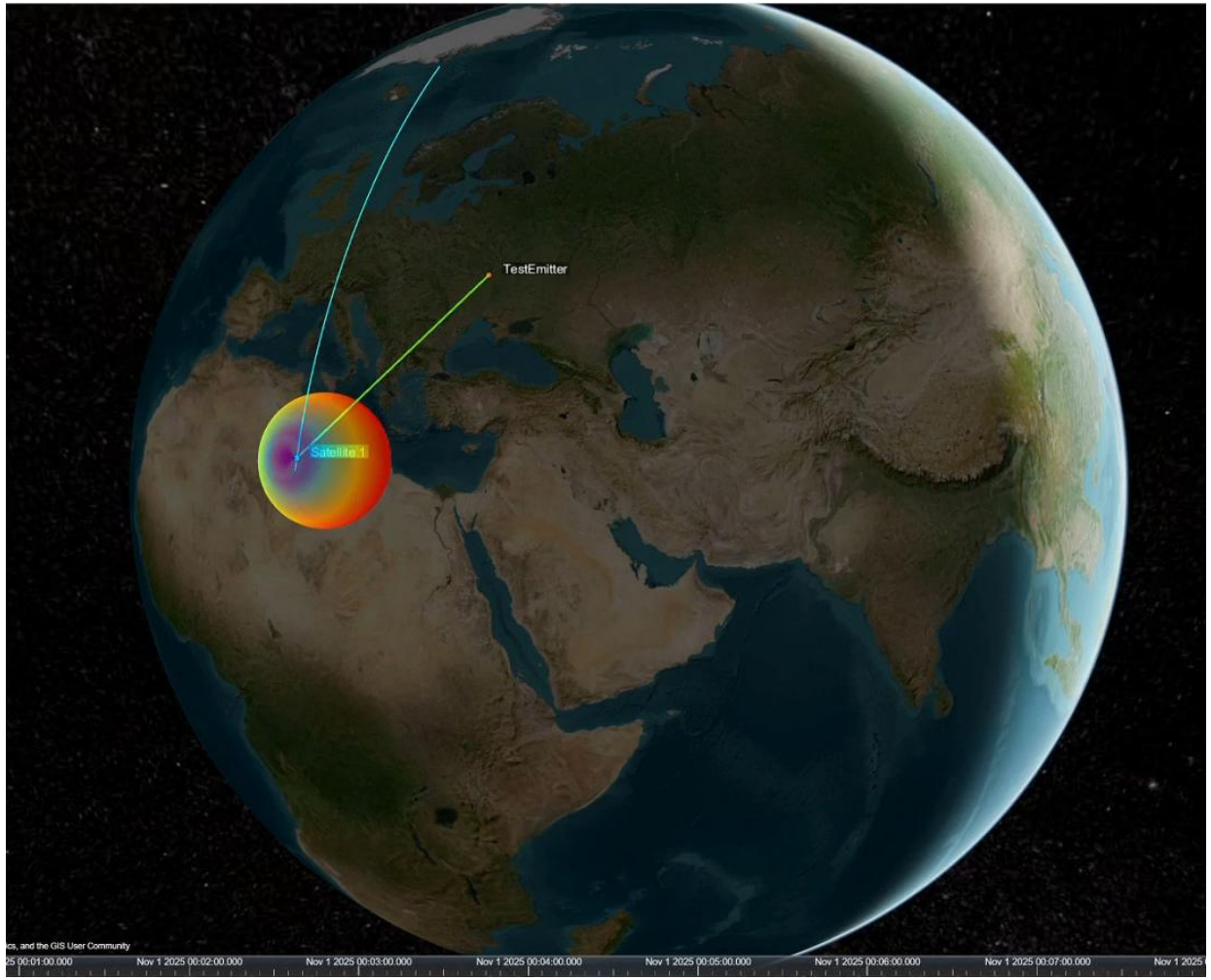
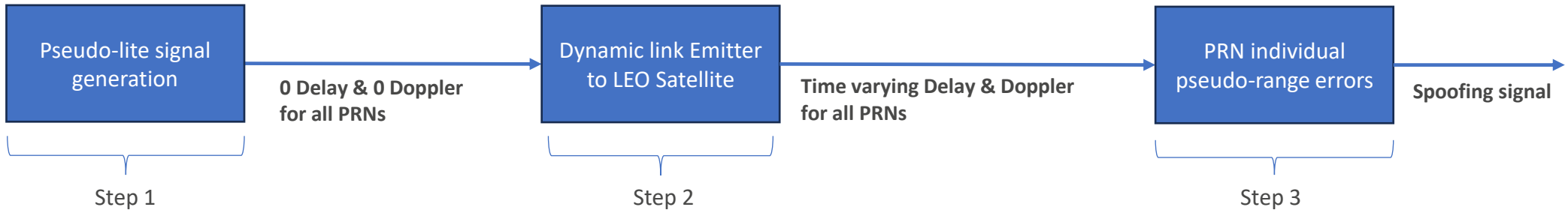


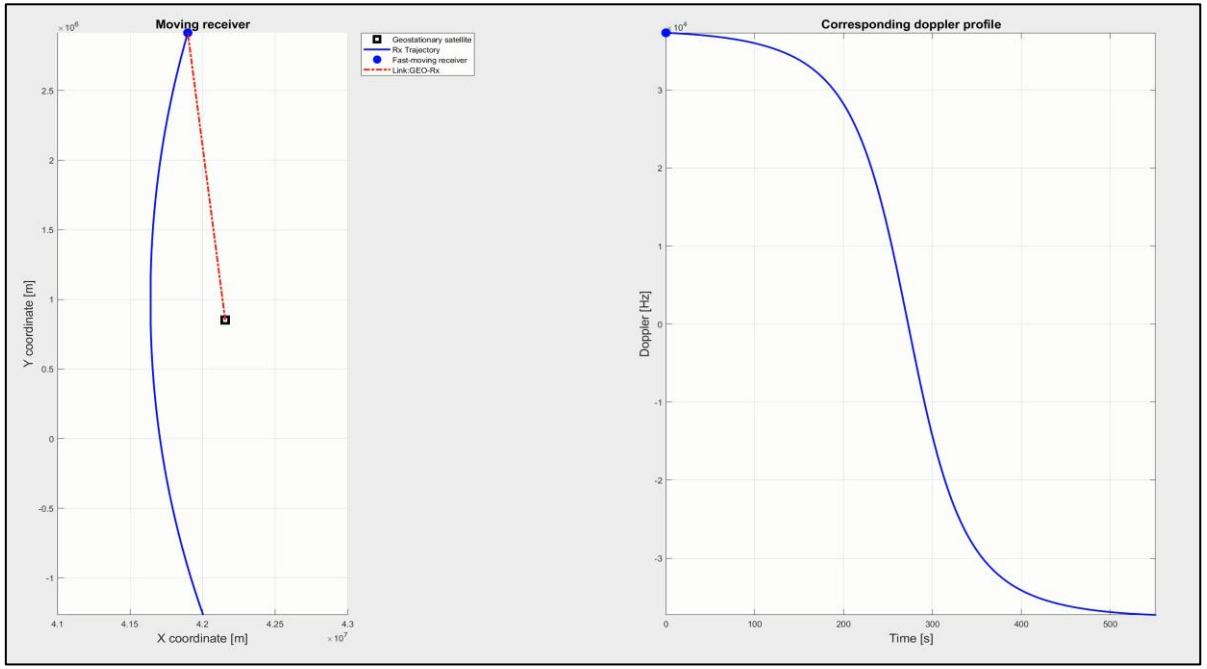
Figure 7: Expected Doppler evolution for a static ground-based pseudolite during a LEO overflight

- LEO trajectory definition
  - Athene-1 Keplerian elements
- Static ground-based pseudolite at known geodetic coordinates
  - Location: Kyiv, Ukraine
- Time-varying slant range, Doppler, and propagation delay
  - Min. range ~ 1473 km
  - Representative Doppler variation ~ ±30 kHz
- Finite visibility window defining the overflight duration
  - Link time ≈ 9min 10s

- Spoofing signal generation
  - **Step 1)** GNSS-Signal as pseudo-lite signal without any additional Delay & Doppler-profiles
    (Tx. & Rx. static with zero distance)
  - **Step 2)** Dynamic link between Emitter and LEO Satellite
  - **Step 3)** Adding PRN individual pseudo-range errors on the constellation of spoofed signals



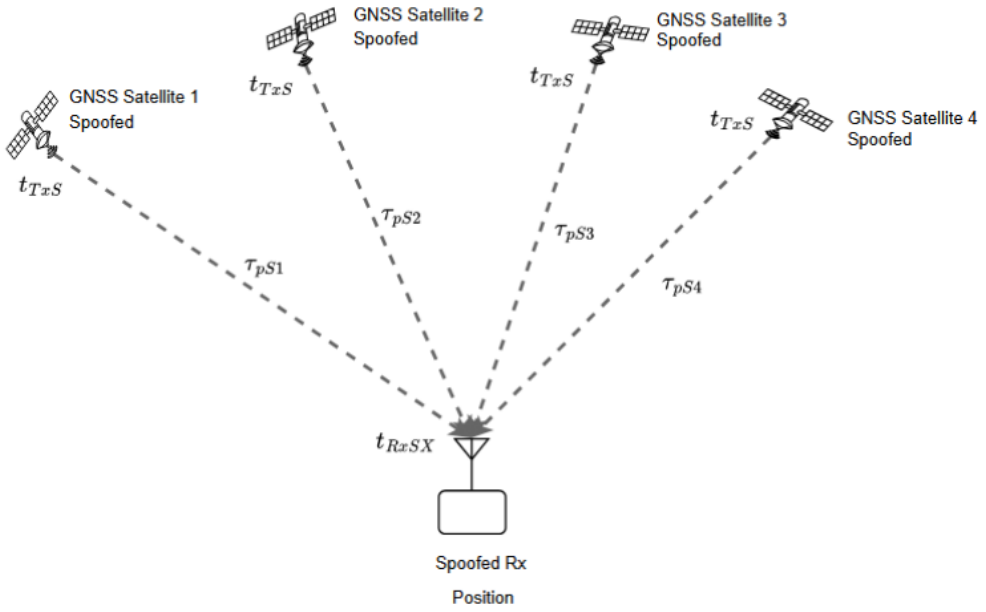
Step 2) Generation of the dynamic link emitter to LEO Satellite via moving receiver & geostationary satellite



Relative motion of the moving receiver in a geostationary orbit with respect to a geostationary satellite

– Transformation of the scenario into a „Geostationary satellite equivalent scenario“. Same link applied to all spoofed satellites.

Step 3) Generation of a spoofing scenario

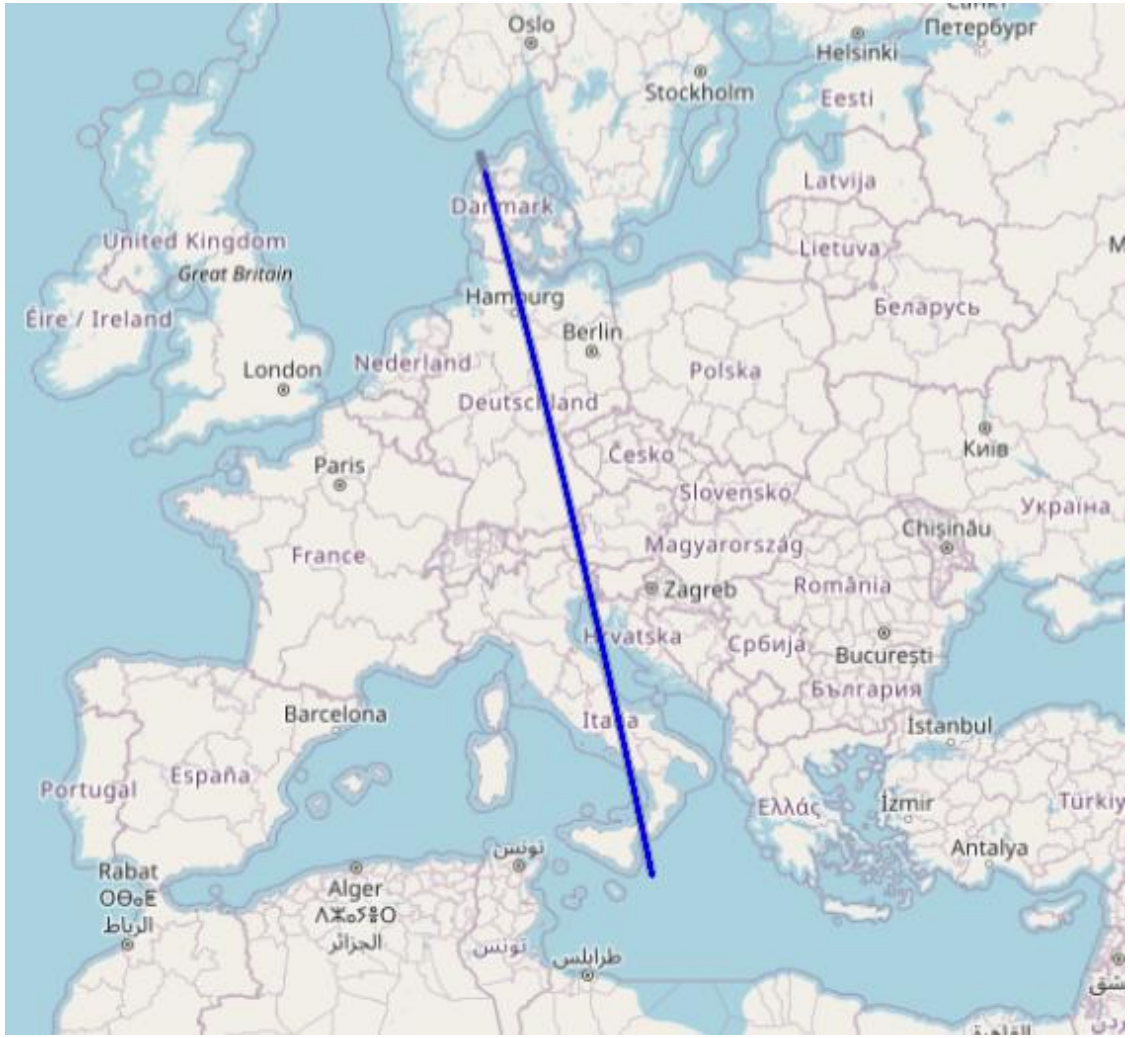


Application of individual pseudo-range errors on each spoofed PRN signal.

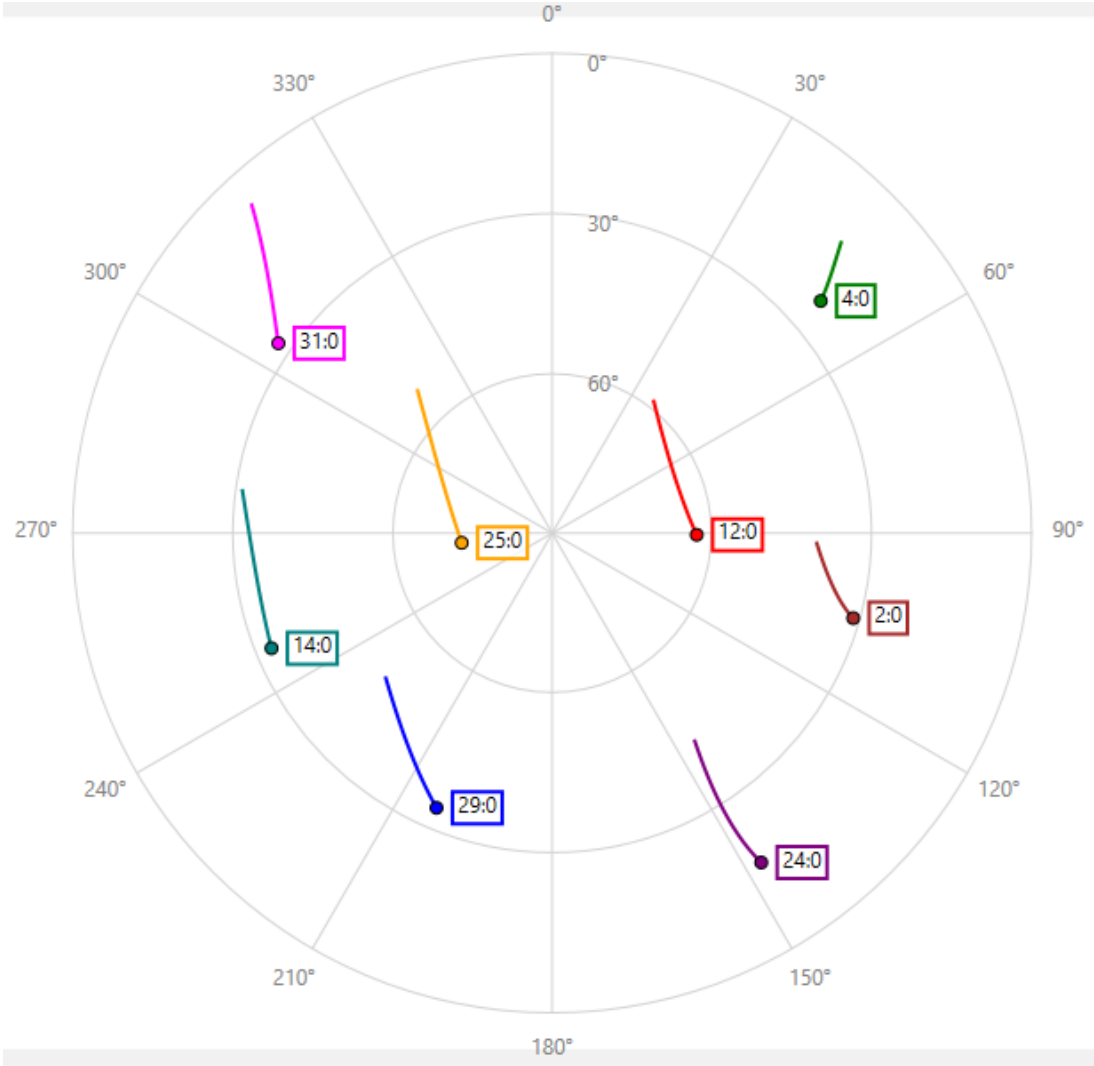
Results

Zenith antenna channel (GNSS-LEO scenario)

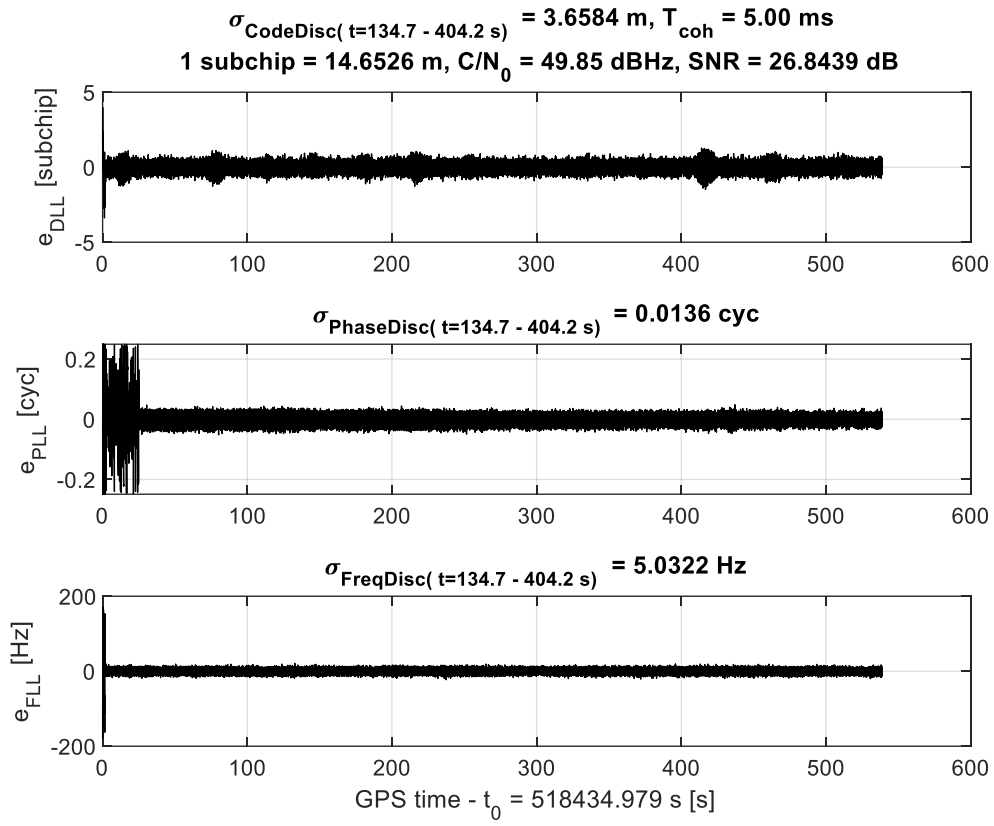
Flight path of the LEO satellite after processing the zenith signal with MuSNAT

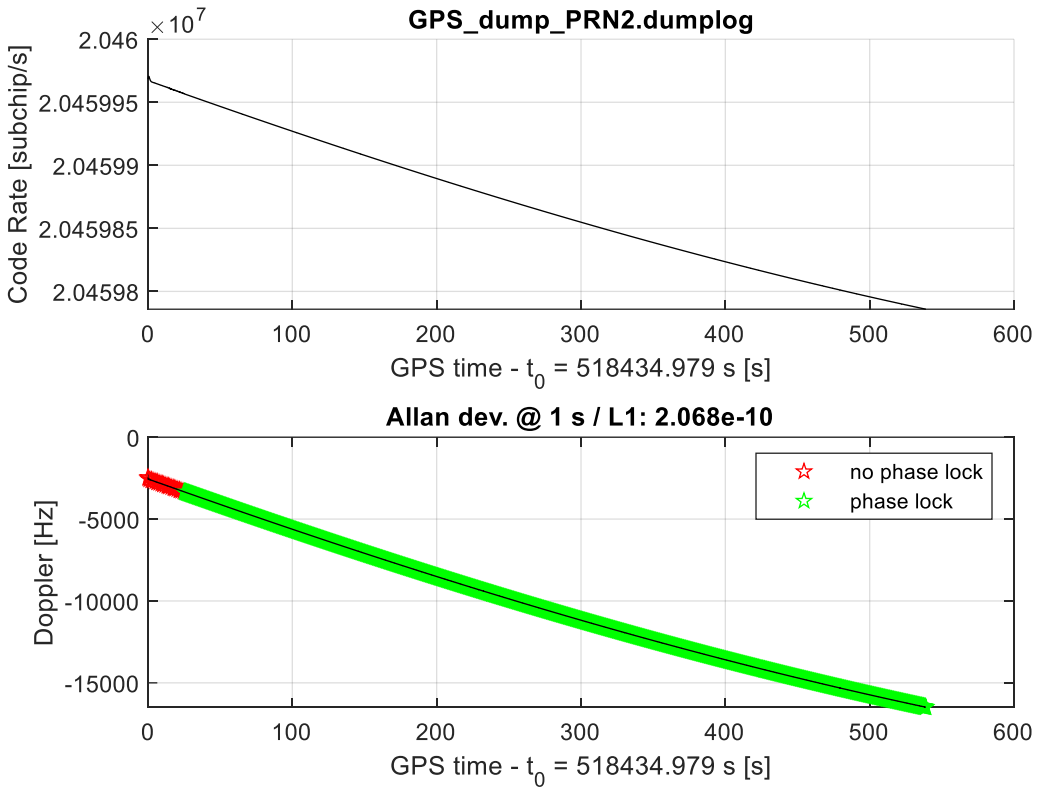


Visible simulated GPS L1 signals within the scenario

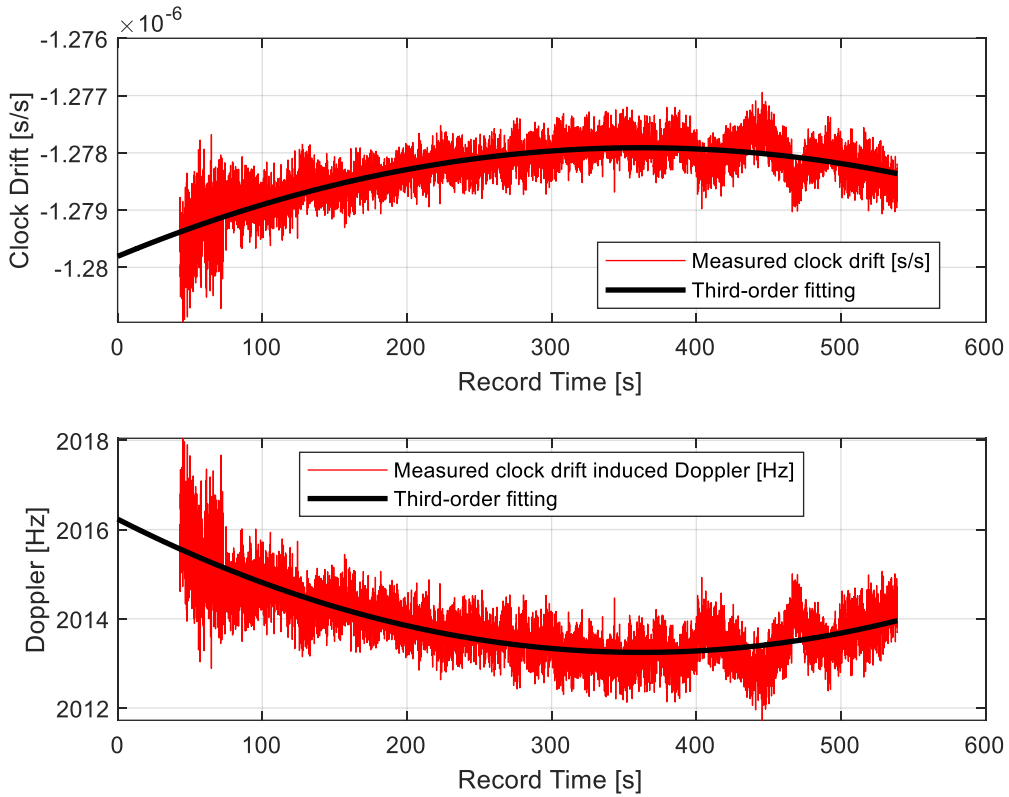


Analyzing the tracking performance of the PRN2 in the zenith channel

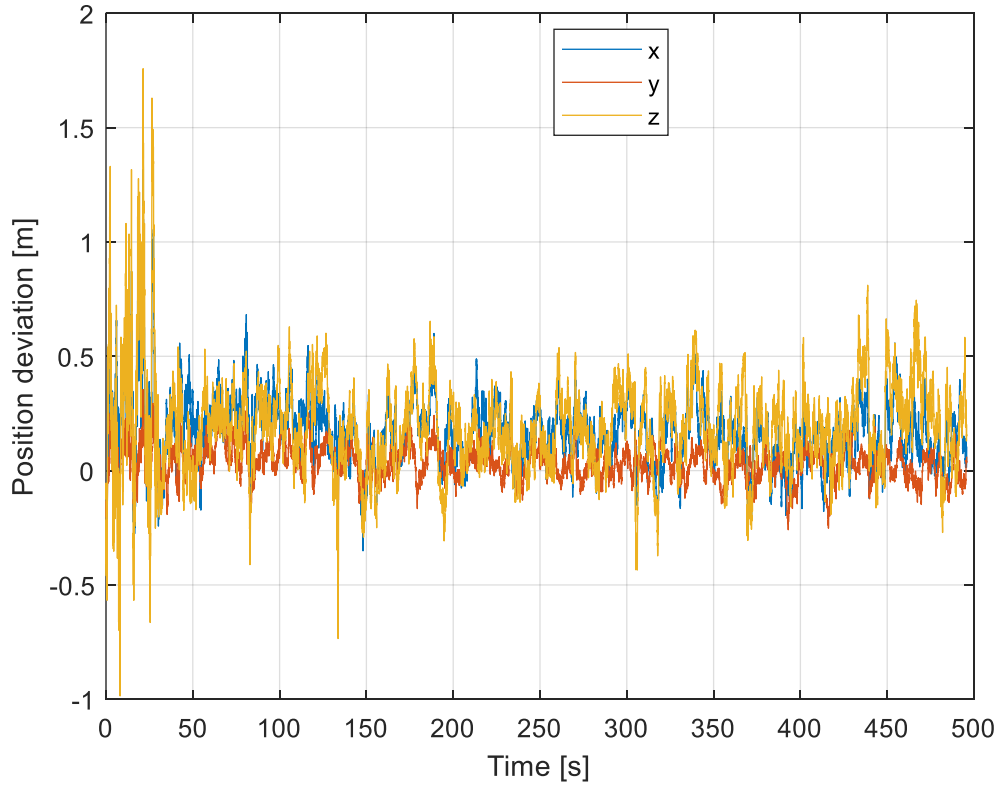




Measured clock drift of the recording unit by processing the GNSS MEO signals (zenith channel)



Position deviation between the set LEO waypoint profile and calculated position after processing with MuSNAT

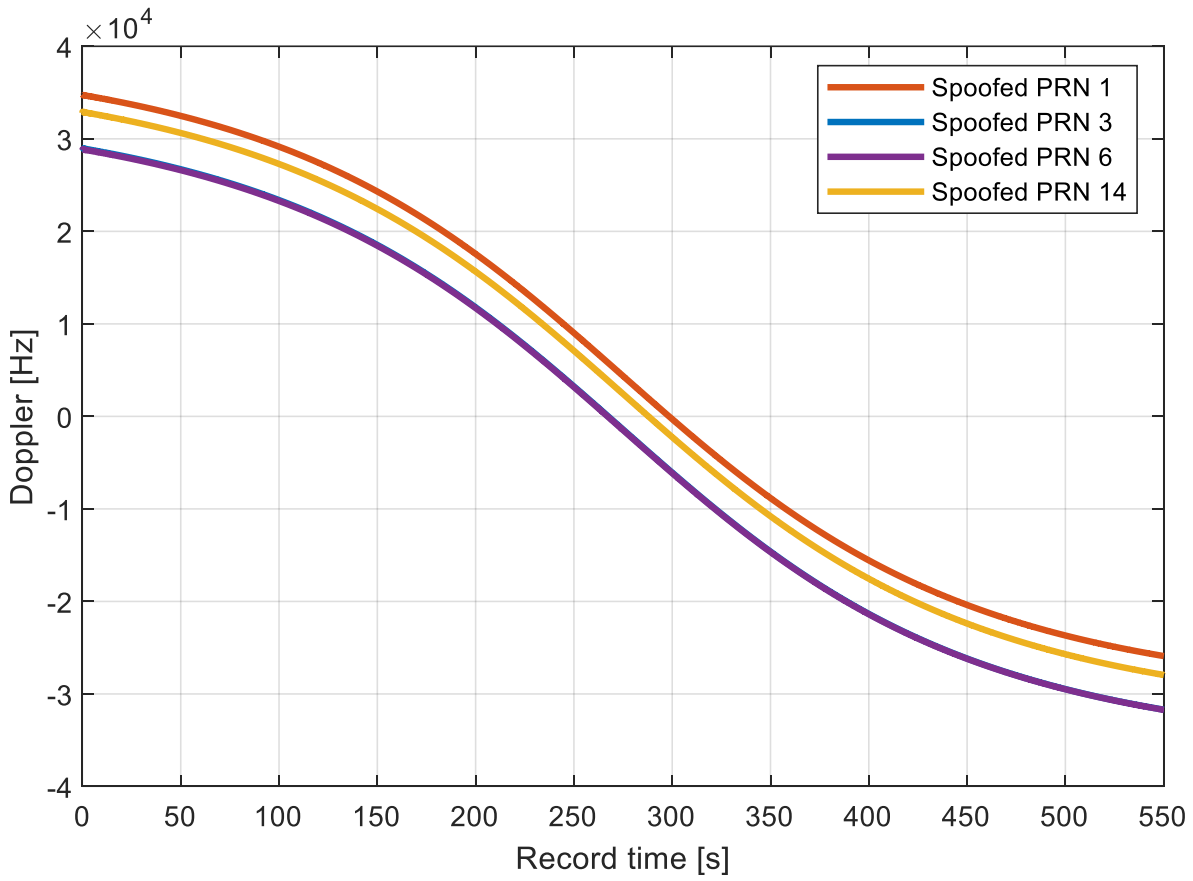


Do the measured PVT observables follow the simulated LEO Receiver position?



Results

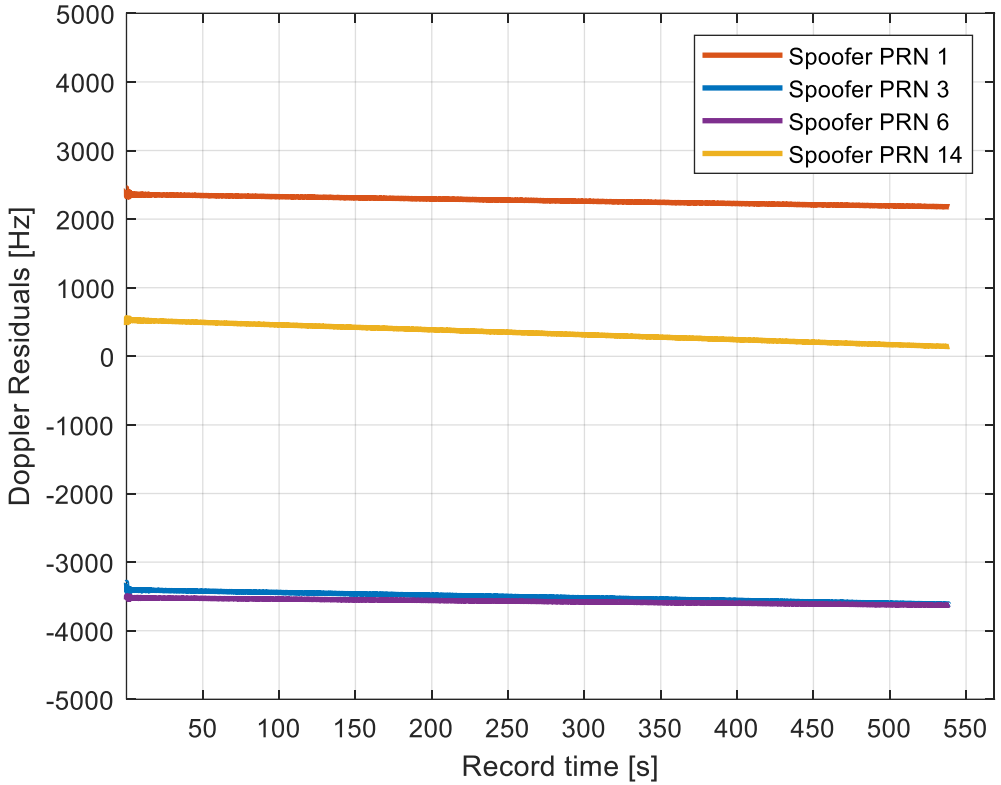
Nadir antenna channel (RFI - GNSS spoofing-like emitter)



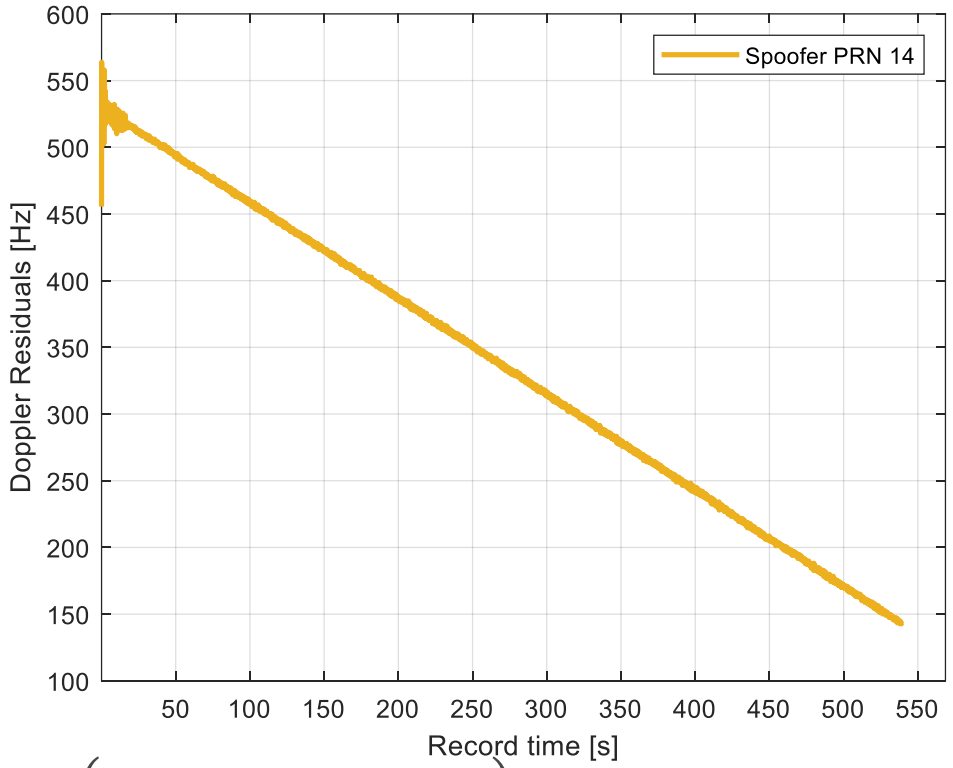
- Ranges of Doppler for this scenario: ~ +/- 35 kHz
- The shape of the Doppler curve is mostly dominated by geometry-related Doppler between emitter and LEO satellite
- Each spoofed PRN shows a slight Doppler offset due to Spoofer induced Doppler shift
- Each Doppler-curve contains a common offset due to clock drifts of the receiver's clock.

Measured Doppler profile = Geometry-related Doppler + Clock drift Doppler + Spoofer induced Doppler shift

Remaining spoofer-induced Doppler residuals after cancellation of the clock-drift and geometry-related Doppler



Zoom-in for PRN 14: Spoofer induced Doppler consist of two main terms: Frequency offset + Frequency drift over time

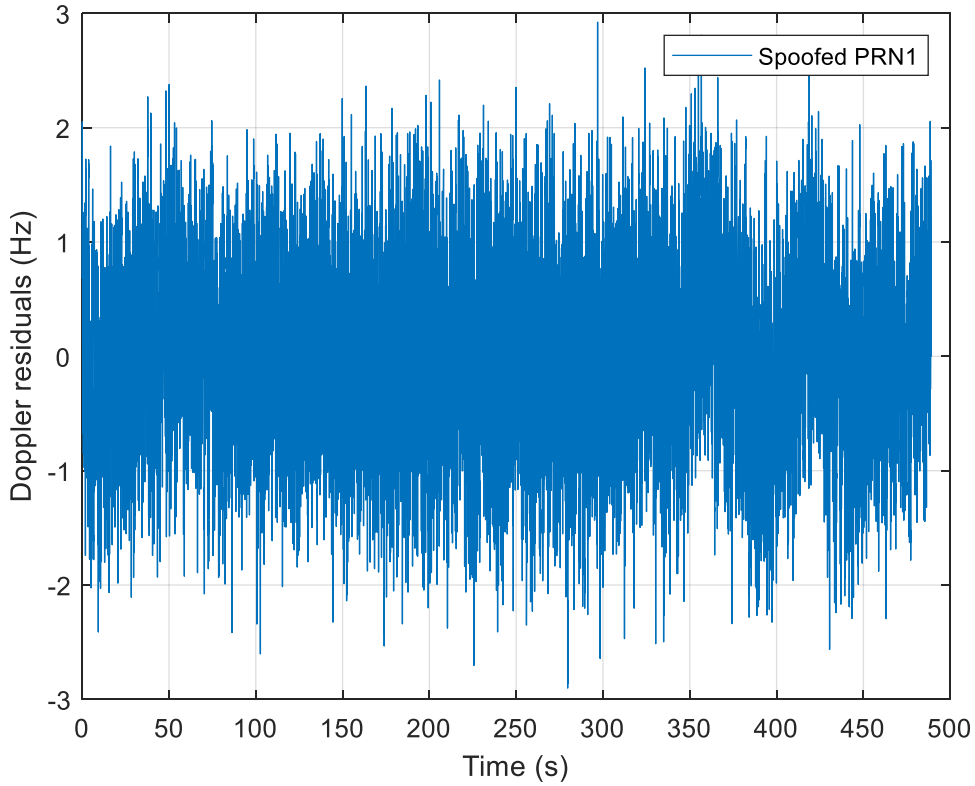


$$\boldsymbol{Residuals} = f_{D_{measured}} - \left(f_{D_{fed}} + f_{D_{clock-drift}}\right)$$

Task for the Geolocation Algorithm:
Additional Estimation of the Doppler offset & Doppler Drift.

Geolocation of the RFI emitter from LEO

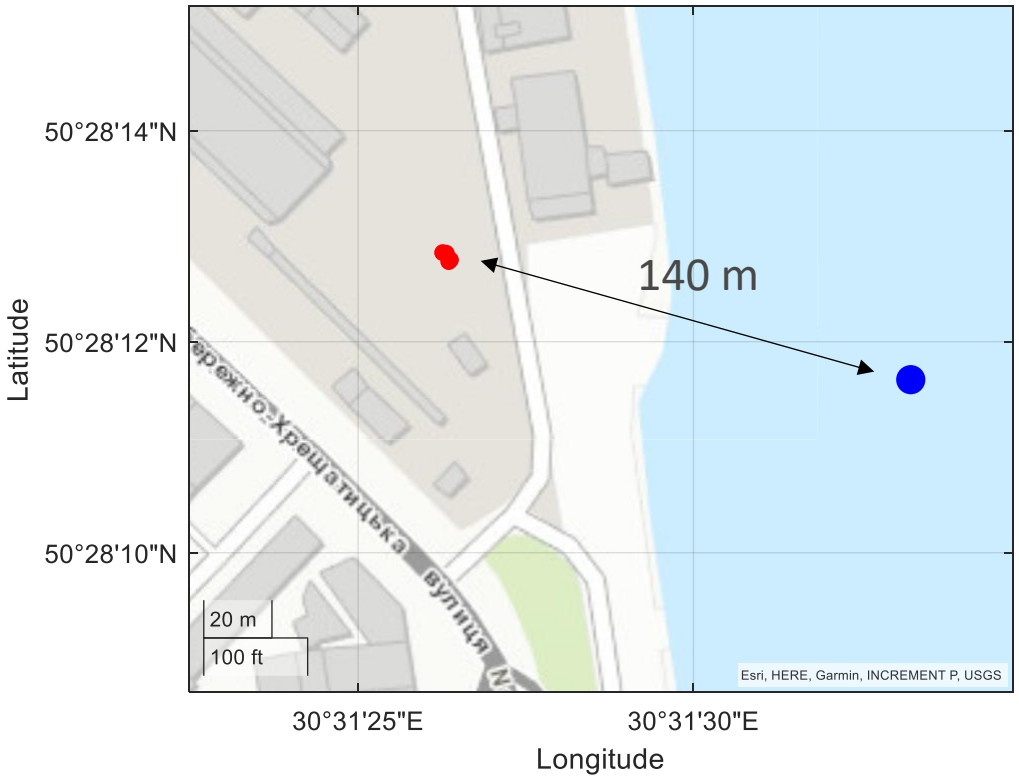
- Principle:
  - Relative motion between the satellite and the emitter causes a Doppler shift
  - Doppler measurements are linked to satellite position at the same time
- Inputs:
  - Satellite position & time – zenith channel
  - Doppler measurements of the received signal – nadir channel
  - Initial position guess
- Processing:
  - Time-align Doppler and satellite position data
  - Interpolate satellite position to Doppler measurement times
  - Model and estimate emitter clock-induced frequency offsets
  - Iterative least-squares estimation to jointly estimate emitter position and frequency offset + frequency drift
- Outputs:
  - Estimated emitter position



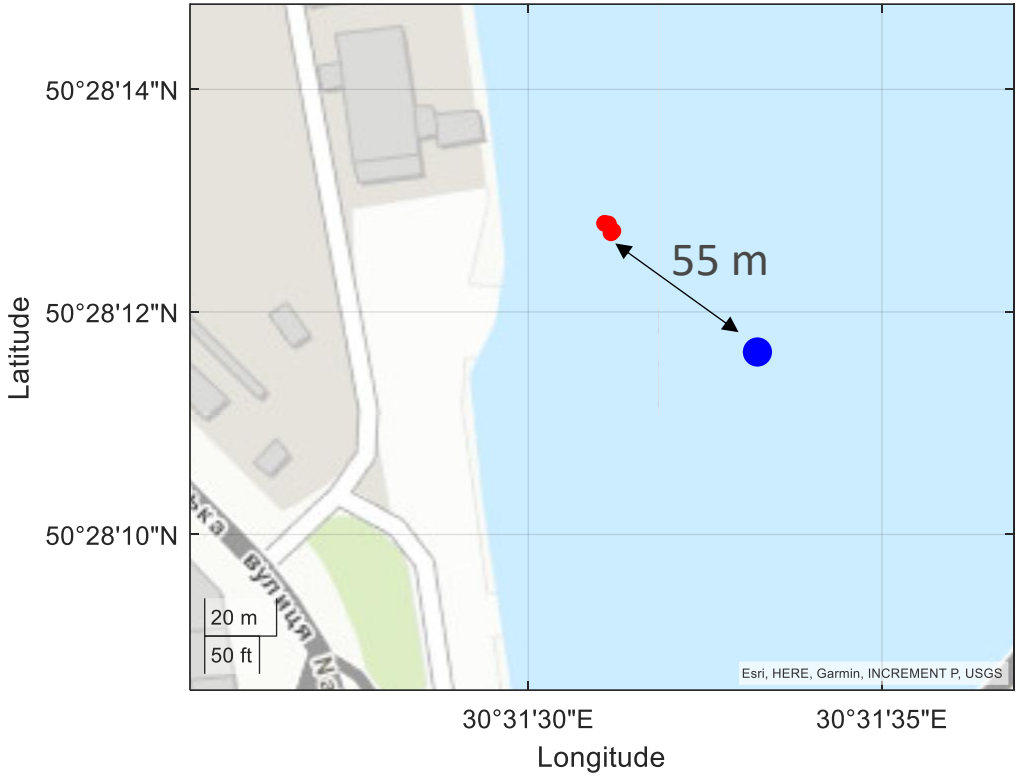
- calculated positions for each PRN
- True emitter position

RFI position (True coordinates) Emitter in Kyiv	
Latitude	50.4699°
Longitude	30.5259°
Altitude	231 m

Solving with zero-altitude constraint of the WGS84-ellipsoid.



Solving with 231 m altitude constraint of the WGS84-ellipsoid.



Expand threat/signal classes

- **Jamming:** programmable interference waveforms via R & S pulse-sequencer software

Timing & oscillator sensitivity

- Evaluate **USO error models** (Short-term stability)
- Quantify impact on:
  - Doppler bias/variance
  - time-tag alignment between channels
  - geolocation accuracy (clock-Doppler coupling)

Acknowledgement

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