Assessment of a Low-Cost GNSS-IR System for Vegetation Monitoring

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Research Vision

- ✓ **Monitoring vegetation status** has become one of the most demanding parameters due to the increasing world population, climate change crisis, and vegetation's vital role in the carbon cycle.
- ✓ In-situ observations at the local scale are key to supporting Crop Growth Models (CGMs) and validating Earth Observation-derived products.
- ✓ GNSS Interferometric Reflectometry (GNSS-IR) is a popular technique for deriving environmental parameters, such as soil moisture, vegetation, and snow depth.

GNSS-IR Campaign in Petzenkirchen, Austria

- In Austria, crops like wheat, corn, potatoes, and vineyards are mostly in small to medium eastern fields.
- Continuous crop monitoring is vital for food security and sustainability.
- Continuous vegetation monitoring optimizes irrigation and detects crop stress and drought early.

We installed **a multi-GNSS receiver** at the Hydrological Open Air Laboratory **(HOAL) in Petzenkirchen,** ~100 km west of Vienna, to **analyze cornfield vegetation signatures in reflected GNSS signals**.

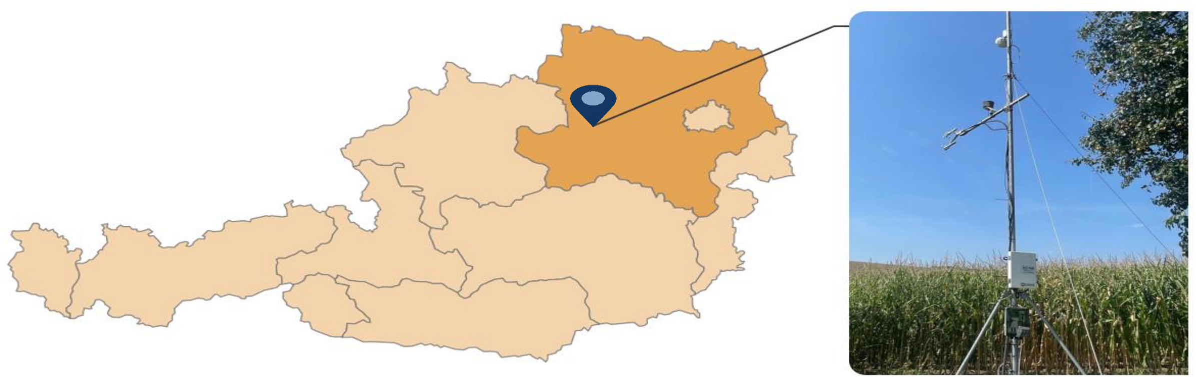
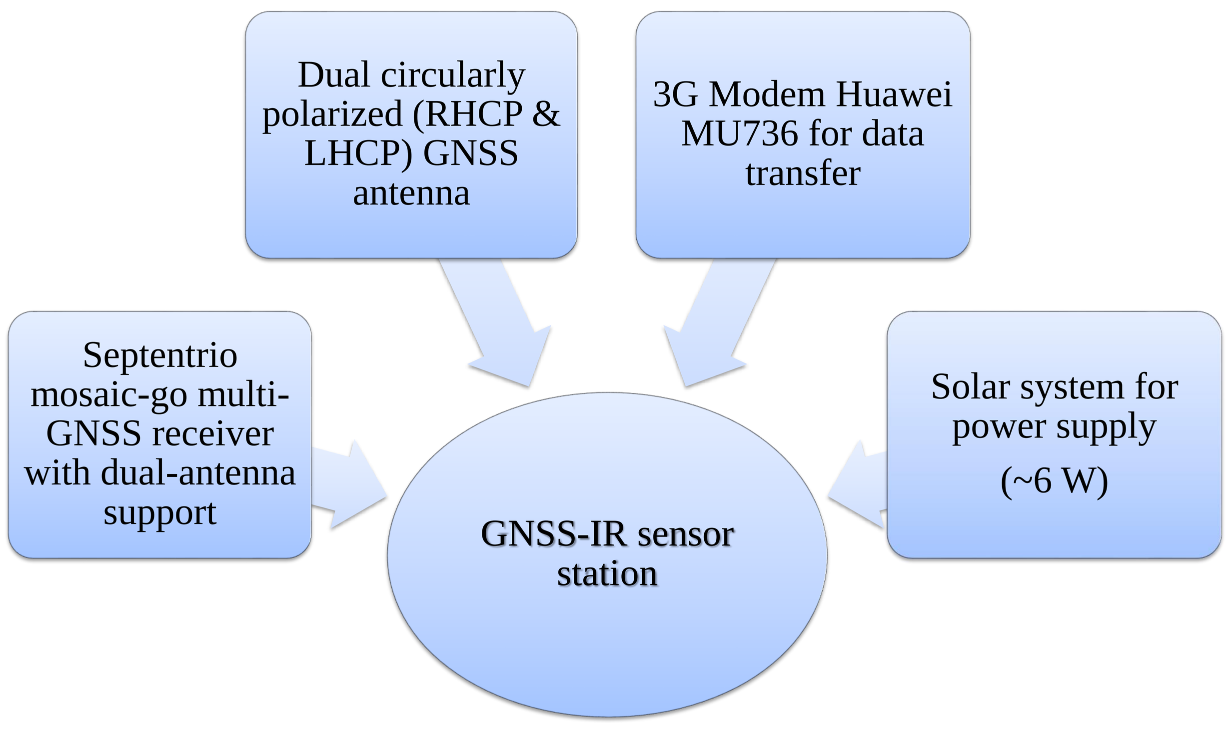


Figure 1: Left - Location of the Hydrological Open Air Laboratory (HOAL) in Petzenkirchen, Austria; Right - Image of the GNSS site selected for the case study.



The field of view of the GNSS antenna, installed at a height of approximately 5 m above the ground, was determined using the Reflection Zone app. It encompasses a relatively flat area of cornfields, covering approximately 500 m². An **azimuth range of 240° to 360°** was also selected by considering factors like satellite geometry and minimal obstructions to provide optimal reflection conditions for GNSS-IR at this site

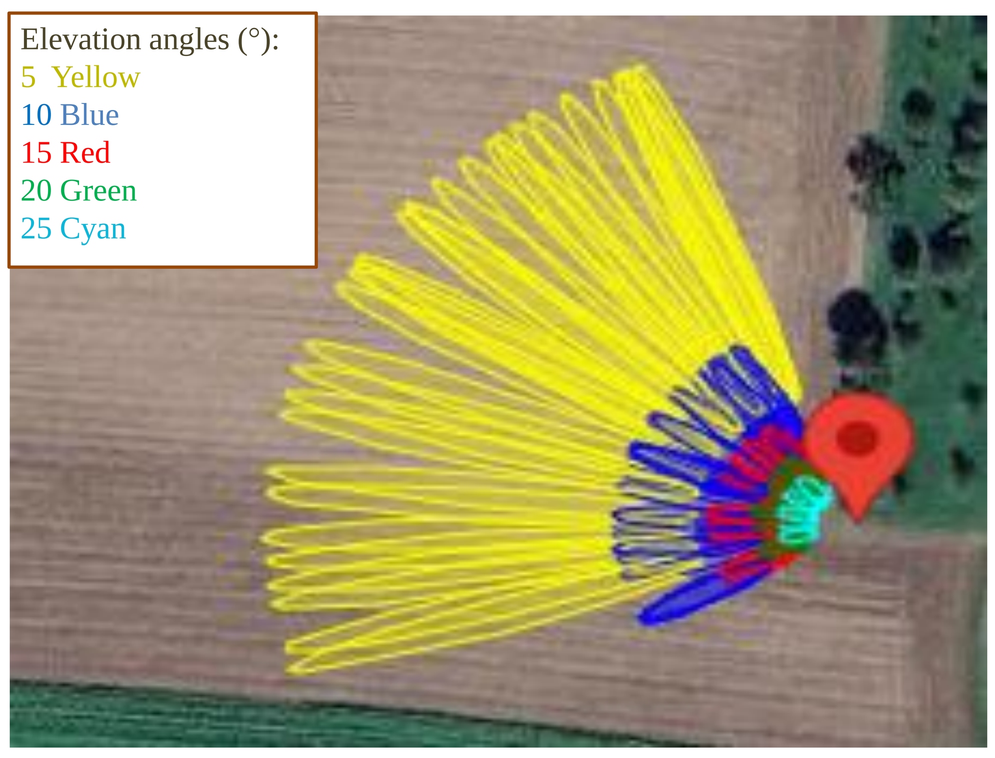


Figure 2: The field of view defined by the Fresnel zone for GPS L1

Table 1 presents detailed information on all the datasets used in this study.

Table 1: Information of used data in this study

Dataset	Spatial Resolution	Temporal Resolution
GNSS Data	~100–500 m² (GRE Obs)	~ 70 minutes
SMAP	9 km	Daily
NDVI[1] Sentinel2	10 m	~ 5 days
CWSI[2] MODIS	500 m (MOD11A1, MOD09GA)	~ 5 days

1. Normalized Difference Vegetation Index
2. Crop Water Stress Index

Assessment of SNR Data

The installed GNSS station generates three distinct types of observations: RHCP, RHCP + LHCP, and LHCP.

In the initial analysis, we focused on RHCP data. Figure 3 presents periodograms for GPS L1 and Galileo E5b signals for an **elevation range of 5–25°** across four azimuth quadrants. Spectral behavior is strongest in the southwest quadrant (180–270°). The results also confirm that the antenna center is approximately 5 meters above the surface, as expected.

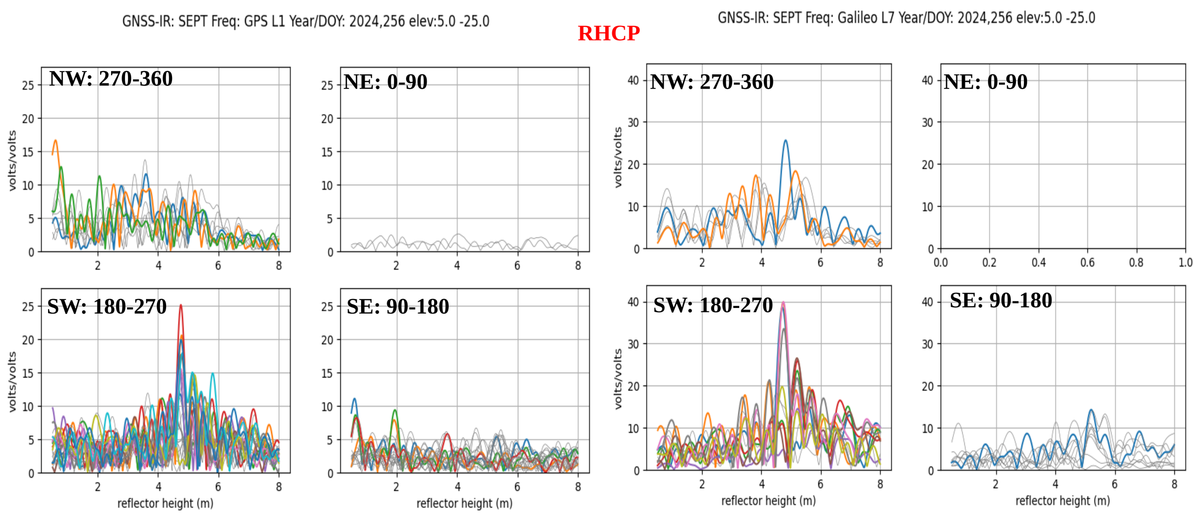


Figure 3: Periodograms for GPS L1 (left) and Galileo E5b (right) RHCP signals from gnssrefl.

In the next analysis, we examined periodograms for RHCP+LHCP and LHCP data using GPS L1 signals, with the elevation range of 10–30° to reduce low-angle noise. The results show that LHCP data alone need further preprocessing and quality checks due to multiple peaks. LHCP signals also appear more sensitive to surface topography than RHCP, requiring careful handling. Therefore, **this study focuses only on RHCP data**.

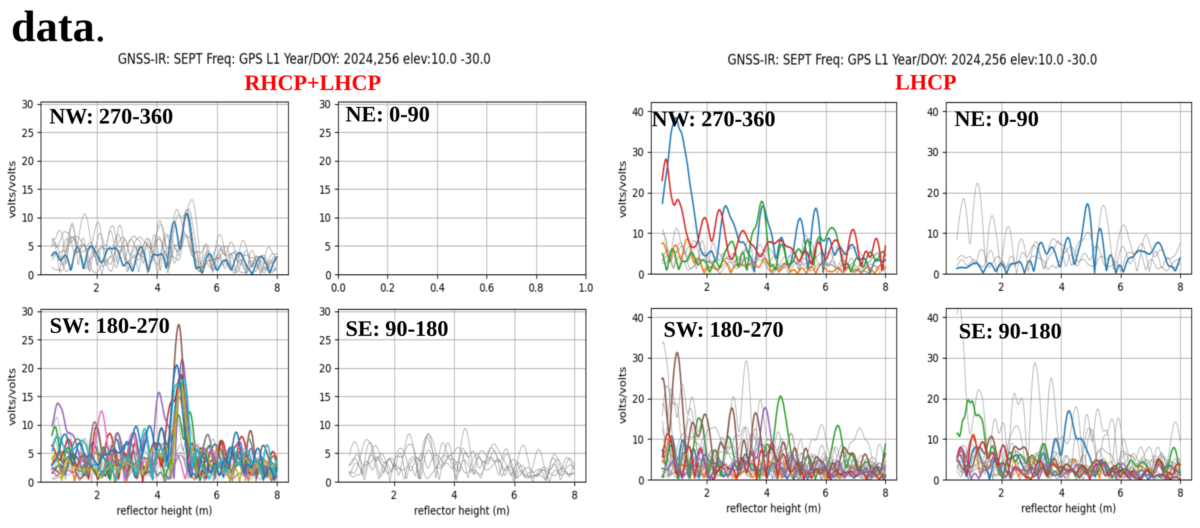


Figure 4: Periodograms for GPS L1 RHCP+LHCP (left) and LHCP (right) signals from gnssrefl.

The GNSS dataset includes observations from periods with vegetation (pre-harvest) and periods after its removal (post-harvest), with harvesting occurring on DOY 264, 2024. Figure 5 shows a clear vegetation signature on DOY 263, while on DOY 265, the vegetation influence is reduced.

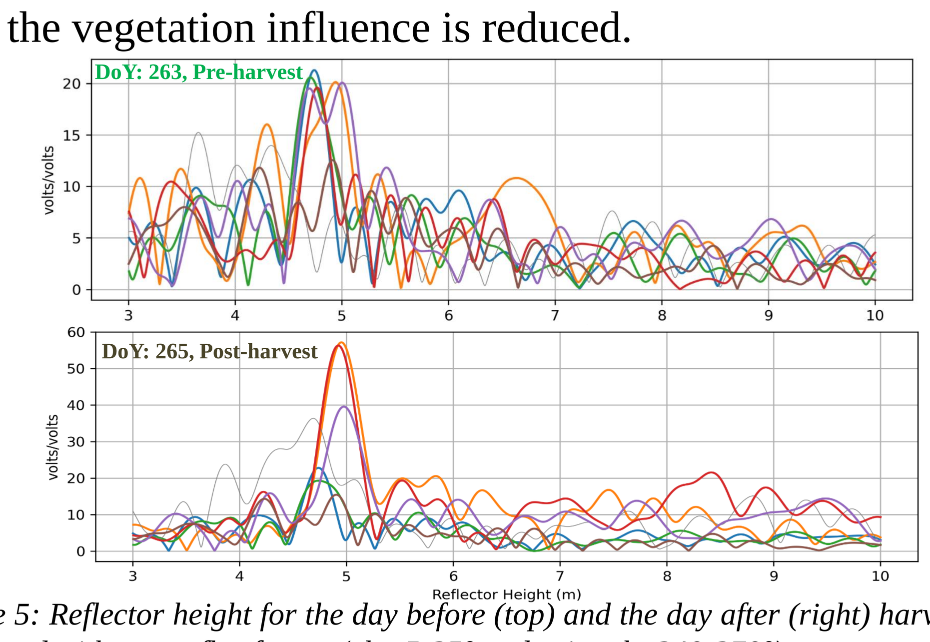


Figure 5: Reflector height for the day before (top) and the day after (right) harvesting, plots generated with gnssrefl software (elv: 5-25° and azimuth: 240-270°).

Retrieved Daily Reflector Height

We compared daily reflector heights (RH) from gnssrefl with SMAP soil moisture (SM) and Sentinel2 NDVI for 2024. The time-series plots reveal the reflector heights tracking soil moisture and NDVI trends, indicating their sensitivity to vegetation and hydrological changes. Additionally, **significant rainfall events occurring in early September 2024 (DoYs 256–260) and in mid-December 2024 (Doy 341)**, appear to have some influence on the reflector height, which might be due to the sensitivity of the retrieval algorithms to the surface wetness.

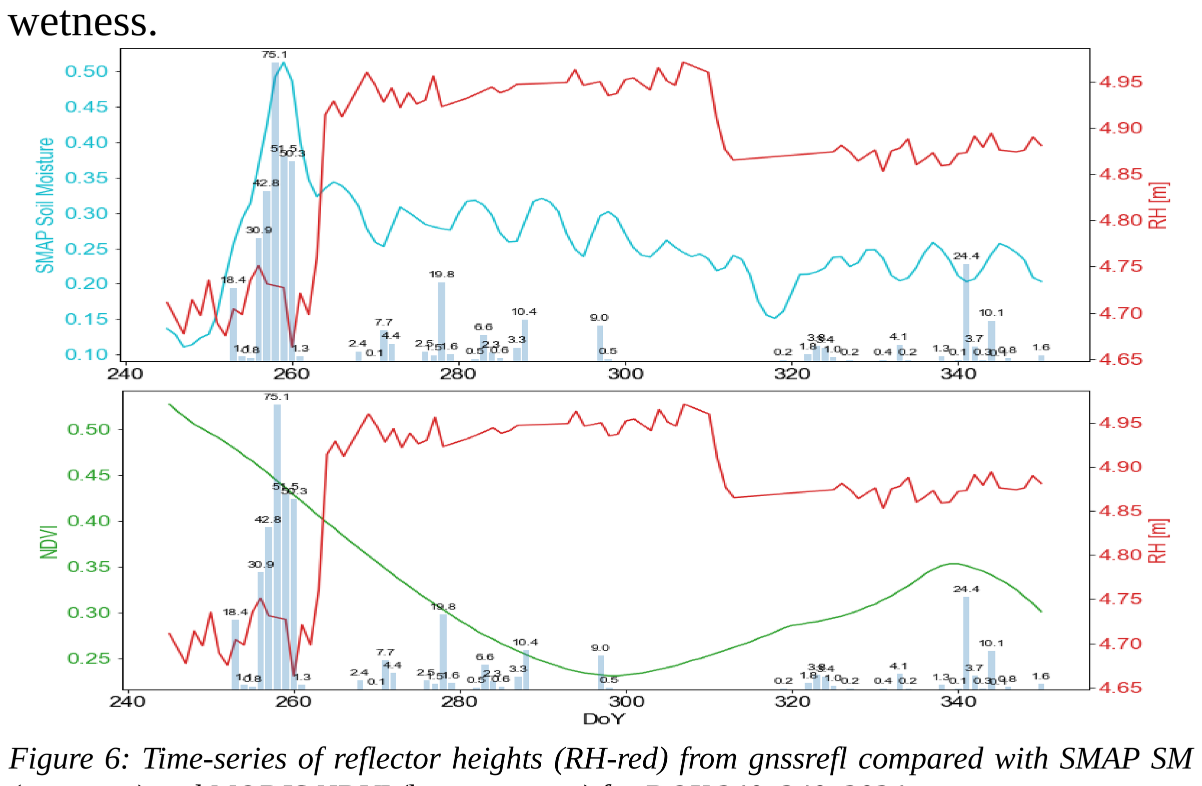


Figure 6: Time-series of reflector heights (RH-red) from gnssrefl compared with SMAP SM (top, cyan) and MODIS NDVI (bottom, green) for DOY 240–340, 2024.

Acknowledgements

We express our gratitude to Petzenkirchen HOAL for providing the test bed for the GNSS-IR station. Moreover, we acknowledge NSIDC DAAC for SMAP data, ESA and Copernicus for Sentinel-2 data, NASA for MODIS data. We also thank Dr. Larson and her team for developing the gnssrefl software used for GNSS-IR analysis.

Retrieved Phase & Volumetric Soil Moisture

To better understand the changes in reflected signals due to surface parameters such as soil moisture, weather, and vegetation conditions, we considered three estimated parameters from the analyzed reflected signals: phase, normalized amplitude, and volumetric soil moisture derived using Chew's multi-stage procedure (Chew et al., 2016).

Vegetation and soil moisture (SM) both affect the phase by attenuating the reflected signal and introducing a phase shift, making the phase a strong candidate for studying their behavior. However, the phase is also used for retrieving soil moisture, meaning it reflects the impact of soil moisture as well. Therefore, for vegetation analysis, we assessed not only the phase but also the normalized amplitude to determine if vegetation-derived changes can be detected in either the phase or the normalized amplitude.

Figure 7 depicts the time series of phase alongside NDVI (top) and CWSI (bottom). After harvesting, a significant jump in the phase is observed, around DoY 264, shifting from positive to negative values. Interestingly, the influence of rainfall is evident in both the phase and CWSI, with a correlation of approximately 50%. Additionally, general trends in NDVI are reflected in the phase; however, since NDVI shows almost no relationship with rainfall, their correlation remains low.

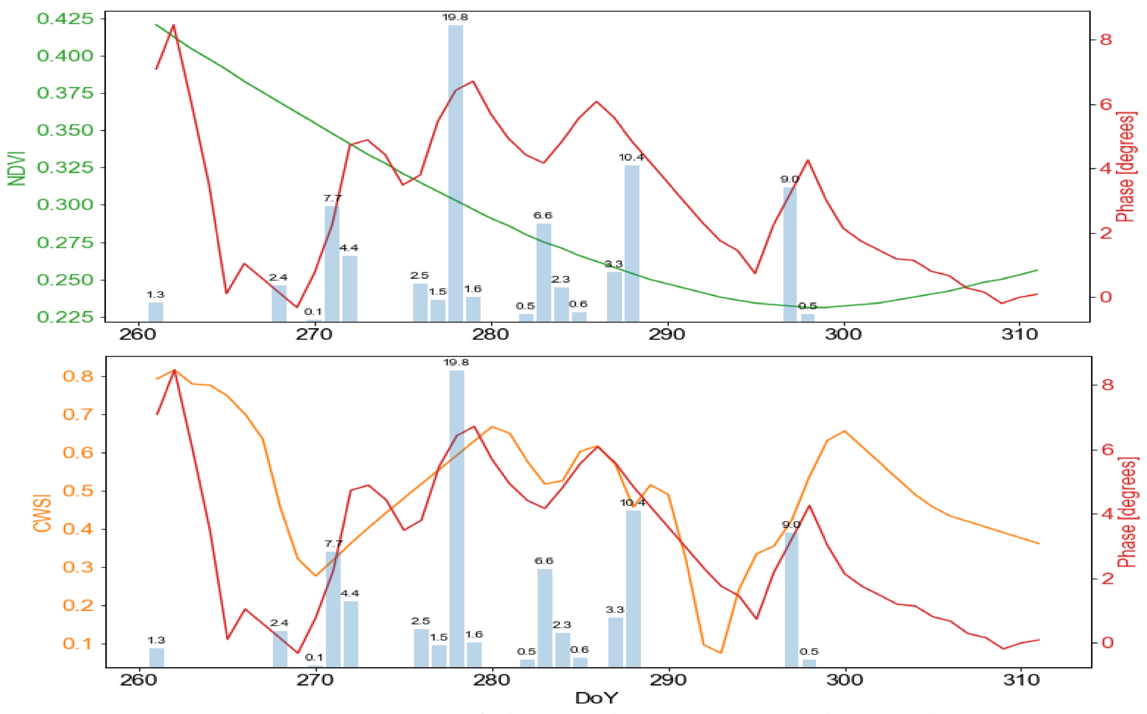


Figure 7: Time series of phase with NDVI (top) and CWSI (bottom).

In the next step, we analyzed the trends in normalized amplitude in comparison to NDVI and CWSI. Interestingly, the normalized amplitude exhibits a strong negative correlation with NDVI, approximately 65%, as it is not significantly impacted by the amount of rainfall. On the other hand, the dependency between CWSI and normalized amplitude is almost negligible.

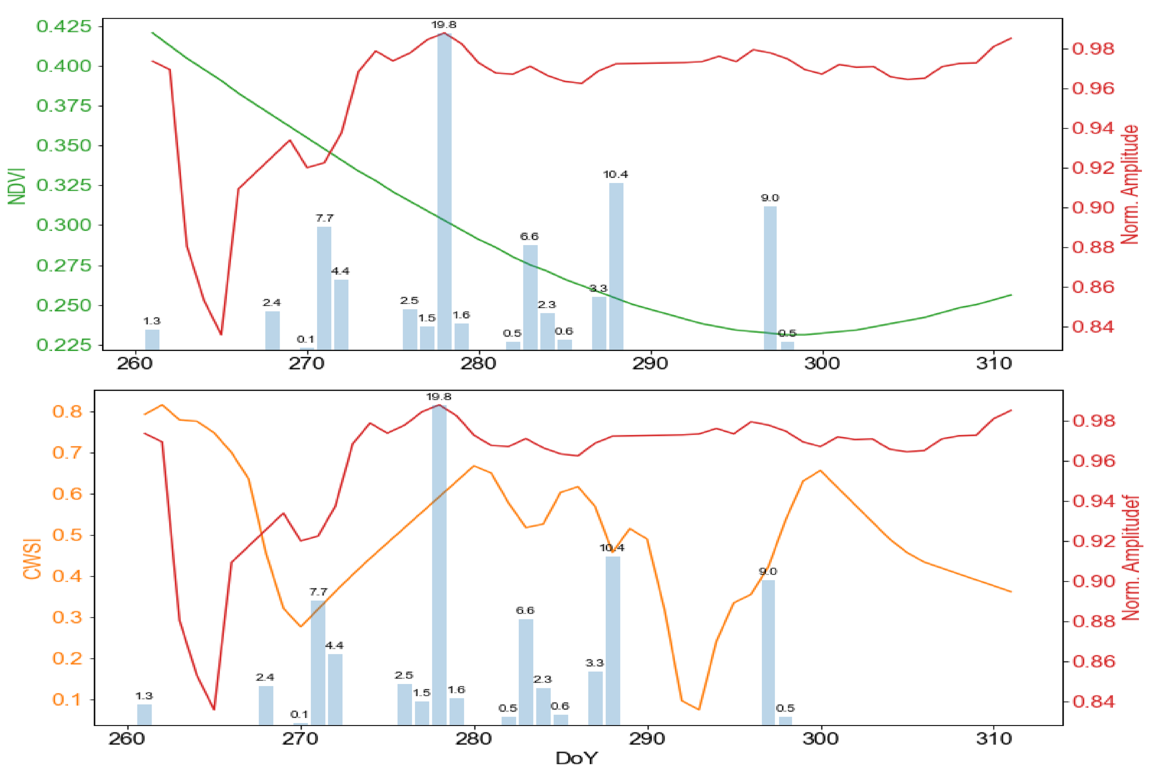


Figure 8: Time series of normalize amplitude with NDVI (top) and CWSI (bottom).

In the final step, we compared the retrieved volumetric soil moisture (SM) against SMAP data. As shown in Figure 9, the general trends of both are nearly identical, with a correlation of approximately 40%. The volumetric SM exhibits a stronger dependence on rainfall events, which can be attributed to its nature as local data with finer resolution, whereas SMAP provides global data with a resolution of 9 km.

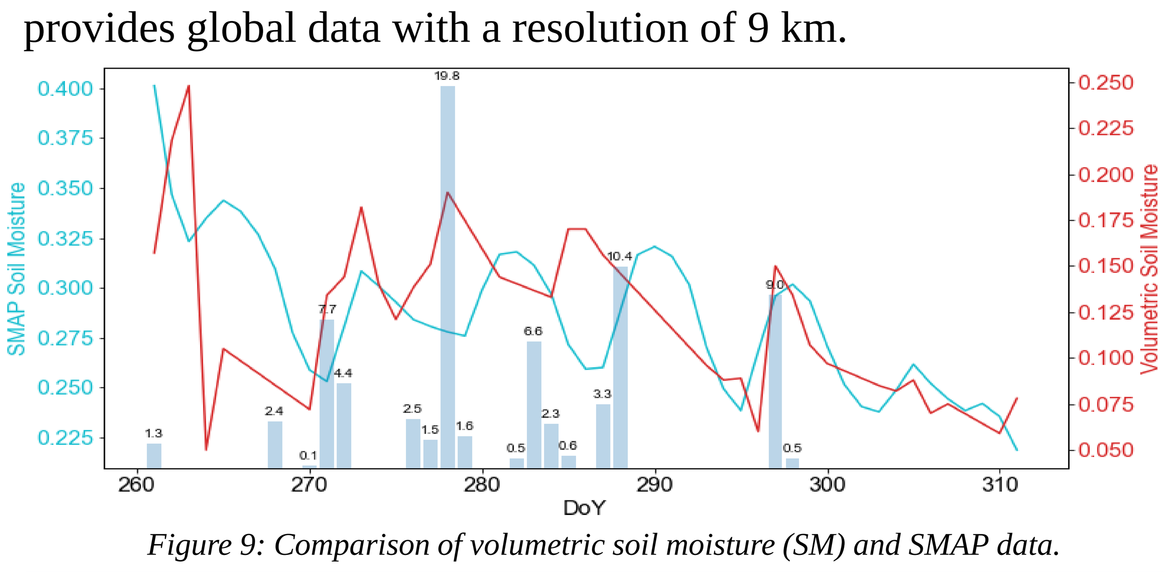


Figure 9: Comparison of volumetric soil moisture (SM) and SMAP data.

Conclusions and Outlook

This research explores GNSS-IR data from the HOAL Petzenkirchen station. The results show its ability to monitor vegetation and soil moisture, alongside rainfall's influence on the parameters. However, validation over a year is needed to cover all vegetation and soil moisture seasonal changes. In future studies, we will use RHCP and LHCP signals to improve retrieval of vegetation and soil moisture dynamics, while also exploring frequencies like GPS L1 and Galileo L7.