https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

Homogenization of integrated water vapour time series using twin GNSS stations and vertical step offsets

Tong Ning[1] and Gunnar Elgered[2]

[1]Lantmäteriet (The Swedish Mapping, Cadastral and Land Registration Authority), SE-80182, Gävle, Sweden.
[2]Physics and Astronomy, Chalmers University of Technology, Onsala Space Observatory, SE-43992 Onsala, Sweden.

Correspondence: T. Ning (tong.ning@lm.se)

Abstract. Accurate long-term GNSS-derived atmospheric water vapour time series are essential when used in climate research. However, these records are frequently affected by interventions, e.g., change of hardware at the station. We investigated the homogenization of integrated water vapour (IWV) time series using two GNSS stations on site. The ERA5 reanalysis product from European Centre for Medium-Range Weather Forecasts (ECMWF) was used as a reference for validation. The results demonstrate that estimating step offsets at the time epoch of the interventions based on the IWV differences between the co-located (twin) GNSS stations significantly improve the agreement with IWV trends from the ERA5 reanalysis. In addition we found a strong negative correlation coefficient, up to -0.92, between step offsets in a single station's vertical component and the corresponding IWV step offsets derived from the twin stations. A 1 mm step offset in the vertical component corresponds to an IWV step offset of approximately 0.03 kg m^{-2}. Such a relationship can be used as a tool for the homogenization of IWV time series for single stations.

1 Introduction

The use of ground-based receiver stations for signals from global navigational satellite systems (GNSS) for the monitoring of the water vapour content above the site becomes more and more interesting as their time series become longer. The principle is that signals travelling from satellites to the ground-based receivers are delayed in the atmosphere. Here we focus on the signal delays caused by the neutral atmosphere and affected by variations in temperature, pressure, and humidity. The equivalent total propagation delay in the zenith direction, referred to as the zenith total delay (ZTD), is estimated from the GNSS observations. It is divided up into two components, the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD) (Davis et al., 1985).

Numerous studies have been carried out on the use of GNSS for monitoring long-term changes in the atmospheric water vapour (Chen and Liu, 2016; Parracho et al., 2018; Jones et al., 2020). Although these datasets provide continuous and high temporal resolution integrated water vapour (IWV) time series, they are also compromised by interventions caused by changes to the GNSS stations, such as changes in hardware (e.g., antenna or radome replacements), software updates, and sudden changes in the local multipath environment. Such changes can introduce a shift in the absolute IWV value that obscure true climate trends. We refer to such interventions as step offsets in the following.

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

In order to correct interventions in GNSS-derived IWV time series, many studies have validated several homogenization strategies, ranging from global reanalysis products to high-precision local comparisons. We have identified three different methods:

1. Using a reanalysis product, e.g., ERA5 from the European Centre for Medium-Range Weather Forecasts (ECMWF) as the reference data is the most common approach, where GNSS-derived IWV is compared against reanalysis time series to identify step offsets (Ning et al., 2016; Quarello et al., 2022; Nguyen et al., 2024). For instance, a recent study by Bai et al. (2026) demonstrated a comprehensive homogenization of GPS-derived IWV time series over China by using both the ERA5 reanalysis and MODIS satellite observations as reference data sets to identify and correct for interventions. While effective for identifying IWV step offsets, this method is susceptible to "representation errors" due to differences in spatial and temporal resolution between localized GNSS measurements and gridded reanalysis products. Additionally, suppressing seasonal variability and noise requires a minimum data span on both sides of an intervention. This is further discussed in Section 3.1.

2. IWV step offsets can be quantified using independent instruments such as very long baseline interferometry (VLBI) or water vapour radiometers (WVR). For example, Ning et al. (2012) identified a step offset of approximately 4 mm in the ZWD caused by a radome replacement at the ONSA station by using the VLBI and WVR data at the Onsala Space Observatory. While highly accurate, the primary drawback of such approach is the scarcity of these instruments; very few GNSS sites have co-located VLBI, or WVR, hardware available for long-term validation.

3. It is common nowadays that permanent GNSS installations are equipped with a secondary "twin" station. This allows us to form IWV differences between co-located stations which can be considered as a robust method for local homogenization. Because both stations sense nearly the same atmospheric volume, common-mode atmospheric noise and representation errors cancel out in the estimated IWV differences. This enables the detection and correction of instrumental step offsets with significantly higher precision and shorter data records than is possible using reanalysis products alone. For example, Nguyen et al. (2024) recently demonstrated that such GPS-GPS differences are among the most effective predictors for accurately attributing interventions to a specific instrument.

We have identified GNSS sites with two stations, in Sweden and Denmark with time series longer than 10 years and documented interventions, in order to evaluate different methods to find and quantify the effect of interventions. The ERA5 reanalysis product from ECMWF was used as a validation reference. Furthermore, we examined the correlation between step offsets in the daily estimates of the station vertical component and step offsets in the IWV. For this study, we used exclusively GPS data, originating from the processing design of the new BIFROST (baseline inferences for Fennoscandian rebound observations, sea level, and tectonics) project (Johansson et al., 2002). In that framework, the decision to utilize GPS data only was made to maintain a homogeneous long-term time series.

The paper is organized as follows: Section 2 describes the GNSS stations and the datasets, the GPS data processing, and the use of ERA5. Details of the procedures applied for IWV homogenization and the results are presented in Section 3. Finally, Sections 4 and 5 provide discussions and conclusions, respectively.

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

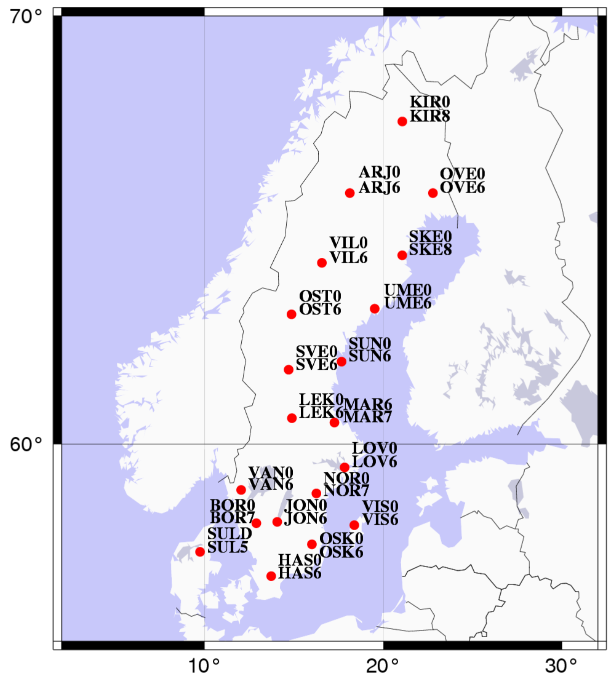

Figure 1. Locations of the twin GNSS stations used in the study.

2 Datasets

2.1 GNSS

The locations of the GNSS sites are shown in Figure 1. The selection of sites is based on that there is at least one inconsistency at one of the two co-located stations (hereafter referred to as twin stations) during the time period January 2011–December 2024. The maximum horizontal distance is 10.9 m (MAR6 and MAR7) and the maximum height difference is 1.2 m (BOR0 and BOR7). Although they are not identical, neither the installation nor the hardware, we refer to them as twin stations. Station specifications are summarized in Table 1.

Table 1: Antenna and radome changes at GNSS stations. Dates indicate the start of use for each equipment.

Station	Date	Antenna	Radome
KIR0	1993-08-01	AOAD/M_T	OSOD
	2016-10-31	JNSCR_C146-22-1	OSOD
	2023-10-17	JAVRINGANT_DM	OSOS
KIR8*	2011-08-12	LEIAR25.R3	LEIT
MAR6	1994-10-11	AOAD/M_T	OSOD

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

Station	Date	Antenna	Radome
	2022-09-02	JAVRINGANT_DM	OSOD
MAR7*	2011-02-15	LEIAR25.R3	LEIT
SKE0	2007-08-01	ASH701945C_M	OSOD
	2022-03-09	JAVRINGANT_DM	OSOD
SEK8*	2011-07-07	LEIAR25.R3	LEIT
	2024-09-26	TPSCR.G5	OSOS
BOR0	1996-05-23	AOAD/M_T	OSOD
	2016-08-23	JNSCR_C146-22-1	OSOD
	2020-08-13	TRM59800.00	OSOD
BOR7*	2011-10-07	LEIAR25.R3	LEIT
VIL0	2010-08-30	ASH701945C_M	OSOD
	2022-03-31	JNSCR_C146-22-1	OSOD
VIL6*	2011-07-20	LEIAR25.R3	LEIT
	2024-09-19	TPSCR.G5	OSOS
VIS0	1993-08-01	AOAD/M_T	OSOD
	2025-03-26	JAVRINGANT_DM	OSOD
VIS6*	2011-05-18	LEIAR25.R3	LEIT
	2024-09-03	TPSCR.G5	OSOS
ARJ0	1993-08-01	AOAD/M_T	OSOD
	2022-08-27	JAVRINGANT_DM	OSOD
ARJ6*	2011-07-20	LEIAR25.R3	LEIT
	2024-09-25	TPSCR.G5	OSOS
HAS0	1993-08-01	AOAD/M_T	OSOD
	2015-11-03	JNSCR_C146-22-1	OSOD
	2024-09-04	JAVRINGANT_DM	OSOD
HAS6*	2011-06-14	LEIAR25.R3	LEIT
	2025-03-20	TPSCR.G5	OSOS
JON0	2002-08-21	ASH701073.1	OSOD
	2020-11-26	JAVRINGANT_DM	OSOD
JON6*	2011-06-16	LEIAR25.R3	LEIT
	2025-03-20	TPSCR.G5	OSOS
LEK0	1998-08-13	ASH700936D_M	OSOD
	2022-03-31	JAVRINGANT_DM	OSOD
LEK6*	2011-05-05	LEIAR25.R3	LEIT

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

Station	Date	Antenna	Radome
	2022-11-09	LEIAR20	LEIM
LOV0	2005-07-21	ASH700936A_M	OSOD
	2021-08-25	JAVRINGANT_DM	OSOD
LOV6*	2011-08-23	LEIAR25.R3	LEIT
	2022-11-10	TPSCR.G5	OSOS
NOR0	2005-07-21	ASH700936A_M	OSOD
	2022-03-15	JAVRINGANT_DM	OSOD
NOR7*	2011-06-21	LEIAR25.R3	LEIT
	2025-03-25	TPSCR.G5	OSOS
OSK0	2005-07-20	ASH700936A_M	OSOD
	2021-08-24	JAVRINGANT_DM	OSOD
OSK6*	2011-07-20	LEIAR25.R3	LEIT
	2023-01-19	TPSCR.G5	OSOS
OST0	1993-08-01	AOAD/M_T	OSOD
OST6*	2011-06-28	LEIAR25.R3	LEIT
	2024-09-20	TPSCR.G5	NONE
OVE0	1995-06-16	ASH700936A_M	OSOD
	2021-08-30	JAVRINGANT_DM	OSOD
OVE6*	2011-08-10	LEIAR25.R3	LEIT
SUN0	1993-08-01	AOAD/M_T	OSOD
	2023-09-29	JAVRINGANT_DM	OSOD
SUN6*	2011-09-22	LEIAR25.R3	LEIT
	2022-11-08	LEIAR20	LEIM
SVE0	2008-05-29	ASH701945C_M	OSOD
	2021-08-31	JAVRINGANT_DM	OSOD
SVE6*	2011-06-20	LEIAR25.R3	LEIT
UME0	1993-08-01	AOAD/M_T	OSOD
	2022-08-26	JAVRINGANT_DM	OSOD
UME6*	2011-07-06	LEIAR25.R3	LEIT
	2024-09-26	TPSCR.G5	OSOS
VAN0	1995-05-22	AOAD/M_T	OSOD
	2022-08-29	JAVRINGANT_DM	OSOD
VAN6*	2011-08-25	LEIAR25.R3	LEIT

Station	Date	Antenna	Radome
	2022-03-16	TPSCR.G5	OSOS
SULD	2005-06-14	ASH701945E_M	UNAV
	2019-01-31	LEIAR25.R4	LEIT
SUL5*	2011-06-27	LEIAR25.R4	LEIT

* Co-located with the station in the line(s) above

The GPS data processing was executed using the GipsyX (v.2.1) software (Bertiger et al., 2020) through a precise point positioning (PPP) strategy (Zumberge et al., 1997). Our analysis utilized ionosphere-free linear combinations of carrier-phase observations at a sampling rate of 30 s, using final GPS orbit and clock products provided by Jet Propulsion Laboratory https://sideshow.jpl.nasa.gov/pub/JPL_GNSS_Products/Final/. We applied an elevation cutoff angle of 7° and implemented absolute phase centre variation (PCV) calibrations via the igs20_2317.atx file (Schmid et al., 2007). The ZTD and the linear horizontal gradients were estimated every 5 min using a random walk model with standard deviation constraints of 3 $\mathrm{mm}\sqrt{\mathrm{h}}^{-1}$ and 0.6 $\mathrm{mm}\sqrt{\mathrm{h}}^{-1}$, respectively. Slant delays were mapped to the zenith using the Vienna Mapping Function 1 (VMF1) (Boehm et al., 2006).

2.2 ERA5

We used the global reanalysis ERA5 from the ECMWF for several purposes. First the ground pressure was used to calculate the ZHD and then obtain the ZWD by subtracting the ZHD from the ZTD. The mean temperature was used to convert the resulting ZWD into IWV (Ning et al., 2016). The calculation of the ZHD has the ground pressure and the site position as input parameters. To assess the quality of the ERA5 ground pressure, interpolated to the location of the GNSS antenna, we have independent pressure observations at the twin IGS stations ONSA/ONS1. No interventions occurred at these stations during the studied time period, and they are therefore not included in the study. This barometer is regularly calibrated and its observations are not input to the ERA5 reanalysis. The calibrations have an uncertainty of ±0.2 hPa, corresponding to ±0.014 kg m^{-2} in the IWV. Pressure observations at ONSA/ONS1 are compared to the hourly ERA5 values in Figure 2. Comparisons were also made for four GNSS sites in the north of Sweden (KIR0, ARJ0, VIL0, and OST0) with observations acquired at four nearby meteorological stations, owned by Swedish Meteorological and Hydrological Institute (SMHI). They are within a distance <35 km to each site. We found no alarming systematics or jumps in either the observations or the ERA5 data. However, the pressure differences exhibits a temperature-dependent seasonal signature due to the height differences between the SMHI sites and the ERA5 model referred to the GNSS sites.

The ERA5 time series of the IWV were used for comparisons with the IWV estimated from the GPS analysis. One comparison was to derive step offsets in the GPS time series and another was to compare estimated linear trends in the IWV between the ERA5 and the GPS time series, obtained using different methods to derive the step offsets. ERA5 has a spatial resolution of 31 km and a temporal resolution of 1 h (Hersbach et al., 2020). The IWV values were interpolated to each GNSS station using the four surrounding grid points and vertically adjusted to the station height.

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

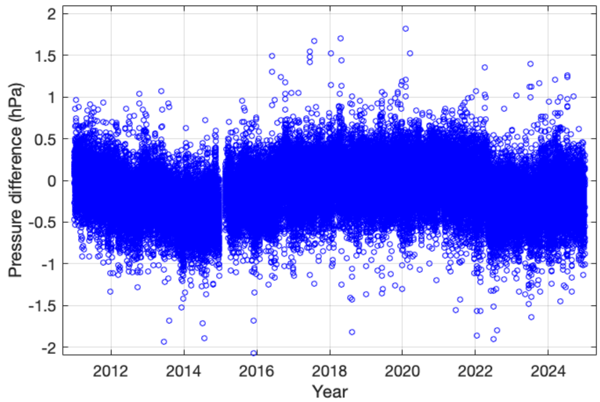

Figure 2. The pressure differences ERA5−observed at the ONSA/ONS1 site. The mean is −0.14 hPa and the standard deviation is 0.26 hPa.

3 Results

3.1 Estimation of IWV step offsets using ERA5 and twin GPS stations

The GNSS stations, listed in Table 1, have experienced antenna and radome replacements, which may introduce step offsets in the GPS-derived IWV time series. To ensure temporal homogeneity, we applied a two-step correction strategy combining comparisons with ERA5 reanalysis IWV and observations from twin GPS stations. IWV difference series were first constructed either between GPS and ERA5 data or between the data from the twin GPS stations. These difference series suppress large-scale atmospheric variability and enhance the detectability of station-specific inhomogeneities. The IWV step offset associated with each intervention was then estimated by comparing the mean levels of the difference series in segments of different lengths before and after the intervention.

For the GPS-ERA5 approach, the resulting difference time series served as a reference. Because ERA5 is not affected by station-specific hardware changes, discontinuities appearing in this series are indicative of local instrumental effects. However, ERA5 is a model-based reanalysis product with relatively coarse spatial resolution and implicit smoothing introduced by the data assimilation system, meaning it may not fully capture small-scale atmospheric variability at the station location. In addition, although reanalyses are designed to provide temporally consistent fields, they are not entirely free of discontinuities. Changes in the observing system (e.g., introduction of new satellite sensors, evolving GNSS radio occultation data streams, or modifications in data usage) can introduce temporal inhomogeneities into reanalysis moisture fields. Therefore, some step offsets in GPS-ERA5 difference series may reflect changes in the reanalysis observing system rather than true station-related effects. This limitation motivates the use of GPS-GPS differences as the primary reference for homogenization whenever suitable nearby stations are available.

For the twin-station approach, IWV differences were computed between the two stations. Since both stations observe almost the same atmospheric volume at similar spatial scales, most atmospheric variability cancels out, and the remaining signal predominantly reflects station-specific effects. The GPS-GPS difference series was therefore used as the primary reference for

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

homogenization. This approach is more robust than GPS-ERA5 because it relies entirely on observational data with consistent retrieval characteristics, avoiding representation errors inherent in reanalysis products. The GPS-ERA5 comparison was mainly used as a complementary reference and it is important to assess its quality since it has frequently been used for homogenization of IWV time series estimated from GNSS data.

Step offsets associated with antenna-related interventions were estimated from the mean difference between the pre- and post-change segments and applied as step corrections to the original GPS IWV series. The step-offset magnitude was derived from the corresponding difference time series (either GPS-ERA5 or GPS-GPS). For GPS-ERA5 differences, a default window length of one year was used on both sides of the intervention to average out seasonal variability and short-term atmospheric fluctuations. If another intervention occurred within this interval, the window was shortened to terminate at the nearest adjacent intervention to avoid mixing multiple discontinuities within the averaging period. This ensured that each step-offset estimate represented a single instrumental change.

One example of the time series of IWV differences given by GPS-ERA5 and GPS-GPS is shown in Figure 3 for the station BOR0. The GPS-ERA5 differences show large variability representing differences between point observations and gridded reanalysis fields. The GPS-GPS differences, formed with the twin station BOR7, show significantly reduced scatter, indicating that common atmospheric variations are largely cancelled. Around documented intervention epochs, potential systematic step offsets are visible in the GPS-GPS series but are obscured in the GPS-ERA5 series.

After estimation, the derived step offset was applied as a correction to all data following the intervention epoch in the GPS IWV series. When multiple interventions were present, corrections were applied sequentially in chronological order. This approach ensures temporal homogeneity while preserving the original atmospheric variability and long-term trend.

All identified interventions across the twin-station network, including their exact dates, and the resulting IWV step offsets calculated from both the GPS-GPS and GPS-ERA5 difference series are summarized in Table 2. All interventions, except one, are antenna changes, some of them with simultaneous radome changes. The intervention on 2019-04-02 at the station BOR0 was a change of the receiver.

3.2 Impact of interventions on station vertical component

Any changes to the station environment, e.g., instrumental changes or sudden variations in multipath effects, can also introduce interventions which result in step offsets in station coordinates, especially in the vertical component. The stations used are far from tectonic plate boundaries and installed on solid bedrock meaning that the station velocity typically remains constant over multi-year periods. Therefore, coordinate step offsets can be estimated when the precise epochs of the interventions are known. This can be done by applying a least-squares estimator to the coordinate time series to simultaneously solve for the station velocity, step offsets and seasonal variations. The estimated step offsets in height are also presented in Table 2.

Besides the least-squares estimation using the original time series, we also carried out outlier detection on the time series of the vertical component for each station using a two-pass residual filter with seasonal sensitivity. A strict 1-σ threshold was applied during winter months (December, January, and February) to aggressively remove outliers often caused by snow on the antenna, while a standard 2-σ threshold was used for the remainder of the year to remove anomalies. As an example, the

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

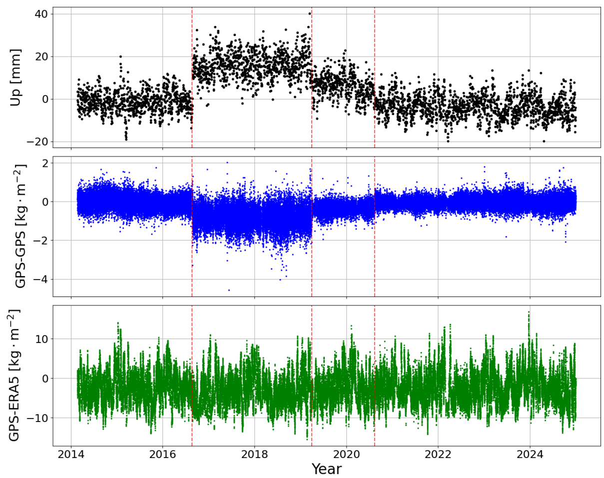

Figure 3. Time series of the up coordinate and IWV differences for GPS-GPS and GPS-ERA5 for the station BOR0. Vertical red dotted lines indicate the times of the interventions given in Table 2.

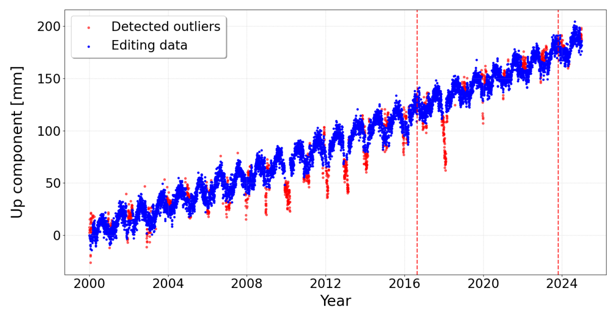

Figure 4. Time series of the up coordinate, before and after removing outliers, obtained from the station KIR0. The vertical red dotted lines indicate antenna changes.

results from station KIR0 are presented in Figure 4. Outliers are predominantly concentrated during winter periods, which is expected given its location in northern Sweden. As seen in Table 2, the inclusion of these outliers can bias the estimated vertical step offsets by up to 5 mm. In addition to random outliers, the vertical coordinate time series for station VAN6 exhibited significantly increasing noise prior to its antenna change which was attributed to lichen growth on the radome (Lilje et al., 2023). Consequently, an additional two years of degraded data (from July 1, 2019, until the day before the antenna change) were excluded for VAN6 prior to the offset estimation. Henceforth, only the step offsets in height estimated after the removal of these outliers and degraded data periods are used in the subsequent analysis.

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

Table 2. Step offsets in height and IWV.

Station	Date	Up[a] [mm]	Up[b] [mm]	IWV[c] [kg m^{-2}]	IWV[d] [kg m^{-2}]
KIR0	2016-08-23	7.39	4.39	−0.06	−0.10
KIR0	2023-10-20	6.81	4.81	−0.13	−0.40
MAR6	2022-09-02	9.07	8.98	−0.19	−0.04
SKE0	2022-03-09	1.16	1.20	−0.02	−0.76
SKE8	2024-09-26	17.95	17.57	−0.41	1.50
BOR0	2016-08-23	15.89	16.11	−0.73	−1.69
BOR0	2019-04-02	−9.93	−10.30	0.44	1.65
BOR0	2020-08-13	−9.69	−9.68	0.32	−0.06
VIL0	2022-03-31	5.63	4.69	0.02	−0.08
VIL6	2024-09-19	18.75	17.99	−0.19	1.31
VIS6	2024-09-03	4.19	3.98	−0.17	−1.28
ARJ0	2022-08-27	3.59	3.92	−0.08	−0.51
ARJ6	2024-09-25	25.09	23.58	−0.47	3.46
HAS0	2015-11-03	4.37	4.41	0.01	−0.17
HAS0	2024-09-04	−3.88	−3.94	0.03	−1.26
JON0	2020-11-26	6.20	5.97	−0.06	−0.86
LEK0	2022-03-31	−3.23	−2.79	−0.03	−0.07
LEK6	2022-11-09	15.07	14.43	−0.64	0.27
LOV0	2021-08-25	−4.36	−4.60	0.03	0.01
LOV6	2022-11-10	11.96	12.23	−0.38	−0.12
NOR0	2022-03-15	−2.07	−1.84	0.01	−0.53
OSK0	2021-08-24	−4.44	−4.74	0.06	−0.28
OSK6	2023-01-19	7.83	7.83	−0.29	0.26
OST6	2024-09-20	4.51	4.74	−0.09	1.02
OVE0	2021-08-30	−1.77	−2.29	0.03	0.83
SUN0	2023-09-29	0.75	0.93	−0.11	0.25
SUN6	2022-11-08	15.33	15.56	−0.52	−0.42
SVE0	2021-08-31	−0.88	−0.57	0.03	−0.13
UME0	2022-08-26	0.21	0.54	−0.11	−0.33
UME6	2024-09-26	15.39	14.51	−0.33	1.12
VAN0	2022-08-29	−1.34	−1.22	−0.02	0.57
VAN6	2022-03-16	−15.57	−6.03	0.02	0.24
SULD	2019-01-31	−7.12	−7.14	0.22	1.15

[a] Step offset with original data.

[b] Step offset after removing outliers.

[c] Step offset given by GPS-GPS.

[d] Step offset given by GPS-ERA.

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

3.3 Correlation between step offsets in height and IWV

In GNSS data processing, the error in the estimated ZTD can be influenced by many other error sources, e.g., receiver clock errors, satellite orbit errors, multipath effects, and errors in the antenna height of the station. Among these, errors in the estimated station height and ZTD are highly correlated because they are both affected by the signal path length in an elevation-dependent way. Some studies, e.g., Herring (1986) and Hill et al. (2009), have shown that a relative ZTD (and hence also ZWD) error of 0.3 mm can lead to a relative vertical error of the order of 1 mm, depending on the observing geometry.

An error in the estimated antenna height introduces a systematic bias in the geometric distance between the receiver and the satellites. During the parameter estimation process, a significant portion of this height error is absorbed by the ZTD. This leads to a strong negative correlation between the two parameters, where the height error is largely compensated for by an error in the ZTD estimate.

One example of this relationship is shown in Figure 3 for the station BOR0, where two clear vertical step offsets are present, caused by antenna changes. Significant offsets, highly correlated with the vertical step offsets, are evident in the GPS-GPS IWV difference series. However, such step offsets are difficult to isolate in the GPS-ERA5 IWV differences, as they are obscured by the high natural variability and representation errors inherent in the reanalysis data.

Figure 5 depicts the relationship between step offsets in height and the corresponding IWV step offsets for all interventions. A clear and strong negative correlation is observed in the GPS-GPS data, with a correlation coefficient of -0.88. The resulting regression slope is -30.4 mm kg^{-1} m^2 which indicates that a 1 mm height step offset corresponds to an IWV offset of approximately 0.03 kg m^{-2}. This value is slightly lower compared to what Herring (1986) obtained for VLBI observations with a 7° elevation cutoff angle.

In contrast, the correlation between height offsets and IWV step offsets derived from GPS-ERA5 differences is weak, resulting in a positive correlation coefficient of 0.22. This poor correlation occurs because several interventions (e.g., stations UME6 and ARJ6 in late September 2024) lacked the required 1-year data window. As demonstrated in Figure 6, discrepancies become larger when the available ERA5 data window drops below 300 days, leaving IWV step offset estimates significantly influenced by uncompensated natural atmospheric variations.

As shown in Figure 7, when the analysis is restricted strictly to interventions that meet almost 1-year window requirement, the GPS-ERA5 correlation increases significantly to $-$ 0.59. Meanwhile, the GPS-GPS differences continue to demonstrate a strong negative correlation of -0.92, further validating the robustness of using twin stations to accurately estimate and quantify instrumental IWV step offsets. Similarly, the direct agreement between GPS-GPS and GPS-ERA5 IWV step offsets improves from 0.05 across all data to 0.61 when a window length of at least 300 days is applied (Figure 8).

3.4 Comparison between IWV trends from GPS and ERA5

The motivation for this study is to assess the possibility of having IWV time series that are less affected by hardware changes or other inconsistencies at the GNSS stations. Therefore, it is of interest to compare the estimated linear trends from the different GPS time series with those from the ERA5 reanalysis at each site. This in done in Figure 9. The largest improvement in terms

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

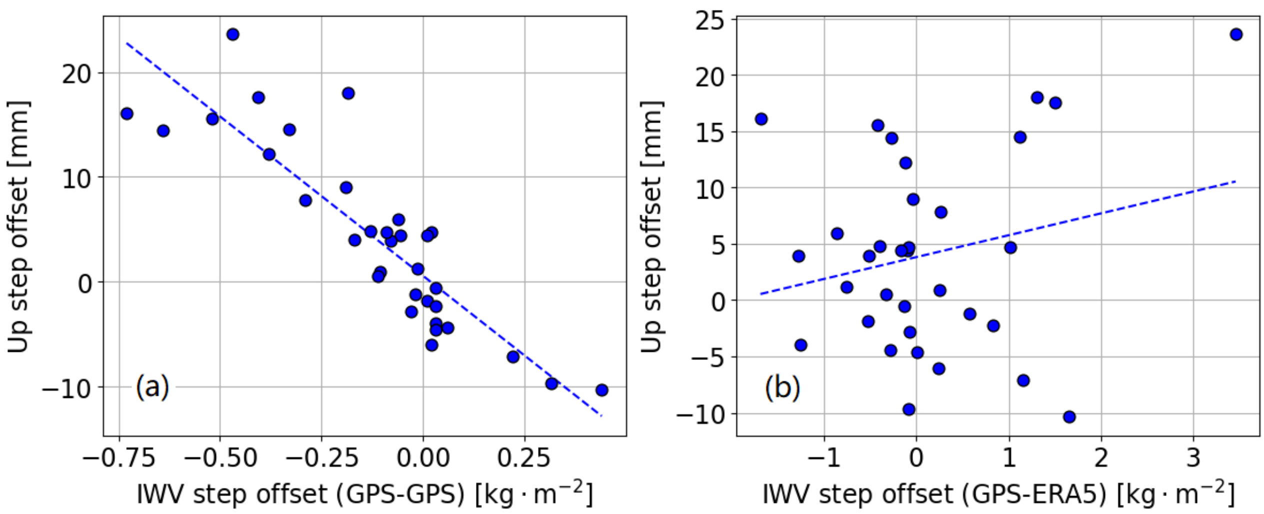

Figure 5. The correlation between the height step offsets and the IWV step offsets. The correlation coefficient for (a) GPS-GPS is −0.88 and for (b) GPS-ERA5 is 0.22.

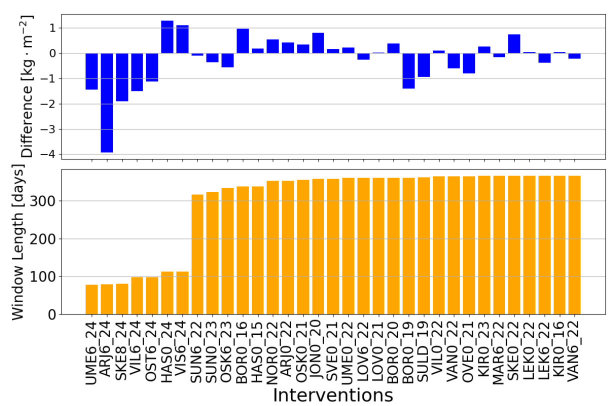

Figure 6. The upper panel shows the IWV differences between the step offsets derived from GPS-GPS and GPS-ERA5. The lower panel shows the window length applied to the GPS-ERA5 data when calculating the IWV step offsets. The differences between the GPS-GPS and GPS-ERA5 estimates become larger when the window length used for GPS-ERA5 is shorter.

of correlation is to obtain the step offsets from the twin stations. We also note a small improvement for single stations when estimating the IWV step offset based on the step offset in the vertical coordinate.

The linear trends obtained from step offsets derived via the GPS-ERA5 method demonstrate a much weaker correlation of only 0.39, see Figure 9d. No improvement in the correlation is observed, even when the analysis is restricted exclusively to stations with a data window length greater than 300 days for the GPS-ERA5 data (not shown).

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

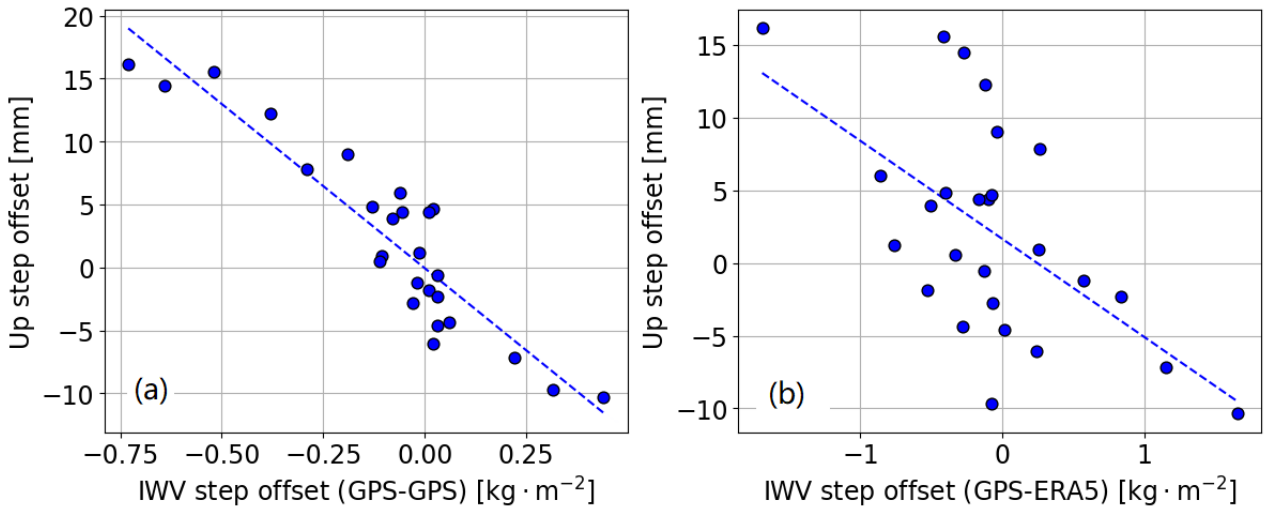

Figure 7. The correlation between the height step offsets and the IWV step offsets restricted to stations with a window length greater than 300 days. The correlation coefficient becomes −0.92 for (a) GPS-GPS and −0.59 for (b) GPS-ERA5.

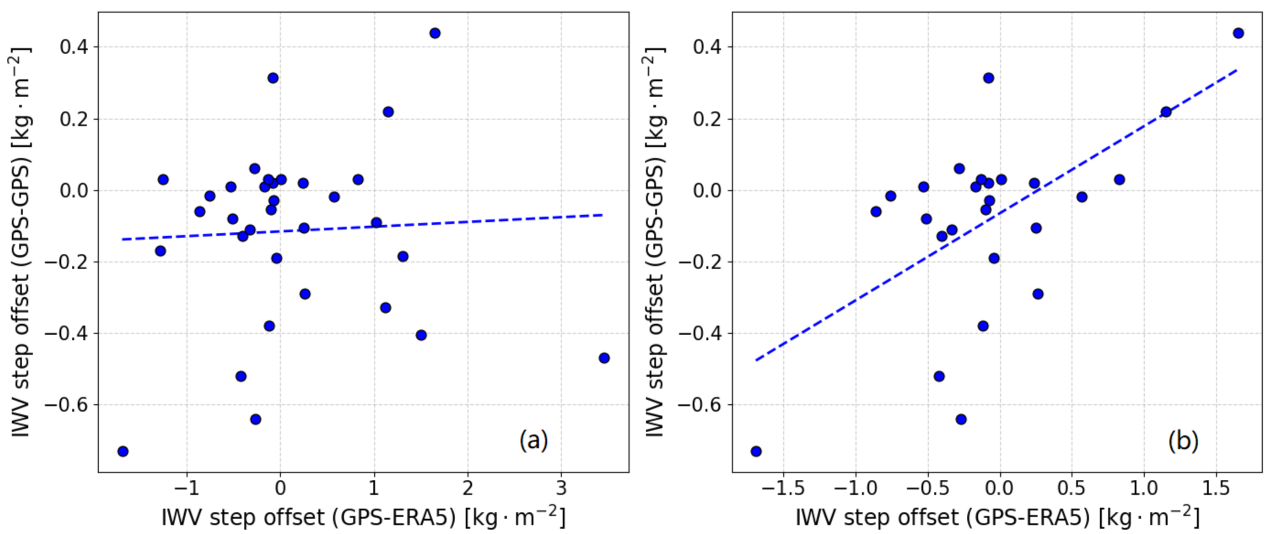

Figure 8. The correlation between the IWV step offsets calculated using the GPS-GPS and GPS-ERA5 methods. (a) shows the correlation across all stations with a coefficient of 0.05, while (b) shows the results restricted to a window length of at least 300 days on both sides of the intervention for the GPS-ERA5 data, with a correlation coefficient of 0.61.

For this limited data set of 14 years and the subset of available sites we found that trends tend to be larger in the south and smaller in the north. As seen in Figure 9a-c this is valid for both the GPS and the ERA5 time series. A question for future studies is why the ERA5 trends in general are larger than those estimated from the GPS data, especially when the GPS trends

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

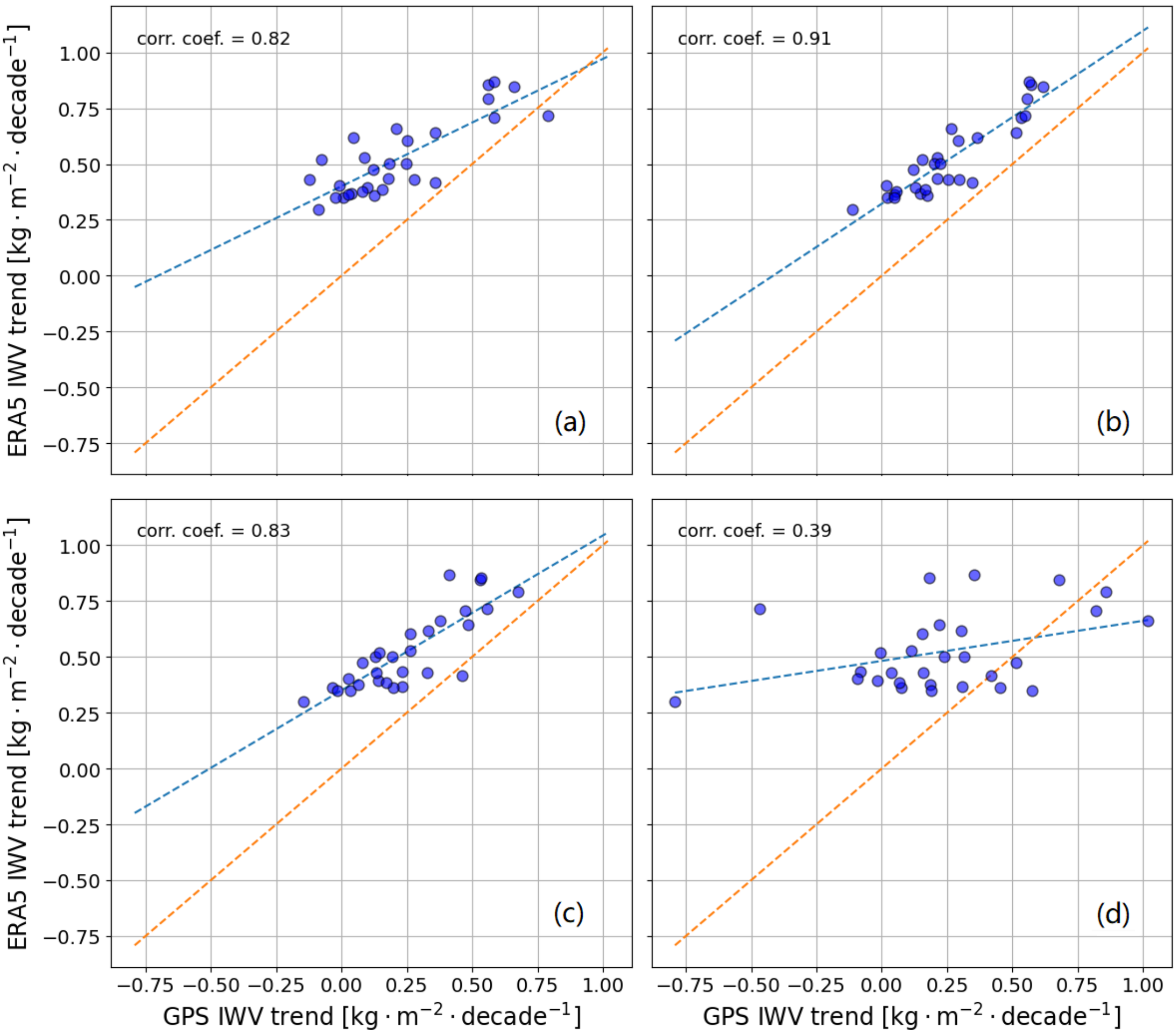

Figure 9. Correlation of IWV trends estimated from GPS and ERA5 for different homogenization cases: (a) using the original uncorrected GPS IWV; (b) using GPS IWV corrected with step offsets derived from the twin stations GPS-GPS IWV differences; (c) using GPS IWV corrected based on the detected vertical step offsets, assuming a relation of -0.03 kg m^{-2} IWV per 1 mm vertical displacement; (d) using GPS IWV corrected with step offsets derived from the GPS-ERA5 IWV differences.

are small, see Figure 9. Studies focusing on the estimation of linear trends should include longer time series compared to the 14 years used in this study which were limited by the existence of twin stations where interventions had occurred.

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

4 Discussion

Our analysis reveals a strong negative correlation between the vertical displacements and the corresponding IWV step offsets at the interventions. A 1 mm vertical step offset corresponds to an approximate 0.03 kg m^{-2} step offset in IWV. This relationship provides a useful validation tool for the homogenization of IWV time series in two primary ways: (1) When an intervention is identified in the IWV time series, the station's vertical coordinate time series can be used as a cross-reference. If a corresponding vertical step offset exists at the same epoch, the IWV step offset can be confirmed. (2) In cases where reference data, e.g., from a twin station, are unavailable such a relationship allows for the estimation of an IWV step offset from the estimated vertical displacement.

The study demonstrates that the homogenization of GPS-derived IWV time series is highly dependent on the quality and length of the reference data used for step-offset estimation. The ECMWF reanalysis product, i.e., ERA5, is a common and valuable tool to be used, which, however, is subjected to representation errors and high-frequency atmospheric noise. The results indicate that the GPS-ERA5 method requires a minimum data span of about one year on both sides of the intervention to effectively average out natural atmospheric variations. When not enough data are used, the estimated IWV step offsets will be inaccurate. As a result, the correlation between the height and IWV step offsets became weak and inconsistent (a positive correlation of 0.34). Furthermore, if GPS data are to be used to examine the accuracy of ERA5, the use of ERA5 to estimate step offsets in the GPS IWV time series, will make such a comparison less meaningful.

In contrast to the limitations of ERA5 data, the use of the data obtained from twin stations is robust for IWV step offset estimation. This approach results in a consistent strong negative correlation coefficient of (-0.88 across all stations, and -0.92 when restricting to stations with a data window length greater than 300 days for the GPS-ERA5 data) between the vertical and the IWV step offsets with a much shorter time window surrounding the intervention. This is because the twin stations sense nearly identical atmospheric variations, the GPS-GPS differences effectively cancel out the common atmospheric noise and seasonal signals.

The degradation in long-term trend agreement after applying the GPS-ERA5 derived step offsets indicates a fundamental vulnerability in utilizing reanalysis products for IWV time series homogenization, as the approach is highly susceptible to representation errors that override small, physically real step offsets. As shown in Figure 8b, the GPS-GPS derived step offsets are tightly clustered, mostly between -0.7 and $+0.3$ kg m^{-2}, with over 50 % of the step offsets having a magnitude smaller than 0.1 kg m^{-2}. In contrast, the GPS-ERA5 step offsets exhibit significantly larger scatter, fluctuating wildly between -1.6 and $+1.6$ kg m^{-2}.

When the requirement of a window length greater than 300 days is not applied, the fluctuations span an even wider range, see Figure 8a. This indicates that the GPS-ERA5 approach requires a minimum data span of approximately one year on both sides of an intervention to average out seasonal noise and localized representation errors. Furthermore, because the uncertainty in the ERA5 reanalysis scales proportionally with the absolute IWV (Ning et al., 2012), asymmetric atmospheric conditions, pre- and post-intervention, can introduce errors that easily overwhelm smaller, physically real step offsets, rendering the GPS-ERA5 corrections highly unreliable in these scenarios.

5 Conclusions

We investigated the homogenization of integrated water vapour (IWV) inferred from 19 twin GNSS stations. During the time period January 2011 to December 2024 hardware changes have been documented, causing inconsistencies in the IWV time series.

In terms of agreement with the estimated linear trends from the ERA5 reanalysis we found that the best agreement was obtained using the twin stations to estimate step offsets at the times of the interventions. The second best method was when estimated step offsets in the vertical component were estimated from observations of the single station. Furthermore, using the ERA5 IWV time series to estimate the step offset resulted in a trend agreement that was worse compared to the original GPS IWV time series. In general we conclude that the estimated step offsets tend to be too large when the ERA5 IWV was used as a reference. Consequently, step offsets derived from the GPS-ERA5 approach must be treated with caution.

This study characterizes a strong negative correlation between the estimated step offsets in the vertical coordinate component and the estimated step offsets in the retrieved IWV. Specifically, we established an empirical relationship which can serve as a valuable, stand-alone diagnostic tool for single-station sites, where no twin-station reference exists. This enables a direct correction of IWV step offsets using the vertical coordinate time series alone.

Data availability. The IWV data obtained from the GNSS stations together with the corresponding ERA5 data are registered and archived by the Swedish National Data Service (SND) (Elgered and Ning, 2026).

Author contributions. The two authors (TN and GE) planned the work and the structure of the paper together. TN performed the GPS data analysis and wrote the main part of first version of the manuscript. Both authors approved the manuscript before submission.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. We are grateful to Tobias Nilsson for the help of retrieving the ground pressure, the mean temperatures, and the IWV time series from the ERA5 data.

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

References

Bai, J., Van Malderen, R., Pottiaux, E., Zhang, W., Lou, Y., and Liu, J.: Long-term variability of homogenized GPS-derived precipitable water vapor over Chinese stations (2000–2020), J. Geophys. Res., 131, e2025JD046275. https://doi.org/10.1029/2025JD046275, 2026.

Bertiger, W., Bar-Sever, Y., Dorsey, A. Haines, B., Harvey, N., Hemberger, D., Heflin, M., Lu, W., Miller, M., Moore, A.W., Murphy, D., Ries, P., Romans, L., Sibois, A., Sibthorpe, A., Szilagyi, B., Vallisneri, M., and Willie, P.: GipsyX/RTGx, a new tool set for space geodetic operations and research, Adv. Space Res., 66, 469–489, https://doi.org/10.1016/j.asr.2020.04.015, 2020.

Boehm, J., Werl, B., and Schuh, H.: Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data, J. Geophys. Res., 111, B02406, https://doi.org/10.1029/2005JB003629, 2006.

Chen, B., and Liu, Z.: Global water vapor variability and trend from the latest 36 year (1979 to 2014) data of ECMWF and NCEP reanalyses, radiosonde, GPS, and microwave satellite, J. Geophys. Res. Atmos., 121, 11,442–11,462, https://doi.org/10.1002/2016JD024917, 2016.

Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E. E., and Elgered. G.: Geodesy by radio interferometry: effects of atmospheric modeling errors on estimates of baseline length, Radio Sci., 20, 1593–1607, https://doi.org/10.1029/RS020i006p01593, 1985.

Elgered, G., and Ning, T.: Data for homogenization of integrated water vapour time series using twin GNSS stations and vertical step offsets (Version 1) [Data set]. Chalmers University of Technology, https://doi.org/10.71870/2qmn-f008, 2026.

Herring, T. A.: Precision of vertical position estimates from very long baseline interferometry, J. Geophys. Res., 91(B9), 9177–9182, doi:10.1029/JB091iB09p09177, 1986.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., et al.: The ERA5 global reanalysis, Q. J. Roy. Meteor. Soc., 146(730), 1999–2049. https://doi.org/10.1002/qj.3803, 2020.

Hill, E. M., Davis, J. L., Elósegui, P., Wernicke, B. P., Malikowski, E., Niemi, N. A.: Characterization of site-specific GPS errors using a short-baseline network of braced monuments at Yucca Mountain, southern Nevada. J. Geophys. Res., 114:B11402. doi:10.1029/ 2008JB006027, 2009.

Johansson, J. M., Davis, J. L., Scherneck, H.-G., Milne, G. A., Vermeer, M., Mitrovica, J. X., Bennett, R. A., Jonsson, B., Elgered, G., Elósegui, P., Koivula, H., Poutanen, M., Rönnäng, B. O., and Shapiro, I. I.: Continous GPS measurements of postglacial adjustment in Fennoscandia, 1, Geodetic results, J. Geophys. Res., 107(B8), doi:10.1029/2001JB000400, 2002.

Jones, J., Guerova, G., Jan Douša, J., Dick, G., Haan, S., Pottiaux, E., Bock O., Pacione, R., and Malderen, R. (Eds.): Advanced GNSS tropospheric products for monitoring severe weather events and climate, Springer, 563 p., https://link.springer.com/book/10.1007/978-3-030-13901-8, 2020.

Lilje, C., and Jivall, L.: Antennas on SWEPOS fundamental stations, presented at the NKG working group of reference frames meeting, Estonia, March 2023, available at: https://www.nordicgeodeticcommission.com/wp-content/uploads/2023/06/NKG_WGRF2023_1-3_Lilje.pdf (last access: 20 May 2026), 2023.

Ning, T., Haas, R., Elgered, G., and Willén, U.: Multi-technique comparisons of 10 years of wet delay estimates on the west coast of Sweden, J. Geod., 86, 565–575, https://doi.org/10.1007/s00190-011-0527-2, 2012.

Ning, T., Wickert, J., Deng, Z., Heise, S., Dick, G., Vey, S., Schöne, T.: Homogenized time series of the atmospheric water vapor content obtained from the GNSS reprocessed data, J. Clim., 48, 2443–2456, https://doi.org/10.1175/JCLI-D-15-0158.1, 2016.

https://doi.org/10.5194/egusphere-2026-3520
Preprint. Discussion started: 9 September 2026

Nguyen, K. N., Quarello, A., Bock, O., and Lebarbier, E.: A statistical method for the attribution of change-points in segmented integrated water vapor difference time series, Int. J. Climatol., 44(6), 2069–2086, https://doi.org/10.1002/joc.8441, 2024.

Parracho, A. C., Bock, O., and Bastin, S.: Global IWV trends and variability in atmospheric reanalyses and GPS observations, Atmos. Chem. Phys., 18:, 6,213–16,237, https://doi.org/10.5194/acp-18-16213-2018, 2018.

Quarello, A., Bock, O., and Lebarbier, E.: GNSSseg, a statistical method for the segmentation of daily GNSS IWV time series, Remote Sens., 14(14), 3379, https://doi.org/10.3390/rs14143379, 2022.

Schmid R, Steigenberger P, Gendt G., Ge, M., and Rothacher, M.: Generation of a consistent absolute phase center correction model for GPS receiver and satellite antennas, J. Geod., 81:781–798, https://doi.org/10.1007/s00190-007-0148-y, 2007.

Zumberge, J.F., Heflin, M.B., Jefferson, D.C., Watkins, M.M., and Webb F.H.: Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks, J. Geophys. Res., 102 (B3), 5005–5017, https://doi.org/10.1029/96JB03860, 1997.