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Hydrological Loading in GNSS Vertical Displacement Time Series: An Amplitude–Phase Analysis in Western Part of Ukraine

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SUMMARY

Seasonal signals in GNSS vertical displacement time series may contain a substantial contribution from surface mass loading and therefore affect the interpretation of crustal motion. This study evaluates the annual hydrological loading signal at permanent GNSS stations of the GeoTerrace network in Western Ukraine. GNSS vertical time series corrected for non-tidal atmospheric and ocean loading were compared with modelled hydrological loading displacements. Annual amplitudes and phases were estimated using harmonic analysis. The final comparison included 34 stations with sufficient common GNSS and loading epochs. GNSS annual amplitudes range from 4.42 to 10.28 mm, whereas modelled hydrological amplitudes range from 3.69 to 4.48 mm. At 24 stations, the difference between the GNSS and hydrological annual maxima is less than 15 days. Hydrological loading correction reduces the annual amplitude at 33 stations, with a median reduction of 56.1%. The absolute phase difference and amplitude reduction show a strong inverse relationship. The results indicate that the model reproduces the timing of seasonal deformation better than its full amplitude and confirm the importance of amplitude–phase analysis for geodynamic interpretation of GNSS vertical displacements.

Keywords: GNSS; Vertical displacement; Hydrological loading; Annual harmonic; Seasonal deformation; Geodynamic monitoring.

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Introduction

GNSS position time series are widely used to determine crustal motion and deformation. Their vertical component is particularly sensitive to non-tectonic processes, including atmospheric, oceanic and hydrological surface loading. Changes in terrestrial water storage produce elastic vertical displacements of the solid Earth that can reach several millimetres and form a pronounced seasonal signal in GNSS observations (Klos et al., 2021; White et al., 2022).

The contribution of hydrological loading is not uniform between regions or individual GNSS stations. Its representation depends on terrestrial water-storage variability, model resolution and local environmental conditions. Comparisons of GNSS observations with hydrological loading models show that the agreement is generally stronger in the seasonal band than in the complete residual time series (Xue et al., 2021; Xu et al., 2024; Usifoh et al., 2024). Accurate separation of seasonal non-tectonic deformation is also important for regional geodynamic and deformation studies based on GNSS and other geodetic observations (Savchuk, Doskich, 2025; Tretyak et al., 2025).

The purpose of this study is to compare the annual amplitude and phase of GNSS vertical displacements with modelled hydrological loading across the GeoTerrace network and to evaluate how their agreement affects the remaining annual signal after hydrological loading correction.

Method and Theory

The initial data set consists of daily coordinate time series from 35 permanent GNSS stations of the GeoTerrace network in Western Ukraine. For the amplitude–phase comparison, 34 stations have sufficient common GNSS and loading epochs. The available time series cover approximately 5–9 years.

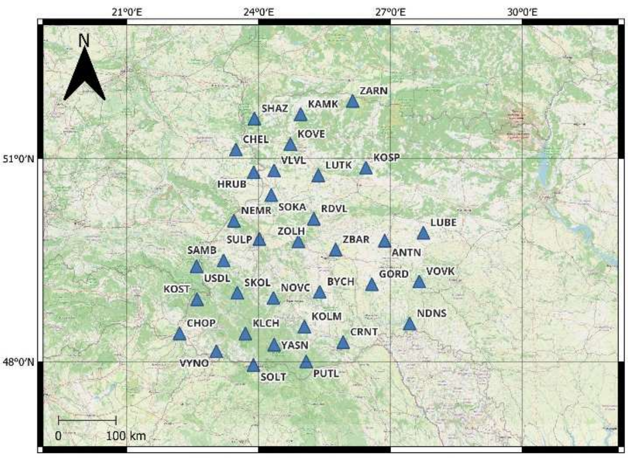

Figure 1. *Location of the GeoTerrace GNSS stations used in the amplitude-phase analysis*

Daily GNSS coordinate solutions were obtained using the Precise Point Positioning approach in GipsyX. The analysis uses the vertical displacement component. Non-tidal atmospheric loading (NTAL) and non-tidal ocean loading (NTOL) were first removed from the original GNSS series:

$$\boldsymbol{V_{NT}(t) = V_{GNSS}(t) - NTAL(t) - NTOL(t)} \quad (1)$$

The hydrological loading displacement $HYDL(t)$was then removed to obtain the fully corrected series:

$$\boldsymbol{V_{FULL}(t) = V_{NT}(t) - HYDL(t)} \quad (2)$$

The same harmonic model was fitted to the GNSS and hydrological loading time series:

$$\boldsymbol{V(t) = a_0 + a_1(t - t_m) + b_1 \sin(2\pi t) + c_1 \cos(2\pi t) + b_2 \sin(4\pi t) + c_2 \cos(4\pi t) + \varepsilon(t)} \quad (3)$$

where a_1 is the linear vertical velocity, b_1, c_1 describe the annual harmonic, b_2, c_2 describe the semi-annual harmonic, and $\varepsilon(t)$ is the residual component.
The annual amplitude was determined as

$$\boldsymbol{A = \sqrt{b_1^2 + c_1^2}} \tag{4}$$

and the annual phase as

$$\boldsymbol{\varphi = \mathrm{atan2}\,(b_1, c_1)} \tag{5}$$

For easier interpretation, phase was converted to the day of year of maximum annual vertical displacement. The phase difference between GNSS and HYDL was calculated as a circular difference. The effect of HYDL correction was evaluated from the reduction of the annual amplitude:

$$\boldsymbol{R_A = \frac{A_{NT} - A_{FULL}}{A_{NT}} \times 100\%} \tag{6}$$

Thus, the analysis evaluates not only how much of the annual signal is removed, but also whether the modelled hydrological deformation occurs at the same time of year as the seasonal displacement observed by GNSS.

Results

The annual GNSS vertical displacement after NTAL and NTOL correction varies considerably across the network (Figure 2a). Its amplitude ranges from 4.42 to 10.28 mm, with a mean value of 6.65 mm. The modelled HYDL amplitudes are more uniform and range from 3.69 to 4.48 mm, with a mean of 4.07 mm. Thus, the model represents a common regional seasonal component but generally underestimates the full annual amplitude observed by GNSS.

The timing of the annual signal shows closer agreement (Figure 2b). Modelled HYDL maxima occur between DOY 248 and 258, while the median GNSS maximum occurs at DOY 249. At 24 of 34 stations, the absolute difference between the GNSS and HYDL annual maxima is below 15 days; at 30 stations it is below 30 days. The model therefore reproduces the timing of annual deformation more consistently than its amplitude.

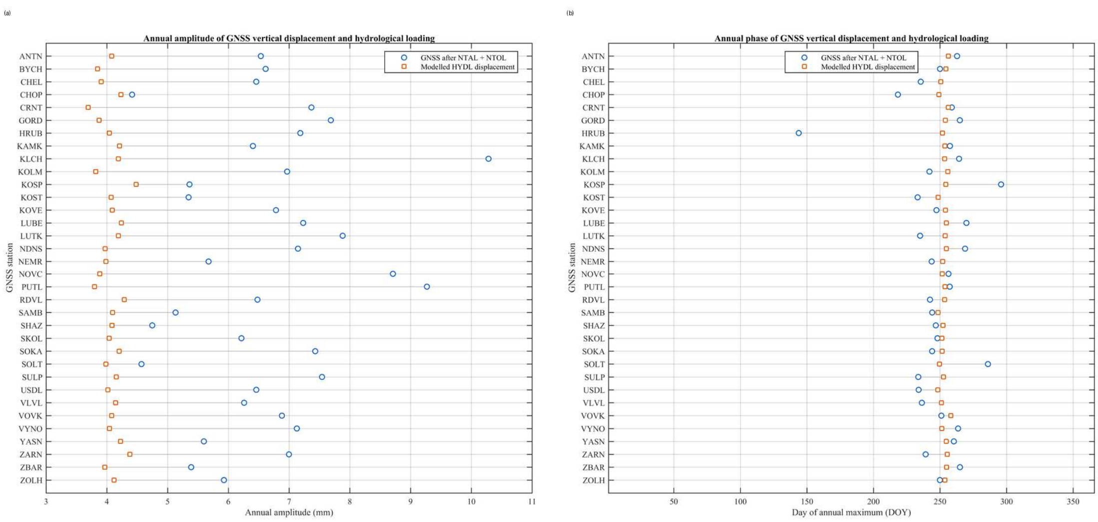

Figure 2. *Comparison of annual GNSS and hydrological loading signals: (a) annual amplitude; (b) day of annual maximum*

After HYDL correction, the annual amplitude decreases at 33 of 34 stations. The median reduction is 56.1%, and the network mean is 54.5%. The residual annual amplitude ranges from 0.78 to 9.19 mm, with a median of 2.83 mm. These results show that HYDL removes a substantial part of the seasonal component at most stations, although the residual signal remains spatially variable.

The effectiveness of the correction is closely related to phase agreement. The absolute GNSS-HYDL phase difference and annual-amplitude reduction show a strong inverse relationship (r = -0.85). This network-wide pattern is physically consistent with harmonic subtraction: annual signals cancel most effectively when their phases are similar.

HRUB is the main exception. Its GNSS and HYDL annual maxima differ by about 108 days, and the annual amplitude increases from 7.18 to 9.19 mm after correction. The modelled seasonal displacement therefore does not reproduce the observed annual component at this station. Residual annual signals at other stations may also contain local site effects, thermoelastic deformation, other environmental processes or imperfections of the loading model (White et al., 2022).

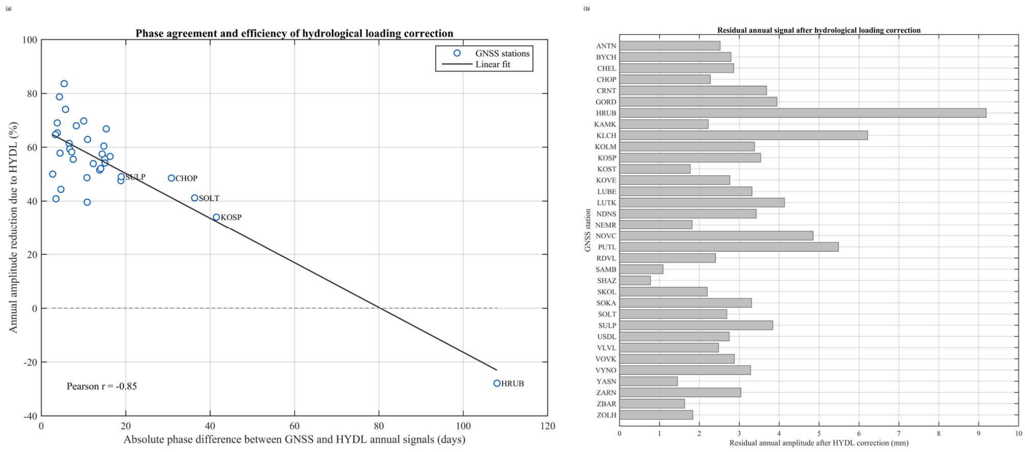

Figure 3. *Evaluation of hydrological loading correction: (a) absolute GNSS-HYDL phase difference versus annual-amplitude reduction; (b) residual annual amplitude after HYDL correction*

The broadband residual RMS changes much less than the annual harmonic: it decreases at 15 of 34 stations, and the mean network change is only about 0.3%. This is expected because HYDL primarily represents seasonal terrestrial water-mass redistribution rather than the complete spectrum of GNSS residual variability (Klos et al., 2021). Consequently, annual amplitude, phase agreement and residual annual amplitude provide a clearer assessment of hydrological loading than RMS alone.

Conclusions

The amplitude–phase analysis confirms that hydrological loading makes a substantial contribution to the annual GNSS vertical displacement signal in Western Ukraine. The modelled HYDL component is generally smaller and more spatially uniform than the annual signal derived from GNSS observations, while the timing of the seasonal maximum agrees much better between the two data sets. At 24 of 34 stations, the difference between the GNSS and HYDL annual maxima is less than 15 days, indicating a consistent regional seasonal response.

Application of the hydrological loading correction reduces the annual amplitude at 33 of 34 stations, with a median reduction of 56.1%. The strongest reductions occur at stations where the GNSS and HYDL annual components are close in phase. The strong inverse relationship between the absolute phase difference and amplitude reduction ($\boldsymbol{r = -0.85}$) confirms that the efficiency of the correction depends not only on the magnitude of the modelled displacement but also on its temporal agreement with the observed GNSS signal. The HRUB station is a clear exception, where a phase difference of about 108 days results in an increase rather than a decrease of the residual annual amplitude.

The residual annual amplitudes after HYDL correction indicate that hydrological loading does not explain the complete seasonal signal at all stations. These remaining variations may reflect local site effects, limitations of the hydrological loading model, monument or thermoelastic deformation, or other unmodelled geophysical processes. At the same time, the relatively small changes in broadband residual RMS show that the effectiveness of hydrological loading correction should not be evaluated from RMS alone.

For geodynamic applications, the combined analysis of annual amplitude, phase agreement, and residual annual signal provides a more physically meaningful assessment of hydrological loading effects on GNSS vertical time series. This approach makes it possible to identify stations where modelled hydrological deformation is well represented and stations that require additional regional or site-specific analysis. Further research should focus on the spatial pattern of the residual annual signal and on comparison with alternative hydrological loading models to determine whether the remaining discrepancies are primarily regional or local in origin.

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