The Impact of a Non-Tidal Ocean Loading Model of High Temporal Resolution on Geodetic GPS Height Time Series

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Abstract Non-tidal ocean loading (NTOL) is a crucial geophysical factor in resulting in the seasonal signals undermining geodetic Geodetic global positioning system (GPS) height time series. Correcting for the NTOL effects has thus been a critical prerequisite for estimating highly reliable secular rates of vertical crustal motions. In this study, we focus on whether a high temporal resolution model can benefit the correction for NTOL effects. We processed 4 years of GPS data from 26 stations around the North Sea of Europe and employed the Proudman Oceanographic Laboratory Storm Surge Model to correct the height components. Hourly and 12-hourly corrections were attempted respectively. We generated 2-hourly heights to investigate the sub-daily signatures of NTOL effects, and also daily heights to assess the potential benefits of NTOL corrections of high temporal resolution to geophysical studies. As expected, hourly NTOL corrections lead to a reduction of the RMS of daily height residuals from 5.1 to 4.4 mm on average, and also a reduction of 21.2% for the integrated signal power over the seasonal to diurnal frequency band. Comparatively, when applying the 12-hourly corrections instead, the RMS of daily height residuals is only slightly deteriorated by 0.01 mm on average and at most 0.06 mm, and the reduction of the integrated power for the seasonal to diurnal frequency band falls slightly to 20.4%. Therefore, we demonstrate that estimating the secular rates of vertical crustal motions will not benefit further from finer than 12-hourly NTOL corrections.

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1 Introduction

Geodetic Global Positioning System (GPS) height time series have been essential in studies such as the estimation of secular rates of sea-level rise, vertical tectonic motion and post-glacial rebound. However, these time series suffer from signals at seasonal timescales, e.g., annual and semiannual, which are detrimental to calculating reliable long-term rates of crustal motions (see [1, 2]). It has been confirmed that the Earth's elastic surface deformation [3] caused by the mass loading of constantly redistributed atmosphere, continental and oceanic water can account for about 40% of the seasonal power in the geodetic GPS height time series [4, 5]. During the past decade, corrections for ocean tide loading have been recommended in GPS processing conventions [6]. The non-tidal component, however, still needs further investigation.

Non-tidal ocean loading (NTOL) is caused by seafloor pressure variation which relates directly to the oceanic response to atmospheric pressure and wind stress. To correct for NTOL effects, a high spatio-temporal resolution model is intuitively deemed beneficial to improving the correction accuracy (e.g., [7]). For example, for the North Sea region, the Proudman Oceanographic Laboratory Storm Surge Model (POLSSM) has approximately 0.1° grid and 1 h sampling [8], the Hydrodynamic Unstructured Grid Ocean model (HUGO-m) has 0.5° grid and 6 h sampling [9], whereas the Estimating the Circulation and Climate of the Ocean (ECCO) model has only a 1° grid and 12 h sampling. Williams and Penna [10] demonstrated that high-resolution models such as POLSSM can maximize the geophysical benefits of correcting for NTOL effects. Boy et al. [11] generated a finer HUGO-m of 0.25° grid and 3 h sampling to correct gravity measurements. Compared with the original HUGO-m, this finer model did not lead to appreciable improvement. van Dam et al. [12] mentioned that a 12-hourly NTOL model actually led to the same conclusions as those based on a 3-day model.

In this study, we only assess the benefits of high temporal resolution (i.e., a few hour sampling) NTOL model in analyzing GPS height time series, e.g., mitigating the seasonal signals and reducing the power on sub-daily frequencies.

2 NTOL Model and GPS Data Processing

The POLSSM was used to calculate the hourly sea level distribution across the North Sea region and convolved using Farrell's greens functions [3]. In this study, hourly NTOL corrections were also decimated to 12-hourly values. Both hourly and 12-hourly corrections will be attempted.

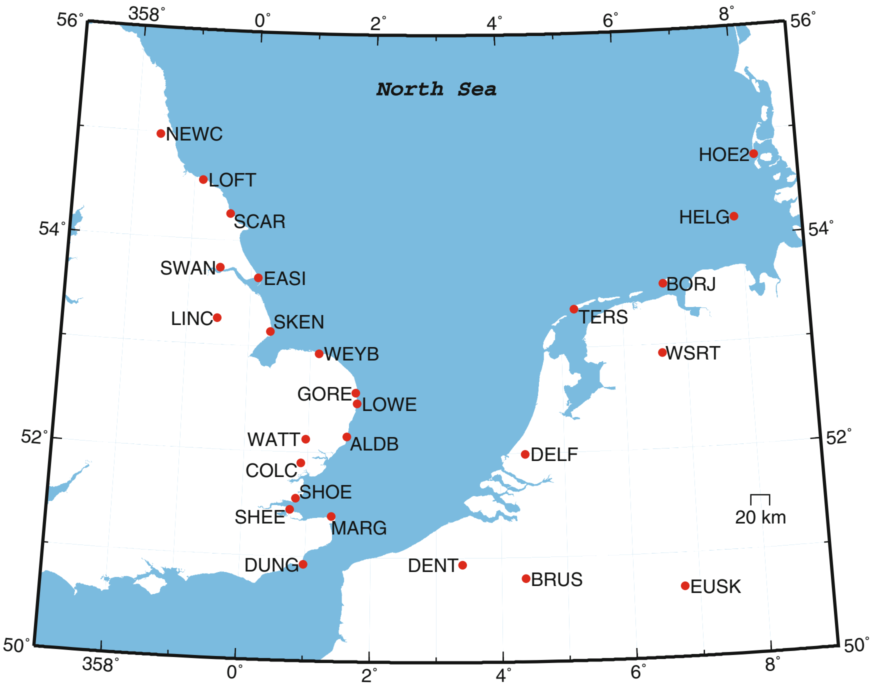

Fig. 1 GPS station distribution. 26 stations with their names aside were used to detect non-tidal ocean loading (NTOL) effects

Four years of GPS data from 2005 to 2008 were collected from 26 stations around the North Sea (Fig. 1). Another group of 70 stations across Europe and around the 26 stations were used to estimate satellite clock corrections and fractional-cycle biases in order to enable ambiguity fixing for precise point positioning [13]. Jet Propulsion Laboratory's (JPL) reprocessed fiducial satellite orbits and Earth rotation parameters were used. We applied the absolute phase centers [14] and solid Earth tide, pole tide loading and ocean tide loading induced displacements using the FES2004 ocean tide model [15, 16]. We estimated residual zenith tropospheric delays every 1 h by applying the Vienna Mapping Function 1 and European Center for Medium-Range Weather Forecasts derived a priori hydrostatic and wet zenith delays [17], along with horizontal tropospheric gradients every 12 h. Ambiguity fixing for each station was carried out successfully with a mean fixing rate of over 96% on each day [18]. In addition, the atmospheric pressure loading corrections calculated by Williams and Penna [10], along with the NTOL corrections, were applied to the 26 stations.

In this study, both daily and 2-hourly solutions were generated for all 26 stations. For the 2-hourly solutions, 24-hour data arcs were used to estimate ambiguities and troposphere-related parameters, while the positions were estimated every 2 h as random walk parameters. In this manner, the ambiguity fixing rate and the precision of troposphere-related parameter estimates can be improved significantly, compared with those when sub-daily data arcs were used [18, 19].

3 Results and Discussion

In this section, we first investigate the scatter of height residuals after correcting for NTOL effects, and then perform both noise and spectral analysis on the height residuals in order to obtain an insight into the effect of hourly NTOL corrections on daily height time series. Note that height residuals indicate height time series where the trend and intercept have been removed.

3.1 Scatter of Daily Height Residuals

In this study, the scatter of heights is quantified using the RMS of residuals. For each station, residual outliers were identified with a threshold of five times the standard deviation. Table 1 presents the RMS of daily height residuals for all 26 stations over 4 years. These stations are sorted according to their shortest distances from the coast and categorized into three groups, i.e., island, coastal and inland stations. The scatter of height residuals is clearly reduced after correcting for NTOL effects (e.g., [10, 20]. Specifically, the mean RMS statistics for all 26 stations falls from 5.1 to 4.4 mm, namely a 12.5% improvement. The RMS reduction ranges from 0.1 to 1.9 mm and the improvement ranges from 1.7% to 30.2%. Furthermore, we find that the RMS reduction for a station relates to its distance from coasts and the distribution of its surrounding oceanic water. The RMS reduction is normally larger than 0.5 mm when the distance from coasts is <1 km, but drops below 0.5 mm if the distance exceeds 1 km and even below 0.1 mm if the distance is over 50 km. Each island station reveals an RMS reduction of over 1 mm and an improvement of over 20%. For most coastal stations, the median RMS reduction falls to 0.7 mm with improvements of between 10 and 15%, whereas for stations 50 km inland, the median reduction is 0.4 mm with improvements of <11%.

Despite the significant improvement after hourly NTOL corrections are applied, we investigate further the performance of 12-hourly NTOL corrections. Table 1 also exhibits the scatter of height residuals if 12-hourly, instead of hourly, corrections are employed. Interestingly, the mean RMS that corresponds to the 12-hourly corrections equals that for the hourly corrections. For each station, the difference of the RMS for the 12-hourly corrections minus that for the hourly corrections is not larger than 0.1 mm. Therefore, we demonstrate that the hourly and 12-hourly corrections perform closely in reducing the scatter of daily height residuals.

Table 1 RMS of daily height residuals (mm) for all 26 stations over 2–4 years

Stations	Distance from coast (km)	RMS of height residuals (mm)		
		No corrections	Hourly corrections	12-hourly corrections
Island stations				
BORJ	0.04	5.4	4.3 (1.1)	4.3
TERS	0.06	5.7	4.5 (1.2)	4.5
HELG	0.09	6.2	4.3 (1.9)	4.4
HOE2	0.16	5.7	4.4 (1.3)	4.4
Coastal stations				
SHEE	0.02	5.6	5.2 (0.4)	5.2
MARG	0.05	4.5	4.1 (0.4)	4.1
DUNG	0.07	4.4	4.0 (0.4)	4.1
LOWE	0.18	5.0	4.2 (0.8)	4.2
ALDB	0.20	5.3	4.6 (0.7)	4.6
GORE	0.36	5.1	4.3 (0.8)	4.3
SKEN	0.38	5.2	4.5 (0.7)	4.5
WEYB	0.71	5.1	4.5 (0.6)	4.5
SCAR	0.81	5.5	4.8 (0.7)	4.8
EASI	0.87	5.4	4.5 (0.9)	4.6
LOFT	0.89	5.7	4.9 (0.8)	4.9
Inland stations				
SHOE	1.38	4.6	4.2 (0.4)	4.2
SWAN	2.47	5.4	4.8 (0.6)	4.8
COLC	7.11	4.6	4.3 (0.3)	4.3
NEWC	11.30	5.0	4.7 (0.3)	4.7
DELF	14.77	5.2	4.7 (0.5)	4.7
WATT	17.40	4.1	3.8 (0.3)	3.8
LINC	44.94	4.8	4.4 (0.4)	4.4
DENT	46.33	4.1	3.9 (0.2)	3.9
WSRT	50.26	4.9	4.4 (0.5)	4.4
BRUS	61.98	4.1	4.0 (0.1)	4.0
EUSK	187.42	4.9	4.8 (0.1)	4.8
Mean		5.1	4.4	4.4

Column 2 shows the shortest distances from coasts. Column 3 shows the RMS of height residuals when no NTOL corrections are applied. Column 4 and 5 show the RMS of height residuals when hourly and 12-hourly NTOL corrections are applied, respectively. The values in parentheses are the differences between Column 3 and 4

3.2 Noise Analysis

In this section, we perform a noise analysis on the daily height time series to further compare the performance of hourly and 12-houly NTOL corrections. A flicker plus white noise model is assumed for the daily height time series [21]. It has been reported that most geophysical signals, including NTOL effects, are perceived as power-law signals in nature (e.g., [5, 21]). An interception, a trend and an annual term were eliminated from the height time series to estimate the

Table 2 Magnitude of the flicker noise (mm/year$^{0.25}$) for 23 stations which have 3–4 years of daily heights

Stations	Magnitude of flicker noise (mm/year$^{0.25}$)		
	No corrections	Hourly corrections	12-hourly corrections
Island stations			
BORJ	16.5 ± 0.8	13.0 ± 0.6	13.0 ± 0.7
TERS	17.8 ± 0.8	13.7 ± 0.6	13.6 ± 0.6
HELG	19.3 ± 2.8	12.8 ± 0.6	12.8 ± 0.6
HOE2	17.0 ± 0.9	12.7 ± 0.7	12.7 ± 0.7
Coastal stations			
SHEE	16.4 ± 3.3	14.9 ± 3.6	15.0 ± 3.6
MARG	13.4 ± 0.7	12.3 ± 0.6	12.4 ± 0.6
DUNG	13.5 ± 0.7	12.5 ± 0.6	12.5 ± 0.6
LOWE	15.3 ± 0.8	12.6 ± 0.6	12.5 ± 0.6
GORE	16.3 ± 0.9	13.8 ± 0.7	13.8 ± 0.7
WEYB	15.5 ± 0.7	13.9 ± 0.6	13.8 ± 0.6
SCAR	18.9 ± 0.8	15.9 ± 0.7	15.7 ± 0.7
EASI	18.8 ± 0.8	15.7 ± 0.3	15.6 ± 0.7
LOFT	19.1 ± 0.4	16.2 ± 0.8	16.0 ± 0.8
Inland stations			
SHOE	12.9 ± 0.8	11.9 ± 0.7	11.8 ± 0.7
SWAN	18.3 ± 0.3	16.2 ± 0.3	16.2 ± 0.7
NEWC	15.9 ± 0.7	15.0 ± 0.7	14.9 ± 0.7
DELF	14.6 ± 0.7	12.7 ± 0.6	12.6 ± 0.6
WATT	13.6 ± 0.6	12.3 ± 0.5	12.3 ± 0.5
LINC	15.5 ± 0.7	14.2 ± 0.7	14.2 ± 0.7
DENT	11.7 ± 0.6	10.7 ± 0.6	10.7 ± 0.6
WSRT	14.7 ± 0.7	13.1 ± 0.6	13.1 ± 0.6
BRUS	11.7 ± 0.6	11.5 ± 0.6	11.5 ± 0.6
EUSK	12.2 ± 0.7	11.8 ± 0.6	11.8 ± 0.6
Mean	15.6	13.5	13.4

The statistics after '±' are the 1-sigma uncertainties

noise contents. The harmonics of the annual signal are ignored in this study because they are insignificant at all stations. Table 2 exhibits the magnitude of the flicker noise for all stations except ALDB, COLC and SKEN which have <3 years of daily heights. From this table, after applying the hourly NTOL corrections, the mean flicker noise magnitude is reduced from 15.6 to 13.5 mm/year$^{0.25}$, namely a 13.5% improvement. The reductions range from 3.5 to 6.5 mm/year$^{0.25}$, 1.0 to 3.1 mm/year$^{0.25}$ and 0.2 to 2.1 mm/year$^{0.25}$, and the median reductions are 4.2, 2.5 and 1.2 mm/year$^{0.25}$ for the island, coastal and inland stations, respectively. In addition, although these reductions are only statistically significant for the island stations, they are still informative in general as they agree with the reductions shown in Table 1. Hence, we demonstrate that correcting for NTOL effects can definitely mitigate the colored noise content in daily height time series.

Furthermore, when the 12-hourly NTOL corrections are applied instead, the magnitudes of the flicker noise change <0.2 mm/year$^{0.25}$, even for island stations, and the mean magnitude varies minimally by 0.1 mm/year$^{0.25}$. This fact implies that the 12-hourly NTOL corrections do not show inferior performance to that of the hourly corrections in mitigating the colored noise.

3.3 Spectral Analysis

We perform a spectral analysis on the 2-hourly height residuals for four island stations which are most susceptible to the NTOL effects. Figure 2 presents the power spectral densities (PSDs) for the 2-hourly height residuals and the height component of the hourly NTOL corrections. Note that the two curves (red and green) for the height residuals where the hourly and 12-hourly NTOL corrections are respectively applied almost totally overlap on the frequency band of over one day. The PSDs on the sub-daily frequency band are ignored for the green curves, because 12-hourly NTOL corrections cannot affect the power for sub-daily frequencies.

From the left panels of Fig. 2, the signal at one cycle/day and its harmonics are evident. These spectra manifest site-to-site variability, which are likely to be caused by multipath effects [22]. Moreover, a peak at the period of about 13.6 days occurs for all height residuals, which may be caused by some potential inconsistencies between our processing strategy and the orbit generation strategy conducted by JPL in dealing with the tidal signals, e.g., M2 and O1 (Ray, private communication, 2011). Errors in modeling these two tidal signals can result in an aliased 13.6-day signal [22, 23]. From the comparison between the black and red curves in Fig. 2, correcting for NTOL effects evidently reduces the power on the frequency band from seasonal to diurnal. For example, the mean amplitude of annual signals in daily height time series of all 26 stations except ALDB, COLC and SKEN is reduced from 2.8 to 2.3 mm, namely a 17.9% improvement, which confirms the finding by Nordman et al. [20] and Zerbini et al. [24] that a high coherence is present between GPS heights and NTOL corrections for the annual cycle. However, the power on the sub-daily frequency band is seldom reduced, but often slightly increased in fact. To investigate this, we calculated the integrated vertical power for the periods of smaller than one day with the PSDs of hourly NTOL corrections (see the right panels of Fig. 2). In particular, the power on the sub-daily frequency band accounts for only 13.6, 14.8, 13.1 and 8.8% of the total power at four island stations, respectively. These low powers are not surprising as the non-tidal sea level changes are small at sub-daily timescales. The power reduction on the sub-daily frequency band, even if existing, should not be appreciable, as confirmed by Boy and Lyard [9] for surface gravity residuals.

Finally, from the comparison between the red and green curves in Fig. 2, it is discernable for some frequencies that the height time series corrected for hourly NTOL corrections have slightly smaller PSDs than those corrected with

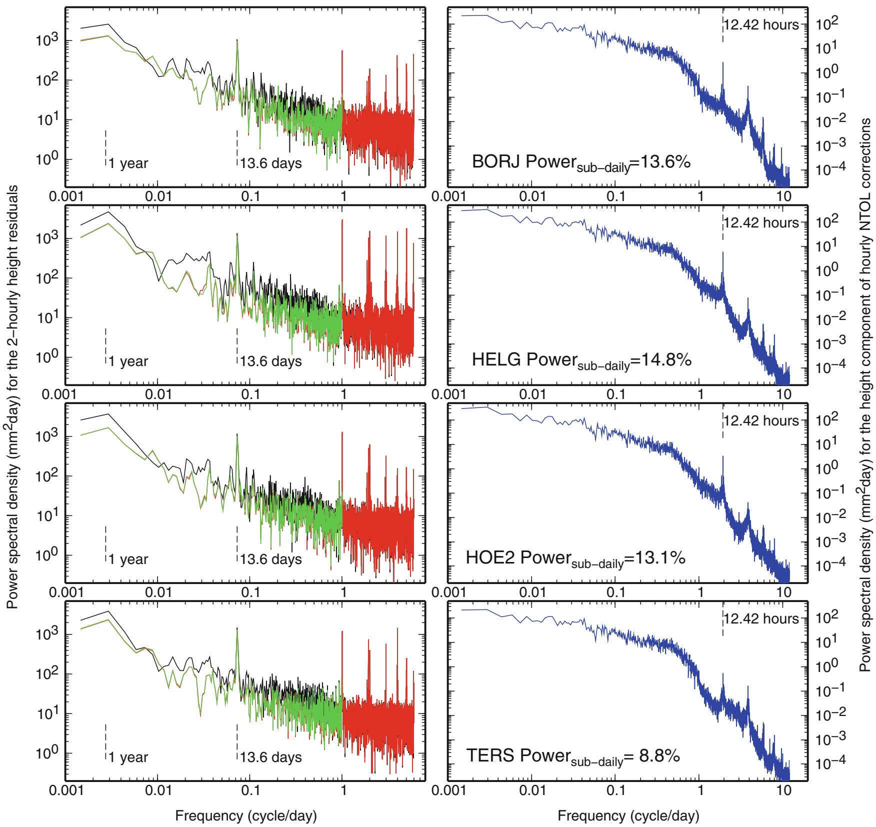

Fig. 2 Power spectral density (PSD, mm^{2}day) for the 2-hourly height residuals at four island stations BORJ, HELG, HOE2 and TERS over 3–4 years. *Black, red* and *green curves* in the *left* panels denote PSDs for the height residuals where no, hourly and 12-hourly NTOL corrections are applied, respectively. Only PSDs for periods of larger than 1 day are plotted for the *green curves*. *Blue curves* in the *right* plots denote PSDs for the height component of hourly NTOL corrections. Power$_{sub\text{-}daily}$ denotes the percentage of the integrated power over sub-daily periods in the total power

12-hourly corrections. However, the hourly corrections perform closely to, if not indistinguishable from, the 12-hourly corrections. This implies that the power reduction on periods of over one day benefits little from a very high rate, i.e., hourly, NTOL corrections. To further verify this, Fig. 3 shows the stacked normalized PSDs for the 23 stations which have 3–4 years of daily height residuals. Original PSDs are normalized in order to impartially assess all 23 stations. Again, the red and green curves overlap closely on the whole frequency band. Particularly, the total power is reduced by 21.2% after applying hourly corrections whereas 20.4% after applying 12-hourly corrections. Hence, the signals on the seasonal to diurnal band can only be minimally further mitigated if we have finer than 12-hourly corrections.

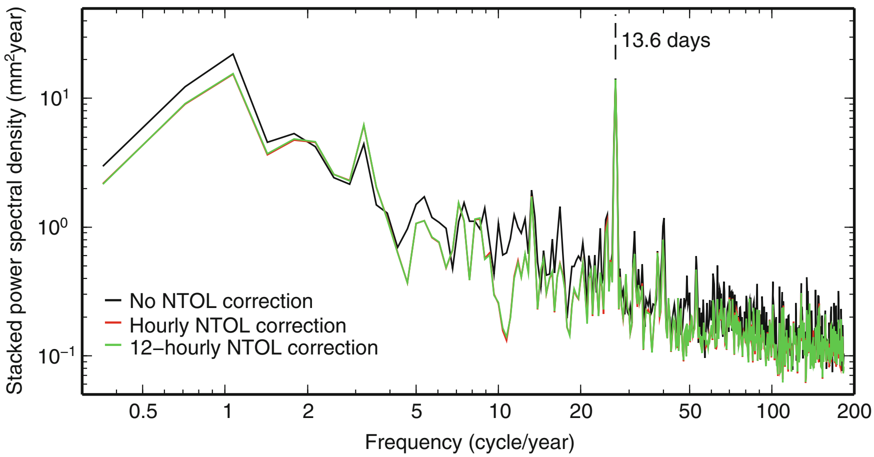

Fig. 3 Stacked normalized PSD (mm^{2}year) for the 3–4 years of daily height residuals at all 26 stations except ALDB, COLC and SKEN. *Black*, *red* and *green curves* denote PSDs for the height residuals where no, hourly and 12-hourly NTOL corrections are applied, respectively. Note that the *red* and *green curves* almost totally overlap

4 Conclusions

In this study, after applying NTOL corrections to 26 stations, the RMS of daily GPS height residuals, where the linear tendency and the mean have been removed, is clearly reduced on average from 5.1 to 4.4 mm, thereby confirming the statistics reported by Williams and Penna [10]. Likewise, the mean magnitude of the flicker noise is reduced from 15.6 to 13.5 mm/year$^{0.25}$, whereas the mean amplitude of the annual signal falls from 2.8 to 2.3 mm. The integrated signal power over the seasonal to diurnal frequency band is also reduced by 21.2%.

Nonetheless, the vertical power on the frequency band of 24 to 4 h is affected minimally after applying the hourly NTOL corrections to the 2-hourly GPS analysis. This result is not surprising if we notice the low sub-daily power level of NTOL which accounts for <15% of the total power.

Due to the minimal benefits of hourly NTOL corrections for GPS analysis, 12-hourly corrections are applied instead. It is found that the RMS of daily height residuals is minimally deteriorated by <0.1 mm. Meanwhile, the mean magnitude of the flicker noise is affected by only 0.1 mm/year$^{0.25}$. In the spectral analysis on daily height time series, the reduction of the integrated power for the seasonal to diurnal frequency band slightly falls from 21.2 to 20.4%. Hence, for daily height time series, the 12-hourly NTOL corrections perform closely to the hourly corrections, implying that estimating the secular rate of a vertical crustal motion will not benefit further from finer than 12-hourly NOTL corrections.

In terms of the discussion above, it should be clarified that the better performance of the POLSSM over the ECCO model illustrated by Williams and Penna

[10] is not related to the superiority of hourly against 12-hourly NTOL corrections. Instead, the higher spatial resolution of POLSSM is likely to be responsible for its better performance over the ECCO model (e.g., [24]). In conclusion, for the geophysical studies based on daily GPS height time series, generating finer than 12-hourly NTOL corrections will lead to minimal, or even negligible, benefits in improving the quality of daily height time series.

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