On Improving Precision of GPS-derived Height Time Series at GEONET Stations

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Abstract

This paper summarizes the effect of various noises on GEONET height time series and demonstrates how the state-of-art analysis technique can improve its quality with the results evaluated by simulations and actual observations. Three factors that may affect the GPS-derived height time series are investigated: 1) mismodeling of atmospheric delays; 2) load deformation by the atmosphere; and 3) load deformation by the ocean. It is found that: 1) the use of conventional mapping functions that are used in the current GEONET routine analysis may introduce spurious annual height variations up to 3mm, and these spurious signals can be considerably mitigated with the use of mapping functions based on numerical weather models; 2) annual height variations caused by the atmospheric loading are up to 3mm; and 3) the annual variations caused by oceanic loading deformations get larger toward the south, reaching 3mm in the Nansei Islands. It is confirmed that when these corrections are applied in the GPS analysis of GEONET data, the annual height variations of GEONET stations are largely reduced. Hence, it may now be possible to detect even these small movements related to the earthquake/volcanic activities that were formally obscured by the annual height noises, offering a hope that more accurate disaster prevention information could be provided.

1. Introduction

Since the GPS Earth Observation Network (GEONET), operated by the Geospatial Information Authority of Japan (GSI), was established in 1996, it has been utilized as a reference station for surveys, an infrastructure for positional information services such as the network-based RTK positioning system and a tool for monitoring crustal activities. Furthermore, the GSI constantly analyzes GEONET data across Japan and provides information on crustal activities to the Coordinating Committee for Earthquake Prediction Japan and other relevant disaster prevention agencies. The information is also released to, and widely used by, the public through the GSI homepage (Geodetic Observation Center, 2004).

The GEONET analysis strategy at the GSI continues to evolve reflecting the global trends in GPS analysis strategies. Lately, a new analysis method called "the analysis strategy version 4" was implemented on April 1, 2009. Along with an upgrade of the analysis software, the following new features are implemented in the analysis strategy version 4: 1) estimation of atmospheric delay gradients; 2) adoption of absolute phase center models for GPS satellites and receiver antennas; 3) adoption of the ITRF 2005 reference frame; 4) change of coordinates of the fixed point (reference station "Tsukuba 1") in the analysis from the nominal values to those obtained by a regional analysis using IGS stations around Japan on a daily basis; and 5) adoption of correction for higher-order ionospheric delay. As a result, systematic errors in the coordinate time series have largely been reduced, successfully improving the quality and stability of the estimated coordinates. This made it possible to detect very slight or slow crustal activities which were once obscured by such errors (Nakagawa et al., 2009).

At the same time, however, large seasonal movements whose origins are unknown are still observed in the coordinate time series, especially in height components, even with the analysis strategy version 4. The strategy, therefore, needs to be improved further. The GPS-derived station heights in general are susceptible to variations in propagation delays of radio waves traveling from GPS satellites to the ground (i.e. atmospheric delays). Changes in surface loads induced by air, snow, land water or seawater will also cause ground deformations, mainly in the vertical direction (e.g. Heki, 2004). Because of these obstacles, it had been a challenge for a long time to develop a method to analyze causes of such height variations and a method to mitigate them.

In recent years, the situation has changed, and methods of analyzing the causes of height variations and mitigating them are being discussed vigorously. This is because the previous method used to correct for atmospheric delays was recognized as insufficient and a new correction method incorporating a numerical weather model was developed. In a GPS analysis, atmospheric delays are estimated simultaneously with the coordinates by employing a simple model on the atmosphere. It is found that the seasonal variations in the estimated station heights can greatly be reduced by improving the atmospheric model using the information derived from the numerical weather model (e.g. Boehm et al., 2006a). As to deformation due to mass loading, the database for the mass load on the earth surface has been developed with the use of space geodesy technologies, such as the Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission (Tapley et al., 2004), which make it possible to quantitatively analyze the loading deformations.

With this advancement in mind, this paper summarizes the effect of various noises on GEONET height time series and demonstrates how the state-of-art analysis technique can improve its quality with the results evaluated by simulations and actual observations. For technical details, readers are advised to refer to Munekane and Boehm (2010).

2. Evaluation of variations in GPS-derived height time series

In this paper, the three major factors that may cause variations in the GPS-derived height time series will be discussed. Those factors include: 1) mismodeling of atmospheric delays; 2) deformation by the atmospheric loads; and 3) deformation by the oceanic loads. Then, the impact of each factor on GPS-derived height time series will be quantitatively estimated.

2.1 Analysis for each factor

2.1.1 Mismodeling of atmospheric delays

As previously mentioned, radio waves transmitted from GPS satellites traveling to an observation station on earth will be delayed by the atmosphere. As the angle of elevation of a GPS satellite is reduced, the travel distance becomes longer, increasing the delay amount (Fig. 1). Since the amount of delays in the line of sight cannot be determined with observation data only, it is generally assumed in GPS analysis that certain functions (mapping functions) can express the relation between the amounts of delays in the zenith direction and line of sight using the angle of elevation of the satellite. Based on this assumption, the amount of delays in the zenith direction is then estimated along with the coordinates of the observation station.

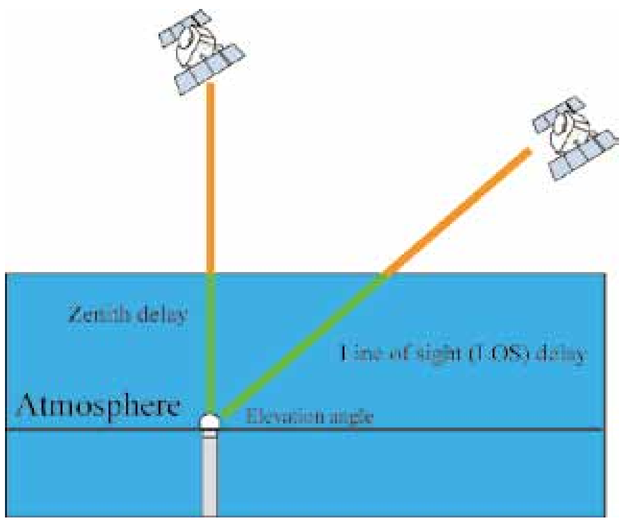

Fig. 1 Relation between the satellite elevation angle and atmospheric delay

A mapping function can be affected by atmospheric conditions, so it changes according to time and location. However, since there were not enough data available before to derive a correct mapping function, the Niell Mapping Function (NMF) (Neill, 1996), which consisted of a simple latitude and seasonal dependence derived from a small amount of radiosonte profiles, has been the standard use. The NMF is also adopted in the GEONET analysis strategy version 4.

Due to improved accuracy of numerical weather models, a plan to use numerical weather models in calculating a mapping function directly for the observation point has recently been proposed. Using the numerical weather models analyzed by the European

Centre for Medium-Range Weather Forecasts (ECMWF), Boehm and Schuh (2004) and Boehm et al. (2006a) derived mapping functions (VMF, VMF1) at a resolution of six hours, applied those in VLBI analyses and consequently found that the baseline repeatability had improved. Their mapping function (VMF1) was also adopted in GPS analyses and its validity has been proved (e.g. Tregoning and Watson, 2009).

Thus, numerical simulations were conducted to see how much the variation in the GEONET height time series, caused by atmospheric delays, could be reduced by replacing the NMF with the numeric weather model-based mapping function. For this, the Mesoscale Analysis Data with the high resolutions of 10km in space and six hours in time released by the Japan Meteorological Agency was used to calculate the atmospheric delays along the line of sight. Then, simulated GPS observation data was created assigning calculated atmospheric delays. Finally, the simulated GPS observation data was analyzed using two mapping functions, the NMF and numeric weather model-based VMF1, to see if the variations in the estimated station heights change.

In GPS analysis, the Precise Point Positioning (PPP) was applied with the use of GIPSY-OASIS II (ver. 5.0), the GPS analysis software developed by the Jet Propulsion Laboratory in the United States. The PPP uses precise satellite orbits and clocks and estimates the coordinates of each individual observation point without referring to control stations. An advantage of this technique is that the variations contained in the observation data of control stations will not affect the outcome.

Fig. 2 shows the amplitude of annual variations in the estimated height time series against the latitude scale. With the NMF used, apparent annual variations of up to over 3mm in amplitudes can be found. On the other hand, the annual variations at almost all locations can be reduced to 1mm or less if the VMF1, the mapping function based on numerical weather models, is used.

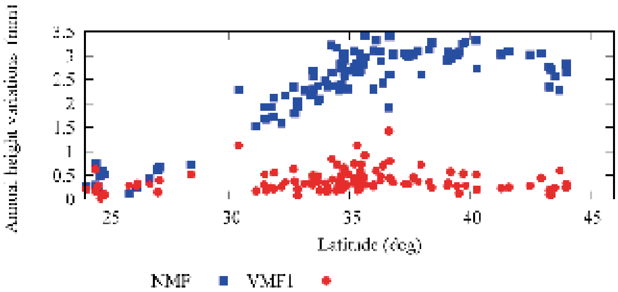

Fig. 2 Difference in the amplitude of spurious annual deformations in GPS-derived heights through the use of two mapping functions

2.1.2 Deformation by the atmospheric loads

The ground can elastically deform due to the pressure applied from the atmosphere. This is called atmospheric loading deformation. It is known that the atmospheric loading deformation is most prominent in the height component. If the atmospheric pressure is constant at all times, deformations caused by such pressure only generate a statistical bias and do not interfere with tasks such as monitoring of crustal activities. In reality, however, atmospheric pressure constantly changes and the degree of load deformation varies accordingly around the average value, which could become noise which obscures crustal deformation signals.

The elastic deformation by the atmospheric load at a particular observation point can be calculated by convolution of the Green’s function, which represents the deformation by a point load and the pressure change around the observation point. In this calculation, because the atmospheric load is known to be canceled out in the ocean (known as the inverted barometer (IB) effect), the load is applied only in the land area.

Calculation of atmospheric loading deformation requires knowledge on wide-range distribution of atmospheric pressure as the deformation at an observation point will be affected by a 1000km-scale pressure distribution around it. For this, the atmospheric pressure distribution in the Global Analysis Data model with the spatial resolution of 1.25 degrees and time resolution of six hours, provided by the Japan Meteorological Agency, was used in the calculation.

Fig. 3 shows estimates of annual height variations at the GEONET stations caused by the atmospheric load. It was found that the amplitude becomes large around mid-latitudes with the maximum of approximately 3mm.

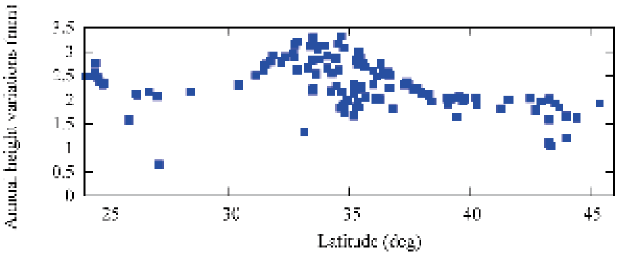

Fig. 3 Amplitude of annual height variations at the GEONET stations caused by atmospheric load

2.1.3 Deformation by the oceanic loads

As for ocean load deformation, one by tides can simply be corrected by using well-developed tide models (e.g. NAO.99Jb (Matsumoto et al., 2000)), which are based on the TOPEX/POSEIDON altimeter data and coastal tide gauge data. However, load deformation due to the ocean mass variations caused by non-tidal factors, such as blowing wind, was once difficult to estimate as there was no mean of obtaining the distribution of ocean mass.

The situation completely changed when the GRACE satellites were launched in March 2002. The twin satellites of GRACE orbit at an altitude around 400km. They can reveal the global time variations in gravity by precisely measuring changes in the distance between the satellites. By translating the obtained gravity change into the mass distribution change of the earth surface, it is now possible to globally estimate the change in load distributions on the earth's surface caused by the movements of seawater or land water over time, which was once considered a difficult task.

On the other hand, because satellites are used in the observation, the spatial resolution and time resolution are limited to approximately 500km and 10 to 30 days respectively, which are lower than those of the atmospheric model. Although the GRACE satellites are generally capable for capturing load deformation not only by seawater but also by land water from snow and other elements, this is, unfortunately, not the case for Japan. Considering the spatial resolution of the GRACE-derived mass variations, it is difficult to measure land water changes over Japan. Nevertheless, making the once-impossible estimation of the load deformation by seawater possible is an important step forward for the Japan region.

In this study, the spherical harmonic coefficient model, produced by the GRACE satellites and processed by the University of Texas at Austin, Center for Space Research, was used to calculate load deformation at the GEONET stations. As stated earlier, it can be considered that the load deformation at these locations was caused by seawater. Fig. 4 shows the amplitude of estimated annual height variations by oceanic loading deformations. It can be observed that the lower the latitude (to the south), the larger the amplitude becomes with the amplitude of 3mm near the Nansei Islands.

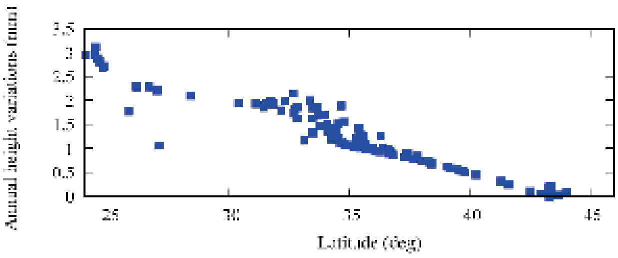

Fig. 4 Amplitude of annual height variations at the GEONET stations caused by ocean load

2.2 Characteristics of time series

The amplitude of annual variations (or deformation) in the GEONET height time series was discussed in 2.1. In this section, how individual variation (deformation) patterns change in a time-series manner will be discussed.

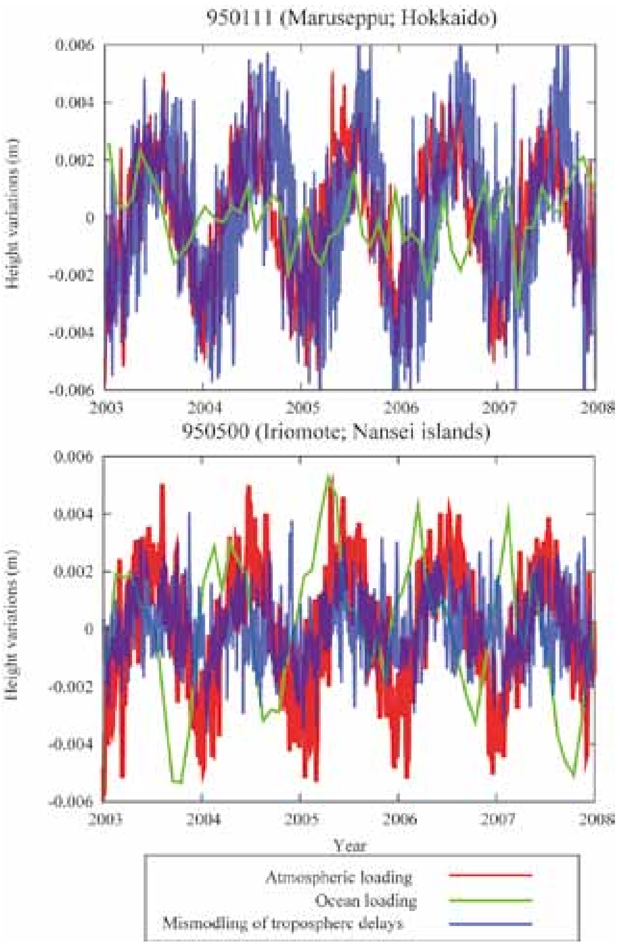

Fig. 5 Example of height variations at the GEONET stations caused by various error (deformation) factors

Fig. 5 shows the height variations (deformation) observed at the two representative GEONET stations (in Hokkaido and the Nansei Islands). When the NMF was used for Maruseppu (Hokkaido), the apparent subsidence in winter can be seen in the time series since, as shown in Fig. 2, the use of NMF mapping function in high latitude leads to greater spurious annual height variations. It can also be observed that atmospheric load poses a significant impact on the variations by which subsidence in winter occurred. This is because lower temperatures during the winter season help grow the atmospheric density and the characteristic high-pressure system is observed on land, especially on the continent. Also, it can be said that the impact from the ocean load is minimal as seen in Fig. 4. On the other hand, atmospheric and oceanic loading deformation is prominent on Iriomote Island (Nansei Islands), which is positioned in lower latitude where variations by mismodeling of atmospheric delays have little impact as shown in Fig. 2. As with the case of Hokkaido, the atmospheric load imposes subsidence in the winter. The ocean load, too, imposes annual deformation characterized as having maximum subsidence around the end of September.

3. Application of correction to observed GPS data

From the section 2, it was learned that mismodeling of atmospheric delays and loading deformation by the atmosphere and ocean produce seasonal variations in the height time series of GEONET stations. Thus, the correction for these variations (deformation) was applied in the analysis of the actual GEONET data, and the impact of the correction on height time series was evaluated.

In this analysis, GIPSY-OASIS II (ver. 5.0) and the VMF1 (mapping function) were used as in the section 2.1.1. As to the atmospheric load, the 6-hour time series of atmospheric load deformation was created for each observation point using the method described in 2.1.2. Then, using the time series, loading correction is applied to the GPS data at the observation level by means of directly editing the RINEX data so as to take the full account of sub-daily variations. As to the ocean load, because the time resolution is as low as 30 days, the ocean loading time series was created for each observation point using the method presented in 2.1.3, and loading correction is applied to the daily heights of the GEONET stations using the daily loading deformation that were obtained by linearly interpolating the loading time series.

Fig. 6 shows the annual height variations before and after applying the correction. The length of the arrows in the figure shows the amplitude of annual movements while their direction indicates the timing of subsidence during the year. Before applying the correction, an annual movement of over 5mm was seen in almost all regions of Japan. After applying the correction, however, no visible annual movements were observed in regions outside the red and blue circles. The regions in the red circle are the area where, as pointed out earlier by Heki (2001), subsidence occurred due to the snow load in the winter. In addition, the site within the blue circle is located in Tsukuba and corresponds to the vertical movement of the ground which was induced by pumping of groundwater for irrigation (Tobita et al., 2004; Munekane et al., 2004). It can be said, as seen above, that the physical interpretation of annual vertical movements can be made simple if correction is applied.

As an example of the effect of correction in the height time series of the GEONET stations, the height time series at the GEONET station 950140 (Oshamanbe) before and after applying the correction is shown in Fig. 7. It can be noted from the figure that although the annual movement, which occurs seasonally, was significant before applying the correction, it has become almost indiscernible after the correction was applied. Conventionally, slight movements, which will be accompanied by earthquakes and volcanic activities, were masked by the seasonal movement; by adopting the correction described above, it may now be possible to detect even these small movements, offering a hope that more accurate disaster prevention information could be provided.

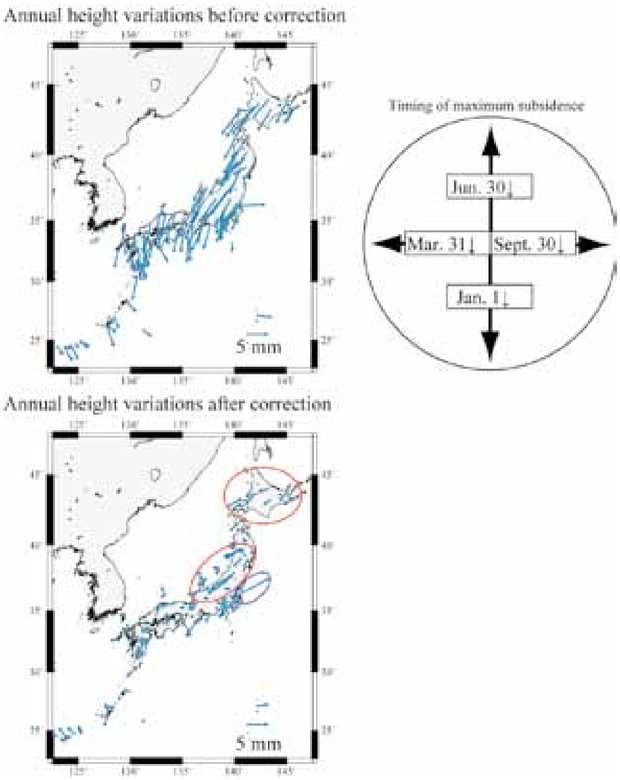

Fig. 6 Comparison of annual height variations at GEONET stations before and after applying correction. The length and direction of an arrow indicate the amplitude and the timing of when the largest subsidence occurs respectively. The regions inside the red circle illustrate winter subsidence from snow load while the site inside the blue circle corresponds to the subsidence occurred in the summer by pumping of groundwater for irrigation.

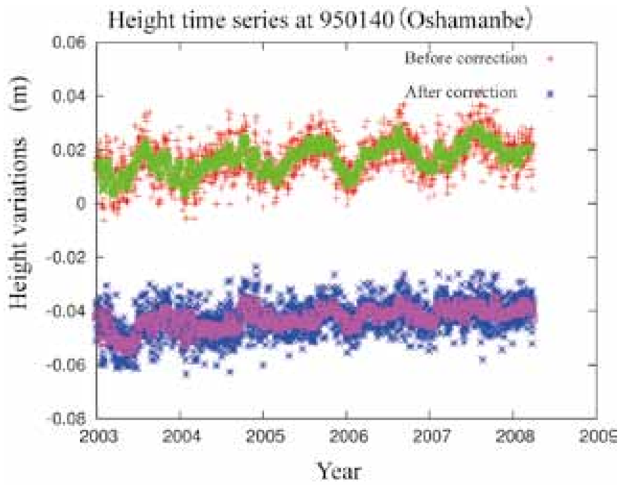

Fig. 7 Impact of correction on the GEONET height time series at 950140 (Oshamanbe). Red and blue marks denote the estimated height time series before and after applying correction respectively, and green and purple marks show their averages with the 10-day moving window. Note that height time series after applying correction (blue and purple marks) are arbitrary shifted for visibility.

4. Conclusion

In this paper, the following three mechanisms that induce variations in the GPS-derived height time series were discussed: 1) mismodeling of atmospheric delays, 2) atmospheric loading deformation, and 3) oceanic loading deformation. Then, the impacts of these factors were quantitatively estimated. By adopting the correction in 1) to 3) in the analysis of the actual GEONET data, most of the seasonal height variations could be eliminated. Moreover, the physical interpretation of remaining seasonal elements, such as snow load, could be made simple as well.

In this study, GIPSY-OASIS II (ver. 5.0) developed by the Jet Propulsion Laboratory in the United States was used as the GPS analysis software. Because the GEONET routine analysis (analysis strategy version 4) of the GSI, however, used the BERNESE 5.0 software developed by the University of Bern in Switzerland, the evaluation result in this study cannot simply be applied to see the effect of correction. Still, it was confirmed that the extent of variations in 1) did not depend on the software, and the actual ground movements were represented in 2) and 3), which make it possible to assume that the GPS-derived station heights measured in the GEONET routine analysis of the GSI holds the equivalent impact. By applying the correction described in this study, it can be expected to reduce the seasonal components in station height time series significantly.

Before adopting the correction discussed in 1) to 3) in the GEONET routine analysis, there are few technical issues to be addressed. First of all, the BERNESE 5.0 software did not support the mapping function of VMF1. With regard to this problem, software upgrading is currently under way. Since the next version (ver. 5.1) will support the VMF1, we are waiting for its release. As to the VMF1, the 6-hourly coefficients necessary for the mapping function are provided by Vienna University of Technology the following day for the public use. Hence, the VMF1 may be applied in the final analysis of the GEONET routine analysis, though it cannot be used in the quick analysis. For the quick analysis, the use of the Global Mapping Function (GMF) (Boehm et al., 2006b) which would not rely on external data at the cost of reduced precision could be of another option. Secondly, an issue of how to apply the atmospheric load deformation in 2) remains. For this problem, lattice models on which to estimate load deformation of each observation point are released by the Goddard Space Flight Center (GSFC). Those models can be obtained three days after and could be used in the final analysis of the GEONET routine analysis. Lastly, as to the ocean load deformation in 3), because GRACE data analyzed by individual analysis centers is already 2-month old at the time of its release and the time resolution of 30 days (or 10 days) is insufficient, there seems little merit of incorporating the data to the routine analysis. It seems to follow that those who want to apply the correction need to correct the GPS-derived station heights afterward on their own.

In the meantime, it is important that both merits and demerits of adopting the correction, discussed in this paper, in the GEONET routine analysis are assessed thoroughly while referring to global trends. For example, in relation to 2), the International GNSS Service (IGS) is currently opposed to the routine correction of load deformation caused by fluid masses on the earth's surface on the ground that the accuracy of correction models is insufficient. As to the atmospheric load, its suggestion is to apply correction only to tidal components (diurnal tide S1; semidiurnal tide S2) which can be formulated in an accurate model. Reflecting these circumstances for the problem regarding 2), an additional option is, as is done with the IGS, that correction is applied only to tidal components for the routine analysis and the correction for other frequency domain may be posteriorly applied by users.

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