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ORIGINAL PAPER

NOISE ANALYSIS FOR ENVIRONMENTAL LOADING EFFECT ON GPS POSITION TIME SERIES

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ABSTRACT

This paper focusses on the impact of environment mass loading on GPS time-series of position changes and noise characteristic. We make use of position time series of 206 GPS station ranging from 2001 to 2013 globally distributed. Firstly, we investigate the spatio-temporal pattern of mass loadings based on QLM dataset. The results show that loading effect is significant for short time series, and the instantaneous impact cannot be ignored especially in high-precision geophysical studies. Meanwhile, the results indicate that loading effect behaves with regional difference in spatial scale, and this explains why there exist significant differences on the contribution of environmental loading on GPS time series in the scientific community. Secondly, among 90 % of the stations the weighted root mean square (WRMS) is reduced after applying the loading correction based on QLM model, improving the accuracy of GPS time series. Finally, we quantify the stochastic of GPS time series. The results show that the noise model of GPS time series can be described by a various combination of those models, mainly by FN+WN model and PL+WN model. From our statistics, we can conclude that the best noise models are either white and flicker or white and power-law. Environment loading has a significant impact on the stochastic noise properties of GPS time series, on 33 %, 15 %, and 39 % of the station's noise properties (noise types) have been changed after loading correction for NEU components, respectively. Environment loading is one of the factor that 'raw' GPS time series exhibited Gauss Markov noise properties. Furthermore, the impact of environmental loading on GPS site velocity cannot be ignored; this is particularly significant for the vertical component.

1. INTRODUCTION

The Global Positioning System (GPS) has seen tremendous advances in measurement precision and accuracy (Bock et al., 2000; Williams et al., 2004; Bos et al., 2008; Ray et al., 2013; Li et al., 2015). To improve the accuracy and stability of the GPS time series, any possible nuisance parameters or errors need to be minimized. With the rapid development of GPS technology (i.e. improved filtering algorithms, error correction models and optimized processing strategies), the impact of various factors (i.e. satellite and receiver clock errors, ionospheric delay, tropospheric delay), and multipath effects have been efficiently removed or greatly reduced (Bertiger et al., 2010; He et al., 2015). Apart from these random and systematic errors, site-position time series generated from continuous GPS stations reveal significant seasonal variations. The strong annual signal observed at most stations is now known to be physical site motion driven by temporal changes in environmental mass redistribution, and can significantly bias site displacement velocity estimates (Cox and Chao, 2002; Kuusniemi et al., 2004; Dong et al., 2006; He et al., 2015). Besides, the aliasing effect (Penna and Stewart, 2003) will also result in periodic signals in GPS coordinate time series. Environmental mass loading (i.e. atmospheric pressure loading, soil moisture mass loading, non-tidal ocean loading and snow cover mass loading) is one of the most important limiting factors on the accuracy of long-term tectonic rates, other effects such as solid tides are already corrected during the GPS processing in various packages (GAMIT/GLOBK, GIPSY, Bernese, etc; Zumberge et al., 1997; Hugentobler et al., 2001; Penna et al., 2008; Herring et al., 2010a, b). Those effects are not considered in this study.

Relative datasets have been established from a number of environmental loading effects caused by atmospheric pressure, non-tidal ocean, snow cover and soil moisture. For instance, the Global Geophysical Fluid Center (GGFC, Jiang et al., 2013) and the Quasi-Observation Combination Analysis based loading model (QLM) are widely used to estimate surface displacements and correct nonlinear

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variations in GPS weekly time series (Dong et al. 2002; Yuan et al., 2008; Jiang et al., 2013; He et al., 2015). These loading effects are either not implemented or taken into account into the GPS processing software, or taken into account during GPS data analysis for geophysical studies that demand high precision (Collilieux et al., 2010; Williams and Penna, 2011; Jiang et al., 2013). Another set of environmental forcing functions is the North American Land Data Assimilation System (Mitchell et al., 2004). For all those tasks mentioned, the proper determination of velocity of a permanent station and its uncertainties is essential. Therefore, the knowledge of environment loading is crucial.

To enable reliable identification of sub-millimeter yearly movement and satisfy the growing demands for high precision geodetic observations, shorter-term deformation time series signatures caused by surface environmental mass loading of the solid Earth (e.g. redistribution of atmospheric, non-tidal oceanic, soil and snow cover masses), need to be removed from the GPS time series. Several studies have been made on loading correction as follows. Dong et al. (2002) assumed that less than half of the observed GPS seasonal variation could be explained by redistributions of environmental surface mass loads. Wang et al. (2005) quantified the effects of ocean tides, atmospheric pressure, snow depth and soil moisture, non-tide ocean loading (NTOL) on the position time series of GPS stations. They demonstrated that these environmental loads could reduce the RMS of the station vertical position by about 1 mm or about 11 % of the total RMS (root mean square). Yuan et al. (2008) evaluated the induced displacement from ATML, NTOL, snow depth and soil moisture mass loading in the Hong Kong GPS fiducial network, finding that the observed 3 mm annual vertical variation of the common mode errors could be explained by this joint contribution. Yan et al. (2009) compared the mass loading contributions from ATML, NTOL and continent water storage (CWS) to the GPS height-component finding that the mean annual amplitude of mass loading with respect to GPS was about 53 %. Rietboek et al. (2011) pointed out that after loading correction, about 80 % of the stations show a reduction of at least 10 % in seasonal amplitude. Studies by Jiang et al. (2013) used three different environmental loading methods to estimate surface displacements on GPS weekly height time series. The result shows that by removing the load-induced height changes from the GPS height time series, the scatter is reduced by 74, 64 and 41 % of the stations with OMD models, GGFC model and QLM model respectively. He et al. (2015) make a comparison of loading effect on two nearby regions with atmospheric pressure, soil moisture, snow depth and non-tidal ocean loading. The analysis revealed that these loading factors can result in position shift at the centimeter level. In addition, the displacement time series exhibit a periodic pattern, which can explain about 13 % to 22 % of the seasonal amplitude on vertical GPS time series. Besides, the loading effect is significantly different among the two nearby geographical regions.

Previous studies demonstrated the existence of significant differences on the contribution of environmental loading on GPS time series. This type of diversity may arise from:

1. geophysical data sources and load model,
2. data processing strategy on GPS coordinates time series,
3. loading has significant regional difference in spatial scale.

It has been generally accepted that the noise in GPS time series was best described as a combination of colored noise (e.g. flicker noise (FN), power-law noise (PL), random walk noise (RW), etc.) plus white noise (WN) (Zhang et al., 1997; Mao et al., 1999; Williams, 2004; Langbein, 2004, 2008; Bos et al., 2008; 2013a). Furthermore, unmodelled surface loading deformations in geodetic position time-series either increase the noise or bias derived secular velocities depending on the time-series length, especially on the vertical component (Santamaria-Gomez and Memin, 2015).

Whether environmental loads will cause a large portion of the color noise component in the GPS time series is still an open question. Little research has focused on the noise characteristic of the relative environmental loading time series and its impact on GPS time-series of position changes and noise characteristic, further investigations on noise characteristic are required, especially with long-term of GPS time series and with global distribution of GPS station. The proposed work quantifies the impact of environmental loading time series generated by QLM, including surface displacements driven by atmospheric pressure loading (ATML), soil moisture mass loading (SMML), non-tidal ocean loading (NTOL) and snow cover mass loading (SCML). We mainly focus on the impact of mass loading deformation on time series of GPS receiver coordinates.

2. DATA DESCRIPTION AND PROCESSING

In this analysis two kinds of data sets are used: environmental loading as well as GPS coordinate time series.

2.1. *ENVIRONMENTAL LOADING DATASET AND PROCESSING*

We used environmental loading data observed over a long period ranging from 2003.0 to 2013.0 with 206 reference stations. The processing includes the following corrections: ATML, SMML, NTOL and SCML based on QLM dataset (Yuan et al., 2008; Jiang et al, 2013; He et al., 2015). The QLM dataset described as follows (for me detail see Dong et al., 2002; Yuan et al., 2008; Jiang et al, 2013; He et al., 2015). For the ATML we used the 6-hourly global grids of surface pressure fields from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis project (Jiang et al., 2013). The displacements induced by NTOL are obtained using the bottom pressure and a data assimilated oceanic general circulation model run at JPL as part of the ECCO consortium (Stammer et al., 2002). Snow depth and soil moisture data are derived from the assimilated model of NCEP/Department of Energy (DOF) Atmospheric Model Intercomparison Project (AMIP)-II Reanalysis. The data of this model is given on a Gaussian grid of 1.875° spacing in longitude and uneven spacing in latitude, the temporal resolution of the model is 24 hours.

The modelled deformation of each loading contribution was computed with QOCA software according to the Green's functions with elastic Earth models (Farrell, 1972; Dong et al., 1998; van Dam et al., 2010, 2012). The QOCA software provides a sub-module called "mload" to calculate site displacements caused by atmospheric pressure, non-tidal ocean, snow depth and soil moisture loading. The outputs of QOCA are the daily displacements induced by the different environmental loads in NEU components in the center of solid Earth (CE) frame for each station (Dong et al., 2002; Jiang et al., 2013).

2.2. GPS TIME SERIES

To evaluate the impact of different loading effects, we apply the loading correction on GPS time series. The raw IGS station position time series used in this paper are obtained from SOPAC GPS data analysis (Bock et al., 1997; Jamason et al., 2004). We discard time series with data gap larger than 5 % of the observation period between 2003.0 and 2013.0, reducing the dataset to 206 stations as shown in Figure 1.

3. LOADING INDUCED DISPLACEMENT AND ITS EFFECT ON GPS TIME SERIES

3.1. STATISTICAL ANALYSIS OF LOADING TIME SERIES

Firstly, we evaluate the amplitudes (NEU component displacement) of the loading signals induced surface deformation. Figure 1 shows the spatial distribution of the maximum (MAX), minimum (MIN), mean (MEAN) value of the amplitude of the time series on GPS sites induced by the four different loading types between 2003 and 2013. From the spatial distribution of the maximum amplitude (Figure 1A and Figure 2), we can see that the loading-induced horizontal displacements are about 4 to 8 times smaller than those in the vertical ones. The maximum vertical displacement caused by ATML, SMML, NTOL and SCML is 20, 12, 16 and 5 mm, respectively. This means that the seasonal loading effect is significant for short time series, and the instantaneous impact cannot be ignored especially in high-precision geophysical studies. Also the northern hemisphere displacement effect is slightly higher than the southern hemisphere, indicating that there is regional regularity in spatial scale. In terms of SMML, the amplitude is small for sites located on islands and in the South Pole region, but relatively large along coastlines. The NTOL effect is relatively small for most of the sites, ranging from 0 to 1.5 mm, from 0 to 1.4 mm, and from 0 to 4 mm for NEU components, respectively. Besides, the amplitude in some coastal site (e.g. the Up component of DLFT (Delft, the Netherlands station) is greater than one centimeter, which is consistent with the study results reported by Williams and Penna (2011). Compared with the other three loading types, SCML's impact on surface deformation is weak, about 1 mm in the horizontal and 5 mm in the vertical component. Besides, with the decreases of latitude the amplitude of the loading induced station displacement decreases. Figure 1B shows the spatial distribution of the minimum value of the loading induced displacement time series, similarly to Figure 1A. This means that the loading effect is the cause of the upward and downward movement of the Earth surface (GPS site). Furthermore, it can be observed from Figure 1C that loading-induced mean displacements are less than 0.2 mm and 1 mm for horizontal and vertical component, respectively. Finally, the statistical results in terms of the minimum, maximum and mean values of the vertical component for the 206 GPS stations are shown in Figure 2. From Figure 1 and Figure 2 we can see that the loading effect is close to zero average for long time series. Meanwhile, their instantaneous impact cannot be ignored, especially in the vertical component, further studies are required to investigate the environment loading effect on GPS time series.

3.2. OUTLIERS ANALYSIS FOR THE LOADING INDUCED DISPLACEMENT TIME SERIES

The previous studies directly use the related existing models to correct the loading effect, but little research has been conducted to determine whether errors or noise may be introduced when implementing the loading effect correction. This work investigates the gross errors (i.e. outliers) of the generated loading induced displacement time series before making loading correction, and focuses on performance analysis of the long-term environmental loading time series. The criteria of 3 and 5 times the standard deviations (3σ , 5σ) as well as median absolute deviation (MAD) were used to find outliers for the loading induced displacement time series on the 206 IGS stations (Klos et al., 2015). Table 1 lists the percentage of removed outliers for ATML, SMML, NTOL, and SCML induced time series. From Table 1 we can see that there are only a small number of outliers, less than 4.5 % for the four loading types. These outliers may be caused by the instantaneous impact of environmental loading (e.g. migration or redistribution of loading, which causes a sudden effect on the Earth surface). Here we recommend a conservative method to deal with the outliers: firstly, making the loading correction with the QLM model on the GPS time series, deal with the outlier during the process of noise analysis and velocity.

3.3. IMPACTS OF ENVIRONMENTAL LOADING ON DAILY GPS HEIGHT TIME SERIES

Previous studies show that environmental loading make a significant contribution on GPS time series, especially in the vertical component (Dong et al., 2002; Yuan et al., 2008; Jiang et al., 2013; Ferenc et al., 2014; He et al., 2015). To evaluate the impact of the environmental loading effect on daily GPS height coordinate time series, we calculate the relative WRMS difference defined as:

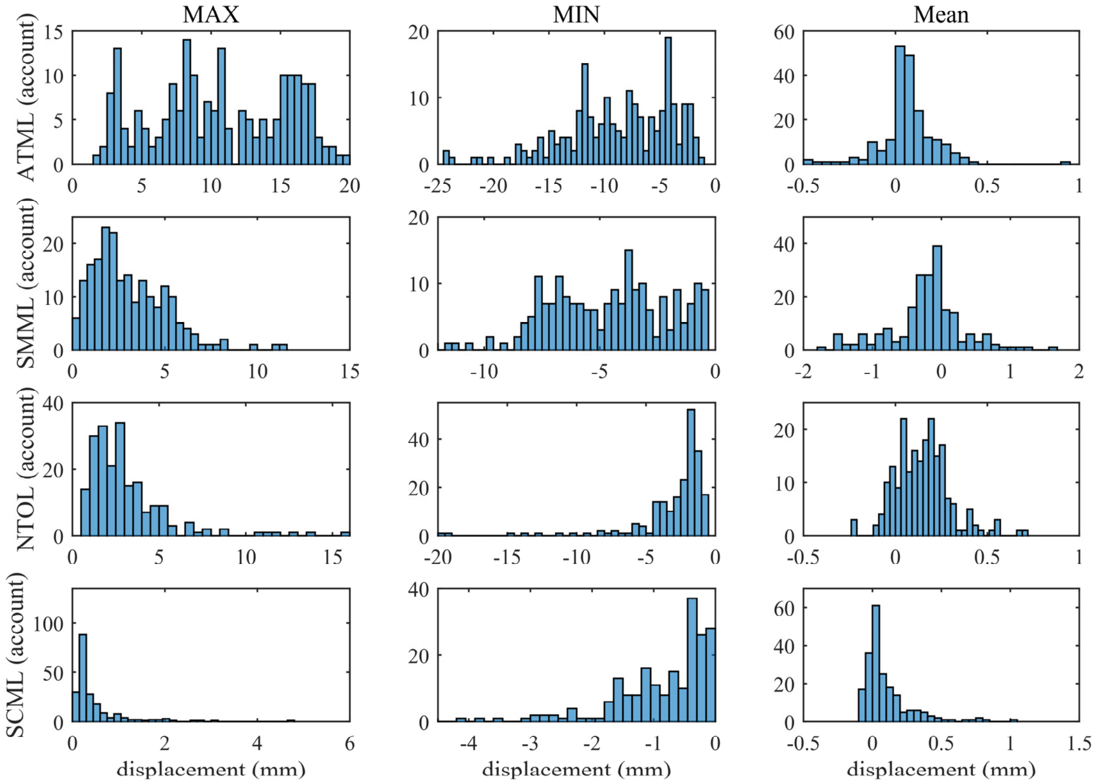

Fig. 2 Statistical analysis of the loading effects for the 206 GPS stations (the minimum, maximum and mean values of the amplitude).

Table 1 Percentage of removed outliers for ATML, SMML, NTOL, and SCML induced time series.

Loading / Method	ATML				SMML			
	Max	Min	Mean	Median	Max	Min	Mean	Median
5 sigma	0.1 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
3 sigma	2.2 %	0.1 %	1.3 %	1.5 %	2.4 %	0.0 %	0.3 %	0.0 %
MAD	1.0 %	0.0 %	0.5 %	0.5 %	1.2 %	0.0 %	0.1 %	0.0 %

Loading / Method	NTOL				SCML			
	Max	Min	Mean	Median	Max	Min	Mean	Median
5 sigma	0.1 %	0.0 %	0.1 %	0.0 %	0.9 %	0.0 %	0.0 %	0.0 %
3 sigma	2.3 %	0.3 %	1.1 %	1.1 %	4.4 %	0.0 %	1.2 %	1.1 %
MAD	1.3 %	0.0 %	0.3 %	0.2 %	4.3 %	0.0 %	0.8 %	0.2 %

$$WRMS_{diff} = \frac{WRMS_{ori} - WRMS_{corr}}{WRMS_{ori}} \times 100\,\% \qquad (1)$$

where $WRMS_{corr}$ and $WRMS_{ori}$ are the WRMS of the corrected and original daily GPS height tie series, respectively. A positive WRMS difference means that after loading correction, the WRMS of the daily GPS time series is reduced. The left side of Figure 3 shows the spatial distribution of the WRMS differences after correcting for loading, while the right side shows a pie chart of WRMS difference within certain ranges.

From Figure 3 we can see that the WRMS of 90 % of the stations is reduced after applying the QLM loading correction. It can be seen that 30 % of the stations have a WRMS decrease of between 0 to 5 %, 22 % between 5 % and 10 %, and 4 % more than 30 %. Stations where the WRMS has decreased by more than 20 % are predominantly coastal sites and in the northern hemisphere (above 35° latitude).

From the above analysis, we can see that even though the loading effect is close to zero average for long time series, the instantaneous impact on GPS time series is non-trivial, especially for high-precision geophysical studies. Besides, the results indicate that the loading effect behaves with regional difference in spatial scale, and this explains why there is significant disagreement on the effect of environmental loading on GPS position time series from various authors (Dong et al., 2002; Wang et al., 2005; Yuan et al., 2008; Yan et al., 2009; Rietboek et al., 2011; Jiang et al., 2013).

4. IMPACT OF ENVIRONMENTAL LOADING ON THE NOISE PROPERTIES OF GPS TIME SERIES

To further investigate the impact of the environment loading on GPS position time series, we quantify the impact of environment loading on noise model and related velocity estimation using the environment loading data and GPS time series as described in section 2. To estimate the parameters of the noise model and related rate uncertainties, we use the Hector Software with Maximum Likelihood Estimation (MLE) method and the function "removeoutlier" is used to remove outliers with Interquartile Range values (IQR, Bos et al., 2013a).

4.1. THE LOADING EFFECT ON STOCHASTIC NOISE PROPERTIES ON GPS TIME SERIES

Based on the extensive studies on noise analysis of GPS time series (Zhang et al., 1997; Mao et al., 1999; Williams, 2004; Langbein, 2004, 2008; Amiri-Simkooei et al., 2007; Bos et al., 2008, 2013a; Wang et al., 2012; Bogusz and Klos, 2016), we choose four different noise models to analyze the environment loading effect on geophysical parameters estimation. These noise models are:

1. a combination of flicker and white noise (FN+WN),
2. a combination of flicker, random walk and white noise (FN+WN+RW),
3. power-law noise (PL),
4. First-Order Gauss-Markov noise (FOGM).

The HECTOR software package (Bos et al., 2013), which employs the standard Maximum Likelihood Estimation method was used to perform the estimation of the functional and stochastic models. The relative goodness of fit of the noise models was tested using the Akaike information criterion (AIC) and Bayesian information criterion (BIC) (Akaike, 1974; Schwarz, 1978). The model with the lowest AIC/BIC value is the most likely to be correct (Bos et al., 2013a, b). For the AIC and BIC agree in most case, here we adopted the AIC criterion for a qualitative description of our results (Bogusz and Klos, 2016).

The results of loading on stochastic noise properties with GPS time series are presented in Table 2. Table 2 shows the percentage of stations with different type of noise model for the “Raw” GPS time series with seasonal signals and linear trend being removed (Dong et al., 2002; He et al., 2015; Bogusz and Klos, 2016) and implemented environment loading correction on the raw time series (denoted as ‘Corrected’). As for the ‘Raw’ time series, the results in Table 1 show that FN+WN, FN+WN+RW, PL and FOGM model account for 51 %, 12 %, 37 %, 0 %; 50 %, 18 %, 32 %, 0.0 % and 50 %, 2 %, 41 %, 6 % for the NEU component respectively. In terms of ‘Corrected’ time series, the above mentioned four type of noise model account for 51 %, 12 %, 36, 0 %; 50 %, 9 %, 40 %, 0 % and 68 %, 4 %, 28 %, 0 % for the NEU component respectively. From the results we can conclude that the noise in the GPS time series can be best described by FN+WN (about 50 % to 67 %) and PL+WN (about 27 % to 39 %) for the position coordinate time series of the 206 IGS stations. This confirms the previous claims by Zhang et al. (1997), Mao et al. (1999), and Williams et al. (2004) that the FN+WH is a suitable stochastic model to describe the noise processes in long GPS time series. However, we also observe that part of the stations (about 2 % to 18 %, mainly in horizontal component) can be best described by the FN+RW+WN model. Besides, there a slight number of raw time series in the vertical component that are best described by a FOGM model. Thus, we can conclude that it is inappropriate to apply only one noise model to study all GPS coordinate time series.

To further analyze the effect of environment loading on the stochastic noise properties of GPS time series, we examine the change of the behavior of noise model before and after loading correction, 33 %, 15 % and 39 % of the stations’ behavior of noise model has been changed for NEU components. We can see that environmental loading has a significant impact on the properties of the stochastic noise in the GPS time series. This is particularly relevant to the vertical component, where deformation is more significant (Ferenc et al., 2014; Santamaria-Gomez and Memin, 2015). Figure 4 shows spatial pattern of noise model for ‘Corrected’ GPS time series. It can be seen that the noise model of GPS time series shows diversity and regional variation, and there is no obvious regular pattern under the global scale. Thus, the influential mechanism of stochastic noise properties of GPS time series is complicated, since the noise is contributed by many different factors such as the monument type, local environment, and un-modeled common-mode error (CME, Wdowinski, 1997).

The red points marked with “x” represents the PSD for the raw observation, while the solid green line is for the PSD the fitted best noise model (the noise model which best describe the noise properties of the NEU component of a GPS time series). The frequency is given in cycles per year (cpy).

To verify if the stochastic noise model behaves “good enough”, we computed the power spectral density (PSD) of the ‘Corrected’ GPS time series as shown in Figure 5 (Bos et al., 2013a). From the plot it can be observed that at high frequencies the noise is flat which represents a property of the white noise, while for the lower frequencies the spectrum obeys a power-law or flicker or a combination of flicker and

Table 2 Percentage of different noise models for East, North and Up components.

Component / Noise Model	East		North		Up	
	Raw	Corrected	Raw	Corrected	Raw	Corrected
FN+WN	51.5 %	51.5 %	50.0 %	50.0 %	50.0 %	68.0 %
FN+WN+RW	11.7 %	12.1 %	18.5 %	9.2 %	2.4 %	4.4 %
PL+ WN	36.9 %	36.4 %	31.6 %	39.8 %	41.3 %	27.7 %
FOGM	0.0 %	0.0 %	0.0 %	1.0 %	6.3 %	0.0 %

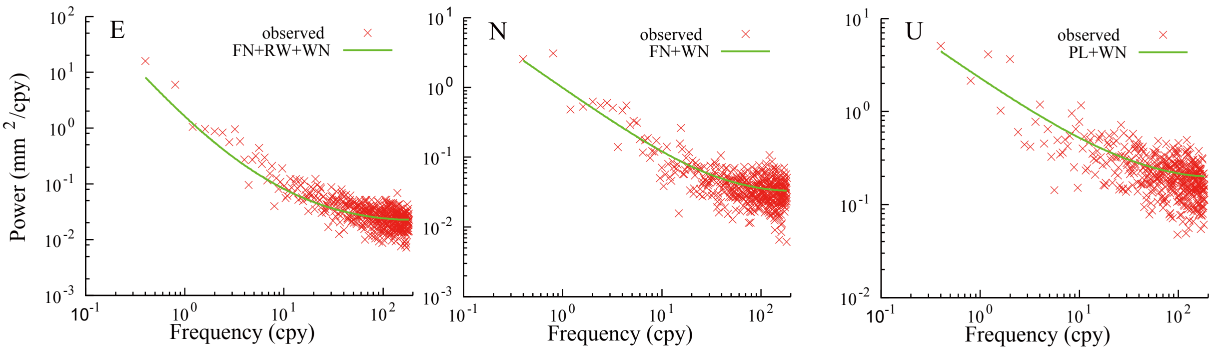

Fig. 5 Power spectral density for North, East and Up component at KERG station.

random walk noise. We can also see that there exist some differences between the NEU components of a GPS station time series (i.e. KERG station in Figure 5).

4.2. *VARIETY OF VELOCITY SIGNAL INDUCED BY ENVIRONMENTAL LOADING*

In this part of the research we investigate how the environmental loading could affect the precision of the GPS site velocity estimation. Both the 'Raw' time series and the 'Corrected' time series are evaluated by fitting a FN+WN noise model. Table 3 shows the statistics of the absolute value of the difference between the velocity (v_{Raw}) estimated with the 'Raw' data and that ($v_{Corrected}$) estimated with the 'Corrected' data. That is, $v_{variety} = \left| v_{Raw} - v_{Corrected} \right|$.

From Table 3 we can see that environmental loading has a slight effect on the estimate of horizontal velocity, with a mean of about 0.01 mm/y for the North and East components, meanwhile, the maximum reach up to 0.07 mm/y and 0.20 mm/y in North and East components, respectively. For the vertical component, the loading effects seem to affect more significantly, with a mean of about 0.06 mm/y over all the 206 sites and the largest impact on the estimate of vertical velocity can reach 0.59 mm/y, which means that the impact of environmental loading on GPS time series velocity cannot be ignored, this is particularly significant to the vertical component, where deformation signals are larger (described in section 3.2). Figure 6 shows the statistical values of the absolute velocity difference estimated using the 'Raw' GPS time series and 'Corrected' GPS time series. It can be observed that the environmental loading effect on horizontal component is less than 0.1 mm/y for most of stations, while in the vertical component the impact is slightly larger than that in the horizontal component, about 41 % of the stations with velocity difference large than 0.05 mm/y and 15 % of the stations with velocity difference large than 0.1 mm/yr.

Table 3 Environmental loading effect on GPS site velocity [mm/y].

Component	E	N	U
Min	0.00	0.00	0.00
Max	0.07	0.20	0.59
Mean	0.01	0.01	0.06
Median	0.01	0.01	0.04

5. CONCLUSION

This paper investigated on the impact of environmental mass loading on GPS time-series of receiver coordinates and noise characteristic. Position coordinate time series of 206 continuous GPS stations between 2001 and 2013 were employed for the study. The analysis focused on the environmental loading effects induced by atmospheric pressure, soil moisture, non-tidal ocean and snow cover mass loading. The following conclusions are drawn from the study.

1. The coordinate displacements induced by environmental loading can be significant, up to centimeter level, so that the loading effect should be taken into account especially in high-precision geophysical studies and applications. Displacements are mainly caused by atmospheric pressure and soil moisture in the GPS station network. Meanwhile, horizontal environmental displacements are about 4 to 8 times smaller than the vertical component. Besides, the environmental loading effect behaves with regional difference in spatial scale.

2. After environmental loading correction, 90 % of the stations' WRMS has been reduced, so that loading can significantly improve the accuracy of the GPS time series.

3. The noise in GPS time series can be best described by FN+WN model and PL+WN model, while noise associated with a small percentage of stations can be characterized by FN+RW+WN model. That proved some previous investigations, that it is inappropriate to apply the same model to describe the noise in all GPS time series. Furthermore, environmental loading has a significant impact on the stochastic noise properties of GPS time series; 33 %, 15 % and 39 % of the station's noise properties (type) have been changed after loading correction for NEU components respectively. Last but not least, the impact of environmental loading on GPS station velocity especially the vertical component can be considerable. Therefore, it is important to pay attention to these environmental loading effects with or without post-processing of GPS time series.

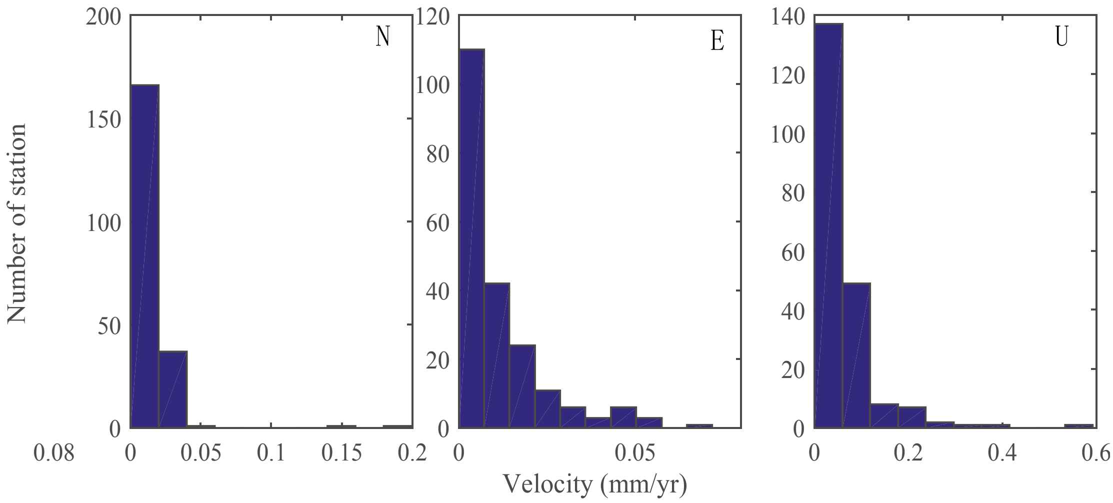

Fig. 6 Statistical values related to the velocity differences before and after loading correction (NEU).

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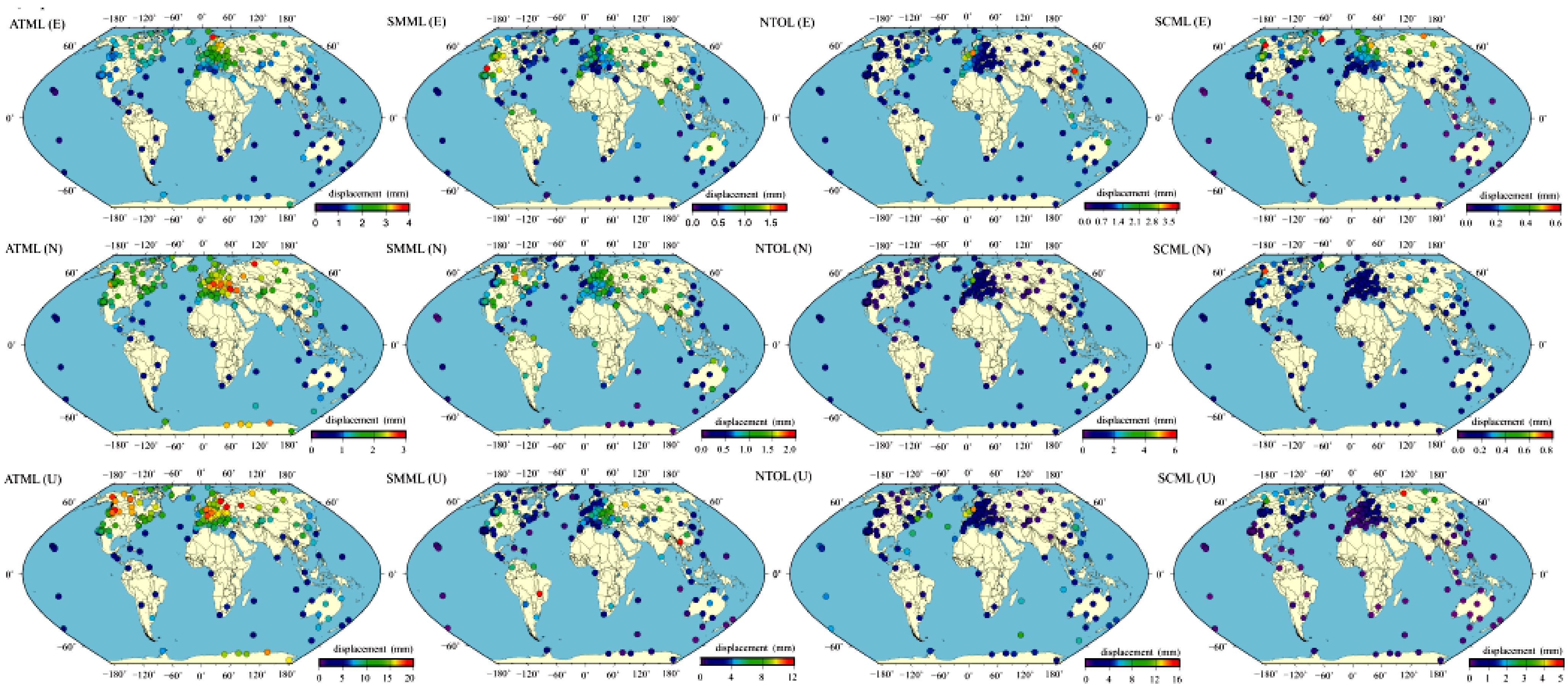

Fig. 1 Spatial pattern of loading effect time series.
A) Spatial distribution of the maximum value: MAX

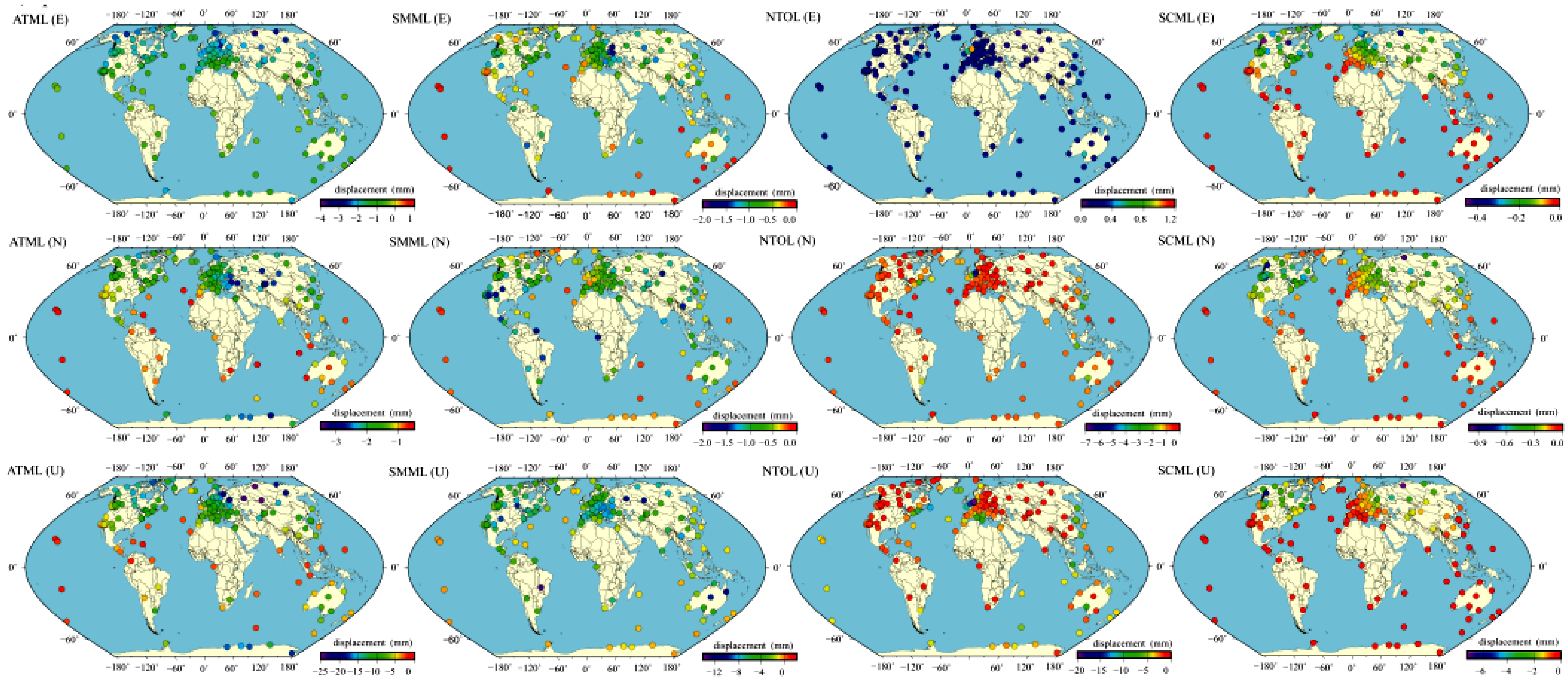

Fig. 1 Spatial pattern of loading effect time series.
B) Spatial distribution of the minimum value: MIN

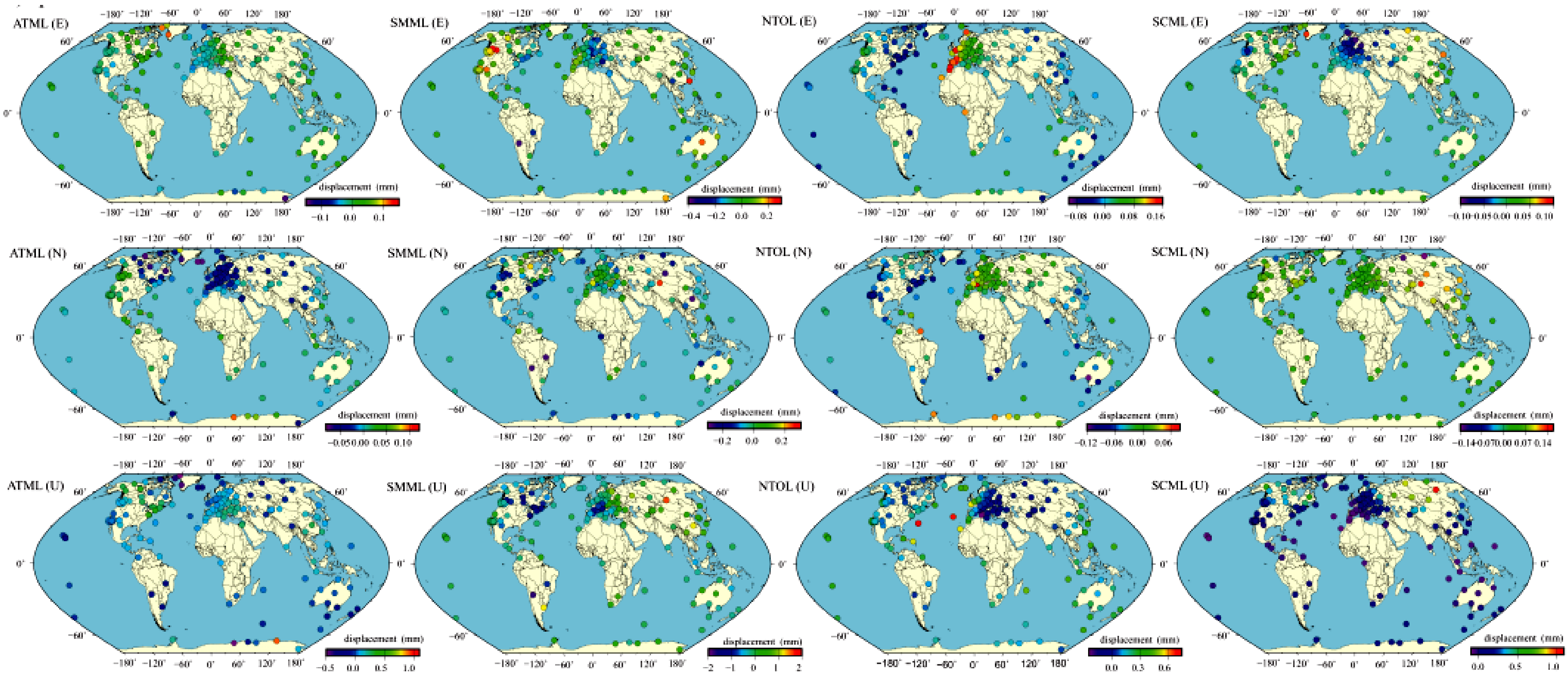

Fig. 1 Spatial pattern of loading effect time series.
C) Spatial distribution of the mean value: MEAN

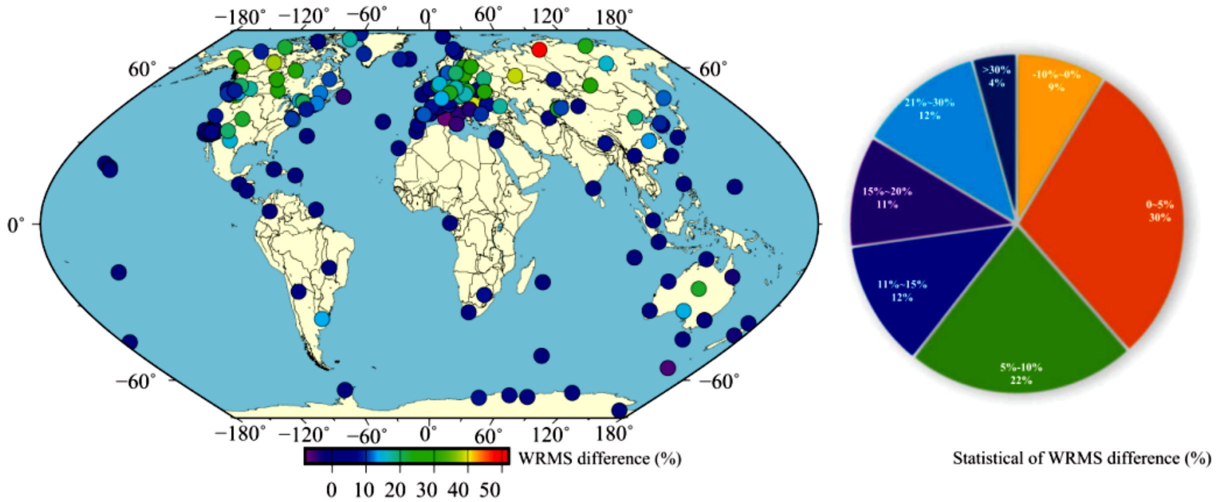

Fig. 3 Spatial distribution of the WRMS differences before and after loading correction.

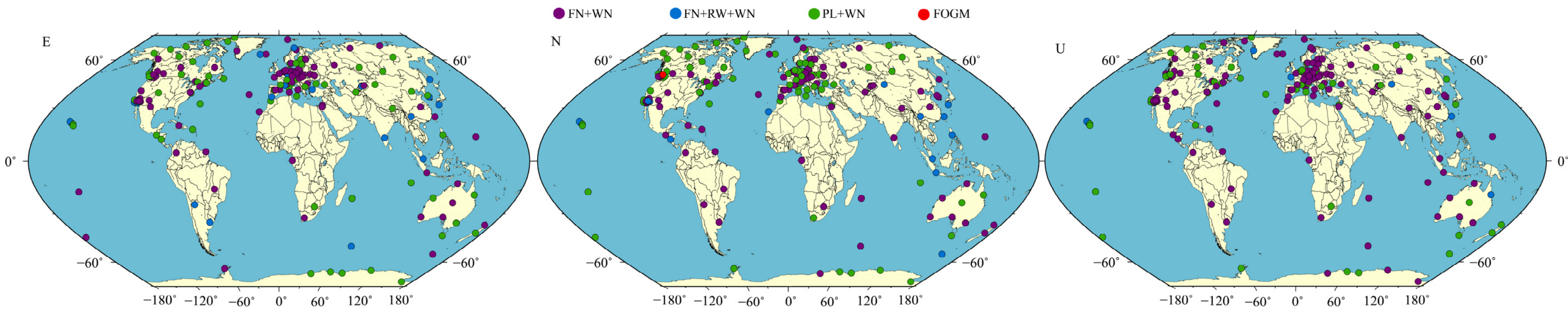

Fig. 4 Spatial pattern of noise model for 'Corrected' GPS time series.