On the Properties of Zenith Total Delay Time Series from Reprocessed GPS Solutions

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INTRODUCTION

The **ZTD time series** is one of the estimated products from the reanalysis of globally distributed Global Navigation Satellite System (GNSS) stations **for the period 1995 to 2015** with a highest consistency using the latest models and methodology at the **University of Luxembourg**. Zenith Total Delay (ZTD) time series reflects the average atmospheric delay of a signal path between the satellite and the receiver antennas in the zenith directions. The ZTD time series can be converted into the Integrated Water Vapour (IWV) using known mean temperature of the atmosphere which is directly interpreted in terms of climate change. Especially, **a trend together with its associated uncertainty that indicates long-term variations of climate** is nowadays of high interest. Currently trend along with uncertainty are widely estimated with assumption of white noise model. A linear trend and seasonal signals with a constant amplitude are fitted to the ZTD residual time series. We analyse the ZTD residual times series assuming that it only represents noise. We first classify the GPS sites to five different major climate zones according to **Köppen-Geiger climate classifications**. The ZTD residual time series undergone a manual inspection to identify offsets in the time series. Next, all significant oscillations were identified with spectral analysis and modelled with a Least-Squares Estimation. Residuals are subjected to noise analysis with different models. We show that **autoregressive model of fourth order** in combination with white noise is optimal for ZTD residual time series **noise characteristics for all the climate zones considered**. We found that the autoregressive model shows **the ZTD uncertainties by a factor 12 higher than the white noise only** model assumption.

REPROCESSING STRATEGY FOR BLT2 REPRO2

Reprocessing strategy and models applied for BLT repro2 solution:

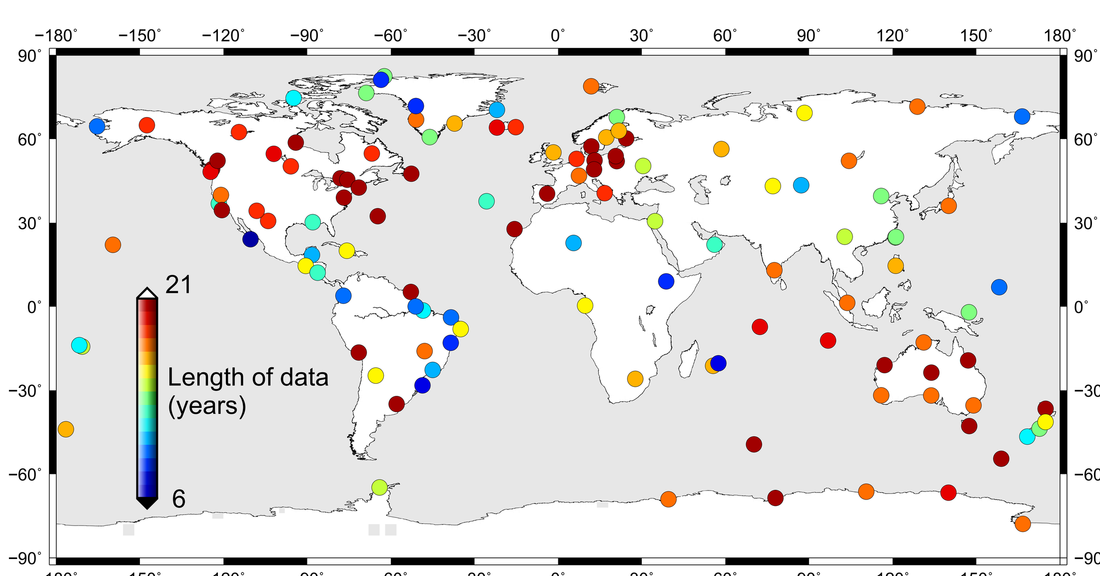
- Bernese GNSS Software BSW5.2 (double difference phase and code observations).
- Satellite and Earth rotation products from the reprocessing at the Centre for Orbit Determination in Europe (CODE).
- International Earth Rotation and Reference Frame Service (IERS) Conventions 2010.
- Vienna Mapping Function 1 (VMF1) and Hydrostatic a priori and Wet troposphere model from VMF.
- Troposphere gradients: Chen and Herring tilt estimation for N-S and W-E directions.
- Estimates of Zenith Total Delay (ZTD) were computed every two hours using a piece-wise linear function and gradients were estimated at 12 hour intervals.
- 3 degrees elevation cutoff and the cosine quartic dependent weighting.

HOMOGENISATION

Reprocessing covered the period **from 1995 to end of 2015**. We have identified a total number of **2500 discontinuities** in the GPS position residual time series of different sources from **750 stations**.
The discontinuity identification and verification is based on:
(1) a manual intervention from the residual position time series,
(2) International Terrestrial Reference Frame 2008 supplied discontinuity file,
(3) earthquakes files.
The discontinuity budget from our reprocessed GPS position time series arise in 67% from change in hardware, 4% from earthquakes and in 9% from unknown reasons. When all epochs of offsets were taken into consideration, we found **a maximum amplitude of offset in ZTD data equal to 83.5 mm**, **a maximum improvement of standard deviation of 1.5 mm** and a maximum, **most dramatic change in ZTD trend of 3.7 mm/decade is found for station POHN (Federated States of Micronesia)**.

CLIMATE ZONES

In this study, we considered **125 stations with hourly sampled ZTD** time series length between 6 and 20 years coming from our reprocessed global network of stations, see Figure 1. On average each of the time series is characterized to contain 2 offsets. The stations are classified into different climate zones: tropical, dry, warm temperate, continental and polar and Alpine based on the Köppen-Geiger classification, see Figure 2.



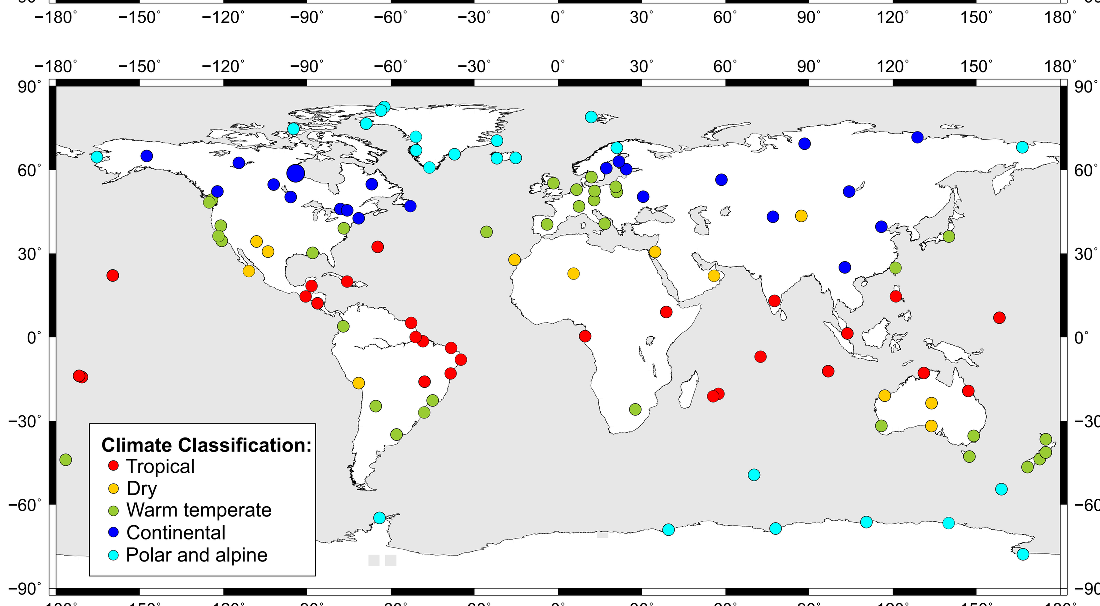


Figure 1 (top): Stations considered in this study.

Figure 2 (bottom): Division of stations into different climate zones.

THE ZENITH TOTAL DELAY SERIES

The ZTD time series are commonly modelled with **Least-Squares or weighted Least-Squares Estimation** when uncertainties of individual observation are taken into account. Focusing on estimation of trend, which is interpreted in terms of climate change, and all significant periodics, derived with spectral method, one can fit a least-squares model as:

$$ZTD(t) = ZTD_0 + v_{ZTD} \cdot \; t - t_0) + \sum_{i=1}^{k}[S_i \cdot \sin(2 \cdot \pi \cdot f_i \cdot (t - t_0)) + C_i \cdot \cos(2 \cdot \pi \cdot f_i \cdot (t - t_0))] + \sum_{j=1}^{m} H_j \cdot x_j^{off} + \varepsilon_{ZTD}(t)$$

where t is time, t_0 is the reference time, ZTD_0 the initial values of the ZTD at time $t = t_0$, v is the trend, C_i, S_i are the coefficients of the harmonic terms and ε is the error, x_j represents the discontinuity which occurs at time t, i is the number of harmonic terms and $f_i = (1/365.25, 2/365.25, 3/365.25, 4/365.25, 1, 1/2)$. This model also accounts for discontinuities using a Heaviside function.

We examined **Power Spectral Densities (PSDs)** of each of analysed stations. Figure 3 shows a PSD for a single selected station, BJFS (Beijing, China) for both original and residual ZTD time series. We have found that 1-hour ZTD time series are characterized by clear peaks of one year and three subsequent overtones in addition to the diurnal and semi-diurnal peaks. **The annual oscillation is the most powerful peak for all examined stations, followed by the semi annual oscillation, which is roughly half as significant as the annual one for 70% of stations.** Peaks of 3 and 4 cpy are clearly seen in the frequency domain for low- and mid-latitude stations, while hardly noticeable for polar and Alpine zones. In this way, we assumed a seasonal model containing all of 6 periodicities.

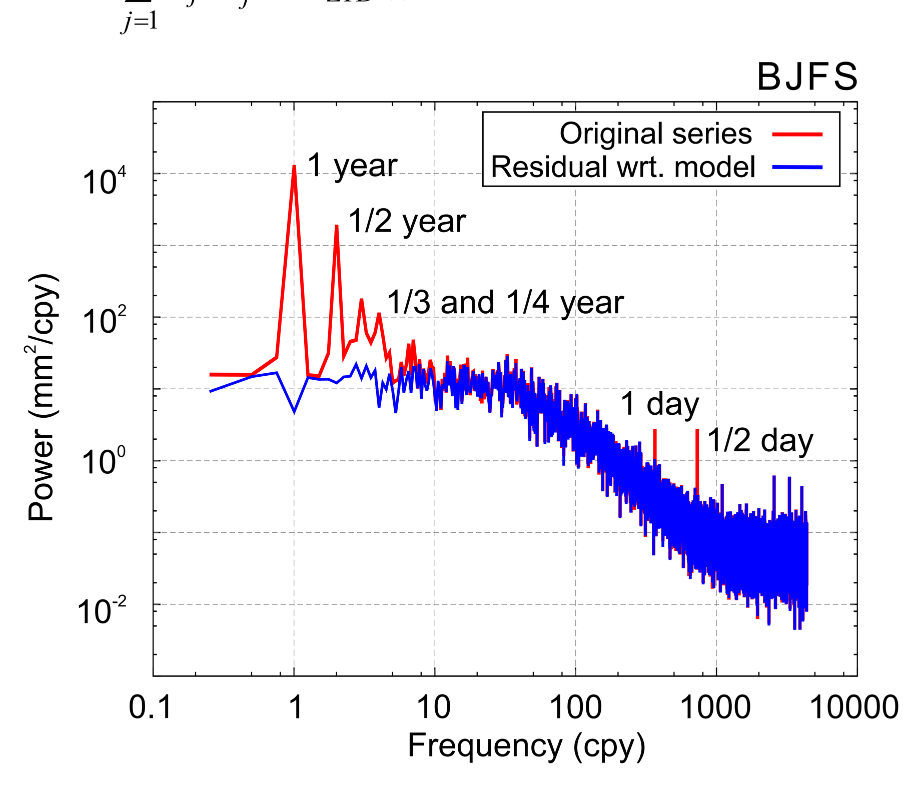


Figure 3: Power Spectral Density of ZTD for BJFS (China), continental zone. One can easily notice the peaks of one year, half a year, 3 and 4 months, 1 day and half a day. Power of original series is plotted in red, while power of residuals with respect to the model in blue.

Acknowledgments. The computational resources used in this study were provided by the High Performance Computing Facility at the University of Luxembourg, Luxembourg. The CODE Analysis is highly appreciated for their data, and products. We are especially thankful to the TIGA data providers and the SONEL archive. Part of this work has been supported by COST Action ES1206 GNSS4SWEC (gnss4swec.knmi.nl).
The results were partially carried out during Short Term Scientific Mission (STSM) that Anna Klos attended to at the University of Luxembourg thanks to the ES1206 COST Action. Janusz Bogusz is financed by the Faculty of Civil Engineering and Geodesy of the Military University of Technology statutory research funds. Addisu Hunegnaw is financed by the University of Luxembourg projects SGSL & GSCG.

TEMPORAL VARIATIONS OF ZTD DATA

The amplitudes and phases of all significant frequencies were estimated with **Least-Squares method** (white noise assumption).

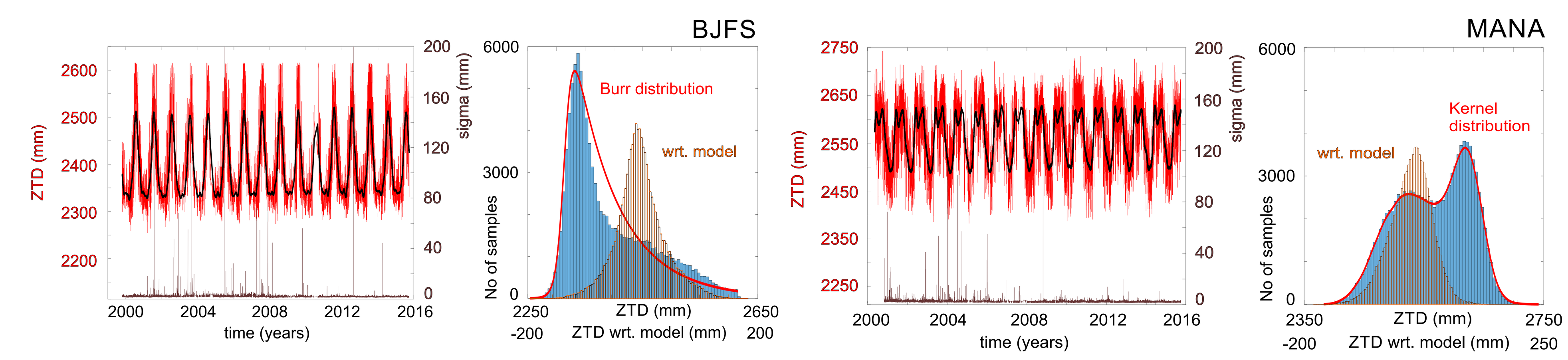
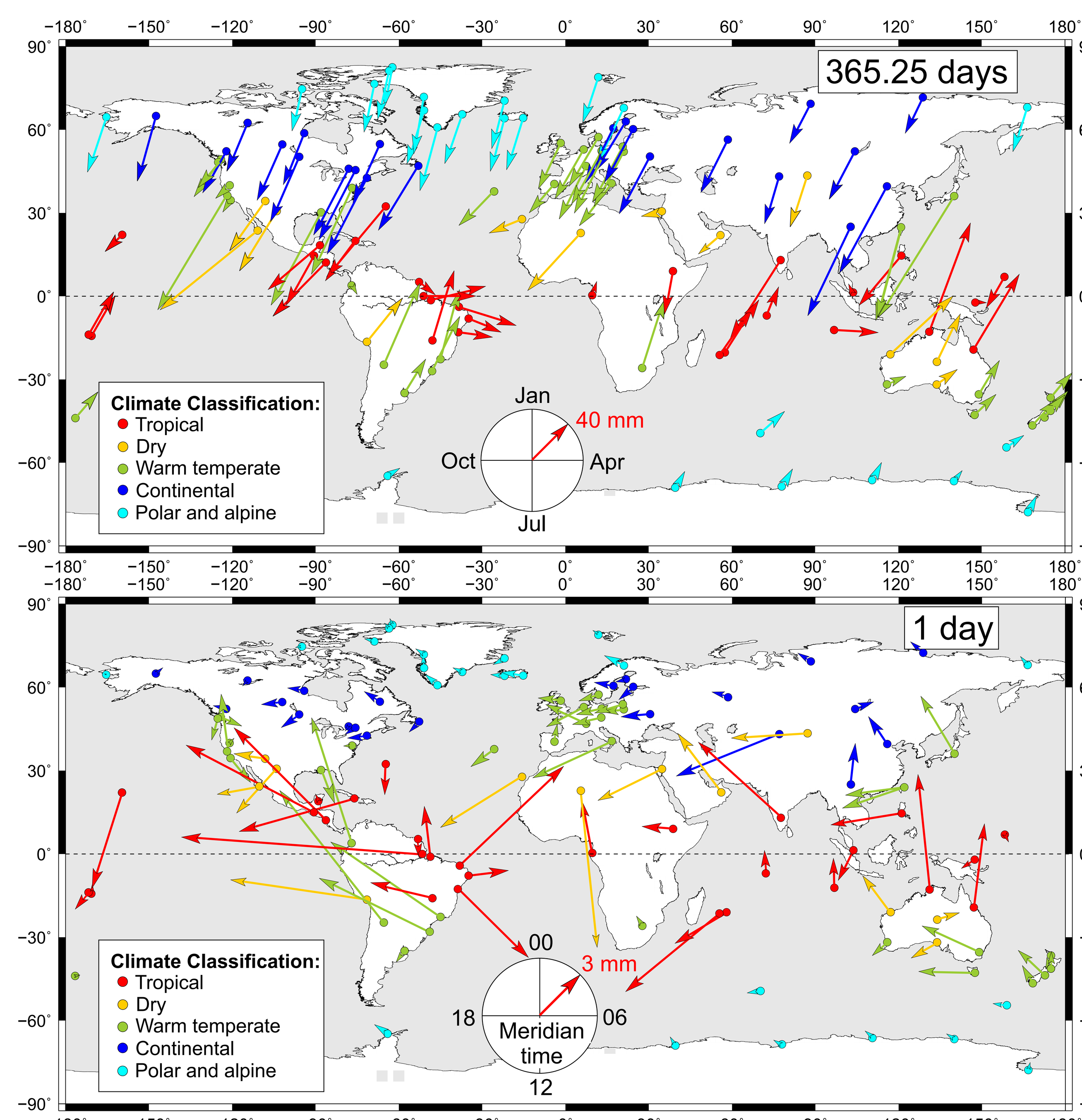


Figure 4: ZTD time series for two chosen stations: BJFS (China, continental zone) and MANA (Nicaragua, tropical zone). Original time series is plotted in red along with one sigma uncertainties of every single observation in brown. Each of time series has a LSE model fitted. The plots are accompanied by histograms of original data in blue and residua with respect to the model in orange. We fitted a probabilistic distribution into each histogram (in red).



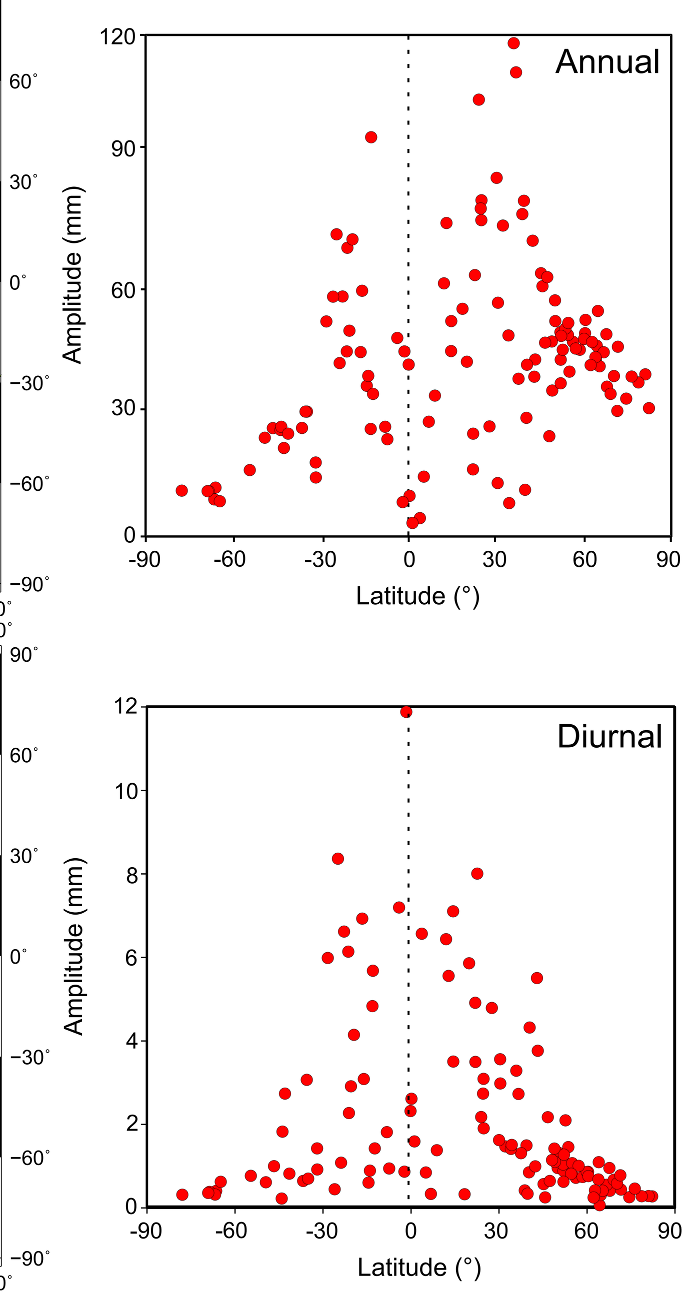


Figure 5: Annual (top) and diurnal (bottom) amplitudes for ZTD series with respect to climate classification, according to Köppen-Geiger. The maximum of annual curve is given in months and the maximum of diurnal variation is given as meridian time for every single station.

Figure 6: Amplitudes of annual (top) and diurnal (bottom) variations with respect to station's latitude. Maximum amplitudes close to meridian are easily noticeable.

ZTD NOISE

Up to date, the **stochastic part** of ZTD series ε_{ZTD} was assumed as **white noise**, having no influence on uncertainties of deterministic part. If ZTD trend was interpreted nowadays in terms of climate change, its **reliable error** is what is desired the most, since may be wrongly interpreted when underestimated. In this research we tested a set of various models: **white and power-law models against the autoregressive process to examine on optimal noise model with Maximum Likelihood Estimation (MLE) and Akaike Information Criterion (AIC).** An autoregressive model of fourth order was chosen as the most suitable to describe the properties of ZTD noise:

$$\varepsilon_{ZTD_t} = \phi_1 \varepsilon_{ZTD_{t-1}} + \phi_2 \varepsilon_{ZTD_{t-2}} + \phi_3 \varepsilon_{ZTD_{t-3}} + \phi_4 \varepsilon_{ZTD_{t-4}} + a_t$$

In this way, we deliver the median prameters of noise for certain climate zones, as in Tab. 1.

Table 1: Median parameters of noise for ZTD series, w.r.t. climate zones.

Median amplitudes of noise (mm)				
Climate zone	WN		AR	
Tropical	12.68		8.74	
Dry	7.44		8.24	
Warm temperate	8.55		10.43	
Continental	7.65		7.20	
Polar and Alpine	6.77		7.37	
Median coefficients of AR(4)				
Climate zone	AR(1)	AR(2)	AR(3)	AR(4)
Tropical	0.90±0.08	0.05±0.08	0.01±0.03	0.03±0.01
Dry	0.78±0.04	0.19±0.03	0.05±0.01	0.01±0.01
Warm temperate	0.72±0.03	0.17±0.02	0.08±0.01	-0.01±0.01
Continental	0.80±0.02	0.08±0.01	0.09±0.01	-0.03±0.01
Polar and Alpine	0.61±0.01	0.27±0.01	0.11±0.01	-0.02±0.01
Median fraction of AR				
Climate zone				
Tropical	0.34			
Dry	0.58			
Warm temperate	0.53			
Continental	0.36			
Polar and Alpine	0.45			

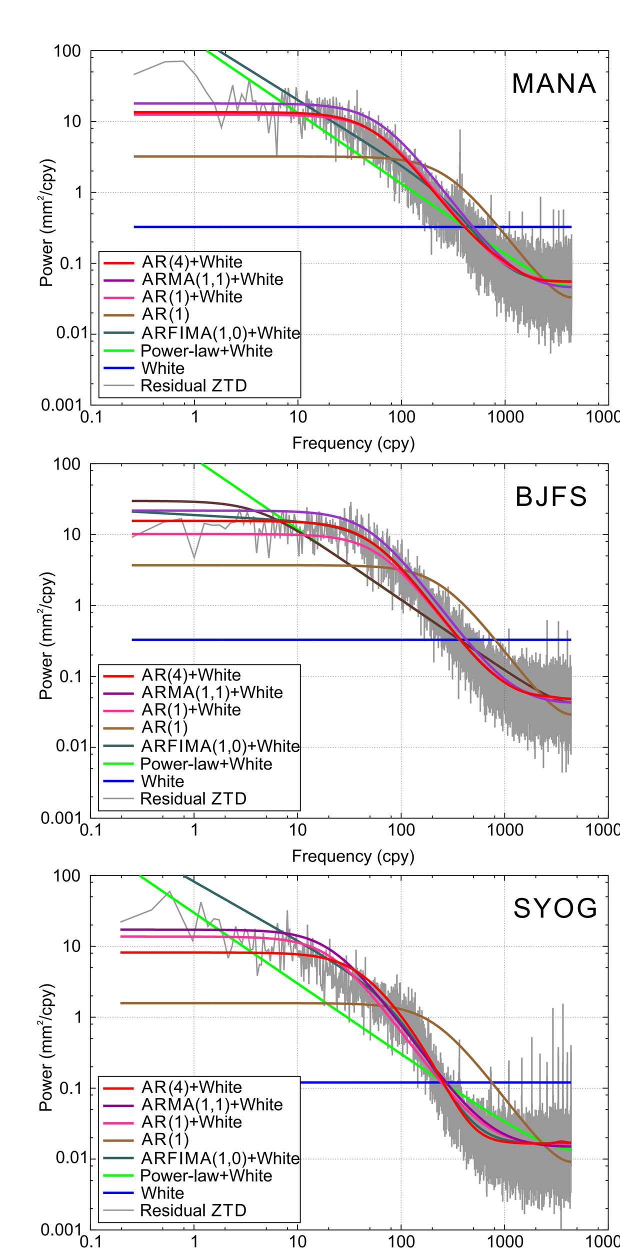


Figure 7: Power Spectral Densities for three chosen stations: MANA (tropical zone), BJFS (continental zone) and SYOG (polar and Alipne).

CONCLUSIONS

The stochastic component of the ZTD residual is widely modelled with white noise process standalone i.e. with no time correlation between the observations. A total number of **125 GPS stations** distributed globally were used for this study from all the **five climates zones**. We examined on all **significant frequencies** after adjusting the data for discontinuities. The residual ZTD time series shows a temporal correlation that appears to be explained by **autoregressive with fourth order combined with white noise model** irrespective of the climate zones considered. The uncertainty of the ZTD residual may be **underestimated by a factor of 12** compared to white noise only assumptions.

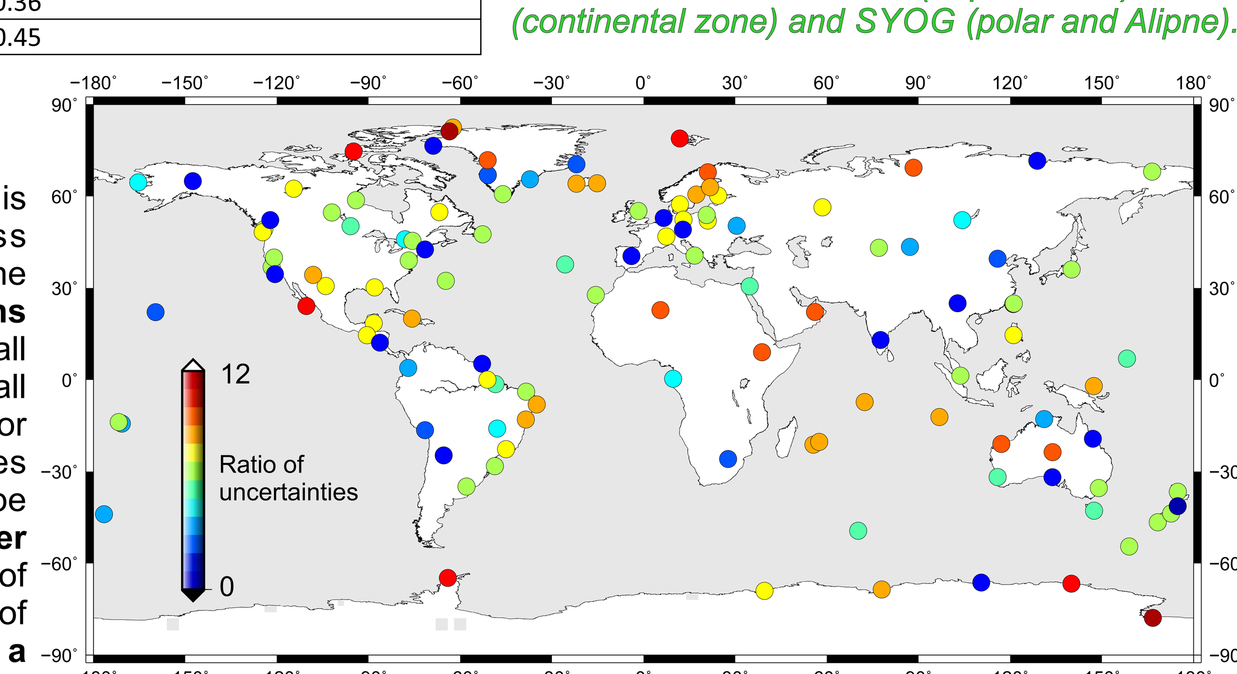


Figure 8: Ratio of uncertainties estimated with AR(4)+WH noise model and pure White process