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# Non-parametric Estimation of Seasonal Variations in GPS-Derived Time Series

Janusz Bogusz, Marta Gruszczynska, Anna Klos, and Maciej Gruszczynski

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## Abstract

In this research, we focus on determining the quasi-annual changes in GNSS-derived 3-dimensional time series. We use the daily time series from PPP solution obtained by JPL (Jet Propulsion Laboratory) from more than 300 globally distributed IGS stations. Each of the topocentric time series were stacked into data sets according to year (from January to December) and then decomposed and approximated with a Meyer wavelet. This approach allowed investigating changes of the amplitudes in time. An observed quasi-annual signal for a set of European stations prompted us to divide the stations into different sub-networks called clusters. For Up component seven clusters were established. The signals were then averaged within each cluster and median quasi-annual signal was revealed. The vast majority of the GNSS time series is characterized by vertical changes of 3 mm with their maximum in Summer. The maximum vertical amplitude was at the level of 14 mm with the minimum equal to  $-13$  mm, giving the peak-to-peak position changes up to 27 mm.

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## Keywords

Clustering • GPS • PPP • Seasonal variations • Wavelet decomposition

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## 1 Introduction

The seasonal variations in a GNSS station's position may arise from gravitational excitation, thermal changes, hydrological effects, or other errors. These, when superimposed, may introduce seasonal oscillations that are not entirely of geodynamical origin, but still have to be included in time series modelling (Dong et al. 2002). Displacements of the surface of the Earth caused by the atmosphere, soil moisture, snow and ocean mass changes can reach several millimetres at some locations (e.g. Mangiarotti et al. 2001; van Dam et al. 2001; Poutanen et al. 2005; Tregoning and Watson 2009). These variations with different periods all affect the reliability of the station's velocity (Blewitt and

Lavallée 2002; Bos et al. 2010), which, in turn, can disturb the quality of kinematic reference frames or rightness of geodynamical interpretations. As shown before by a number of authors (e.g. Chen et al. 2013), the commonly modelled annual signal is not time-constant either in amplitude or in phase due to season-to-season variability. However, some components of the seasonal changes observed by satellite navigation techniques are due to artefacts such as the aliasing of periodic signals (e.g. Dong et al. 2002; Penna and Stewart 2003) or mismodelling at sub-daily periods (e.g. Watson et al. 2006; King et al. 2008; Bogusz and Figurski 2012). In this research, we focus on the amplitudes and phases of seasonal changes from globally distributed IGS (International GNSS Service) stations and present results for European stations. The determination of the quasi-annual signals was performed by dividing the stations characterized by similar temporal patterns into different clusters. As a result, the median quasi-annual curves are presented for each cluster.

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J. Bogusz • M. Gruszczynska (✉) • A. Klos • M. Gruszczynski  
Faculty of Civil Engineering and Geodesy, Military University  
of Technology, Warsaw, Poland  
e-mail: [marta.gruszczynska@wat.edu.pl](mailto:marta.gruszczynska@wat.edu.pl)

## 2 Data

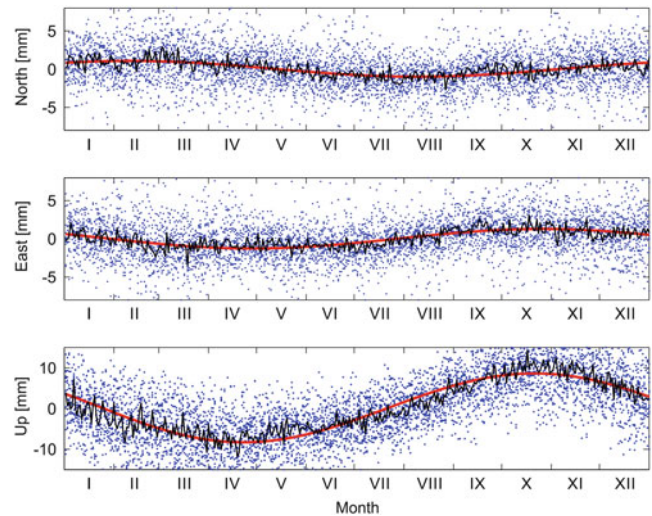
We used position time series obtained from the Jet Propulsion Laboratory (JPL) using the GIPSY-OASIS software in a Precise Point Positioning mode. The details concerning the processing of the GNSS observations can be found at <https://gipsy-oasis.jpl.nasa.gov>. The pre-analysis consisted of removing outliers and offsets. Short data gaps (up to 40 days) were interpolated using a white noise assumption. Having introduced a 6.5-year threshold in time series length, the number of 320 globally distributed GPS permanent stations were taken here.

## 3 Stacking and Smoothing

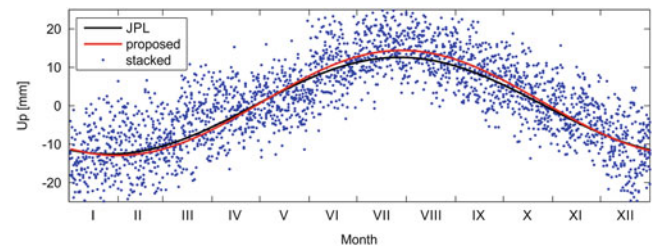
Within this research the significant seasonal peaks around 1 cpy and its overtones in the power spectral densities (using the Lomb-Scargle method) of the IGS time series were found. Other researchers have previously discovered similar results (e.g. Ray et al. 2008; Collilieux et al. 2007). To focus on the annual signal, the daily topocentric time series (North, East and Up) were stacked here as proposed in Freymueller (2009).

The North, East and Up time series of each station were sorted by day of year (from January to December) into specific years. Observations from the day of year were stacked in order to emphasize the annual signal in the observations. In this way, we created the matrices of  $356 \times n$  size, where  $n$  is a number of years in the time series. Then for each day of the year, i.e. each row of the matrix, the values of the weighted median and the weighted median absolute deviation (WMAD) were calculated providing the averaged representative quasi-annual signal for each of the three components for each station. These series will be referred to as “stacked” and “smoothed”, respectively.

One of the methods for determination of the seasonal signals is approximation with a set of sinusoidal functions (e.g. Kenyeres and Bruyninx 2009; Bogusz and Figurski 2014). However, many seasonal signals are not purely sinusoidal (e.g. snow loading and precipitation can vary from year to year) and are not time-invariant (Santamaría-Gómez et al. 2011). For that reason, in this research we performed wavelet decomposition on the smoothed data. The wavelet transform allows us to decompose the original time series into a number of new time series, each with a different degree of resolution. We used a symmetric and orthogonal Meyer’s wavelet (Meyer 1990) for this task, because it is compact in



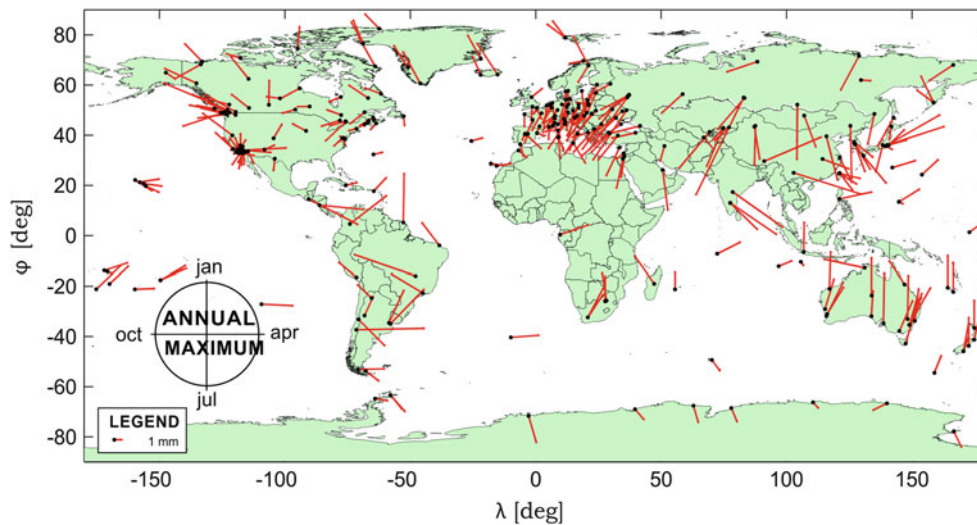
**Fig. 1** The stacked and smoothed data for the BRAZ (Brasilia, Brazil) IGS station using 19.5 years of observations. The blue dots represent the original (yearly stacked) data; a black curve represents the daily medians; a red curve represents a wavelet quasi-annual approximation. The North component is shifted in phase when being compared to East and Up. The amplitude in the Up direction is twice as large in amplitude for North or East



**Fig. 2** The comparison of JPL-derived sine wave determined for annual signal (a black curve) with the non-parametric approach so the quasi-annual curve proposed in this research (a red curve) for the NOV (Novosibirsk, Russian Federation) station

the frequency domain. Seasonal signals dominate the spectrum near the lowest (annual) harmonics (e.g. Blewitt and Lavallée 2002; van Dam et al. 2007; Ray et al. 2008; Amiri-Simkooei 2013), so for further analysis we took the quasi-annual approximation from wavelet decomposition (Fig. 1).

Then, we compared our approach to the one provided by the JPL, available at <http://sideshow.jpl.nasa.gov/post/tables/table4.html>. Although the vast majority of amplitudes determined with wavelets on the smoothed data is almost the same as the ones from the JPL sine waves, some of them show the evident change during year. Figure 2 shows stacked and smoothed 1-year signal for the NOV (Novosibirsk, Russian Federation) station presented with blue dots. A black curve



**Fig. 3** The amplitudes and phases of quasi-annual curves in the vertical direction. The length of the *arrow* means the value of the amplitude, while the azimuth-like angle stays for phase of the quasi-annual maximum

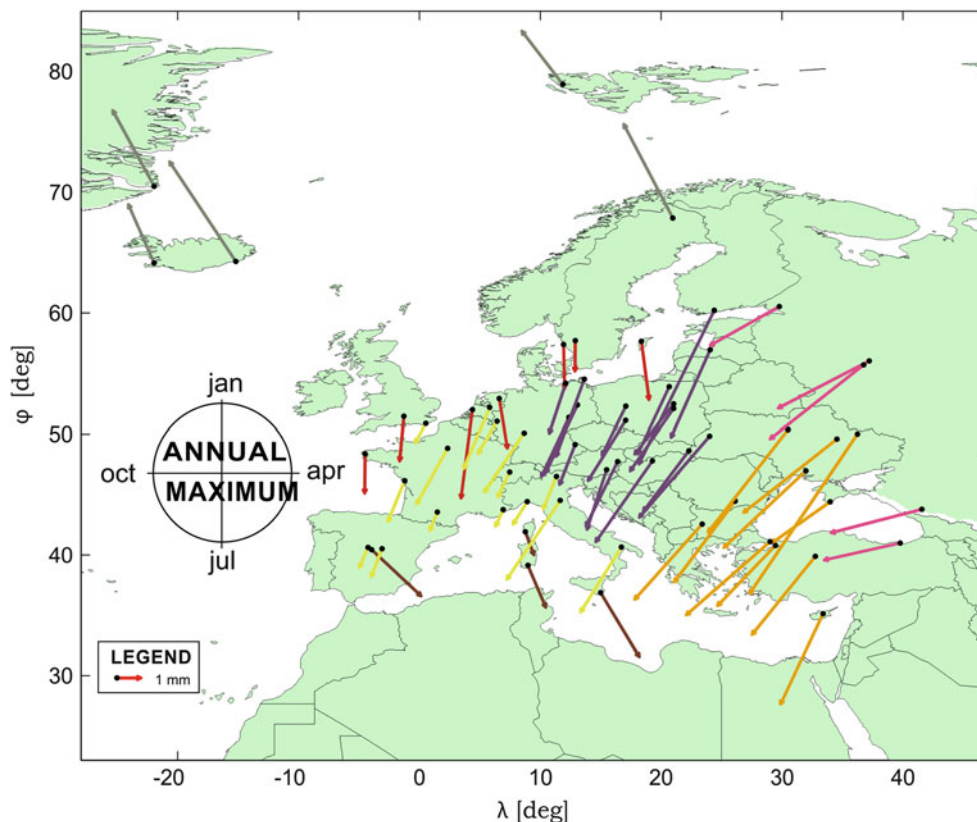
indicates a sine parametric function used to estimate the seasonal components by the JPL. This curve is being compared with our non-parametric approach presented with a red line. It can be easily noticed, that both of the estimated seasonal variations are quite similar to each other, however, the proposed approach shows the amplitude changing in time. This change is at the level of 2 mm, but when taking into consideration the growing demands of the models that value seems to be significant. The quasi-annual curves determined here from the JPL PPP solutions for the vertical component show similar amplitudes and phases when the stations close to one another are being analyzed (Fig. 3). The maxima for the vast majority of stations are directed “latitudinal”, which means that they have their maxima in Spring or Autumn. The stations situated in North America have their quasi-annual maxima during August and November being close to August on the East coast of America and to November as you move toward to the West Coast. For these stations, the quasi-annual amplitudes are about 3 mm. All stations situated on the ocean islands have their quasi-annual maxima close to April with the median amplitude of 2 mm. Stations situated in South America are also characterized by a “latitudinal” direction of quasi-annual maxima. Here, two of the IGS stations (BRAZ, Brasilia, Brazil and BOGT, Bogota, Colombia) have prominent annual amplitudes of about 7 mm. All stations situated in Antarctica have their quasi-annual maxima in July with amplitudes close to 1.5 mm. The quasi-annual signal estimated for stations situated in South-East Asia have their maximum in May. The amplitudes are quite similar from East to West part of Asia. The largest amplitude

of 14 mm was noticed for NOV (Novosibirsk, Russian Federation) station. The Western part of Asia is characterized by maxima close to July with the median amplitudes of 6 mm.

Nearly one hundred of permanent IGS stations are situated in Europe. They are discussed in details in the next section of the paper.

## 4 Clustering

The idea of clustering for investigating the annual signal was successfully introduced by Tesmer et al. (2009) for homogeneously reprocessed VLBI and GPS height time series or Poutanen et al. (2005). We investigate the magnitude of seasonal oscillations for the 90 of IGS permanent stations located in Europe. The longest time series were 22 years of available data (e.g. GRAZ, Graz, Austria), while the shortest duration of our observational series was 6.8 years (e.g. ROAP, San Fernando, Spain). The analysis of the quasi-annual curve determined with wavelet decomposition for each station allows us to sort the IGS stations into various sub-networks, called clusters, whose annual signals display similar characteristic. We defined the  $X$  parameter, which specifies the maximum acceptable phase difference for stations classified within a cluster. The next parameter,  $Y$ , is defined as the maximum distance between any two stations within a cluster. Stations were examined whether their vertical components meet the criterion of the maximum phase difference,  $X = 30$  days, and in the maximum distance



**Fig. 4** The quasi-annual signal in vertical component of 65 European permanent stations. The different clusters are marked with different colours. They strictly show different characteristics of annual signals

between stations,  $Y = 2,000$  km. Sixty-five of the ninety European IGS stations were grouped in this way into seven clusters (Fig. 4). Each cluster consists, on average, of 9 stations, however, some of 5. Such differences in the size of clusters indicate a local and regional nature of the phenomena that generates seasonal signal in the GPS time series. For the remaining 25 stations, we found no similarities in their quasi-annual signal with any nearby station. This result might be caused by local effects as snow or radome effects or by numerical artefacts as multipath or mismodelling in short periods. Therefore, these stations were excluded from clustering.

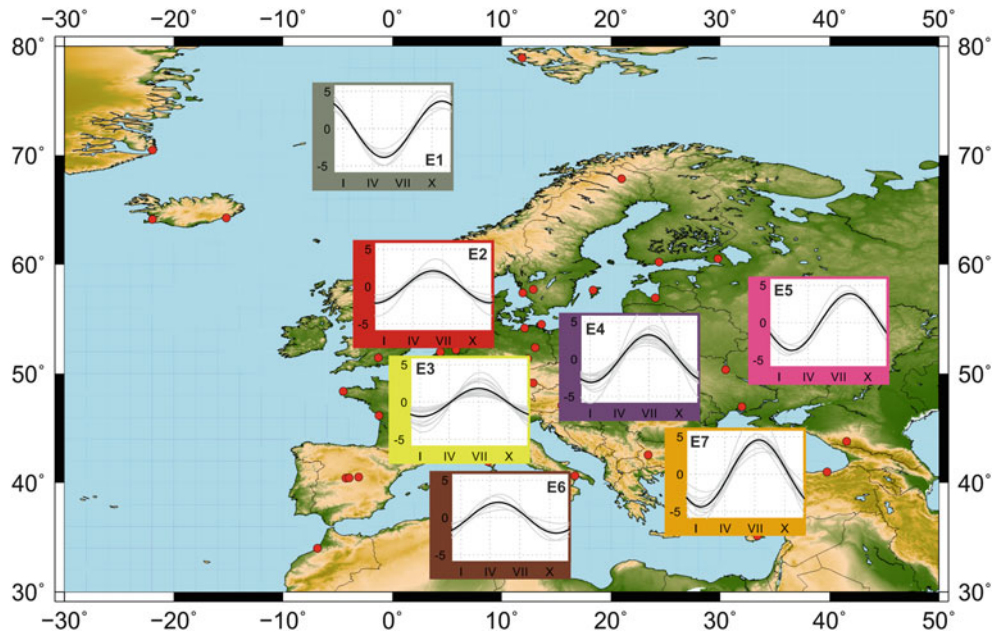
For the majority of the clusters, the quasi-annual signal in the vertical component has a minimum in Winter and a maximum in Summer (Fig. 5, Table 1). The clusters differ in terms of their quasi-annual amplitude of 1 or 2 mm, and phase of more than 30 days. The E6 cluster has a clear maximum in Spring, whereas the E1 cluster has its maximum in Autumn. Both of previously mentioned include stations located near to the sea/ocean. Worth noting is the fact that

stations situated in Eastern Europe (especially the E7 cluster) have larger annual amplitudes when being compared to the remaining clusters.

## 5 Discussion

Some part of the annual signal in the GPS coordinates reflects the real geophysical effects. Dong et al. (2002) estimated their amplitudes into 4 mm for atmospheric mass changes, 2–3 for ocean non-tidal loading, 3–5 for snow mass, 2–7 for soil moisture and 0.5 mm for bedrock thermal expansion. Freymueller (2009) underlined that the seasonal signal has nothing in common with sine function of annual plus semi-annual curve and revealed that non-parametric approach is more suitable for GPS-derived time series. Extended studies have been conducted by Tesmer et al. (2009), who has performed a cluster analysis on the basis of globally distributed stations. These authors were using similar methods based on the moving average for “mean year” determination.





**Fig. 5** The mean quasi-annual signal for individual European clusters that stations were divided into in this research. Each cluster has its description from E1 to E7

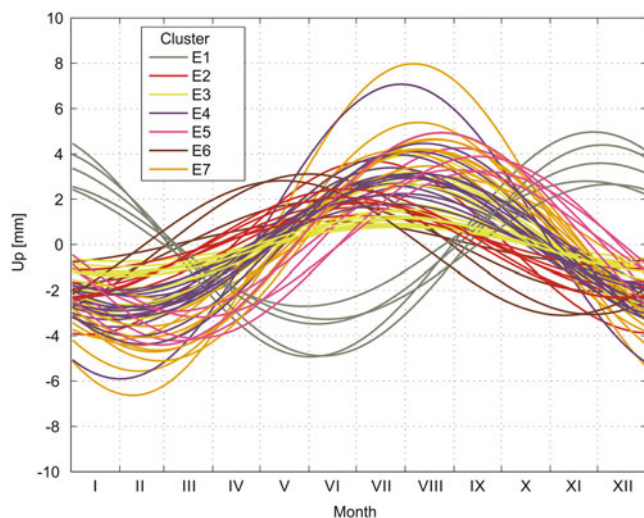
**Table 1** All clusters with the names of stations included within it; the amplitudes of quasi-annual oscillation is given both with phase in days and months

Cluster	Station included	Amplitude (mm)	Phase (days)	Phase (months)
E1	HOFN KIRU NYA1 NYAL REYK SCOR	3.67	334	November
E2	BRST DLFT HRM1 ONSA SPT0 VIS0 WSRT	2.10	182	July
E3	BZRG FFMJ GENO GRAS HERT KOSG LROC MADR MAT1 MEDI OPMT TITZ TLSE YEBE ZIMM	1.81	211	July
E4	BOGI BOR1 GRAZ JOZ2 LAMA LEIJ METZ MTBG PENC POTS RIGA SASS SULP UZHL WARN WROC WTZR	3.24	211	July
E5	MDVJ SVTL TRAB ZWE2 ZECK	3.86	248	September
E6	AJAC CAGL NOT1 RABT VILL	2.03	146	May
E7	ANKR BUCU CRAO GLSV ISTA KHAR MIKL NICO POLV SOFI TUBI	4.56	224	August

The method proposed in this paper deals with weighted median and wavelet decomposition for quasi-annual curves estimation. In this way a greater reliability of non-parametric seasonal variations model by assuming year-to-year changes is ensured.

Secondly, the method of clustering is an effective algorithm to describe the spatial phenomena whereas geophysical studies are conducted. We proposed realistic model, in which phase shift is important as well as amplitude value. We found a good consistency in the quasi-annual signal for nearby stations. Figure 6 presents all quasi-annual curves estimated with wavelet decomposition for the 65 European IGS stations

plotted together. The vast majority of the stations have their minima during the Winter with maxima in Summer. The remaining stations with the maxima in Spring and Autumn are those situated near the sea/ocean. Although the quasi-annual curves determined here look at a first glance like perfect sine functions, they are in fact not sinusoidal. The amplitudes of the maxima differ from one another at the level of one-tenth of mm. Our results show that a station’s location (near or distant to the ocean) impacts the annual signal. Here, the seasonal amplitudes for the Up component may arise from atmospheric and hydrospheric changes (see van Dam et al. 1997).



**Fig. 6** The quasi-annual curves in vertical direction. Different colours means cluster number that the certain station was classified to (as in Fig. 3)

**Acknowledgments** This research was financed by the Military University of Technology, Faculty of Civil Engineering and Geodesy Young Scientists Development funds, grant No. 739/2015. JPL repro2011b time series accessed from [ftp://sideshow.jpl.nasa.gov/pub/JPL\\_GPS\\_203\\_Timeseries/repro2011b/raw](ftp://sideshow.jpl.nasa.gov/pub/JPL_GPS_203_Timeseries/repro2011b/raw) on 2014-11-10.

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**Part VI**

**Georeferencing in Practice**