Least-Squares Spectral and Coherency Analysis of the Zenith Total Delay Time Series at SuomiNet Station SA56 (UNB2)

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Abstract

Zenith Total Delay (ZTD) from ground-based Global Navigational Satellite Systems (GNSS) observations plays an important role in meteorology. It contains information about the troposphere due to the interactions that GNSS signals have with the atmosphere while traveling from satellites to ground receivers. Since almost all weather is formed in the troposphere, the analysis of a collection of ZTD time series would provide insight about the periodic characteristics of the weather of a place. It would also provide insight about the influences that meteorological parameters such as pressure, temperature and relative humidity have on the weather’s periodic nature. In this study, the least-squares spectral analysis approach is employed to determine the periodic oscillations in a 7-year time series of ZTD obtained from collocated GNSS and meteorological stations at the University of New Brunswick, Fredericton. Least-Squares Coherency Analysis of the time series spectra of the ZTD and its component hydrostatic and wet delays, and pressure, temperature and relative humidity is also performed. This is done to evaluate the level of contributions those parameters have in the periodicities inherent in the ZTD time series. Except for the zenith hydrostatic delay and pressure which show no annual periodic oscillation, the spectra of all the other time series show strong annual and semi-annual oscillations. Being the most dominant oscillation in the ZTD time series, the annual oscillation is largely driven by temperature, and this is maybe due to the high temperature variation characteristic of the climatic zone Fredericton falls under.

Keywords

Global Navigation Satellite Systems · Least-Squares Coherency Analysis · Least-Squares Spectral Analysis · Zenith Total Delay

1 Introduction

The Zenith Total Delay (ZTD) is an essential parameter that can be used to describe the various temporal and spatial characteristics of the weather and climatic processes of a place through the analysis of a time series of observations. The ZTD is estimated during the analysis of Global Navigation Satellite Systems (GNSS) observations for accurate positioning application. In meteorology however, these estimates are very useful for improving the short-term forecasting accuracies of the various numerical weather (prediction) models that they are assimilated into. The ZTD is made up of the zenith hydrostatic and zenith wet delays, ZHD and ZWD respectively. While the ZHD varies predictably and can be modeled sufficiently from observed meteorological parameters, the ZWD varies unpredictably and is difficult to model. Although the ZWD can be mod-
eled using water vapor pressure, temperature and relative humidity (Mendes and Langley 1998; Younes 2016), due to its unpredictability, it is estimated when processing GNSS observations.

Various studies have been conducted to determine the periodic oscillations of the ZTDs from GNSS observations collected at stations in various parts of the world (Baldysz et al. 2015; Isioye et al. 2017; Jin et al. 2007; Klos et al. 2016). These studies have shown the presence of dominant annual (first harmonic) periodic components in the ZTD time series, with varying amplitudes and phases based on the station’s location in the world. ZTD is a function of meteorological parameters such as pressure, temperature and relative humidity. These parameters are subject to short- and long-term oscillations/variations typically caused by disturbances within the atmosphere. These disturbances are influenced directly or indirectly by solar radiation, resulting in the periodic oscillations of the parameters; oscillations that could be diurnal or seasonal in nature. Time series analyses of a collection of observations of these parameters allow for the determination of the inherent oscillations, the knowledge of which is vital for weather forecasting and climatology (Kipp and Zonnen n.d.).

The focus of this study is to evaluate the contributions of the meteorological parameters to the periodicities in a ZTD time series. In this study, Least-Squares Spectral Analysis -LSSA- (Vaníček 1969, 1971; Wells et al. 1985; Pagiatakis 1998) of observations from collocated GNSS and meteorological stations respectively in Fredericton, New Brunswick (NB), Canada is performed. These observations are the ZTD with its ZHD and ZWD components from UNAVCO’s SuomiNet SA56 GNSS station (also known as UNB2), and pressure, temperature and relative humidity observations from the collocated meteorological station. Least-Squares Coherency Analysis -LSCA- (Pagiatakis et al. 2007; Mtamakaya 2012) was also performed to determine the contributions of the meteorological parameters to the periodic oscillations in the ZTDs. Fredericton is located inland in the province of NB and because of this, its climate resorts under the humid (warm summer) continental climate class, “dfb”, as defined by the Köppen climate classification. Due to Fredericton’s inland location, its climate has warmer summers and colder winter nights than other surrounding coastal areas. On average, the warmest month is July while the coldest month is January.

The paper is structured as follows. The data used, and the methodology employed are discussed in Sect. 2. In Sect. 3, we present the results with discussions on the periodicities in the ZHD, ZWD and meteorological parameters time series and their effects on the periodicities in the ZTD time series. Conclusions finalize the paper.

## 2 Data and Methodology

Daily SA56 GNSS RINEX and meteorological observation files, spanning the years 2009–2015, with data logging intervals of 30 s and 1 min respectively were obtained from the UNAVCO ftp server. The RINEX files were processed using the GNSS Analysis and Positioning Software -GAPS- (Leandro et al. 2007) to obtain GPS-only ZTD estimates. GAPS employs the precise point positioning -PPP- technique (Zumberge et al. 1997) for the processing of GNSS observations. The adopted processing options follow the ones used in Mayaki et al. (2018). The plots of the time series of the ZTD, ZHD and ZWD, with outliers removed and pressure, temperature and relative humidity are given in Figs. 1 and 2 respectively. From visual inspection, there were no discernible offsets in the plots of the time series and no record of instrumentation change from the station’s site log documentation. Therefore, data homogenization was not done on the time series before processing. However, outliers in the ZTD and ZWD time series were removed by applying the three-sigma rule using the median.

To compute the least-squares spectra of the time series, the LSSA version 5.02 program was used and it can be obtained from the website of the department of Geodesy and Geomatics Engineering, University of New Brunswick.1 LSSA is based on the developments by Vaníček (1969, 1971) with improvements and implementation done by Wells et al. (1985) and Pagiatakis (1998). Notable advantages provided by LSSA are: (1) the analysis of time series with data gaps and unequally spaced values without pre-processing, (2) no limitations for the length of the time series, (3) time series with an associated covariance matrix can be analyzed, (4) the systematic noise can be rigorously suppressed without causing any shift in the existing spectral peaks, and, (5) statistical tests on the significance of spectral peaks can be performed. The choice of LSSA was additionally supported by its use in other studies for the proven integrity of its results (Mayaki 2019; Mtamakaya 2012; Hui and Pagiatakis 2004). In LSSA, the observed time series $f$ is considered as a function of time $t$, $i = 1, 2, \ldots, n$. Here, the time series may or may not have equally spaced values. The main objective of LSSA is to determine and clarify the periodic signals in $f$, especially when $f$ includes both random and systematic noise. Comprehensive details about the LSSA are given in Vaníček (1969, 1971), Wells et al. (1985) and Pagiatakis (1998).

The computation was done at every 3 h, and due to the length of the time series, three bands of 2,000 spectral values each were used to represent the spectra of the

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1 http://www2.unb.ca/gge/Research/GRL/LSSA/leastSquares.html.
time series. These bands were chosen to portray the yearly, monthly and daily periods respectively. The first band captures the periods between 4,740 h (a little more than half of a year or 197.5 days) to the extent of the time series (61,344 h). The second band captures the periods between 576 h (24 days) to 4,740 h, and the third band is between 3 h and 576 h. The critical level for detecting significant peaks and the level of significance for statistical testing is defined on a 99% confidence level, which represents the most stringent option. Several executions of the LSSA were carried out, with the strongest period (that is, the period with the largest significant percentage variance) suppressed in succeeding executions. The percentage variance is the least-squares spectrum. The suppression of strong periods in subsequent executions give rise to new significant periods which may have been weak or invisible in previous executions. Also, from the suppression, the amplitudes and the phases of the strong periods from the preceding executions are given. Only detected significant periods up to half of the length of the time series under analysis are considered.

For the LSCA, the products of the LS spectra of the ZTD with those of the ZHD, ZWD, pressure, temperature and relative humidity are computed. This was done to speculate which of pressure, temperature or relative humidity is the main contributor to the periodic oscillations/periodicities found in the ZTD by way of using the ZHD and the ZWD. The product spectra are determined by the summation of the natural logarithms of the percentage variances obtained from the LS spectra of the ZTD with those of the ZHD, ZWD, pressure, temperature and relative humidity (Mtamakaya 2012; Elsobei 2017).
Meteorological observations from the Fredericton CDA (Canadian Department of Agriculture) CS (Campbell Scientific) meteorological station, less than 6 km from the SA56 station, were also obtained from Environment Canada and processed for comparison with the results obtained from the SA56 station. These observations include the dew point and dry bulb temperatures, the corrected mean sea level and uncorrected station pressure observations, and the relative humidity.

3 Results and Discussions

3.1 LSSA of Time Series

Figures 3, 4, 5, 6, 7 and 8 show the least-squares (LS) spectral plots of the first execution (with their corresponding three bands) of the ZTD, ZHD, ZWD, pressure, temperature and relative humidity time series respectively. Considering the percentage variances, the most dominant peak across the three bands as seen in the Figs. 3(i), 5(i), 7(i) and 8(i) is centered about the annual period (first harmonic). Also visible is the peak around the semi-annual (second harmonic, 6 months) period as seen in Figs. 3(ii), 5(ii), 7(ii) and 8(ii). In Figs. 4(ii) and 6(ii) however, the semi-annual period has the highest peaks in terms of percentage variances. Tables 1 and 2 contain the periods and phases of the strongest periodic components from the LSSA for the SA56 station and the Fredericton CDA CS meteorological station respectively. The standard deviation of the phases as estimated by the LSSA are also provided. The results show similar periods and phases (times of occurrences) of the annual periodic component in the ZTD, ZWD and temperature time series, at around 366 days and between 198° and 203° (corresponding to days in the month of July). The semi-annual periodic component seen in the ZHD and
pressure time series occur approximately every 186 days between 180° and 185°. The similarities in results for the ZHD and pressure are expected to a certain degree since the ZHD from PPP is primarily modeled as a function of pressure. A study by Pikridas (2014) compared ZWD estimated from PPP to ZWD modeled through the application of Saastamoinen (1972), which uses temperature and the partial water vapor pressure. The results showed good agreement between the estimated and modeled ZWDs and so, it is conceivable that the ZWD estimated from GAPS PPP would show similar spectral results to a modeled ZWD.

### 3.2 LSCA of Time Series

Figures 9, 10, 11, 12 and 13 show the plots of the product of the time series LS spectra of the ZTD with those of the ZHD, ZWD, pressure, temperature and relative humidity. The contributions from the meteorological parameters to the periodicities in the ZTD can be observed since these parameters, through the ZHD and ZWD, can be used to model the ZTD. According to Jin et al. (2007), although the ZWD makes up 10% of the ZTD, the variations seen in the ZTD are caused by the ZWD. Figure 10 shows that the ZWD contributes more than the ZHD (Fig. 9) to the annual
periodicity in the ZTD. Also, since the ZWD can be modeled using relative humidity and temperature, their contributions to the annual periodicity in the ZTD are seen to be higher in Figs. 12 and 13 compared to the pressure contributions in Fig. 11.

4 Conclusion

The Zenith Total Delay (ZTD) is an important parameter that reflects the state of the weather and climatic processes of a place. The time series analysis of a collection of observations of the ZTD facilitates the understanding of the periodic nature of the weather. In this work, the 3-h temporal resolution time series of the ZTD, the zenith hydrostatic and wet delays (ZHD and ZWD respectively), and meteorological parameters (pressure, temperature and relative humidity) are analyzed. These data were from the SA56 UNAVCO station in Fredericton, New Brunswick, Canada and span 2009–2015. Least-Squares Spectral Analysis was performed on the time series to determine their inherent periodicities. Least-Squares Coherency Analysis was also performed to evaluate the contributions of the meteorological parameters to the periodicities in the ZTD time series.
**Fig. 7** Spectral plot of SA56 temperature least-squares spectrum

**Fig. 8** Spectral plot of SA56 relative humidity least-squares spectrum

**Table 1** Periods and phases of the dominant peaks for SA56

| Time series   | Period (Days) | Phase with std dev (Degrees) |
|---------------|---------------|------------------------------|
| ZTD           | 366.51        | 201.67 ± 0.07                |
| ZHD           | 186.70        | 180.47 ± 0.01                |
| ZWD           | 366.20        | 201.25 ± 0.07                |
| Pressure      | 186.70        | 185.39 ± 5.93                |
| Temperature   | 366.20        | 199.51 ± 3.68                |
| Relative humidity | 357.03       | 299.18 ± 13.17               |

**Table 2** Periods and phases of the dominant peaks for Fredericton CDA CS

| Time series             | Period (Days) | Phase with std dev (Degrees) |
|-------------------------|---------------|------------------------------|
| Sea level pressure      | 186.70        | 180.85 ± 5.31                |
| Station pressure        | 186.70        | 181.39 ± 5.27                |
| Dew point temperature   | 366.51        | 203.60 ± 3.29                |
| Dry bulb temperature    | 366.51        | 198.53 ± 3.19                |
| Relative humidity       | 366.51        | 279.29 ± 10.27               |
Annual periodicities of approximately 1 year (366 days) are detected in the ZTD, ZWD and temperature time series, with their phases between 198° and 203°. Semi-annual periodicities are detected in all the time series but are strongest in those of the ZHD and pressure. The annual periodic oscillation detected in the ZTD time series is primarily due to the temperature. The phases of these annual variations also coincide with days in the month of July. The results from this study agree with those from previous studies.

The continuation of this study would include similar analyses for the ZTD time series of other stations with co-located GNSS and meteorological instrumentation, enabling the characterization of the climate based on GNSS observations.
Fig. 13 Spectral plot of SA56 ZTD-Relative humidity least-squares coherency spectrum

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