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On correlation between SID monitor and GPS-derived TEC observations during a massive ionospheric storm development

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Abstract

Space weather, geomagnetic and ionospheric conditions are the most prominent single cause of the Global Navigation Satellite System (GNSS) positioning performance degradation, through introduction of the GNSS signal ionospheric delay. This affects numerous GNSS- based technology and socio-economic systems and services. Analyses of case-studies of GNSS positioning performance degradation contribute to characterization of the GNSS positioning error, and support error correction methods and models development. Here a case of rapidly developing ionospheric storm is examined, with the aim of the event characterization using a low-cost Sudden Ionospheric Disturbance (SID) monitor observations of lower ionospheric levels condition through continuous reception of Very Low Frequency (VLF) signal strength values. Time series of observations, taken in Croatia during the St Patrick 2015 event of fast development of the large ionospheric storm, were compared with time series of dual-frequency GPS-derived observations of Total Electronic Content (TEC), a parameter linearly related to GNSS ionospheric delay. A comparison framework has been developed in the open-source R programming framework for statistical computing. Time series of SID and GNSS-based TEC observations were examined for cross-correlation. The research revealed correspondence between two time series. Although not linear, the correspondence identified may be used for an early warning for potential GNSS positioning performance deterioration. Further to this, it may serve as the foundation for understanding of the lower ionosphere contribution to the over-all TEC, and thus to formation of the GNSS ionospheric delay. Our team intends to explore both research directions in forthcoming studies.

1. Introduction

Detection of an approaching ionospheric storm with potential effects on GNSS positioning performance, and on GNSS-based applications, subsequently, is of utmost importance for sustainable provision of the core GNSS and GNSS-related services.

SID monitor is a low-cost low-ionosphere activity sensor, developed by a Stanford University, CA team to facilitate scientific activity in the space weather field across the globe [1]. We hypothesize that Sudden Ionospheric Disturbances (SID) monitor observations may serve as the early warnings for the ionospheric disturbance development that increase TEC, thus affecting the GNSS positioning performance accuracy of single-frequency GNSS receiver, which dominates the market. In hypothesis validation, here we examined the case of rapid development of the St Patrick's Day (DOY076) 2015 ionospheric storm. Time series of Dst, TEC and SID monitor observations during were assessed in this study, with the aim of characterizing relationship between the cause (ionospheric storm development, described by Dst), effect (GNSS ionospheric delay, and, consequently, GNSS pseudorange measurement error, described by TEC), and a candidate descriptor for forecasting of, and alerting for, ionospheric storm development (SID monitor observations).

The Disturbance Storm Time (Dst) index [2] measures the level of the globally symmetrical equatorial electro-jet, also known as the 'ring current'. Additionally, it has been recognized as an accurate descriptor of ionospheric conditions, especially in sub-equatorial regions. Dst observations are calculated from experimental observations from the network of near-equatorial observatories using the methodology developed by Kyoto University, Japan.

The Total Electron Content (TEC) [3] is defined as the over-all free-electron density encountered by a satellite signal on its path from a GNSS satellite aerial towards a GNSS receiver aerial, as traditionally defined by (1), with N(h) denoting the vertical ionospheric profile.

$$TEC = \int_{lower\ ionospheric\ boundary}^{upper\ ionospheric\ boundary} N(h)dh \qquad (1)$$

Considering recent developments in identification of the additional sources of temporal ionization (thunderstorms, earthquakes, volcanic eruptions), we recently extended the

TEC definition to account for contribution of below-ionosphere layers, as presented with (2) [4].

$$TEC = \int_0^{upper\ ionsopheric\ boundary} N(h)dh \quad (2)$$

Utilization of dual-frequency GNSS observations allows for accurate estimation of TEC, as expressed in (3), where f1 and f2 denote different GNSS carrier frequencies (as an example, for GPS: f1 = 1575.42 MHz, and f2 = 1227.60 MHz), respectively, and ρ1 and ρ2 measured pseudoranges at related frequencies [3, 4].

$$TEC = \frac{1}{40.3}\left[\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right](\rho_2 - \rho_1) \quad (3)$$

TEC serves as an essential estimator of GNSS pseudorange measurement error, as expressed in (4) [2, 3], with: $\omega = 2\pi f$, f denotes carrier frequency, $e = 1.60217662 \times 10^{-19}$ C, $\varepsilon_0 = 8.854187817 \cdot 10^{-12}$ V/m, $m = 9.109 \times 10^{-31}$ kg, $c = 2.99792458 \cdot 10^8$ m·s^{-1}.

$$\Delta t = \frac{e^2}{2\epsilon_0 m \omega^2 c}\int_0^{h_{max}} N(h)dh \quad (4)$$

The GNSS pseudorange measurement error propagates into GNSS position estimation error [5]. The error propagation model varies with selection of position estimation method [4]. It can be shown that the error propagation model can be expressed for the case of the Weighted Least-Square (WLS) position estimation method using the information matrix $\boldsymbol{H^\tau R^{-1} H}$, and the information state $\boldsymbol{H^\tau R^{-1} y}$, as expressed in (5) [5], with $\boldsymbol{H}$ denoting geometry matrix, $\boldsymbol{R}$ weighting matrix, $\Delta\hat{\mathbf{x}}$ GNSS positioning error vector, and $\Delta\mathbf{y}$ as the vector of GNSS pseudorange measurement errors.

$$\Delta\hat{\mathbf{x}} = (\boldsymbol{H^\tau R^{-1} H})\boldsymbol{H^\tau R^{-1}}\Delta\boldsymbol{y} \quad (5)$$

Model (5) reveals a direct relationship between GNSS pseudorange observation errors and the GNSS position estimation vector components.

2. Data description

This section outlines the details on the three data sets examined in the study, as follows: (i) Disturbance Storm-Time (Dst) index, determined by Kyoto University methodology, (ii) Total Electron Content (TEC), as an ionospheric condition index, and (iii) Sudden Ionospheric Disturbance (SID) monitor observations.

Dst index observations were taken as products of Kyoto University processing facility, without further consideration of the original calculation methodology. Observations are provided at hourly sampling intervals, and are available at: http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html.

Time series of TEC observations was derived from dual frequency GPS pseudorange observations at the SONEL (data available at: http://www.sonel.org/-GPS-.html?lang=en) network reference station Poreč, Croatia (φ = 45.22601300°N, λ = 13.59504100°E), at the 30 s-sampling intervals. We used an open-source software tool for TEC estimation using the process defined by (1), developed by Dr Gopi Seemala [6]. TEC estimates defined by (1) are compromised by satellite and receiver bias. The former were mitigated using Differential Code Bias (DCB) data provided by University of Bern, Switzerland at: ftp://ftp.aiub.unibe.ch/CODE/. The latter, presented in a form of an additive model with receiver and receiver inter-channel biases, were left uncorrected.

Time series of SID monitor observations (available through: http://sid.stanford.edu/database-browser/ calendar.jsp consists of data collected at Požega, Croatia observation site (φ = 45.331032°N, λ = 17.676991°E). Data set contains signal strength observations of the VLF signal broadcast by Rosnel, France station (φ = 46.713129°N, λ = 1.245248 °E). SID monitor observations are taken at the 5 s-sampling intervals.

Locations of observing and transmitting stations involved in the study are shown in Figure 1.

Figure 1. Locations of GPS-TEC Poreč, Croatia (blue), and SID Požega, Croatia (red) observation sites, and VLF broadcasat station Rosnel, France (magenta)

3. Methodology

Time series of Dst, TEC and SID monitor observations were examined with the aim of characterizing relationship between the cause (ionospheric storm – Dst), effect (ionospheric dynamics, and, consequently, GNSS pseudorange measurement error – TEC), and potential indication in lower ionospheric dynamics, as a candidate descriptor for forecasting of, and alerting for, ionospheric storm development (SID monitor observations) [7, 8, 4].

Time series of SID observations comprised the observation samples of the received VLF signal strength at the observing station at Požega, Croatia. VLF signals were continuously transmitted by Rosnel, France transmitter.

A software-based data processing framework was developed by authors in the R open-source environment for statistical computing [9]. Dst observations were used as a control data set that describes the ionospheric storm development. SID monitor and the GPS-derived TEC observations were re-sampled to the 1 min-sample interval to allow for their inter-relationship analysis. Additional procedures, such as data smoothing, were not deployed. We performed the examination of SID monitor and TEC time series [10] for DOY076 (17 March) in 2015 data to identify prospects for utilization of SID observations for identification of TEC enhancement due to ionospheric storm development, including analysis of: (i) time-series diagrams (waveforms) comparison, (ii) kernel density plots, (iii) Q-Q diagrams; (iv) anomaly assessment.

4. Study results

We performed time series analysis as outlined in Section 3., with the results presented comprehensible in this Section.
Dst waveform analysis revealed development of a massive and fast developing ionospheric storm (Figure 2., green, above). TEC and SID waveforms (Figure 2., blue and red, middle and below, respectively) depict a sudden commencement of the ionospheric activity immediately after 1400 UTC that lasted with considerable variations until the end of the day in observation.

Kernel density plot (Figure 3.) analysis of TEC and SID time-series revealed non-Gaussian TEC distribution, and a skewed Gaussian-like SID distribution. This finding was confirmed with examination of Q-Q diagrams (not shown here) for the respected time series.

Finally, anomalies assessment in SID and TEC observations time series, compared with the waveforms in stable (unperturbed) ionospheric conditions, revealed notable time-/phase-shift (advancement) in SID waveform, compared with the TEC-related ones. Throughout the morning hours of DOY076 of 2015, SID and TEC values followed the daily pattern characteristic for unperturbed space weather and ionospheric conditions.

However, the rapid development of the ionospheric storm commenced on the day under observations, soon after 1400 UTC. The event caused an immediate anomaly in SID observations time series, followed by anomaly occurrence in TEC time series later.

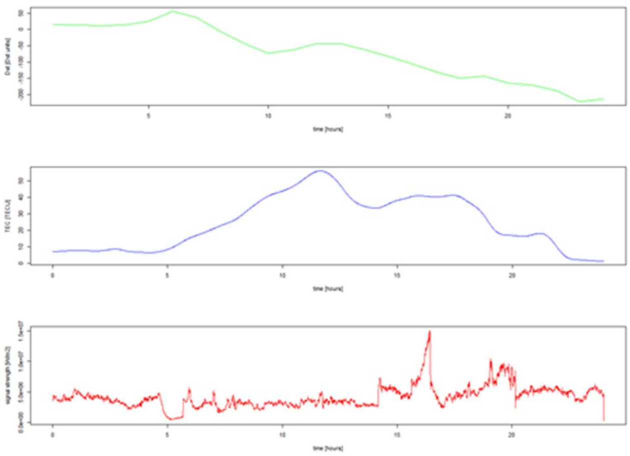

Figure 2. Time series of Dst (green), TEC (blue), and SID monitor (red) observations, during the 2015 St Patrick ionospheric event.

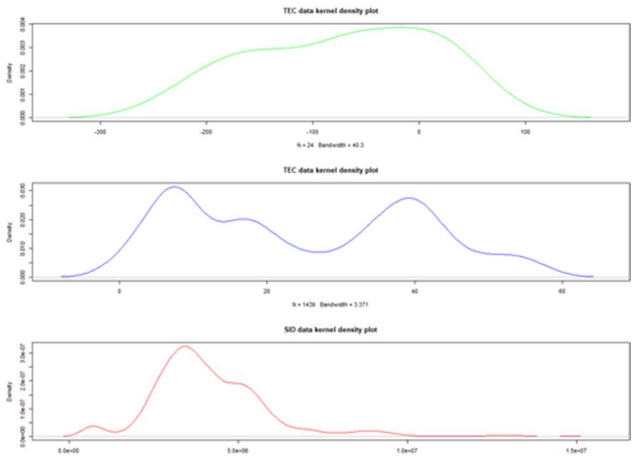

Figure 3. Kernel density plots of Dst (green), TEC (blue), and SID monitor (red) observations, during the 2015 St Patrick ionospheric event.

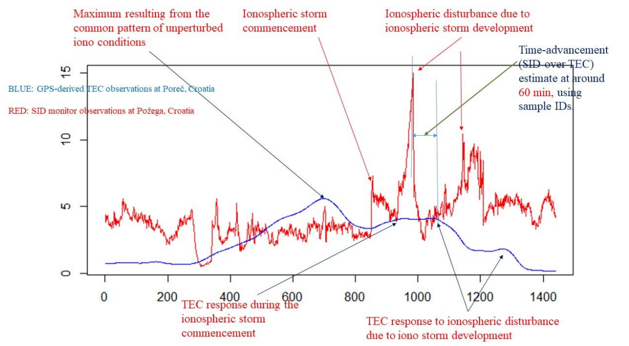

Figure 4. Observed consistent time/phase advancement of SID time series over the TEC ones

The observed waveform time-/phase shift was consistent in cases of two separated major ionospheric disturbances, one around 1400 UTC and the other at around 1830 UTC, identified during the rapid development of the St Patrick's Day 2015 ionospheric storm (Figure 4.). Using sample IDs, we were able to estimate the time-advancement value at approx. 60 min.

5. Discussion and Conclusion

Dst observations depicted clearly a textbook-case of the ionospheric storm development. The St Patrick's Day 2015 storm commenced suddenly during afternoon hours of DOY076 in 2015, foundering immediately into its negative phase, according to available Dst data.

The ionosphere responded to storm development, as evident from SID and TEC time series dynamics. Individual disturbances related to storm development were followed by SID and TEC responses.

A consistent time-advance of SID time series observations over TEC time series was observed in extent of 60 min. The observed time-advanced allow for precious time to be utilized for the ionospheric storm alert issuance, for the benefit of growing community of human population affected by space weather events due to increased utilization of technology. In particular, established models define the mechanism for ionospheric disturbance effects propagation into GNSS pseudorange measurements and GNSS position estimation results, thus affecting a wide range of GNSS-related and GNSS-based applications. Identification of time-advancement of SID time series over TEC time series renders the former a valuable descriptor candidate for the GNSS positioning performance forecasting model development. We intend to pursue and exploit the prospects of utilization of SID observations for the matter in our forthcoming research. Additionally, evidence point to assumption that the clear SID-based identification of individual disturbance may result from correspondence between SID monitor site selection and direction of the ionospheric disturbance propagation. We intend to address the prospects for exploitation of the VLF propagation direction-related impact on the quality of SID-based ionospheric storm observation, for TEC and GNSS positioning performance forecasting model in our future research.

Wisely crafted as a an equipment aimed at raising awareness of, and engage more people in, scientific activities, SID monitors have already been recognized as invaluable scientific equipment in numerous studies worldwide, including ours. We intend to exploit them further as an invaluable source of information for advanced understanding of both the ionospheric processes, and the causes and nature of GNSS positioning performance degradation.

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