# Seven days in Chile: Impact of the 2011 Puyehue-Cordon Caulle volcanic eruption on GPS ionospheric delay

*Oliver* Jukić[1,*], *Nenad* Sikirica[2,3], *Ivan* Rumora[3], and *Mia* Filić[4]

[1]College for Management in Tourism and Informatics, Virovitica, Croatia
[2]University College of Applied Sciences Hrvatsko Zagorje Krapina, Krapina, Croatia
[3]PhD Student, Faculty of Maritime Studies, University of Rijeka, Rijeka, Croatia
[2]Independent satellite navigation, statistical learning, and space weather researcher, Zagreb, Croatia

**Abstract.** Satellite navigation is a global utility and an essential component of national infrastructure. Disruptions of GNSS PNT services may be considered a threat to society and civilisation in general. Natural hazards may cause the conditions that disrupt or temporarily deny GNSS PNT services. As a contributor to ionospheric dynamics, volcanic activity is considered a source of GNSS positioning performance degradation. Here we studied the 2011 Puyehue-Cordon Caulle event, the largest 21st century volcanic eruption so far, in terms of its contribution to formation of Total Electron Content (TEC), the source of ionosphere-caused GNSS positioning error, and the effects the event made on GPS positioning accuracy. TEC values were derived from dual-frequency GPS observations collected experimentally at the International GNSS Service Network reference stations in Santiago, central Chile closest to the Puyehue-Cordon Caulle volcano. We identified considerable anomalous behaviour of TEC dynamics prior to, during and after the volcanic eruption, and examined the extent to which it affected GPS positioning accuracy. The research presented here will continue with the aim of characterisation of TEC anomalous dynamics around the eruption, and its effects on GNSS positioning performance.

## 1 Introduction

Proliferation of satellite navigation technology requires stable and robust Global Navigation Satellite System (GNSS) positioning performance for numerous GNSS-based technology and socio-economic systems and services. Ionospheric effects are the most prominent single cause of GNSS positioning performance degradation and even disruptions of GNSS Positioning, Navigation, and Timing (PNT) services [1]. Usually resulting from much wider space weather disturbances [2], [3], the ionospheric effects on GNSS positioning performance may be caused by the other terrestrial natural sources of additional ionisation in the Earth's atmosphere, including earthquakes and volcanic eruptions [4], [5], [6].

We studied the problem through examination of ionospheric conditions deterioration, and GNSS positioning performance degradation during the 2011 Puyehue-Cordon Caulle volcanic eruption, the largest volcanic eruption in the XXI. Century. Our study was based on post-processing of experimental data [7] taken at the International GNSS Service (IGS) network reference stations close to volcano immediately prior, during, and after its eruption in 2011, with statistical analysis of obtained position estimation error samples, and TEC estimation

The manuscript reads as follows. This Section outlines the motivation, and provide the overview of the study Section 2 presents the methodology applied, including a brief description of the software tools utilised, and outlines research results. Section 3 discusses results and outlines our contribution to the problem understanding and mitigation.



**Fig. 1**. Puyehue-Cordon Caulle volcano and the neighbouring stationary IGS reference station in Santiago, Chile

* Corresponding author: oliver.jukic@vsmti.hr

## 2 Methodology and study results

Puyehue-Cordon Caulle volcano is situated in Central Chile (Fig. 1.). It began to erupt on 4th June, 2011 (DOY 155). The IGS Network stationary reference GPS station at Santiago, Chile collected continuously raw GPS pseudorange measurements, which have been available since then to scientific community from the IGS web-site (http://www.igs.org/). We examined the TEC and GPS positioning error components time series [2], [7] for a selected period around the day or eruption, between 31 May, 2011 and 6 June, 2011.

We processed dual GPS pseudorange observations to obtain Total Electron Content (TEC) time series, as an index of ionospheric conditions [2]. An open-source software (http://seemala.blogspot.com) developed by Dr Gopi Seemala, than at Boston College, Chestnut Hill, MA, was used for derivation of TEC time series from dual-frequency GPS pseudorange observations. Time series of TEC observed at Santiago, Chile, and Coyahaique, Chile are presented in Figs 2. and 3., respectively.
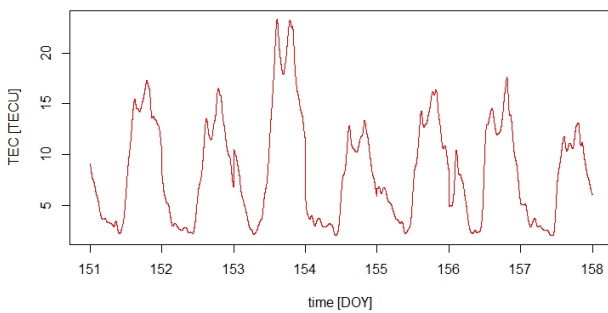


**Fig. 2.** TEC time series derived from dual-frequency GPS pseudorange observations at Santiago, Chile (30 s sampling period) around the time of volcanic eruption.
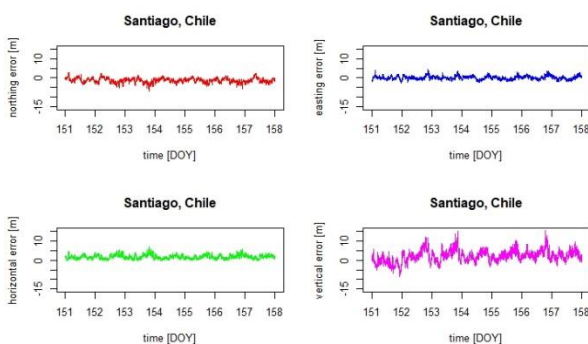


**Fig. 3.** Santiago, Chile RINEX-derived GPS positioning error components around the time of volcanic eruption

Additionally, we utilised single-frequency GPS pseudorange observations to simulate positioning performance of a commercial-grade single-frequency GPS receiver that utilises regularly provided parameters of correction models (satellite clock corrections, Saastamoinen tropospheric corrections, and Klobuchar ionospheric correction with broadcast parameters) during the time of eruption [7]. Simulation was conducted using

RTKLIB (http://www.rtklib.com/), an open-source GNSS Software-Defined Radio receiver, in post-processing mode. RTKLIB was configured to operate as a commercial-grade single-frequency GPS receiver that utilise broadcast parameters of pseudorange error correction models [7]. It was deriving position estimate and positioning error samples using real observations of single-frequency GPS pseudoranges (RINEX o files) and broadcast navigation messages (RINEX n files), both archived on IGS.

We developed a bespoke framework for GNSS positioning error time series statistical analysis. Modelling and forecasting in the open-source R programming environment for statistical computing (https://www.r-project.org). Using the framework developed, we generate time series of northing, easting and vertical components of positioning error vector, through comparison of observed position samples with the actual (true) position of an IGS stationary reference station. Horizontal GPS positioning error was derived using (1).

$$\epsilon_H = \sqrt{\epsilon_N^2 + \epsilon_E^2} \tag{1}$$

Where:

$\epsilon_H$ … denotes horizontal GPS positioning error [m]

$\epsilon_N$ … denotes northing component of positioning error [m]

$\epsilon_E$ … denotes easting component of positioning error [m]

Time series of GPS positioning error components are depicted in Fig. 3., respectively.

Histograms of TEC, and the GPS positioning error components are presented in Figs 4. and 5., respectively.
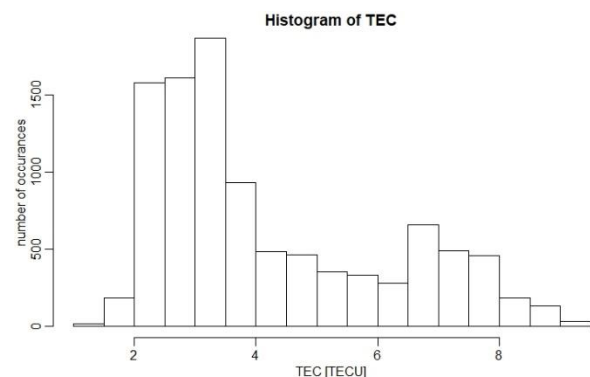


**Fig. 4.** Histogram of TEC during the observed period around the volcanic eruption

The Q-Q (normality) plot of TEC in the observed period of the volcanic eruption is presented in Fig. 6.

Finally, we examined the histograms of the TEC index derived from the Santiago, Chile observation site for a selected period (day 27 in 2017) when a mild ionospheric disturbance (Kp <= 4) occurred, as the reference for

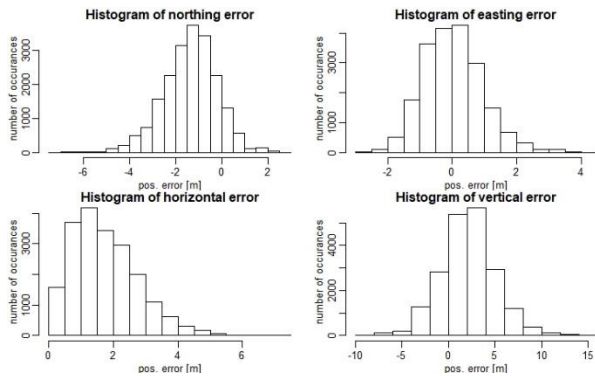comparison. Histogram of TEC fr the controlled experiment on DOY27, 2017 is depicted in Fig. 7



**Fig. 5.** Histograms of the respective components of GPS positioning error during the observed period around the volcanic eruption
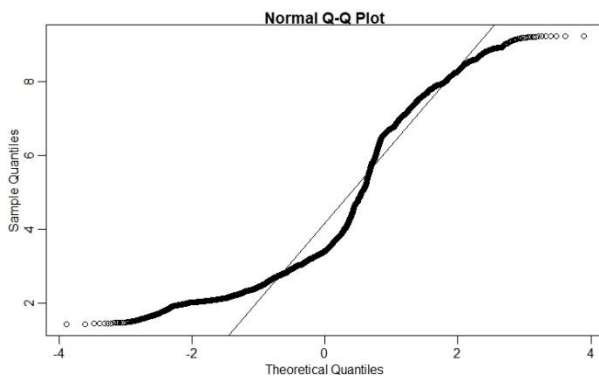


**Fig. 6**. TEC Q-Q plot

Histograms of TEC, and GPS positioning error components are depicted in Figs 7 and 8, respectively.
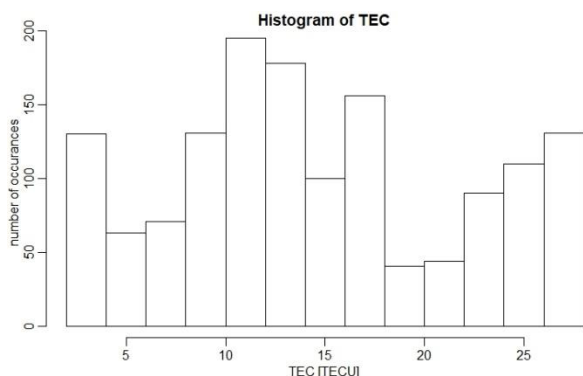


**Fig. 7**. Histogram of TEC during controlled period (Day 27 in 2017).

## 3 Discussion

Study results revealed several findings, as follows: (1) TEC daily dynamics extend two local maxima, instead of one, usually assumed as a pattern for Klobuchar ionospheric correction model; (2) TEC time series shows unusual waveform for DOYs 152, 153, 154, and 155, respectively; (3) TEC histogram for the observed period

did not follow normal distribution. Further examination of geomagnetic and solar data revealed brief and moderate space weather-caused geomagnetic disturbance in the evening of DOY 155 (Kp up to 5+ level, the day eruption started, lasting for 6 hours, until midnight), and in the early morning of DOY 156 (Kp at 6+ level, lasting three hours). The event coincided with development of volcanic eruption, mimicking partially the effects of the latter on ionisation processes and GPS positioning performance. The occurrence of a moderate geomagnetic disturbance in combination with volcanic eruption that went underway at the same time may explain the rise in TEC in late hours of DOY 155 in 2011. However, disturbed waveforms of DOYs 152, 153 , and 154, and the considerable enlargement of TEC on 153 cannot be explained by any geomagnetic and/or space weather event. We believe the anomalies were correlated with volcanic activity before the main eruption on DOY 155.

Descriptive statistical analysis of the GPS positioning performance revealed the respective range of positioning error components: (1) for northing error component: between -7.02 m and 2.68 m; (2) for easting error component: between -2.72 m and 4.20 m; (3) for horizontal error component: between 0.05 m and 7.15 m; and (4) for vertical error component: between 8.38 m and 15. 51 m. Vertical and easting error components followed normal distribution fairly well, while the histogram of northing error component (and therefore the one of horizontal error, as well) shows skewed and translated distribution, compared with the normal one.

The same analysis performed on control experiment (DOY27 in 2017) observations revealed the following range of error components: (1) for northing error component: between -3.86 m and 2.34 m; (2) for easting error component: between -3.14 m and 1.65 m; (3) for horizontal error component: between 0. 06 m and 3.99 m; and (4) for vertical error component: between -3.05 m and 9.71 m.

Results show that a mild geomagnetic disturbance (Kp up to 4+ level) caused milder deterioration of GPS positioning performance then combined (at worst) effects of volcanic eruption and moderate geomagnetic disturbance. It should be noted that volcanic eruption, as well as a geomagnetic disturbance, modifies the statistical character of events, calling for cautious approach in attempts to model the events in question.

GPS position degradation we observed around the time of the 2011 Puyehue-Cordon Caulle volcanic eruption may affect usual daily GPS-related services, but to affect disaster relief activities as well. Emergency services and autonomous rovers may suffer from enlarged GPS position estimation errors. The fact calls for advanced TEC and GNSS performance monitoring and modelling [2], implementation of advanced position estimation methods [8], utilisation of network-supported satellite position estimation, and sensor data fusion to assure reliability, resilience and robustness of satellite-based position estimation.

Development of models describing TEC and GPS positioning error components dynamics is still not impossible, although it remains a challenging task. As one us has shown, careful examination of statistical properties of data, with utilisation of advanced forecasting model development methods based on statistical learning, may provide unexpectedly good results. We intend to continue our research activity on examination of various cases of GNSS positioning performance degradation due to space weather and terrestrial natural causes, as well as those caused by artificial threats, in order to contribute to GNSS resilience development, and sub-sequently to assist in stable technology development for the benefit of modern civilisation.

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