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An SDR-based Study of Multi-GNSS Positioning Performance During Fast-developing Space Weather Storm

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ABSTRACT: The understanding of the ionospheric effects on GNSS positioning performance forms an essential pre-requisite for resilient GNSS development. Here we present the results of a study of the effects of a fast-developing space weather disturbance on the positioning performance of a commercial-grade GPS+GLONASS receiver. Using experimentally collected pseudoranges and the RTKLIB, an open-source software-defined GNSS radio receiver operating in the simulation mode, we assessed GNSS positioning performance degradations for various modes of GNSS SDR receiver operation, and identified the benefits of utilisation of multi-GNSS and ionospheric error correction techniques.

1 INTRODUCTION

The ionospheric effects on Global Navigation Satellite Systems (GNSS) performance and operation are long-standing research subjects for research groups across the world (Canon *et al*, 2013). The nature of GNSS deterioration process due to ionospheric and space weather effects determines the approach in modelling and mitigation of such effects in continuity of efforts in developing the resilient GNSS and thus smoothing and mitigating effects of the failures and degradations of the GNSS performance (Thomas *et al*, 2011, Petrovski and Tsujii, 2012).

We conducted a study aimed at addressing the GNSS positioning performance degradation due to development of a space weather/ionospheric event from the perspective of commercial-grade GNSS receiver capable of processing signals broadcast from at least to GNSS systems (the US GPS nad Russian GLONASS), with the ability to deploy the GPS ionospheric correction (Klobuchar) model (Klobuchar, 1987, Sainz Subirana *et al*, 2013, Petrovski and Tsujii, 2012). A case-study of a fast-developing space weather disturbance on 17th March, 2015 was chosen for this study. The experimentally collected GPS and GLONASS pseudoranges data was used as an input for a simulation-based study that utilised RTKLIB (Takasu, 2013), an open-source software-defined GNSS radio receiver, with capabilities for post-processing pseudoranges with a flexibility of modelling the positioning environment through tailored RTKLIB settings (Takasu, 2013). Obtained northing, easting and height time series were analysed further with an R-based software we developed for targeted purposes. Finally, the analysis results were discussed and interpreted, yielding contribution to understanding of transitional effects of developing space weather on GNSS positioning performance.

The manuscript is organised as follows.

- This Section presents the aim and scope of the manuscript.
- Section 2 outlines the problem and previous research.

– Section 3 details the aim, data sources, methodology and the software utilised for the research reported in this manuscript.
– Section 4 presents in detail research results.
– Section 5 discusses and interprets the research results, providing the recommendation for their practical utilisation.
– Section 6 concludes the manuscript and proposes subjects of further research.

2 PROBLEM DESCRIPTION AND PREVIOUS RESEARCH.

Global Navigation Satellite Systems (GNSS) are essential components of every national infrastructure, regardless of the system ownership (Filjar, 2011). Technology and socio-economic systems increasingly rely on satellite navigation systems, and the robustness, resilience and reliability of their operation and performance (Thomas *et al*, 2011, Filjar and Huljenic, 2012).

Causes of satellite navigation malfunctioning and performance deteriorations are known in essence (Sainz Subirana *et al*, 2013). Still, the task of overcoming and mitigation their effects remains unsolved, both in general and platform- and application-specific sense. (Thomas *et al*, 2011) assessed systematically the risk of GNSS failures and performance deteriorations, and its effects on technology and socio-economic systems that utilise satellite navigation systems as enabling and underlying technology.

Ionospheric effects have a major impact on GNSS positioning performance among all known causes of deterioration of GNSS positioning performance (Canon *et al*, 2013, Hapgood, 2010). Ionospheric disturbances result from more broader and powerful processes of solar energy transport throughout space (Booker, 1954, Davis 1990, Mendillo, 2006). Although the understanding of the processes behind the GNSS ionospheric effects advances steadily (Mendillo, 2006), overcoming the problem remains a far-reaching aim (Canon *et al*, 2013). The overcoming and mitigation techniques and methods remain application-oriented and limited in their spatio-temporal outreach (Sainz Subirana *et al*, 2013, Petrovski and Tsujii, 2012).

The impact of developing space weather/ionospheric disturbances on GNSS positioning performance is even less understood, since the transitional effects are often unrecorded. The lack of experience and knowledge distilled from the assessments of such events prevents successful modelling, characterisation and correction of such space weather/ionospheric effects on GNSS positioning performance.

3 GNSS POSITIONING PERFORMANCE DURING DEVELOPMENT OF ST PATRICK'S DAY 2015 IONOSPHERIC STORM.

Here we address the effects of the fast-developing space weather event, and the geomagnetic and ionospheric storms, on the GNSS positioning performance (accuracy and availability of positioning service) using experimentally collected data fed into a software-defined GNSS radio receiver. Particular consideration was given to assessment of potential risks to maritime navigation.

3.1 *St Patrick's Day 2015 ionospheric storm*

A sudden solar event occurred on 17th March, 2015 causing severe geomagnetic (G4, on the scale of G1 – G5) and ionospheric storm conditions in the Earth's vicinity (Jacobsen and Andalsyik, 2016). Immediately dubbed the *St Patrick's Day 2015 storm*, the event was unique in several ways, as follows:

1 It was the strongest space weather event in the year 2015.
2 International space weather watchdogs failed to predict it.
3 The event commenced suddenly, and with the fast rising intensity, in the late afternoon hours (UTC) of 17 March, 2016, intensifying towards the midnight.

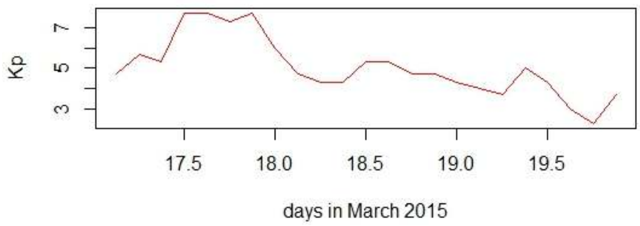

Figure 1. Planetary Kp index of geomagnetic disturbance during the St Patrick's Day storm event (based on data from)

The St Patrick's Day storm development can be described with the time series of the planetary Kp index of geomagnetic disturbance, as shown in Fig 1.The storm's effects lasted for three days, affecting numerous technology systems, including satellite navigation. The character of the St Patrick's Day 2015 storm offers a suitable case for studying the GNSS positioning performance during the fast developing space weather event.

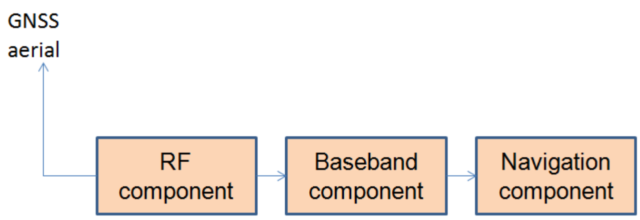

Figure 2. GNSS SDR receiver components

3.2 *Data sources*

The study presented here was established on post-processing the experimentally collected GPS and GLONASS raw pseudoranges at the stationary International GNSS Service (IGS, 2016) reference station in Padua, Italy. The station's position is known, thus allowing for the positioning error estimation through comparison between the estimated position fixes and the known reference point position.

Additionally, the IGS standards require mitigation of all the effects of local environment, in a manner similar to processes of the meteorological data collection. Such a procedure exposes the space weather/ionospheric effects and allows for their impact on GNSS performance and operation. The choice of data source was driven by its proximity to maritime environment (the Adriatic Sea), as well as the station's equipment ability to collect both GPS and GLONASS pseudoranges. The collected daily data sets were stored in the RINEX format and offered freely to interested parties (scientists, researchers, engineers etc.). The RINEX pseudoranges collected on 17 March, 2016 only were used to assess the impact of the storm in development, particularly in the period from the late afternoon to midnight (both UCT time).

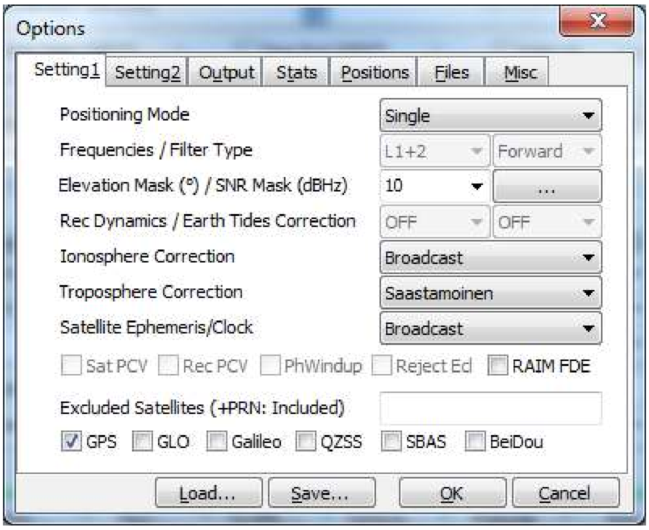

Figure 3. RTKLIB GNSS SDR receiver setting selection menu (set to Case 2)

3.3 *Software tools*

RTKLIB, an open-source software-defined GNSS receiver (Stewart *et al*, 2015), was used for position estimation using raw GPS and GLONASS RINEX-formatted pseudoranges (Takasu, 2013).. RTKLIB provides a complete set of the GNSS receiver functionalities (Stewart *et al*, 2015), comprising algorithms and architecture for SDR signal processing and estimation at Radio Frequency (RF), baseband and navigation/application levels (Stewart *et al*, 2015), as depicted in Fig 2. Since the experimentally collected GPS and GLONASS pseudoranges were used as input data, only the navigation (position estimation) component RTKPOST of RTKLIB GNSS SDR receiver was used in this study (Takasu, 2013).

3.4 *Methodology*

Raw GPS and GLONASS pseudoranges, along with the information from GPS and GLONASS navigation messages, were fed into RTKLIB, an open-source software-defined GNSS receiver. With the already identified pseudoranges at hand, only the navigation/application component RTKPOST of the GNSS SDR RTKLIB receiver was utilised. The RTKLIB processing and estimation methodology and algorithms are presented in detail in the RTKLILB manual, provided within the RTKLIB software package (Takasu, 2013). RTKLIB returned position and positioning error x-, y-, and z-component estimates at the 30 s-interval. Five dedicated use-cases were examined, that utilised assisting information as provided by core satellite navigation systems, GPS and GLONASS, respectively, as presented in Table 1.

RTKLIB/RTKPOST was configured for a particular use-case study through the RTKLIB GNSS SDR setting selection menu (Takasu, 2013), depicted in Fig 3. In general, the settings resemble those activated in commercial-grade GNSS receivers designed for use in maritime navigation, thus allowing for simulation of the real user GNSS equipment.

Time series of position and positioning error estimates calculated by RTKLIB/RTKPOST were analysed by our own software developed in the R statistical software environment (R Development Core Team, 2016). Separate analyses were conducted for northing, easting and height error components, respectively.

Table 1. Use-case description

Case	Pseudo-ranges	Frequency	Ionospheric corrections
1	GPS	Single	No
2	GPS	Single	Yes
3	GPS+GLONASS	Single	No (GPS)
4	GPS+GLONASS	Single	Yes (GPS)
5	GPS+GLONASS	Dual	Iono-free LC

4 AN OUTLINE OF RESEARCH RESULTS.

Time series analysis of GNSS positioning error components during the day 076 in 2015 (17th March, 2015 – the day of the commencement of the St Patrick's Day storm) are presented in this Section.

Graphical presentations (Figs 4-8) comprise diagrams of the easting (E-W), northing (N-S) and height (U-D) errors time series, respectively, segmented per use-case scenarios depicted in Table 1, as returned by RTKPOST software component of RTKLIB (Takasu, 2013).

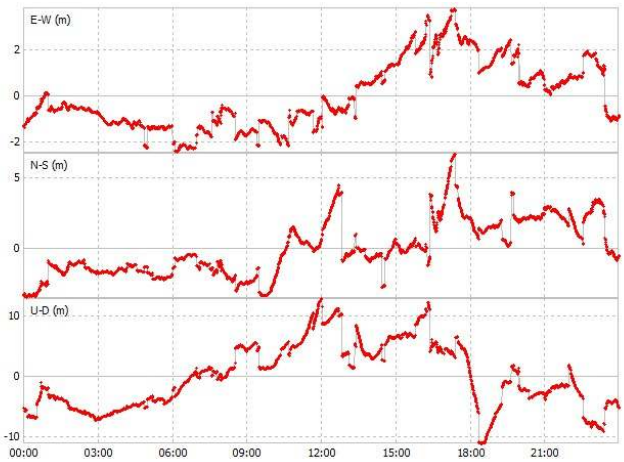

Figure 4. GPS-only, without ionospheric corrections

Figure 5. GPS-only, with broadcast ionospheric corrections

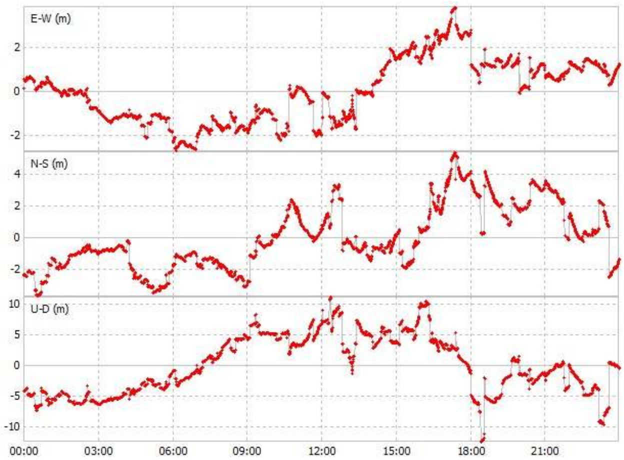

Figure 6. GPS/GLONASS, without ionospheric corrections

Figure 7. GPS+GLONASS, with broadcast ionospheric correction

Figure 8. Iono-free double-frequency GPS

Time series are further processed with a dedicated R-based software package developed by our team in order to calculate the basic descriptive statistics of the time series under assessment. The statistical analysis results are summarised in Table 2.

Finally, the nature of positioning error processes was assessed through positioning error component histogram analysis. Histograms of northing, easting, and height error time series, respectively, for the five use-case scenarios were produced using R-based software, and are presented in Figs 9-13.

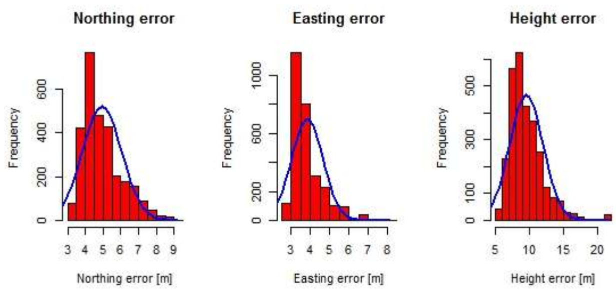

Figure 9. Histograms of northing, easting, and height GPS-only uncorrected positioning errors, respectively, on 17 March, 2015

Table 2. GPS positioning performance daily statistics for 17th March, 2015

	Northing error mean	Easting error mean	Heigh error mean	Northing error standard deviation	Easting error standard deviation	Height error standard deviation
Case 1	4.941	3.842	9.533	1.106	0.824	2.468
Case 2	3.504	2.670	6.450	1.108	0.748	2.080
Case 3	3.508	3.001	7.112	0.428	0.462	1.099
Case 4	2.699	2.221	5.219	0.668	0.549	1.321
Case 5	2.170	1.775	4.299	0.309	0.260	0.788

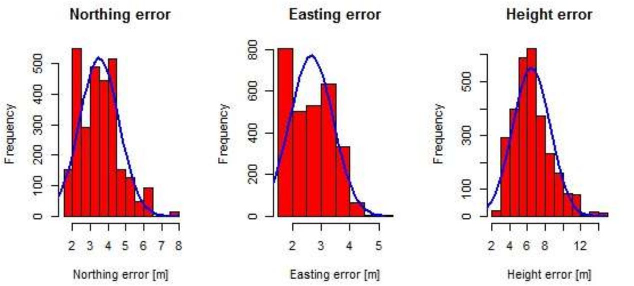

Figure 10. Histograms of northing, easting, and height iono-corrected GPS-only positioning errors, respectively, on 17 March, 2015

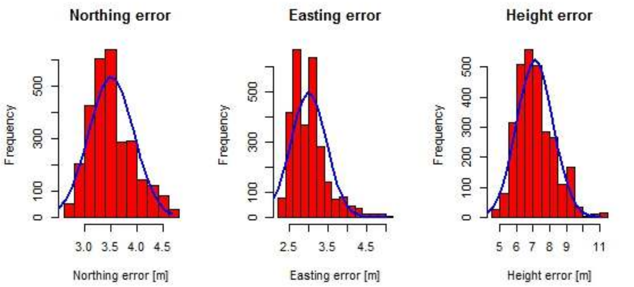

Figure 11. Histograms of northing, easting, and height uncorrected GPS+GLONASS positioning errors, respectively, on 17 March, 2015

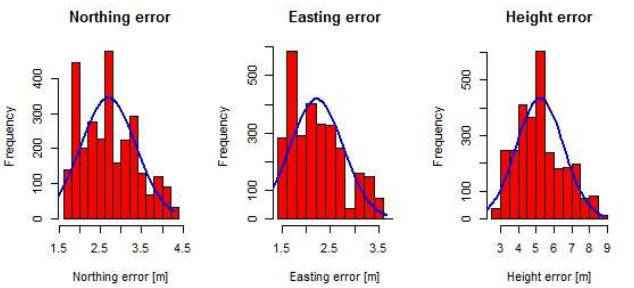

Figure 12. Histograms of northing, easting, and height iono-corrected GPS+GLONASS positioning errors, respectively, on 17 March, 2015

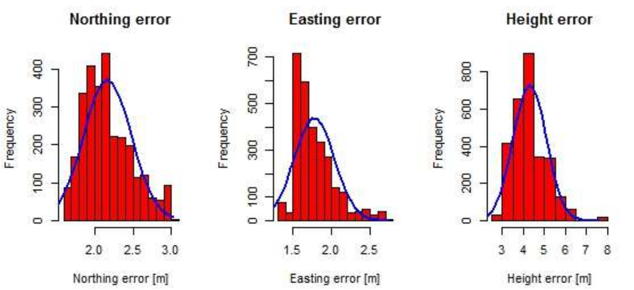

Figure 13. Histograms of northing, easting, and height iono-free GPS+GLONASS positioning errors, respectively, on 17 March, 2015

5 DISCUSSION

The analysis and interpretation of the study results (Section 4) reveals a number of effects on the GNSS positioning performance, as follows. Those listed below may be considered in GNSS resilience development and the risk assessment of the GNSS utilisation as an underlying and enabling technology, as well as in modification of the experimental GNSS positioning performance assessment procedures.

5.1 *Multi-GNSS approach reduces considerably standard deviation of positioning errors*

The utilisation of the combined satellite navigation systems' signals (GPS+GLONASS) slightly improves the means of the positioning error components. However, the standard deviations of the positioning error components are considerably improved, with the dissipation of the positioning samples lowered up to 50%, compared with the single-GNSS approach. Further to this, the time series diagrams analysis reveals more smoothed dynamics of positioning error samples, compared with the case of utilisation of single-system pseudoranges.

5.2 *Utilisation of the broadcast parameters of the GPS ionospheric model improves daily mean positioning error*

The utilisation of the standard Klobuchar model for GPS ionospheric correction reduced by up to 30% the positioning error, even when the commencement of a space weather storm occurred.

5.3 *Dual-frequency iono-free GNSS position estimation provides the best GNSS positioning performance*

This is the fact well-established in conclusions of numerous research studies. Still, the navigation market is overwhelmingly populated with single-frequency GNSS/GPS receivers. The GNSS modernisation is expected to change the trend and initiate increasing market share of multi-GNSS multi-frequency user equipment. While this is to happen, the researchers may consider the utilisation of dual-frequency data as the reference for comparison in studies of GNSS performance.

5.4 *Commencement of a space weather storm causes non-Gaussian distributions of the GNSS positioning error components*

The analysis of histograms of the northing, easting and height positioning error components reveals distraction from normal (Gaussian) distribution. While the similar effects may be found in situations of multiple GNSS error sources in operation (combined influence of the ionospheric storm and a strong urban-area multipath, for instance), the IGS-based data used in this study assures no other effects apart from the ionospheric ones. Thus, the conclusion may be drawn of the direct effect of the developing ionospheric storm on the daily GNSS positioning error statistical distribution.

The results of the study revealed a considerable impact on maritime navigation and the applications in maritime segment. A space weather event development may cause considerable degradation of GNSS positioning performance, but situation may become worsened due to a more complicated positioning error dynamics resulting from storm development. Such effects may affect not only the traditional GNSS-based maritime navigation services and applications, but also the emerging ones, including: autonomous surface and underwater vessels, automated search & rescue operations and various robotic applications. The above-stated findings of this study aimed to contribute to development of more robust and resilient GNSS development related to maritime segment.

6 CONCLUSION AND FUTURE RESEARCH

Studies of GNSS operation and positioning performance in situations and events of potential GNSS disruptions create a evidence-based foundation for the resilient GNSS development. Here we present the results of a study of GNSS positioning performance in a transitional period of a developing space weather/ionospheric event. The study was conducted through deployment of a fully-functional open-source software-defined GNSS radio receiver RTKLIB, fed with the experimentally collected the GPS and GLONASS pseudoranges collected experimentally at the IGS reference station in Padua, Italy during a G4-grade space weather event (storm) in 2015.

The study revealed potentials for mitigation of the effects of developing space weather processes on GNSS positioning performance, including:

– smoothing the positioning error dynamics and confinement of positioning error samples dispersion through utilisation of multi-GNSS systems (the utilisation of satellite signals belonging to different satellite navigation systems),
– reduction of daily mean positioning error through utilisation of the ionospheric delay correction models,
– non-Gaussian statistical distributions of daily positioning errors at the times of space weather disturbances development, which suggests development of correction models that respect the character of the causes of positioning errors, and
– utilisation of dual-frequency positioning error estimates as the reference in GNSS positioning performance assessment.

This study addressed the case of utilisation of GPS and GLONASS, the two fully-operational global navigation satellite systems. Future research will take into account effects and benefits brought by emerging (BeiDou and Galileo) and augmentation (EGNOS) systems.

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