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Modelling GPS Positioning Performance in Northwest Passage during Extreme Space Weather Conditions

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ABSTRACT: New shipping routes are emerging as a result of iceberg melting in polar regions, allowing for more efficient transport of people and goods. Opening of the Northwest Passage, the maritime route connecting Pacific Ocean with Atlantic Ocean through Arctic region, is considered such a development. The increasing transport exploitation of the Northwest Passage requires the quality assessment of maritime navigation aids for compliance with the established requirements. Here we contribute to the subject with addressing the polar commercial-grade GPS positioning performance in the Northwest Passage in the extreme positioning environment conditions during the massive 2003 space weather storm, a space weather event similar to the Carrington Storm of 1859, the largest space weather event recorded. The GPS positioning environment in the Northwest Passage during the Carrington-like storm in 2003 was reconstructed through the GNSS SDR receiver-post processing of the experimental GPS observations. The raw GPS dual-frequency pseudoranges and navigation messages were collected at the International GNSS Service (IGS) reference station at Ulukhaktok, Victoria Island, Canada. Pseudorange processing and GPS position estimation were performed in three scenarios of pre-mitigation of the ionospheric effects, known as the single major contributor GPS positioning error: (i) no corrections applied, (ii) Klobuchar-based corrected GPS positioning, and (iii) dual-frequency corrected GPS positioning. Resulting GPS positioning error vectors were derived as positioning error residuals from the known reference station position. Statistical properties of the northing, easting, and vertical components of the GPS positioning error vector were analyzed with a software developed in the R environment for statistical computing to select suitable methods for the GPS positioning error prediction model development. The analysis also identified the most suitable theoretical fit for experimental statistical distributions to assist the model development. Finally, two competitive GPS positioning error prediction models were developed, based on the exponential smoothing (reference) and the generalized regression neural networks (GRNN) (alternative) methods. Their properties were assessed to recommend their use as mitigation methods for adverse massive space weather effects in polar regions.

1 INTRODUCTION

New shipping routes are emerging as a result of icebergs melting in polar regions, allowing for more efficient transport of people and goods. The opening of the Northwest Passage, the maritime route connecting the Pacific Ocean with the Atlantic Ocean through the Arctic region, is considered such a development [8]. The Northwest Passage location in polar region renders satellite navigation, as a navigation-supporting technology, vulnerable to space weather effects [1]. Space weather is defined as a set of conditions and events of variable energy transfer originated in the Sun and spread through the

Earth's surroundings that can affect space-borne and ground-based technological systems. Geomagnetic storms represent extreme forms of space weather that can affect radio wave propagation across the spectrum, degrading the positioning performance of the Global Navigation Satellite System (GNSS) and reducing the quality of the GNSS-based applications [1, 7]. Here we address the effects of the 2003 geomagnetic storm on the polar commercial-grade GPS positioning performance in the Northwest Passage. The 2003 extreme space weather event, also known as the 'Halloween Storm', is often compared to the Carrington Storm of 1859, by far the largest solar storm recorded [1, 2]. Considering the expected increase in maritime traffic in the Northwest Passage with the extensive utilization of satellite navigation on-board the vessels, this study aimed at assessment of the GPS positioning performance using the common on-board equipment and compliance with the requested and required GPS positioning performance [4]. The study results with the recommendation proposal to mitigate GNSS positioning degrading ionospheric delay effects of massive space weather developments on satellite navigation performance in the polar region

2 METHOD AND MATERIAL

The GPS positioning environment in the Northwest Passage during the Carrington-like storm in 2003 was reconstructed throuvenrgh the GNSS SDR receiver-post processing of the experimental GPS observations taken in the region during the space weather event [3, 5, 7]. The research aims at addressing the excess GNSS ionospheric delay caused by considerable space weather event, and its contribution to the over-all GNSS positioning error. As the result, a prognostic model is to be developed to forecast the GPS positioning error during a massive space weather deterioration in the region of Northwest Passage. It should be noted that we consider the other sources of GPS positioning errors (multipath, GPS tropospheric delay etc.) of the unchanged (unaffected) nature. Additionally, while the research focuses on the GPS ionospheric delay, we do not consider effects of the GPS ionospheric scintillation in this research. Observations were collected of raw (uncorrected) GPS dual-frequency pseudouranges and GPS navigation messages broadcast at the International GNSS Service (IGS) reference station at Ulukhaktok, formerly Holman, Victoria Island, Canada (latitude: 70.7364000N, longitude: 117.7609000W, 39.5 m above the mean sea level), and made available through the IGS internet archives (ftp://cddis.nasa.gov/gnss/data/daily). The IGS is set to assist scientists and the other interested parties with the provision of the GNSS pseudoranges uncorrected for ionospheric effects to allow for research into the ionospheric effects on GNSS performance and operations. Nominally established to provide with daily records of observed raw (uncorrected) GNSS pseudoranges at 30 s sampling time, the reference stations may occasionally provide reduced sets of observations, and/or present observations in faulty and inconsistent manner. External events may also cause tempral suspension of pseudorange collection. In an approach similar to the essence of differential GNSS, we consider the GNSS ionospheric delay to be approximately constant in the bounded region around the observation site, thus allowing the generalisation of the observed ionospheric delay effects on GNSS performance at stationary site to be applicable on the near-by dynamical environment of mobile maritime objects (vessels).

We used the Ulukhaktok (Holman) GPS pseudorange observations from the period DOY298 (25th October) – DOY315 (11th November) in 2003 to cover the most intensive phase of the largest space weather event observed in modern history. Pseudorange processing and GPS position estimation were performed in three scenarios of pre-mitigation of the ionospheric effects, known as the single major contributor to GPS pseudorange measurement error, and, consequently, GPS positioning error: (i) GPS positioning exposed to ionospheric effects, with no corrections applied, (ii) Klobuchar-based corrected GPS positioning, as defined with (1) using the GPS-broadcast correction model parameters ($\alpha_i, \beta_i, i = 1, \ldots, 4$) and (iii) dual-frequency corrected GPS positioning procedure utilizing pseudorange measurements $\rho(f_1)$ and $\rho(f_2)$ on carrier frequencies f_1 and f_2, respectively, taken instantaneously, to obtain TEC, and consequently the GPS pseudorange observations freed from the first-order ionospheric effects (2).

$$t_{iono}(t) = DC + A(\phi) \cdot \cos\left(\frac{2\pi (t - t_0)}{P(\phi)} \right), \text{day}$$
$$A(\phi) = \sum_{n=0}^{3} \alpha_n \phi_m^n \, , \; P(\phi) = \sum_{n=0}^{3} \beta_n \phi_m^n \qquad (1)$$

$$\rho(f_2) - \rho(f_1) = 40.31 \cdot \left[\frac{1}{f_2^2} - \frac{1}{f_1^2} \right] \cdot STEC + b_s + b_r$$
$$TEC = STEC \cdot \left(1 - \left(\frac{R_{Earth}}{R_{Earth} + h} \cdot \cos E \right)^2 \right) \qquad (2)$$

In the Klobuchar model (1), symbols may be identified as follows: DC = 5e-9 s, $A(\varphi)$ denotes amplitude of the day-time cosine component of the GPS ionospheric delay, determined with the GPS-broadcast (α_i, $i = 1, \ldots, 4$) parameters and the user position's geomagnetic latitude, $P(\varphi)$ denotes period of the day-time cosine component of the GPS ionospheric delay, determined with the GPS-broadcast (α_i, $i = 1, \ldots, 4$) parameters and the user position's geomagnetic latitude, t denotes the time instant for which the GPS ionospheric delay is determined in [s], and t_0 = 14 hours local time in [s], and $t_{iono}(t)$ denotes the resulting GPS ionospheric time delay in [s] at the time instant t.

Position estimates were obtained using the open source GNSS Software-Defined Radio receiver RTKLIB (developed by Dr T Takasu, available form: http://www.rtklib.com). Resulting GPS positioning error vectors were derived as positioning error residuals from the known reference station position. Statistical properties of the northing, easting, and vertical components of the GPS positioning error vector were analyzed with a tailored software developed by these authors in the R environment for statistical computing to improve the understanding of the positioning error generation process, and to select suitable methods for the GPS positioning error prediction model development [3].

We deployed the Cullen and Fray method to estimate the theoretical statistical distribution of closest fit to the experimental one, derived from the GPS position error estimates. Developed by Pearson, and described later by Cullen and Fray, the method extend the suggestion for the best fit. We conduct the actual analysis using the bespoke software developed in the R environment for statistical computing, and its external package *fitdistrplus* [9].

The analysis identified the most suitable theoretical fit for experimental statistical distributions to assist the model development. Finally, two competitive GPS positioning error prediction models were developed, based on the exponential smoothing (reference) and the Generalized Regression Neural Networks (GRNN) [6] (alternative) methods. Model development and properties assessment were performed using a tailored software developed in the R environment for statistical computing to recommend the utilization for mitigation of contribution to GPS positioning performance deterioration of the excessive GPS ionospheric delay caused by adverse massive space weather effects in polar regions.

Performance analysis of the models developed was based on the analysis of residuals, obtained as a difference between the model-based position forecast in the particular scenario (i) … (iii) , and th etrue position of the reference station.

3 RESEARCH RESULTS

The methodology described in the previous Section was applied on the Ulukhaktok GPS raw pseudorange data, taken during the Carrington-like space weather storm of 2003. As a result, insight was gained into statistical properties of the northing, easting, and vertical components of the GPS positioning vectors, in three scenarios of the ionospheric effects mitigation, as depicted in Figures 1. (for all ionospheric mitigation scenarios), and 2. (no-corrections ionospheric mitigation scenario only).

The most suitable theoretical statistical distribution to fit the experimental one was selected using the Cullen & Fray diagram, as shown in Figure 3. for the northing component of the GPS positioning vector in the no-correction scenario.

A time series of horizontal GPS positioning errors was constructed from time series of northing and easting positioning errors. Using the horizontal GPS positioning error time series, two candidate prediction model development methods were selected and tuned, i.e., the exponential smoothing and the generalized regression neural networks (GRNN), to develop candidate models of the horizontal GPS positioning error. The original time series of 2872 single-point horizontal GPS positioning errors was split into the first 2857 elements training set, and the remaining 15 elements test set to assess the prediction models performance.

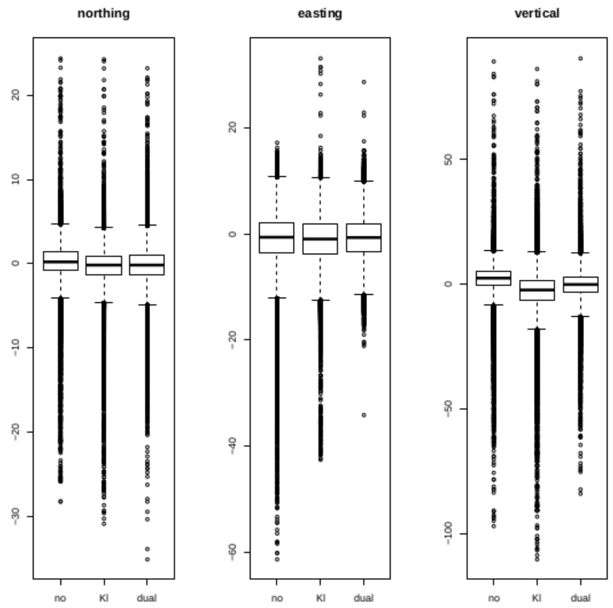

Figure 1. Exploratory analysis results of the components of the GPS positioning error vector in the ionospheric effects mitigation scenarios of (i) no correction (no), (ii) broadcast Klobuchar corrections (Kl), and (iii) dual-frequency correction

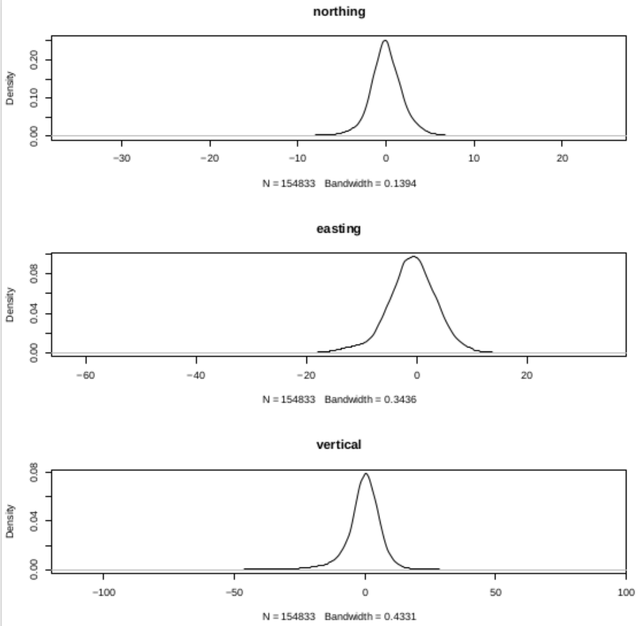

Figure 2. Experimental statistical distribution density functions for the northing, easting, and vertical components of the GPS positioning error vector in the no-correction ionospheric effects mitigation scenario

The most suitable theoretical statistical distribution to fit the experimental one was selected using the Cullen & Fray diagram, as shown in Figure 3. for the northing component of the GPS positioning vector in the no-correction scenario.

Table 1. The Exponential Smoothing (ES) and the Generalized Regression Neural Networks (GNNR) GPS positioning error prediction models performance based on residual analysis.

	Scenario (i): No corrections			Scenario (ii): Klobuchar corrections			Scenario (iii): Dual-frequency corrections		
	Mean	Median	Max	Mean	Median	Max	Mean	Median	Max
ES	0.2208	0.0527	2.5948	0.1208	0.0515	2.6363	-0.1390	0.3251	2.4469
GRNN	0.0527	-0.1154	2.4266	0.0292	-0.0401	2.5448	-0.1128	0.3212	2.4648

A time series of horizontal GPS positioning errors was constructed from time series of northing and easting positioning errors. Using the horizontal GPS positioning error time series, two candidate prediction model development methods were selected and tuned, i.e., the exponential smoothing and the generalized regression neural networks (GRNN), to develop candidate models of the horizontal GPS positioning error. The original time series of 2872 single-point horizontal GPS positioning errors was split into the first 2857 elements training set, and the remaining 15 elements test set to assess the prediction models performance. The reduction of number of GPS pseudorange observations in comparison with the nominal determination for provision of 30 s-sampled data was not explained by IGS.

The most suitable theoretical statistical distribution to fit the experimental one was selected using the Cullen & Fray diagram, as shown in Figure 3. for the northing component of the GPS positioning vector in the no-correction scenario.

The model performance analysis was conducted on the basis of residuals between the estimated positions and the true position of the IGS reference station. Two candidate models extend similarly in their performance, as evident from the performance assessment results outlined in Table 1.

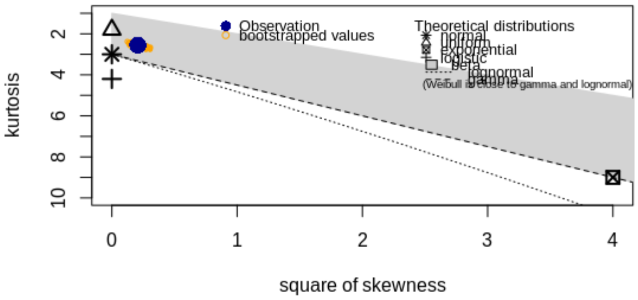

Figure 3. Cullen & Fray diagram for the northing component of the GPS positioning vector in the no-correction scenario.

We suggest the preference should be given to the GRNN model for its ability to accommodate a larger variance in GPS positioning performance during the extended period of observations, and for the method's ability to learn from new cases.

4 DISCUSSION

The commercial-grade GPS positioning performance in the Northwest Passage was assessed in three scenarios of the ionospheric effects mitigation. In general, the GPS positioning performance observed during a massive deterioration of space weather does not meet the requirements for maritime navigation and non-navigation applications. Notable biases and variations were identified in three components of the GPS positioning error vector in all three scenarios of presumed GPS use in the Arctic region of the Northwest Passage during a massive space weather disturbance. Deterioration of the GPS positioning error was understood to result from the inadequate GPS receiver design, as well as from the unaccounted space weather deterioration of the unknown statistical properties, thus its effects were not being accounted when using common correction models and procedures. Those were exploited for the GPS positioning error prediction model development based on the observed northing, easting, and vertical positioning errors, and on two competing model development methods: the exponential smoothing, and the Generalised Regression Neural Networks (GRNN). Based on this study results, a set of recommendations on the GNSS receiver design and the standalone and assisted GNSS use in the newly opened and emerging transport routes in polar regions are proposed for improvement of safety, accuracy, and sustainability of maritime navigation. The recommendations are as follows:

GNSS receiver design that benefits from dual-frequency GNSS ionospheric effects corrections is recommended for use in the Northwest Passage.

Use of the Klobuchar correction model is not recommended in the Northwest Passage during the periods of intensive space weather disturbance, and/or geomagnetic and ionospheric storm.

Use of the Generalised Regression Neural Networks (GRNN) GPS positioning error prediction model on either un-corrected, or dual frequency-corrected GPS pseudoranges-based position estimates is a recommended practice in the Northwest Passage during a period of intensive space weather disturbance and/or geomagnetic and ionospheric storm.

Utilisation of recommended GRNN model may lead to the transition from infrastructure-assisted mitigation of the GNSS ionospheric effects towards the adaptive GNSS positioning process, capable of the GNSS positioning environment awareness, as proposed in [10]. The adaptive GNSS positioning process is particularly suitable for maritime vessels, which may offer power stability and sufficiency, as well as required computational capacity.

REFERENCES

1. Cannon, P.: Extreme space weather: impacts on engineered systems and infrastructure,

https://www.raeng.org.uk/publications/reports/space-weather-full-report, last accessed 2021/04/01.

2. Cliver, E.W., Dietrich, W.F.: The 1859 space weather event revisited: limits of extreme activity. Journal of Space Weather and Space Climate. 3, (2013). https://doi.org/10.1051/swsc/2013053.
3. Crawley, M.J.: The R Book, 2nd Edition | Wiley. Wiley (2012).
4. European GNSS Agency (GSA): Report on Maritime and Inland Waterways User Needs and Requirements: Outcome of the European GNSS' User Consultation Platform. , Prague, Czech.
5. Filic, M., Filjar, R.: Forecasting model of space weather-driven GNSS positioning performance. Lambert Academic Publishing, Riga, Latvia (2018).
6. Martinez, F., Frias, M.P., Conde, A., Martinez, A.M.: Time Series Forecasting with GRNN in R: the tsfgrnn Package, https://cran.r-project.org/web/packages/tsfgrnn/vignettes/tsfgrnn.html, last accessed 2021/04/01.
7. Parkinson, B.W., Spilker, J.J.: Global Positioning System: Theory & Applications (Volume One). Amer Inst of Aeronautics, Washington, DC (1996).
8. Pizzolato, L., Howell, S.E.L., Dawson, J., Laliberté, F., Copland, L.: The influence of declining sea ice on shipping activity in the Canadian Arctic. Geophysical Research Letters. 43, 23, 12,146-12,154 (2016). https://doi.org/10.1002/2016GL071489.