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An Assessment of Long-term Spatial Agnosticism of GNSS Positioning Degradation Risks Due to Ionospheric Conditions

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ABSTRACT: The Global Navigations Satellite Systems (GNSS) have been evolved into an essential infrastructure of modern civilisation, a public goods, and enabler of rapidly growing number of technology and socio-economic applications. However, GNSS applications often lack fundamental details on GNSS Positioning, Navigation, and Timing (PNT services performance to define and determine their Quality of Service (QoS). The lack of alignment with the core GNSS PNT deprives GNSS applications of assessing the risks of the GNSS PNT utilisation, thus leaving GNSS applications unable to prepare alternatives and mitigate the causes of GNSS PNT performance disruptions. Here we contributed to solution of the problem with the introduction and long-term performance assessment of the risk model of ionospheric-caused GNSS positioning degradation. Called the Probability of Occurrence (PoO), our team defined the risk model of GNSS positioning degradation caused by ionospheric conditions based on the long term observations of occurrences of degraded GNSS positioning performance. In the process of the GNSS risk model validation, the long-term PoO risk models are developed using the annual 2014 stationary GNSS horizontal positioning error observations derived from the GNSS pseudoranges collected at the International GNSS Service (IGS) reference stations situated in polar (Iqaluit, Canada) and sub-equatorial regions (Darwin, Australia). Two GNSS risk models are compared for similarity using statistical methods of Hausdorff distance and Cramér–von Mises statistical test. Research results show that two GNSS risk models are spatially agnostic, since no significant difference in two long-term GNSS risk models is found. The research results supports the conclusion of generality of the PoO GNSS risk model, and its ability to serve GNSS applications developers, operators, and users in determination of the QoS of particular GNSS applications.

1 INTRODUCTION

The Global Navigation Satellite System (GNSS) become an essential enabler of technology and socio-economic applications (systems and services) [5, 6]. Based on a dedicated technology infrastructure and the fulfilled presumptions of the GNSS PNT operations, the GNSS offers the Positioning, Navigation, and Timing (PNT) service of the unprecedented quality [5], even in scenarios of exceptional conditions (such as: space weather/geomagnetic/ionospheric storms, outstanding multipath conditions, severe meteorological events) of the GNSS positioning environment [15]. As with the all technology systems, the nature of the system design, operations shortcomings, and the consequent vulnerabilities render the GNSS PNT performance susceptible to a number of natural ionospheric and tropospheric delay, multipath effects), operational (inaccurate ephemeris data) and artificial (spoofing, jamming) effects [8, 9]. Development of the resilient GNSS PNT has become the research subject of the prime importance, as rising number of the GNSS PNT applications require robust, available, affordable and stable PNT Quality of Service

(QoS) that should propagate into the QoS of targeted GNSS applications, rendering them of the same nature [2, 6, 8]. Developers, operators, and users of the GNSS-based applications are particularly concerned with the lack of integration between the GNSS PNT QoS and the QoS of the particular GNSS application, which may have its own set of the PNT performance requirements [5]. The risk of the GNSS PNT performance not meeting the needs and requirements of the targeted GNSS application has become the prime issue and potential obstacle in the market acceptance of the GNSS PNT as the fundamental enabler and driver of a fast range of the PNT applications [5]. Currently, developers, operators, and users cannot assess such a risk in an easy, formal, and convincing manner. Furthermore, the characterisation of such a risk for GNSS application in terms of long-term behaviour is still in its infancy [12].

Recently, we introduced a novel GNSS performance degradation risk assessment model, which allows developers, operators, and users of a GNSS application to assess the risk of the GNSS PNT QoS failure to meet the requirements and needs of the targeted GNSS applications [12]. The GNSS PNT risk assessment mode, dubbed the Probability-of-Occurrence (PoO) model allows the GNSS application's evaluators to assess the probability that the GNSS PNT performance will not meet the exact GNSS application requirement for positioning accuracy in the observed scenario of the GNSS usage [12]. The PoO model was demonstrated as successful in the case of the risk of GNSS PNT degradation due to ionospheric effects, the single principal natural cause of the GNSS positioning performance degradation, among the others in the core GNSS PNT error budget [12, 15, 16].

Here a research is presented as an application the introduced PoO model in evaluation of the long-term spatial characterisation of the risk of GNSS PNT degradation due to ionospheric effect. The research hypothesises that the long-term GNSS PNT degradation risk due to ionospheric effects should be considered spatially agnostic, in sense that it does not variate significantly worldwide. In that terms, the generalised, global nature of models of the GNSS PNT degradation risks due to ionospheric effects will be confirmed, which will render them applicable for GNSS applications regardless of the intended geographical area of deployment.

The manuscript presenting the research reads, as follows. This Section introduces the reader to the problem, and outlines the motivation and the research approach taken. Section 2 describes the methodology and material (data, observations, models) used in the research. Section 3 outlines research results. Section 4 discusses the research results in terms of the problem solution, and summarises the research contributions, their shortcomings, and plans for the research continuation in the future.

2 METHOD AND MATERIAL

The GNSS PNT performance suffers from the ionospheric conditions, as the single major cause of degrading effects. This research addresses the issues affecting the mass-market of the single-frequency commercial-grade GNSS receivers, such as those found in smartphones, utilising the essential GNSS position estimation algorithm. Such devices comprise a majority of GNSS receivers used currently and projected to remain as such in the near future. The ionospheric effects cause a delay in the satellite signal propagation, and consequently in the pseudorange measurement $\Delta\rho_i$ [m] from the i-th satellite, which is determined by frequency of satellite carrier wave f [Hz], and the vertical ionospheric profile $N(h)$ [electrons/m^2] with h [m] being the height above the mean sea level, as shown in (1), while the slant factor F reflects the effects of the actual angle at which a satellite signal enters the ionosphere [4, 15].

$$\Delta\rho_i = \frac{40.3 \cdot F}{f^2} \int_{\text{lower ionospheric boundary}}^{\text{lower ionospheric boundary}} N(h)\,dh = \frac{40.3}{f^2} \cdot F \cdot TEC \tag{1}$$

The vector of GNSS ranging errors $\Delta\rho$, related to the set of satellites used in a single-frequency single position estimate determination, is mapped onto GNSS positioning error vector Δx, comprising the three-dimensional error components, northing, easting, and vertical, as given in (2) [15].

$$\Delta x = \left(G^\tau G\right)^{-1} G^\tau \Delta\rho \tag{2}$$

At the same time, the GNSS positioning error vector is determined for every GNSS positioning estimate as a difference between the estimated position and the true position of a GNSS receiver. Error determination is performed per components of the positioning vector, as desscribed in more details in [12]. The true position of an IGS GNSS receiver is specified in the IGS network description [11].

The horizontal GNSS positioning error, x_{hor} in [m], is determined using the northing, $x_{northing}$ in [m], and easting, $x_{easting}$ in [m], components of the GNSS positioning error vector Δx, as given in (2).

$$x_{hor} = \sqrt{x_{northing}^2 + x_{easting}^2} \tag{2}$$

Horizontal GNSS error is used for development of the Probability-of-Ocurrence risk model of GNSS PNT degradation due to ionospheric effects, with the GNSS pseudoranges used in the position and positioning error estimation retaining the effects of the ionospheric conditions only. Determination of the horizontal GNSS errors may be performed using a bespoke software, by collection of empirical data, or by post-processing of archive GNSS pseudorange observations by a GNSS Software Defined Radio (SDR) receiver, such as RTKLIB [17] and gLAB Tool Suite (Research group of Astronomy and Geomatics [14], configured to work as a post-processing tool.

Using the GNSS pseudoranges observed using a stationary GNSS receiver, with observations uncorrected for ionospheric effects, over the sufficiently long period, a database of horizontal GNSS positioning errors will serve as a reasonable sample of population of various scenarios of ionospheric disturbances and their effects on GNSS PNT performance. A suitably selected period of data collection will represent sufficiently well not only the depth of various ionospheric events, but the frequency of their occurrences, in real situation manner. The horizontal GNSS errors database established in a such manner may serve in development of the PoO risk model development, as described previously in [12].

We defined the PoO model as a Complementary Cumulative Distribution Function (CCDF) of an annual (year-long) set of horizontal GPS positioning errors, taken every 30 s, throughout the year [12]. Thus, the PoO model may be understood as an application of the CCDF, a statistical method, on a suitably crafted context statistically defining the GNSS PNT degradation risk.

Here we argue that PoO models developed in the manner described above for stationary receivers set in different geographical regions may serve for assessment of the long-term spatial agnosticism of GNSS positioning degradation risks due to ionospheric conditions. The aim of the research is therefore to determine if two PoOs developed for geographically separated test sites show similarity or statistically significant difference. The risk of the GNSS PNT utilisation results from the statistically independent probability of the harmful event and the damage, as its consequence. The contribution of this research is focused on the former, while the GNSS application developers, operators, and users may find the latter either in references, such as [5], or in their own specifications of QoS.

The comparison of two PoOs may be performed in various ways. Our team selects three statistical methods for comparing two PoO curves, including: (i) Dynamic Time Warping (DTW) method [7, 18], (ii) the Hausdorff distance [10], and (iii) the Cramér–von Mises statistical test [1, 3].

The *Dynamic Time Warping* (DTW) method calculates the distance between two given vectors representing points on two respective PoOs in consideration, resulting with two new vectors showing the best possible matches between data points on PoO curves [7, 18]. The matching may be presented in a graphical form, with the data points matched in the one-to-one manner [7]. Vertical and horizontal lines mean that a single point on the one axis matches/represents more than one point on the another [7, 18].

The *Hausdorff distance* of two sets of points is defined as the largest of all the distances from a point in one set to the closest point in the other set [10].

The *Cramér–von Mises statistical test* essentially aims at determination of the goodness of fit of an theoretical cumulative distribution function and a given empirical one [1, 3]. Additionally, the test may serve the purpose of assessing fit between the two given empirical cumulative distribution functions [1, 3]. This research utilises Cramér–von Mises statistical test for determination of the similarity/fit between the two given PoO models.

The proof of similarity between the PoOs concerned will then serve as the proof of that the GNSS positioning degradation risk due to ionospheric conditions is spatially agnostic. The presented methodology may be summarised with the generalised algorithm depicted in Figure 1.

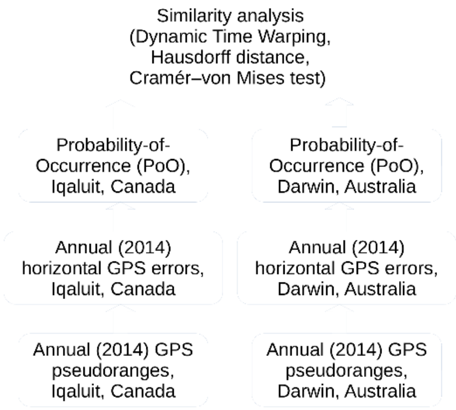

Figure 1. Research methodology

The research presented use two sets of the GPS pseudorange observations taken at the International GNSS Service (IGS) [11] reference stations at Iqaluit, Canada and Darwin, Australia, depicted in Figure 2, every 30 s throughout the year 2014 to determine the PoOs. The IGS reference stations shall comply to the IGS standard on the reference station set-up, configuration, and operation. Interested parties are advised to find details on the IGS internet-site [11]. The authors select a single GNSS system (GPS) to present the case of the proposed PoO and its characterisation in a clearer terms, without the need to complicate the research procedure with a concern of multi-GNSS positioning. Future research will consider the multi-GNSS usage effects on the PoO model.

The selection of the IGS reference stations for this research is motivated by the aim of the research to cover the long-term case of extremes of the ionospheric conditions in polar and sub-equatorial regions, respectively. Since both regions extend harsh ionospheric conditions, caused by different processes, the aim of presented research is to show that those produce the statistically similar PoO outcomes.

Figure 2. Positions of the two IGS stationary reference stations at Iqaluit, Canada and Darwin, Australia, respectively.

The GPS position estimates are obtained from the respective GPS observations using the RTKLIB GNSS SDR [17], configured as a commercial-grade single-frequency GNSS receiver, with configuration shown in Figure 3.

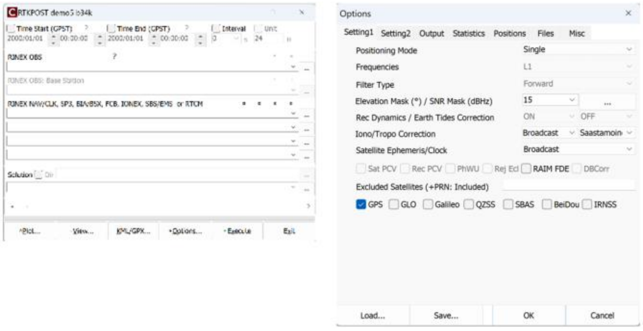

Figure 3. Configuration of a commercial-grade single-frequency RTKLIB GNSS SDR receiver

A tailored software for horizontal GNSS positioning errors determination, and the PoO model development and validation is developed for the purpose of this research in the open-source R environment for statistical computing (R project team, 2025).

3 RESEARCH RESULTS

Two datasets, with the respected number of horizontal GPS positioning errors per testing site, are used in the presented research for the PoO model determination, as follows: Darwin, Australia – 1,042,933 instances, Iqaluit, Canada – 1,028,597 instances. The respected PoO models are developed to determine the risk of GNSS PNT degradation due to ionospheric effects for Darwin, Australia, and Iqaluit, Canada. The PoO models are depicted graphically in Figure 4, together with the results of the DTW analysis. The DTW analysis shows a reasonably good match between the points of two PoO curves in consideration. Visible difference in the assessed risks of surpassing the horizontal GPS error threshold may be found in the range [2 m, 6 m].

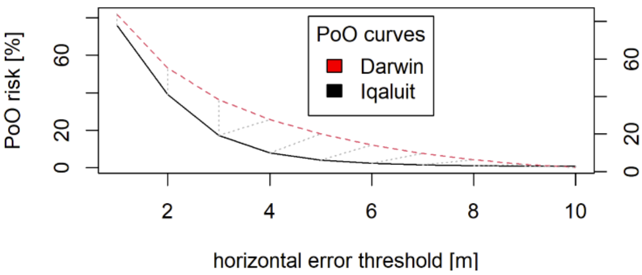

Figure 4. The PoOs of Darwin, Australia and Iqaluit, Canada, with the graphical presentation of DWT analysis

The DWT diagram shows the reasonable correspondence between the two PoO curves, as depicted in Figure 5.

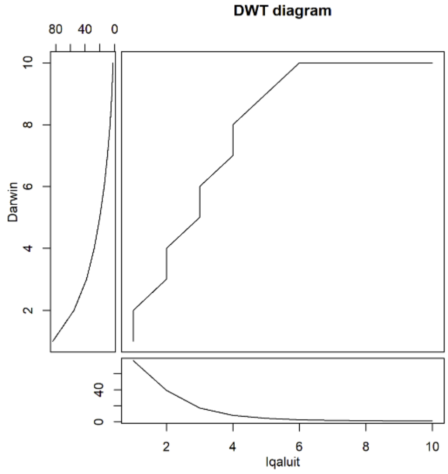

Figure 5. The DWT diagram of the PoOs of Darwin, Australia, and Iqaluit, Canada

Results of statistical analysis of the two PoOs are summarised in Table 1.

Table 1. Results of statistical test examining similarity of the two PoOs in consideration

	value of statistic	p-value, with $\alpha = 0.05$
Hausdorff distance	16.13018	-
Cramér–von Mises statistical test	1.340	0.114

Determined Hausdorff distance for the two PoOs compared shows a maximal discrepancy of 16.13%, which may be considered a proof of a good similarity between the models examined. The Cramér–von Mises statistical test examines the null-hypothesis of two set of the PoO points having the same cumulative distribution functions. The statistical tests returns the p-value = 0.114, which suggest retaining the null-hypothesis, with the statistical significance $\alpha = 0.05$. The three tetsing methods deployed prove the two PoOs develop using data from distant geographical region have the spatially agnostic long-term risk of the GPS positioning performance degradation due to ionospheric conditions and disturbances.

4 CONCLUSION

Presented research aims at evaluation of spatial characterisation of the long-term risk of the GNSS positioning performance degradation due to ionospheric conditions and disturbances. Therefore, the research does not attempt to address either the real-time PNT performance improvement, including the improvement of the GNSS positioning accuracy, or nowcast/forecast/correct in real time the disturbing natural and artificial effects to the GNSS PNT performance.

Two Probability-of-Occurrence (PoO) risk models of GPS positioning performance degradation due to ionospheric conditions are developed for geographically separated experimental IGS data collection sites at Darwin, Australia (sub-eqatorial region) and Iqaluit, Canada (polar region). The selection of experimental sites is driven by the fact of both regions being exposed to extreme ionospheric conditions, but of different respected natures. Two datasets of horizontal GPS positioning errors during Year 2014 contain more than one million observations each, thus covering all scenarios of ionospheric disturbances by their intensity as well as the frequency of appearance. The universality of the proposed PoO model in terms of spatial agnosticism, i. e. spatially independent performance is not immediately obvious, thus needed to be scrutinised objectively. The two PoO models are assessed for their similarity and potential spatial agnosticism using three statistical analysis methods: (i) Dynamic Time Warping (DTW) method, (ii) the Hausdorff distance, and (iii) the Cramér–von Mises statistical test. All three tests return results in favour of significant similarity between the two PoOs under consideration, with the Cramér–von Mises statistical test of the null-hypothesis of the same cumulative distribution function returning the p-value = 0.114, at statistical significance of $\alpha = 0.05$. The tests present the objective justification for retaining the null-hypothesis of the research that the long-term risk of GNSS positioning performance degradation due to ionospheric conditions is spatially agnostic.

The Solar activity, the main driver of ionospheric conditions, extends a cyclic dynamics, with the identified periods of 11, 22, and 84 years. The research presented in the manuscript addresses the year 2014, which has been selected for its vigorous solar activity, characteristic for a year at the times of the Solar maximum. Considering the GNSS PNT utilisation risk assessment, it makes a case close to the worst one, rendering it suitable for the evaluation of the near-worst-case risk assessment scenario. Further to this, a consideration of a ful-year scenario covers all four seasons, reflecting the actual seasonal dynamics. The authors believe that the experimental set-up will suffice in demonstration of the proposed methodology. Future research will take into account a wider period of the two-times the base period of Solar activity, until the limitations of experimental IGS data availability are reached.

The presented research contributes to understanding of the risk of GNSS Positioning, Navigation, and Timing (PNT) utilisation in fulfilment of the Quality of Service (QoS) of a targeted GNSS-based application. Furthermore, the PoO model appear as a valuable tool for GNSS application developers, operators, and users, which may allow them to easily and transparently assess the risk of the GNSS positioning performance degradation due to ionospheric conditions. Massive datasets arranged for the presented research remain an invaluable starting point for future research on the nature of GNSS PNT performance variability, and for further validation of the introduced PoO GNSS utilisation risk model. Finally, the approach and methodology developed for this research may remain applicable for the risk assessment of GNSS PNT degradation casued by other positioning environment adversarial effects.

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