Mitigation of GNSS ionospheric effects using statistical learning-based self-adaptiveness to positioning environment conditions, embedded in GNSS SDR user equipment

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- Statistical learning TEC predictive model for GNSS ionospheric delay mitigation - Validation
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**Problem statement and motivation**

- **Natural and artificial interference in the positioning environment** (space weather/ionospheric, multipath, spoofing etc. effects) cause degradation of GNSS PNT performance
- **Standard GNSS ionospheric correction models are inefficient:**
  - **Generalised**, not addressing geographically constrained effects
  - **Inflexible** to mitigate rapid and short-term effects
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Problem statement and motivation

• Importance of understanding sources of GNSS ionospheric effects: detection -> identification -> classification -> mitigation

Source: doi: 10.33012/2021.17852
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**State-of-the-art**

- Numerous advancements are not exploited in full: (i) **Software-Defined Radio (SDR)**, (ii) **statistical and machine learning**, (iii) computational capacity of mobile devices, (iv) mobile platforms with **SDR GNSS receivers AND embedded sensors** (smartphones, connected vehicles, IoT devices, etc.), (v) open access to **position environment data in near-real time** (space weather, geomagnetic, and ionospheric indices, spatial databases etc.), (vi) **mobile internet and Internet of Things (IoT)**
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**State-of-the-art**

- GNSS position estimation algorithm’s transparency → opportunity for a vast improvement in GNSS PNT quality through utilisation of statistical learning and positioning environment situation awareness

\[
\begin{align*}
    d_1 &= \sqrt{(x-x_{s1})^2 + (y-y_{s1})^2 + (z-z_{s1})^2 + c \cdot d_T} \\
    d_2 &= \sqrt{(x-x_{s2})^2 + (y-y_{s2})^2 + (z-z_{s2})^2 + c \cdot d_T} \\
    d_3 &= \sqrt{(x-x_{s3})^2 + (y-y_{s3})^2 + (z-z_{s3})^2 + c \cdot d_T} \\
    d_4 &= \sqrt{(x-x_{s4})^2 + (y-y_{s4})^2 + (z-z_{s4})^2 + c \cdot d_T}
\end{align*}
\]

\[
\begin{align*}
    \mathbf{\rho} &= (d_1, d_2, d_3, d_4)^T \\
    \mathbf{v} &= (v_1, v_2, v_3, v_4)^T
\end{align*}
\]

\[
\begin{align*}
    \mathbf{x} &= (x, y, z, d_T)^T \\
    \mathbf{x}_{1:3} &= \mathbf{x}[1:3] \\
    \mathbf{s}_i &= (x_i, y_i, z_i)^T
\end{align*}
\]

\[
\hat{\mathbf{x}} = \arg \min_{\mathbf{x}} \mathbf{p}(\mathbf{x})^T \Sigma^{-1} \mathbf{p}(\mathbf{x})
\]

\[
\Sigma \overset{\text{def}}{=} \text{cov}(\mathbf{v})
\]


**Conclusion:** Mitigation of the GNSS positioning environment effects may be embedded within the GNSS position estimation algorithm, should the statistical properties of the effects are known or identified.
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**State-of-the-art**

- Statistical learning multi-predictor models based on immediate SW/ionospheric conditions awareness improve GNSS ionospheric effects correction considerably

Source: doi:10.33012/2018.16016
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**Statistical learning TEC predictive model for GNSS ionospheric delay mitigation - Concept**

- Mobile unit → **observing immediate positioning environment conditions** (space weather, ionosphere) itself, and/or utilising trusted third-party real-time observations or predictions for pseudorange corrections

Recognition of the actual positioning environment conditions → a pre-requisite for improved adverse effects mitigation
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Statistical learning TEC predictive model for GNSS ionospheric delay mitigation - Concept
United Nations International Meeting on the Applications of Global Navigation Satellite Systems
Vienna, Austria, 5th - 9th December, 2022

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Statistical learning TEC predictive model for GNSS ionospheric delay mitigation – Realisation & demonstration

1. Mitigation of space weather/ionospheric effects on GNSS position estimation performance:
   - direct observations of immediate positioning environment
   - trusted third-party data (stream, server-application access), with optional processing (interpolation)
2. Tailored framework developed in the open source R environment for statistical computing
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Demonstration

- Case-study of a short-term rapidly developing geomagnetic storm in sub-equatorial area (Darwin, NT, Australia)

LRM ... Linear Regression Model, MMLPNN ... Monotone Multi-layer Perceptron Neural Network Model, RFM ... Random Forest Model, Klobuchar ... standard Klobuchar Model

Klobuchar model considered as the benchmark / reference model.
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Statistical learning TEC predictive model for GNSS ionospheric delay mitigation - Validation

- Case-study of short-term rapidly developing geomagnetic storm in sub-equatorial area (Darwin, NT)
- Single-frequency GPS-based position estimation, no additional infrastructure utilised → GPS position estimation process self-adapted to the immediate environment conditions
- Ionospheric corrections: (i) Klobuchar model, (ii) geomagnetic field density-based statistical learning Linear Regression Model (LRM)

Source: doi: 10.33012/2022.18247

<table>
<thead>
<tr>
<th>in [m]</th>
<th>mean</th>
<th>standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Klobuchar corrections</td>
<td>self-adaptive</td>
</tr>
<tr>
<td>northing error</td>
<td>-1.5368</td>
<td>-0.1098</td>
</tr>
<tr>
<td>easting error</td>
<td>0.72717</td>
<td>-0.02663</td>
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<tr>
<td>vertical error</td>
<td>0.2225</td>
<td>-0.09773</td>
</tr>
</tbody>
</table>
Discussion

- Proposed utilisation of situation awareness of immediate positioning environment conditions for self-adaptive SDR GNSS position estimation.

- GNSS positioning performance demonstrated in the case of short-term rapidly developing ionospheric disturbance.

- The need for space weather/geomagnetic/ionospheric observations and indices data standardisation (access, structure and format), access, and inter/multi-disciplinary competence development

- Activities, potentially through International Space Weather Action Teams (ISWAT, COSPAR)
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Discussion

- Source: https://www.iswat-cospar.org/

<table>
<thead>
<tr>
<th>S: Space weather origins at the Sun</th>
<th>H: Heliosphere variability</th>
<th>G: Coupled geospace system</th>
<th>Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1: Long-term solar variability</td>
<td>H1: Heliospheric magnetic field and solar wind</td>
<td>G1: Geomagnetic environment</td>
<td>Climate</td>
</tr>
<tr>
<td>S2: Ambient solar magnetic field, heating and spectral irradiance</td>
<td>H2: CME structure, evolution and propagation through heliosphere</td>
<td>G2a: Atmosphere variability</td>
<td>Electric power systems/GICs</td>
</tr>
<tr>
<td></td>
<td>H4: Space weather at other planets/planetary bodies</td>
<td>G3: Near-Earth radiation and plasma environment</td>
<td>Navigation/Communications</td>
</tr>
</tbody>
</table>

Overarching Activities:
- Assessment
- Innovative Solutions

Information Architecture & Data Utilization
- Education & Outreach

(Aero)space assets functions
- Human Exploration
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**Recommendations**

1. Positioning environment (SW/iono) conditions awareness to improve GNSS positioning estimation algorithm, GNSS PNT performance and resilience against adverse effects.

2. Bespoke self-adaptive statistical learning GNSS ionospheric effects model to be developed based on positioning environment awareness, for and by every positioning process.

3. Positioning environment (SW/iono) conditions awareness to be obtained from: (i) direct SW/iono observations in the immediate vicinity of receiver, and/or (ii) trusted third-party sources.

4. International co-operation to be facilitated, established, and operated to:
   - 4.1 develop standards for SW/iono data structure, formats, and exchange protocols for internet-based data exchange;
   - 4.2 collect, assemble, aggregate, collate, and allow access to location-based real-time and archived SW/iono observations;
   - 4.3 foster self-adaptive GNSS correction model development, validation, and standardisation as a part of industry process, and in relation to GNSS applications;
   - 4.4 develop inter-/multi-disciplinary competence in support of transition to positioning environment-aware self-adaptive GNSS positioning.
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In appreciation of your attention, and with invitation to

Baška SIF (Spatial Information Fusion) Meetings,
every October in Baška, Krk Island, Croatia

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