Ionospheric space weather monitoring and its applications on GNSS

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Satellite navigation and ionosphere
1. Satellite navigation and ionosphere

- Global Navigation Satellite System (GNSS) has become one of the main technical means of navigation.
1. Satellite navigation and ionosphere

- The 25th solar cycle is approaching its peak year, which is expected to be 2024-2028
- The occurrence and amplitude of ionospheric anomalies will be significantly increased

![ISES Solar Cycle Sunspot Number Progression](image)

- Solar activities is the main driver of ionospheric variations

![Ionospheric disturbance](image)
Recent progress in ionospheric monitoring
Ionospheric correction for GNSS

<table>
<thead>
<tr>
<th>Single-frequency Users</th>
<th>Multi-frequency Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Point Positioning</td>
<td>The convergency time</td>
</tr>
<tr>
<td>The positioning accuracy</td>
<td></td>
</tr>
<tr>
<td>Precise Point Positioning</td>
<td>The convergency time</td>
</tr>
<tr>
<td>The convergency time and positioning accuracy</td>
<td></td>
</tr>
<tr>
<td>Real-Time Kinematic</td>
<td>Aid in ambiguity fixing</td>
</tr>
<tr>
<td>Aid in ambiguity fixing</td>
<td>Aid in ambiguity fixing</td>
</tr>
</tbody>
</table>
2. Recent progress in ionospheric monitoring

- Ionospheric correction model

The cooperative real-time GIMs from International GNSS Service (IGS)

- Chinese Academy of Sciences (CAS)
- Centre national d’études spatiales (CNES)
- Universitat Politècnica de Catalunya (UPC)
- Wuhan University (WHU)

CAS real-time combined GIM

HENU+UPC real-time combined GIM
2. Recent progress in ionospheric monitoring

- Ionospheric correction model

The cooperative real-time GIMs from IGS

- GNSS real-time data
- IGS real-time ionosphere combination center
- RT-GIMs of different centers
- CAS, CNES, UPC, WHU
- IGS real-time combined GIM (IRTG)

- HTTP
- NTRIP Caster

[Liu+, 2021 ESSD; Wang+ 2022 URSI]
Recent progress in ionospheric monitoring - Ionospheric storm scale

The characterization of Ionospheric storm in global scale

✓ Propose a standardized scale of ionospheric storm based on GIM

\[ P_{\text{TEC}} = 100 \times \left( \frac{O_{\text{TEC}} - R_{\text{TEC}}}{R_{\text{TEC}}} \right) \]

\[ \hat{P}_{\text{TEC}} = \frac{P_{\text{TEC}} - \mu}{\sigma} \]

<table>
<thead>
<tr>
<th>IsUG</th>
<th>Description</th>
<th>Definition</th>
<th>Probability on a global scale (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP3</td>
<td>Severe positive storm</td>
<td>( 5 &lt; \hat{P} )</td>
<td>0.17</td>
</tr>
<tr>
<td>IP2</td>
<td>Strong positive storm</td>
<td>( 3 &lt; \hat{P} \leq 5 )</td>
<td>0.72</td>
</tr>
<tr>
<td>IP1</td>
<td>Moderate positive storm</td>
<td>( 1 &lt; \hat{P} \leq 3 )</td>
<td>12.43</td>
</tr>
<tr>
<td>I0</td>
<td>Quiet</td>
<td>( -1 &lt; \hat{P} \leq 1 )</td>
<td>73.96</td>
</tr>
<tr>
<td>IN1</td>
<td>Moderate negative storm</td>
<td>( -2 &lt; \hat{P} \leq -1 )</td>
<td>11.72</td>
</tr>
<tr>
<td>IN2</td>
<td>Strong negative storm</td>
<td>( -3 &lt; \hat{P} \leq -2 )</td>
<td>0.95</td>
</tr>
<tr>
<td>IN3</td>
<td>Severe negative storm</td>
<td>( \hat{P} &lt; -3 )</td>
<td>0.06</td>
</tr>
</tbody>
</table>

[Liu+, 2021 Space Weather] (130°E, 30°N)
2. Recent progress in ionospheric monitoring

- Ionospheric storm scale

- Evolution of ionospheric storm on 2015 St. Patrick's Day storm
2. Recent progress in ionospheric monitoring - Ionospheric gradient indices

The characterization of ionospheric gradient

- Propose the ionospheric spatial gradient (non-relative) indices based on GIM

\[
\overline{\nabla V_x} = \sum_{i=1}^{N} \sum_{j=1}^{M} \nabla V_{x,i,j} / N_S
\]

\[
\nabla V_{x,P95^+} = P_{95}(\nabla V_{x,i,j,\varphi})
\]

\[
\nabla V_{x,P95^-} = -P_{95}(|\nabla V_{x,i,j,n}|)
\]

\[
\overline{\nabla V_y} = \sum_{i=1}^{N} \sum_{j=1}^{M} \nabla V_{y,i,j} / N_S
\]

\[
\nabla V_{y,P95^+} = P_{95}(\nabla V_{y,i,j,\varphi})
\]

\[
\nabla V_{y,P95^-} = -P_{95}(|\nabla V_{y,i,j,n}|)
\]

Regional indices

\[
\overline{\nabla V} = \sum_{i=1}^{N} \sum_{j=1}^{M} \nabla V_{i,j} / N_S
\]

\[
\sigma_{\overline{\nabla V}} = \sqrt{\left( \sum_{i=1}^{N} \sum_{j=1}^{M} \nabla V_{i,j}^2 / N_S - \overline{\nabla V}^2 \right)}
\]

\[
\nabla V_{x,i,j} = (VTEC_{i,j} - VTEC_{i-1,j}) / \Delta DLON
\]

\[
\nabla V_{y,i,j} = (VTEC_{i,j} - VTEC_{i,j-1}) / \Delta DLAT
\]

\[
\nabla V_{i,j} = \sqrt{\nabla V_{x,i,j}^2 + \nabla V_{y,i,j}^2}
\]

\[
\overline{\nabla V} = (\nabla V_{x,i,j}, \nabla V_{y,i,j})
\]

Grid indices

[\text{Liu+}, 2022 \text{Space Weather}]
2. Recent progress in ionospheric monitoring

Comparison of the quiet and storm periods around 2015 St. Patrick's Day

- Ionospheric gradient indices

- St. Patrick's Day
2. Recent progress in ionospheric monitoring - Ionospheric gradient indices

The regional ionospheric gradient indices on 2015 St. Patrick's Day storm
The characterization of ionospheric perturbation

\[
\text{IDTEC} = \sum_{i=1}^{n} \text{DTEC}(i) \cdot \Delta t
\]

\[
\text{IROTI} = \text{IDTEC} \cdot \text{ROTI}
\]

\[
\text{DTEC}(i) = \text{STEC}(i) - \frac{1}{N} \sum_{j=i-N/2}^{i+N/2} \text{STEC}(j)
\]

\[
\text{ROT} = \frac{\text{STEC}_i^k - \text{STEC}_{i-1}^k}{t_i - t_{i-1}}
\]

\[
\text{ROT} = \sqrt{\langle \text{ROT}^2 \rangle} - \langle \text{ROT} \rangle^2
\]

2. Recent progress in ionospheric monitoring - Ionospheric perturbation index

- ROTI fail to detect TEC slow variations
2. Recent progress in ionospheric monitoring - Ionospheric perturbation index

- Comparison of ROTI and IROTI when TID occurs

![Comparison of ROTI and IROTI when TID occurs](image)
2. Recent progress in ionospheric monitoring

- GEO spatiotemporal monitoring

Total Electron Content (TEC) extracted from Beidou GEO satellite

- Ionospheric spatio-temporal TEC monitoring based on Beidou GEO

[Hu +, 2017 Space Weather; Liu +, 2023 JGR; Yang +, 2022 RS]
2. Recent progress in ionospheric monitoring

- GEO spatiotemporal monitoring

**GEO spatiotemporal monitoring in China**

[Liu+, 2022 RS]

✓ Obvious day-to-day and zonal differences
GEO spatiotemporal monitoring in China

Drastic ionospheric fine structure occurs in narrow latitude band
2. Recent progress in ionospheric monitoring - GEO spatiotemporal monitoring

- **Zonal structure of TEC in GIM products**

  ![Graph showing TEC (TECU) vs. Longitude (°) for different UT times and dates for 20° N.](image)

  - **@20° N; 15-December-2019**
  - **@20° N; 16-March-2020**

✓ GIMs need to improve the ability to capture ionospheric zonal structures
The applications of ionospheric monitoring
3. The applications of ionospheric monitoring – GNSS positioning

## Ionospheric correction for GNSS positioning

- **BDGIM**: BDS-3 Global broadcast Ionospheric Model;
- **IONO00IGS1**: HENU+UPC-combined RT-GIM;
- **IONO01IGS1**: CAS-combined RT-GIM;
- **IGRG**: IGS rapid-GIM;
- **IONO00IGS1**: HENU+UPC-combined RT-GIM;
- **IONO01IGS1**: CAS-combined RT-GIM;

### Horizontal and vertical accuracy of SF-PPP using different ionospheric models (95% percentile)

<table>
<thead>
<tr>
<th>Items</th>
<th>Ionospheric models</th>
<th>Mean / m</th>
<th>Minimum / m</th>
<th>Maximum / m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizontal component</strong></td>
<td>BDGIM</td>
<td>1.84</td>
<td>0.51</td>
<td>6.20</td>
</tr>
<tr>
<td></td>
<td>IONO00IGS1</td>
<td>1.48</td>
<td>0.47</td>
<td>5.69</td>
</tr>
<tr>
<td></td>
<td>IONO01IGS1</td>
<td>1.50</td>
<td>0.48</td>
<td>4.97</td>
</tr>
<tr>
<td></td>
<td>IGRG</td>
<td>1.41</td>
<td>0.48</td>
<td>4.70</td>
</tr>
<tr>
<td><strong>Vertical component</strong></td>
<td>BDGIM</td>
<td>3.31</td>
<td>1.16</td>
<td>8.68</td>
</tr>
<tr>
<td></td>
<td>IONO00IGS1</td>
<td>3.12</td>
<td>1.03</td>
<td>7.76</td>
</tr>
<tr>
<td></td>
<td>IONO01IGS1</td>
<td>3.08</td>
<td>1.05</td>
<td>8.13</td>
</tr>
<tr>
<td></td>
<td>IGRG</td>
<td>2.94</td>
<td>0.91</td>
<td>7.53</td>
</tr>
</tbody>
</table>
3. The applications of ionospheric monitoring — smartphone navigation

- Ionospheric correction for smartphone navigation (Huawei)

(Wang et al. 2020, 2022)
3. The applications of ionospheric monitoring – smartphone navigation

**Ionospheric correction for smartphone navigation (Huawei)**

<table>
<thead>
<tr>
<th>Horizontal Pos.</th>
<th>RMS / m</th>
<th>CEP 68 / m</th>
<th>CEP 95 / m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Android raw location</td>
<td>2.93</td>
<td>2.90</td>
<td>5.26</td>
</tr>
<tr>
<td>RT-PPP</td>
<td>1.25</td>
<td>1.09</td>
<td>2.66</td>
</tr>
<tr>
<td>Improvement</td>
<td>57.3%</td>
<td>62.6%</td>
<td>49.4%</td>
</tr>
</tbody>
</table>

* RT orbit and clock offset corrections are also available from Galileo HAS or BDS-3 B2b-PPP services
Conclusions and outlooks
4. Conclusions and outlooks

- Beidou GEO is a powerful tool for detecting the **regional zonal structure of ionosphere**
- Ionospheric storm and ionospheric gradient methods can facilitate the **monitoring of ionospheric space weather and warning**
- The real-time high-precision ionospheric model can effectively **improve the positioning of GNSS users** such as mobile phone navigation.
- It is necessary to **improve the ability to capture the fine structure of ionosphere**. The mass low-cost GNSS receivers might be the extra data source for ionospheric sounding.
It is recommended that more countries and scientific research organizations will participate in the joint monitoring and early warning service of the global ionosphere and its application in positioning.

Ionospheric model

Ionospheric space weather monitoring and warning

The positioning for users
Thank you!

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