4-D observation of traveling ionospheric disturbances using a dense GPS receiver array

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Introduction

- Travelling Ionospheric Disturbances (TIDs) are wave-like structures observed in the Earth’s plasma density.

- **Signatures in the ionosphere of:**
  - Atmospheric gravity waves (AGW) due to geomagnetic activity at high latitude, (as a result of Joule heating, Lorentz forces or particle precipitations, e.g., Valladares et al., 2009; Ding et al., 2007).
  - Atmospheric gravity waves propagating from low – upper atmosphere (associated with atmospheric tides, tropospheric weather, volcanic explosions, earthquakes, rocket launches).
Classification:

- Small-Scale (SS TIDs)
  - Period: 1-10 min
  - Horizontal wavelength 0.1 to 1 km

- Medium-Scale TIDs (MS TIDs)
  - Velocities from 50 to 300 m/s
  - Period: 20 - 60 min (e.g. Hunsucker, 1982, Tsugawa et al. 2007)
  - Horizontal wavelength: < 1000 km.
  - They are confined to mid and high-latitude zones (Bruinsma and Forbes, 2008; Mayr et al., 1990).

- Large Scale TIDs (LS TIDs)
  - 400 – 1000 m/s
  - Period: > 1 hr
  - Order of thousands of kilometers in horizontal scale.
• **Focus** is on MSTIDs that are characteristic wave phenomenon in the ionospheric F-region at mid-latitudes.
Problem

- Most studies have been limited two-dimensional imaging (2-D Total Electron Content, TEC, maps that infer information on the horizontal structuring of the electron density)

An example of a 2D TEC map.
Mainly:

- Due to the **paucity of Global Positioning System (GPS) receivers** and **limited projection angles**.
  - Where, projection angle is the line integral along a given view.
Luckily, Japan has a GPS Earth Observation Network (GEONET) of more than 1000 receivers (with average distance between two neighbouring points being 25-30 km).
Investigation (Tomography)

The possibility of using a MART and Calibrated IRI model to observed TIDs
With multiple ground stations each being able to “see” **6-8 GPS** satellites at time, tomography is possible. To do this, we set up a three-dimensional grid of voxels (*i.e.* volume pixels), each bounded in **latitude, longitude and altitude**.

- Compute the length of each element of a satellite-to-receiver signal propagation path through each intersected voxel.
The contribution to the line integrals in each voxel is decomposed into a matrix, \( A \).

Given the measurements of these line integrals, \( m \text{ (Slant-TEC)} \), the problem becomes one of inverting \( A \) to solve for the unknown electron concentration, \( x \).

\[
Ax = m
\]

However, the inverse problem is ill-posed and ill-conditioned.
To solve the inverse problem we use the MART (Multiplicative Algebraic Reconstruction Technique)

\[ x_j^{k+1} = x_j^k \ast \left( \frac{m_i}{\langle A^i, x^k \rangle} \right) \frac{\lambda_k A_j^i}{A_{\text{max}}} , \quad j = 1, \ldots, N . \]

\( A_{\text{max}} \) is the maximum path-pixel intersection length in the grid.

- \( \lambda_k \) is the relaxation parameter and controls the convergence of the algorithm, is bounded between 0 and 1 (Pryse et al., 1998; Raymund et al., 1990).

- **Advantage:** Low memory requirements, non-negative electron density values.

- **However,** MART is sensitive to the initial guess \((x_0)\), IRI-2012 model
Calibrated IRI-2012 (Cal-IRI-2012)

- The most recent version, IRI-2012, is used.
- Two input indices, **Sun Spot number** (SSN) and **Ionospheric index** (IG12), are adjusted in relation to derived GPS vertical TEC (VTEC).
- Only a few stations within the grid are needed to reach the optimal solution.
Algorithm
foF2 analysis

- Percentage improvement = 50.5%
  *Regional optimization of IRI-2012 output (TEC, foF2) using derived GPS-TEC (Ssessanga Nicholas and Yong Ha Kim., In press)

- Use TEC to adjust foF2 values

Table 3: RMSE at four ionosonde stations

<table>
<thead>
<tr>
<th>Station</th>
<th>RMSE (MHz) Cal-IRI-2012</th>
<th>RMSE (MHz) IRI-2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC437 (37.1°N, 127.5°E)</td>
<td>1.3261</td>
<td>2.5213</td>
</tr>
<tr>
<td>OK426 (26.3°N, 127.8°E)</td>
<td>1.5620</td>
<td>3.0515</td>
</tr>
<tr>
<td>TO536 (35.7°N, 139.5°E)</td>
<td>1.9320</td>
<td>2.7574</td>
</tr>
<tr>
<td>YG431 (31.2°N, 130.6°E)</td>
<td>0.9285</td>
<td>3.2816</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>1.4372</strong></td>
<td><strong>2.9030</strong></td>
</tr>
</tbody>
</table>
We use Cal-IRI-2012 (X₀) as the initial guess. Hence:
- Quick convergence
- A better solutions for resolving small scale structures.
Setup

Grid size
Latitude: 20° N : 1° : 50° N
Longitude: 120° E : 1° : 150° E
Height: 100 : 10 : 1000 Km
Time resolution: (15 min)
utilised stations: 700

A plot of utilised stations
Day of Analysis
The selection was done through a **visual examination** of these sequences of maps. If there were TIDs passing by, there would be regularly moving **band-like structures**.

The perturbation components of TEC values were derived by subtracting a trend of the TEC values that is a 30-min running average.

The data from satellite receiver paths with low elevation angles below 30° were not included. (using a program a from NICT)
Results
Slice a vertical plane with most number of data points
Smooth Ionosphere - Cal-IRI 2012

- 15 minute resolution, spatial representation
- The ionosphere is quite moderately modulated by the TIDs

Results from algorithm
- In local time = UT + 9
- In local time = UT + 9
In local time (LT) = UT + 9

Spatial period ≈ 333.6 Km
Choose two points along the plane

Time series variation at each point

- Distance between the two points = 594.4 km
- Use cross correlation to determine time lag = 3436.6s
- Velocity of TID = \( \frac{\text{Distance}}{\text{time lag}} \) = 173 m/s
Take FFT of the two signals and determine average period

Period = 48 minutes

Period = 51 minutes

Average period ≈ 49.6 minutes
Medium-Scale TIDs (MS TIDs)

- Velocities from 50 to 300 m/s ($\approx 173$ m/s)
- Period: 20 - 60 min ($\approx 49$ min)
- Horizontal wavelength: < 1000 km ($\approx 333.6$ Km)
• Summary:

- This investigative procedure has provided promising results,

- that a dense network of GPS receivers could be used to infer further information about the vertical structure of TIDs.
THANKS