Space Weather Monitoring and Forecast in Taiwan

Tiger J.Y. Liu (劉正彥)
National Space Organization, (NSPO) TAIWAN
National Central University (NCU), TAIWAN
jyliu@jupiter.ss.ncu.edu.tw

I.T. Lee (李奕德)
Center Weather Bureau (CWB), TAIWAN
Space Weather Center

- **R & D Office** (Academia Sinica + Universities: NCU, NCKU)
- **Operation Office** (Center Weather Bureau; CWB)
- **Mission Office** (National Space Organization; NSPO)
Content

- Introduction
- FORMOSAT-3/COSMIC
- 3D Plasma Structure and Dynamics
- Ionospheric Scintillation
- Thump the Ionosphere
- FORMOSAT-7/COSMIC-2
The Past, Present, and Future

- Space Science education: 1958 -
- Ionosonde observation: 1951 -
- Magnetometer observation: 1965 -
- HF Doppler observation: 1989 -
- GPS TEC observation software: 1994 -
- Magnetopause location prediction: 1997 -
- FORMOSAT-2/ISUAL: 2004 -
- FORMOSAT-3/COSMIC: 2006 -
- FORMOSAT-5/AIP: 2015
- FORMOSAT-7/TGRO: 2016/2018
- Ionospheric Weather (Data Assimilation Model): 2012 -
The Magnetopause

- The total pressure (including magnetic and thermal pressure) is balanced across the magnetopause.
- The magnetopause location is controlled by IMF Bz and solar wind dynamic pressure Dp.
The Shue et al. [1997] Magnetopause Location Model

The formula of the Shue et al. [1997] model is listed below:

\[ r = r_0 \left( \frac{2}{1 + \cos \theta} \right)^\alpha \]

\[ r_0 = \begin{cases} 
(11.4 + 0.013 B_z) (D_p)^{-\frac{1}{8.6}}, & \text{for } B_z \geq 0 \\
(11.4 + 0.14 B_z) (D_p)^{-\frac{1}{8.6}}, & \text{for } B_z < 0 
\end{cases} \]

\[ \alpha = (0.58 - 0.010 B_z)(1 + 0.010 D_p) \]

where \( r_0 \) is the subsolar standoff distance and \( \alpha \) is the flaring degree of the magnetopause.
A Demonstration of the Shue et al. [1997] model
More Information about the Shue et al. [1997] model

- The formula of the model is simple and accurate.
- The model has been widely used in the Space community.
- According to the citation report from Web of Science, this paper has been cited in 364 times as of today.
The FORMOSAT-3/COSMIC program is an international collaboration between Taiwan and the United States that will use a constellation of six remote sensing microsatellites to collect atmospheric data for weather prediction and for ionosphere, climate and gravity research. Data from the satellites will be made freely available to the international scientific community in near real-time.
FORMOSAT-3/COSMIC

- **FORMOSAT-3/COSMIC Constellation** was launched at 01:40 UTC, April 14, 2006 (Taiwan Time: April 15, 2006) at Vandenberg Air Force Base, CA. **Minotaur Launch**

- Maneuvered into six different orbital planes (inclination ~72°) for optimal global coverage (at ~800 km altitude).

- Five out of Six satellites are in good health and providing science data.
GPS Radio Occultation

Wavelength and amplitude of in the vertical direction

Global 3D structure
Distribution of occultation events observed by FORMOSAT-3
3D Plasma Structure and Dynamics

- Equatorial Ionization Anomaly
- Mid-latitude Trough
- Weddell Sea Anomaly
3D Ionospheric plasma Structure

(a)

(b)

Liu et al. (JGR 2010)
Equatorial Ionization Anomaly
2007 M-month
2007 J-month
2007 S-month

FORMOSAT-3/COSMIC Global FixUT MAP, S-month, 0000UT

350 km

250 km

200 km

150 km

37.5

25

12.5

0

-12.5

-25

-37.5

x 10^5

9

8

7

6

5

4

3

2

1

-180 -150 -120 -90 -60 0 30 60 90 120 150 180
Equatorial Ionization Anomaly

Lin et al. [GRL 2008]  July-August 2006
Remark 1

Results suggest that in addition to the asymmetric neutral composition effect, interactions between the summer-to-winter (transequatorial) neutral winds and strength of the equatorial plasma fountain effect play important roles in producing asymmetric development of the EIA crests as imaged by the F3/C.
Mid-latitude Trough

FORMOSAT-3/COSMIC NmF2 Persudo-3D structure Northern Hemisphere, M-month

Terminator waves?
The seasonal averaged pseudo 3-D images of the F2 peak density map \((\log_{10}(Ne), \text{cm}^{-3})\) from February 2008 to January 2009 in magnetic polar coordinates for the March equinox, June solstice, September equinox, and December solstice. The inner and outer perimeters are 80° and 30° in magnetic latitude. The left and right columns are results in the Northern and Southern hemispheres, respectively. The color and vertical change refer to the electron density, and the numbers around each plot give the geomagnetic local time.

Lee et al. (JGR, 2011)
Remark 2

Results show that the mid-latitude trough extends from dusk to dawn in all four seasons and is most pronounced in the winter hemisphere.

The troughs in the two hemispheres are asymmetric, where the trough in the Northern Hemisphere is more evident and stronger than that in the Southern Hemisphere during the equinoctial seasons.
Ionospheric Weddell Sea Anomaly

Stronger electron density Ne in nighttime than that in daytime over the Weddell Sea area during the Summer
The Ionospheric Weddell Sea Anomaly

1. Stronger nighttime Ne than that during daytime
2. Discovered 50 years ahead of renewed observation by FORMOSAT-3/COSMIC
3. First glance of its vertical structure by F3/C!

Ionosonde Observation
(Bellchambers and Piggott, 1958)

Lin et al. [2009]
Not only occurred in the Southern hemisphere but also in the North - Categorized as the Mid-latitude Summer Nighttime Anomaly (MSNA) $\text{Ne}(2200\text{LT}) > \text{Ne}(1400\text{LT})$
- driven by equatorward meridional neutral wind

Lin et al. [2010]
Diurnal variations of F3/C electron density maps at 300km altitude at various global fixed local times in the four months in the southern hemisphere

Chang et al. [2014]
Diurnal variations of F3/C electron density maps at 300km altitude at various global fixed local times of the four months in the northern hemisphere.  

Chang et al. [2014]
Remark 3

It is found that the multiple-speeds in the eastward phase shift are about of 167 and 296m/s for the WSA feature in the southern hemisphere, while the peaked double MSNA feature with speeds yield 91 and 121m/s in the northern hemisphere.

The simultaneous eastward phase shifts in the electron density and the plasma flows suggest that the neutral winds are essential.

The WSA/MSNA features in fact yield eastward phase shift and appear all year round.
Fig. 1. Schematic of the global morphology of scintillations at L-band frequencies during the solar maximum (left panel) and solar minimum (right panel) conditions. Reproduced from S. Basu and K.M. Groves, Specification and forecasting of outages on satellite communication and navigation systems, Space Weather, Geophysical Monograph 125, 424–430, 2001. Published 2001 by the American Geophysical Union. Reproduced/modified by permission of American Geophysical Union.
S4 Max altitude slice at various MLT in Solar min 2008-2009
Conversion of Scintillation S4 Experienced on the Ground
(a) SolarMin

M-month

J-month

S-month

D-month
(a) SolarMin

March in solarmin.

June in solarmin.

September in solarmin.

December in solarmin.
SolarMax

March in solar max.

June in solar max.

September in solar max.

December in solar max.
Remark 4

The most prominent signatures of the F3/C S4 max in the E- (F-)region are in middle (equatorial-low) latitudes of the Summer J-month (equinox) months.

The F3/C S4 max in the E-region is mainly contributed by the Es (sporadic-E) layer. Neutral wind is essential!

The F3/C S4 max in the F-region lies between 20N and 20S and expends to higher latitudes in the equinox and D months. ExB plasma fountain is essential!
Thump the Ionosphere

- magnetic storm
- earthquake
- solar eclipse
Storm the Ionosphere

Progression of Tangent Point for a Setting (descending) Occultation

$\mathbf{v}_{\text{GPS}}$

Solar wind

$\mathbf{v}_{\text{LEO}}$
Vertical fluctuation profile

Quiet time

Storm time

Mother wavelet - Morlet

Wave number 42
Solar wind

- 0900 LT
- 0300 LT
- 1500 LT
- 2100 LT

Sunward

Noon

Dusk

Dawn

Midnight

60°

30°
2010/05/02 TEC vertical fluctuation
Midnight side

Before

After

Magnitude

15km~30km
2010/05/02 TEC vertical fluctuation
Dawn side

Before

After

Magnitude

15km~30km
2010/05/02  TEC vertical fluctuation
Noon side

Before

After

Magnitude

15km~30km
2010/05/02 TEC vertical fluctuation
Dusk side

Before

Low

Mid

High

After

15km~30km

Magnitude

Altitude (km)

Wavenumber (1/km)
# Earthquake Details

This is a computer-generated message -- this event has not yet been reviewed by a seismologist.

<table>
<thead>
<tr>
<th><strong>Magnitude</strong></th>
<th>8.9 9.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Date-Time</strong></td>
<td>Friday, March 11, 2011 at 05:46:23 UTC</td>
</tr>
<tr>
<td></td>
<td>Friday, March 11, 2011 at 02:46:23 PM at epicenter</td>
</tr>
<tr>
<td></td>
<td><a href="#">Time of Earthquake in other Time Zones</a></td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>38.322°N, 142.369°E</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>24.4 km (15.2 miles) set by location program</td>
</tr>
<tr>
<td><strong>Region</strong></td>
<td>NEAR THE EAST COAST OF HONSHU, JAPAN</td>
</tr>
<tr>
<td><strong>Distances</strong></td>
<td>130 km (80 miles) E of Sendai, Honshu, Japan</td>
</tr>
<tr>
<td></td>
<td>178 km (110 miles) E of Yamagata, Honshu, Japan</td>
</tr>
<tr>
<td></td>
<td>178 km (110 miles) ENE of Fukushima, Honshu, Japan</td>
</tr>
<tr>
<td></td>
<td>373 km (231 miles) NE of TOKYO, Japan</td>
</tr>
<tr>
<td><strong>Location Uncertainty</strong></td>
<td>horizontal +/- 13.5 km (8.4 miles); depth fixed by location program</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>NST=350, Nph=351, Dmin=416.3 km, Rmss=1.46 sec, Gp= 29°, M-type=&quot;moment&quot; magnitude from initial P wave (tsuboi method) (Mi/Mwp), Version=A</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>USGS NEIC (WDCS-D)</td>
</tr>
<tr>
<td><strong>Event ID</strong></td>
<td>usc0001xgp</td>
</tr>
</tbody>
</table>
The electron density profile observed 22 minutes after earthquake.

53.36°N, 137.58°E 06:08UT setting 608sec

The electron density profile observed 22 minutes after earthquake.
Disturbances in F3/C electron density profiles during the 11 March 2013 Tohoku earthquake

Table 1: Observation Points Near the Epicenter 0-8 hr after the Tohoku Earthquake

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Arrival (UT)</th>
<th>Travel (second)</th>
<th>Distance (km)</th>
<th>Speed (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38.32°N, 142.37°E</td>
<td>05:46</td>
<td></td>
<td>Epicenter</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>53.28°N, 137.36°E</td>
<td>06:08</td>
<td>1320</td>
<td>1581</td>
<td>2196</td>
</tr>
<tr>
<td>3</td>
<td>49.83°N, 159.58°E</td>
<td>08:31</td>
<td>9900</td>
<td>2072</td>
<td>223</td>
</tr>
<tr>
<td>4</td>
<td>56.26°N, 158.19°E</td>
<td>08:33</td>
<td>10020</td>
<td>2394</td>
<td>239</td>
</tr>
<tr>
<td>5</td>
<td>45.98°N, 155.66°E</td>
<td>10:13</td>
<td>16020</td>
<td>1535</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>43.99°N, 151.39°E</td>
<td>10:23</td>
<td>16620</td>
<td>1067</td>
<td>67</td>
</tr>
<tr>
<td>7</td>
<td>60.28°N, 132.12°E</td>
<td>13:41</td>
<td>27420</td>
<td>2425</td>
<td>87</td>
</tr>
<tr>
<td>8</td>
<td>51.86°N, 121.44°E</td>
<td>13:49</td>
<td>28980</td>
<td>2494</td>
<td>88</td>
</tr>
</tbody>
</table>

*speed=Distance/(Travel-600)
Electron density profiles observed by F3/C RO within 3000 km from the epicenter. The black circle indicates 3000km from the epicenter. The star and triangle symbols denote locations of the epicenter and the profiles 1-8 hours after the earthquake. The open triangle symbols denote locations of the profiles 1-5 hours before the earthquake.
The electron density profiles 1-5 hours before the earthquake (top panels), and those 1-8 hours after (bottom panels).
Spectra derived by using HHT.
2010/01/15 Annual Solar Eclipse
(Ring of Fire)
2010/01/15 Annual Solar Eclipse (Ring of Fire)

Eclipse period 05:18-08:55 UT

Observation zone: 5

Reference data point in each zone: 7/11/8/12/23

(http://eclipse.gsfc.nasa.gov/eclipse.html, NASA)
Power spectra on day 1 before, eclipse day 2010/01/15, and day 1 after.
F7/C2 TriG RO sounding shall be a powerful tool observing disturbances of the lithosphere-ionosphere-solar wind coupling triggered by earthquakes, tsunami, volcano eruptions, typhoons, magnetic storms, solar eclipses, etc.
FORMOSAT-7/COSMIC-2

(a) 2nd Launch inclination angle ~ 72 degrees
(b) 1st Launch inclination angle ~ 24 degrees

Mission Orbital Planes

Precise Orbit Determination Antenna
Tri GNSS receiver
Occultation Antenna

Toward the Earth
ram direction

Solar Panel
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sequence</strong></td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Launch</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; Launch</td>
</tr>
<tr>
<td><strong>Constellation</strong></td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>Mission Orbit Altitude</strong></td>
<td>800 km</td>
<td>520-550 km</td>
</tr>
<tr>
<td><strong>Inclination Angle</strong></td>
<td>72°</td>
<td>24-28.5°</td>
</tr>
<tr>
<td><strong>Mission Payload</strong></td>
<td>GOX</td>
<td></td>
</tr>
<tr>
<td><strong>RO Signals</strong></td>
<td>GPS</td>
<td>GPS, GLONASS, Galileo</td>
</tr>
<tr>
<td><strong>Launch Schedule</strong></td>
<td>Launched in 2006</td>
<td>2016</td>
</tr>
</tbody>
</table>

- Descriptions are provided by NSPO (http://www.nspo.org.tw).
- F7/C2 is illustrated by Surrey Satellite Technology LTD.
What is future impact of F7/C2 on ionospheric research?

With 6 satellites + GPS, 60 minutes
About 80-100 profiles per hour

With 12 satellites + GPS, 60 minutes
About 400 profiles per hour

F7/C2 vs F3/C
Ionospheric Weather Monitoring

F3/C observations at 08:00 UT within 2 hours x 30 days accumulation period

- Solar activity variations
- Seasonal variations
- Monthly variations
- Tidal effects
- Diurnal variations
- Semi-diurnal variations
- Disturbed period effects
- Other temporal variations
- Irregularities

Latitudinal slices are at -120°, -60°, 0°, 60° and 120° longitude with a interval of ±2.5°.

Could it be advanced by F7/C2?
Simulated F7/C2 observations at 08:00 UT within 1 hour x 1 day accumulation period

12 satellites, 28 GPS and 24 GLONASS

Lee et al. [2013]
Ionospheric Data Assimilation
TIE-GCM + F3/C EDPs + DART

Lee et al. [JGR 2013]
Model Truth around 300 km

Result of F3/C

Result of F7/C2

RMSE of Control Run

RMSE of F3/C

RMSE of F7/C2

Global RMSE

\[ \% = \frac{\text{Ensemble} - \text{Truth}}{\text{Truth}} \times 100 \]
Shorted assimilation window

The F7/C2 data latency might not be less than 15 minutes for operational assimilation.

Lee et al. [JGR 2013]

The F7/C2 data latency might not be less than 15 minutes for operational assimilation.
Conclusion

FORMOSAT-7/COSMIC-2 could reconstruct 3D electron density structures for ionospheric space weather monitoring within a rather short data accumulation period.

F7/C2 comparing to F3/C could yield reliable results within an assimilation window of less than 30 minutes.

F7/C2 shall have significant impacts on ionospheric weather monitoring and researches.
Thank you!!!