Ionospheric TEC Assimilation and Now-casting System over China

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The National Space Science Center (NSSC) of Chinese Academy of Sciences (CAS) was established in 1958 with the mandate to develop the first artificial satellite of China, the DFH-1.

To meet the space weather requirements for China’s space missions, SEPC was established in 1992 in NSSC, CAS, and became the 1st professional organization providing space weather services in China.

In 1998, SEPC set up the first generation of an operational space weather forecasting system, and since then started to issue operational space weather forecasting services via internet 365 days/year.
International Cooperation of SEPC/NSSC

- The International Space Environment Services (ISES) is a space weather service organization. The mission of ISES is to improve, coordinate, and deliver operational space weather services.

- SEPC/NSSC is now an Associate Warning Center of ISES

Space weather cooperation efforts made by SEPC/NSSC and other ISES members

- Enhance the exchange of self-monitoring data and relevant information of space weather
- Establish standardized verification methods for space environment forecasting services
- Improve collaboration on verification and validation of space weather operational models
Contents of Basic Space Weather Services

• **Space Environment Nowcasts**
  - Sunspot Number/F10.7 index/solar X-ray flux
  - IMF Solar wind speed & density
  - High energy electron/proton flux
  - Planetary K-index

• **Space Environment Reviews and Forecasts**
  - Presenting analyses of current conditions and developing trends of solar and geomagnetic activities

• **Space Weather Event Alerts**
  - Solar X-ray Flare
  - Solar Proton Event
  - Relativistic Electron Enhancement
  - Geomagnetic Storm
Space Environment Nowcasts

- **Space Environment Nowcasts** (real time status)
  - Sunspot Number
  - F10.7 index
  - solar X-ray flux
  - IMF Solar wind speed & density
  - High energy electron flux
  - High energy proton flux
Space Environment Reviews and Forecasts

- Space weather reviews and forecasts focus on presenting analyses of current conditions and developing trends of space weather activities, such as solar X-ray flares, geomagnetic activity, solar proton events (SPEs), the relativistic electrons in the radiation belts.

**Space Environment Summary**

During the past 24 hours, solar activity was low. Only one C-class flare was produced. There were 2 active regions on the visible disk. The region 2529(N10W52) maintained at 780 sunspot area units with Beta-Gamma type. The solar wind speed maintained at about 400 km/s. The geomagnetic field was at active levels for 9 hours, and was quiet to unsettled for the rest of time.

**Published:** 2016-04-18 00:12 UTC  
**Forecaster:** 032027

**Space Environment Forecast**

Within the next three days, solar activity is expected to be low to moderate with a chance for M-class flares. The geomagnetic field will reach to isolated active level on 18-19 Apr due to the effect of the recurrent coronal hole high speed stream, and is expected to be quiet to unsettled on 20 Apr.

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Space Weather Event Alerts

- Space Weather Event Alerts
  - Solar X-ray Flare
  - Solar Proton Event
  - Relativistic Electron Enhancement
  - Geomagnetic Storm
Delivery of Space Weather Services

http://eng.sepc.ac.cn

Website

Text Message

Mobile App

Micro-blog [Twitter]

“e SpaceWx”

http://www.sepc.ac.cn

 (>14k followers)
The Space Environment Monitoring Network (SEMnet) of China Academy of Science is composed of 17 stations with 39 ground-based instruments, and a processing prediction center in Beijing.
NSSC/SEPC has developed and put into use an ancillary online analyzing software. This software is customer-configurable and adaptable, which can be used as a powerful decision-making and drawing tool.

This analysis tool can be downloaded from the website: [http://eng.sepc.ac.cn](http://eng.sepc.ac.cn)
Space Weather Operational Models

### Solar and Interplanetary
- Solar Cycle F10.7
- Solar Cycle Rz
- 27-day F10.7
- CME Propagation
- Coronal Hole HSS
- Solar Proton Event

### Geomagnetic and Magnetosphere
- 27-day Ap
- Kp Model
- AU, AL, AE Models
- Dst Model
- Regional GMD
- Magnetopause Model
- Plasma Sheet
- Relativistic Electron
- Radiation Belt
- Regional TEC Assimilation

### Ionosphere
- Regional Ionospheric Index
- Scintillation

### Thermosphere
- 400 km Thermospheric Density
TEC GIM/RIMs

Who provides Global Ionospheric Maps?

- Center for Orbit Determination of Europe (CODE)
- Jet Propulsion Laboratory (JPL)
- European Space Agency (ESA)
- Polytechnical University of Catalonia (UPC)
- MIT Automated Processing of GPS (MAPGPS)

Regional Ionospheric Maps and real-time TEC product?

- N. America
  ~2,700 Receivers
  [Tsugawa et al., 2007]

- Europe
  ~1,200 Receivers
  [Otsuka et al., 2012]

- Japan
  ~1,200 Receivers
  [Tsugawa et al., 2011]

- Europe TEC (DLR)

- NATEC (NOAA/SWPC)

- GEONET TEC (NICT)
Ionospheric modeling via data assimilation

• The data assimilation technique has been proved as an effective and efficient way of specifying ionosphere, which is implemented by using certain optimization schemes to incorporate measurements into background models.

• There are three essential elements in data assimilation techniques:
  - the background model (IRI) and observations (TEC data)
  - the optimization assimilation algorithm
  - the associated error covariance matrices

• Typical Data Assimilation Models/Products
  - Utah State University: Global Assimilation of Ionospheric Measurements (USU GAIM)
  - University of Southern California and the Jet Propulsion Laboratory: Global Assimilative Ionospheric Model (USC/JPL GAIM)
  - University of Texas: Ionospheric Data Assimilation Three/Four-Dimensional algorithm (IDA3D/IDA4D)
  - NOAA/SWPC: U.S. Total Electron Content (US-TEC)
GNSS Data Processing & TEC Derivation

- GNSS Receivers over China and adjacent areas (15°-55°N, 70°-140°E)

<table>
<thead>
<tr>
<th>Crust Movement Observation Network of China (CMONOC)</th>
<th>International GNSS Service (IGS)</th>
<th>Space Environment Prediction Center (SEPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~300+ Receivers</td>
<td>38 Receivers</td>
<td>9 receivers</td>
</tr>
<tr>
<td>260+ Receivers</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data Acquisition and Update → RINEX files (~300 stations) → System Configuration Files

Navigation files → Data Input

Orbit Parameters Calculating → Observation files → Sat. and Receiver DCDs

IPPs Position Calculating → Cycle Slip Removal

VTEC and STEC at IPPs → Data Input

Map showing distribution of GNSS receivers and data.
Data assimilation: 3DVAR + Gauss Markov Kalman filter

There are three essential elements in data assimilation techniques:
- the background model (IRI) and observations (TEC data)
- the optimization assimilation algorithm (3DVAR)
- the associated error covariance matrices

3-Dimensional Variational (3DVAR) is a statistical optimization method that seeks to minimize a cost function which represents the measure of the closeness between background model predictions and the measurements.

### Time Update (“Predict”)
1. Project the state ahead
2. Project the error covariance

\[
x_f(t_{n+1}) = x_b(t_{n+1}) + [x_a(t_n) - x_b(t_n)]e^{-\frac{\Delta t}{\tau}}
\]
\[
P_f(t_{n+1}) = P_b(t_{n+1}) + [P_a(t_n) - P_b(t_n)]e^{-\frac{2\Delta t}{\tau}}
\]

### Measurement Update (“Correct”)
3. Update the estimate
4. Update the error covariance

\[
x_a = x_f + P_f H^T [R + HP_f H^T]^{-1} (y - H x_f)
\]
\[
P_a = P_f - P_f H^T [R + HP_f H^T]^{-1} HP_f
\]

- **Format of cost function** $J(x)$
  \[
  J(x) = \frac{1}{2}(x - x_b)^T P^{-1}(x - x_b) + \frac{1}{2}(y - H x)^T R^{-1}(y - H x),
  \]
- $x$: the state variable (the analyzed $N_e$)
- $x_b$: the background field (IRI estimation)
- $P$: the background error covariance matrix
- $R$: the observation error covariance matrix
- $y$: the observation vector (slant TEC)
- $H$: the observation forward operator (length that each satellite-receiver ray passes through every grid point)
Setting of error covariance matrix

- The error covariance matrices $P$ and $R$ are critical parameters in the assimilation process, and the effects of 3DVAR objective analysis depend largely on the determination of these two factors. In a number of studies, the observation error is assumed to be independent and proportional to the square of the observation; the background error is also considered to be proportional to the square of state variable and is considered to have Gaussian correlations; the horizontal and vertical correlations are assumed to be independent and thus separable.

- Error covariance matrices $P$ and $R$
  
  $$P_{ij} = C_P \delta_{ij} e^{-(z_i-z_j)^2/(\sigma_P^2)^2},$$
  $$R_{ij} = C_R \delta_{ij} \eta_j^2,$$

  - $z$: the altitude
  - $\delta_{ij}$: the horizontal great circle distance between grid points $i$ and $j$
  - $L_V$: the ionospheric vertical correlation length
  - $L_H$: the ionospheric horizontal correlation length
  - $C_P$ and $C_R$: User-configurable coefficients
  - $\delta$: the Dirac delta function

- Expression of ionosphere correlation length
  
  $$\left(\frac{L_V}{L_H}\right)^2 = \frac{L_z^2 L_{\phi}^2}{L_{\phi}^2 L_0^2} + \sin^2(\alpha)$$

  - $\alpha$: azimuth between two grid points
  - $L_z$: ionospheric meridional correlation length
  - $L_{\phi}$: ionospheric zonal correlation length
  - $L_0$: ionospheric altitudinal correlation length

Figure 2: Diurnal variation coefficients of ionosphere correlation length; vertical ionosphere correlation length with respect to altitude; meridional and zonal ionosphere correlation length with respect to magnetic latitude.
Assimilation results: Geomagnetic storm and ionospheric storm on March 17-18, 2015

Kp index
Assimilation results: St. Patrick Storms, March 2015

\[ \text{DTEC} = \text{TEC} - \text{TEC}_{\text{Quiet time average}} \]

DTEC

Kp index

Total Electron Content Unit: \(10^{16}/m^2\)
Assimilation results: St. Patrick Storms, March 2015

foF2

ΔfoF2
TEC maps: [http://eng.sepc.ac.cn/TEC_eng.php](http://eng.sepc.ac.cn/TEC_eng.php)

currently: driven by ~60 receivers

~ Oct 2017: driven by ~300+ receivers \((1^\circ \times 1^\circ \times 15\text{ min})\)
Summary

• First, the statistical analysis demonstrates that the data assimilation results pushes the climatological IRI model toward the observation. A general error reduction and accuracy improvement of 15-30% can be expected for quiet time assimilation, while the improvements under active conditions are more variable.

• Second, the regional gridded TEC maps are publicized online in quasi-real time with the resolution being $1^\circ \times 1^\circ \times 15$ min. It is the first ionospheric now-casting system in China based on data assimilation algorithm, which can be used in providing accurate and effective specification of regional ionospheric TEC and error correction for satellite navigation, radar imaging, shortwave communication, and other relevant applications.

Reference


Thank You!