Ionospheric TEC Assimilation and Now-casting System over China

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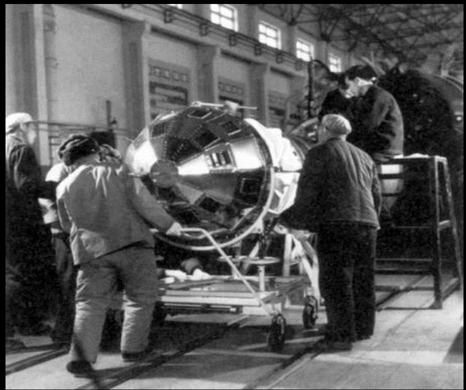
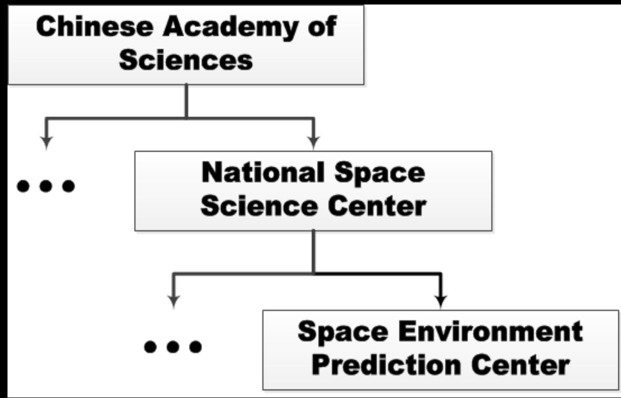
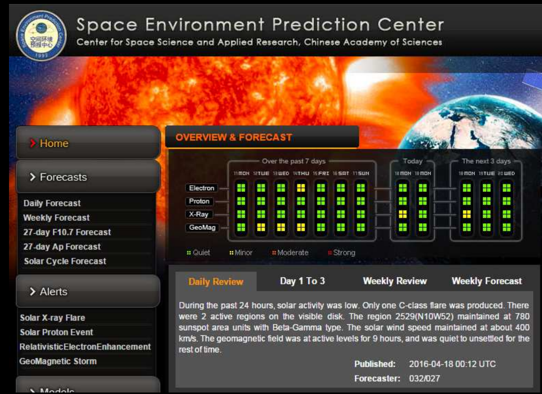






NSSC Established | **SEPC Constructed** | **Issuing Operational Services**

1958 | **1992** | **1998**

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.

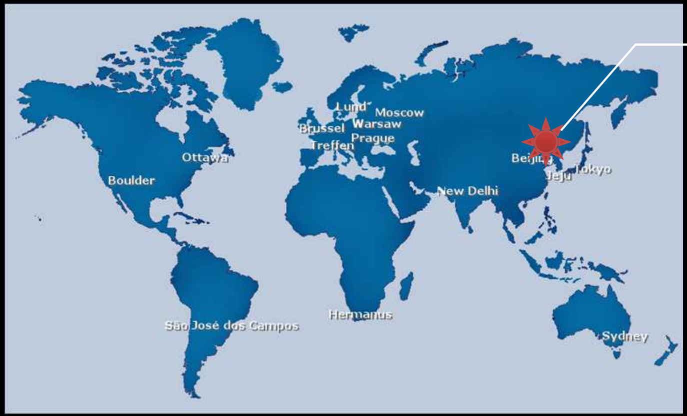
To meet the space weather requirements for China's space missions, SEPC was established in 1992 in NSSC, CAS, and became the 1st professional organization providing space weather services in China.

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**

- IPS (Australia)
- KSO (Austria)
- SIDC (Belgium)
- EMBRACE (Brazil)
- CSWFC (Canada)
- SEPC (China)
- SAPC (China)
- IAP (Czech Republic)
- NPL (India)
- NICT (Japan)
- KSWC (Republic of Korea)
- SCiESMEX (Mexico)
- SRC (Poland)
- IAG (Russia)
- SANSA (South Africa)
- LSWC (Sweden)
- MOSWOC (UK)
- SWPC (USA)
- ESA (Noordwijk)



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: 032/027

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 recurent coronal hole high speed stream, and is expected to be quiet to unsettled on 20 Apr.

Published: 2016-04-18 00:12 UTC

Forecaster: 032/027

F10.7 Index

The 10.7-cm solar radio flux forecast for the next 24/48/72 hours.

24HR	48HR	72HR
100	100	100

Ap Index

Geomagnetic Ap index forecast for the next 24/48/72 hours.

24HR	48HR	72HR
10	12	6

Solar X-ray Flare

Probabilities for M and X class solar flares for the next 24/48/72 hours.

CLASS	24HR	48HR	72HR
M	60%	40%	10%
X	10%	1%	1%

Geomagnetic Storm

Probabilities for minor and major disturbances in Geomagnetic field for the next 24/48/72 hours.

CLASS	24HR	48HR	72HR
Minor	1%	10%	1%
Major	1%	1%	1%

Solar Proton Event

Probabilities for solar proton event for the next 24/48/72 hours.

24HR	48HR	72HR
1%	1%	1%

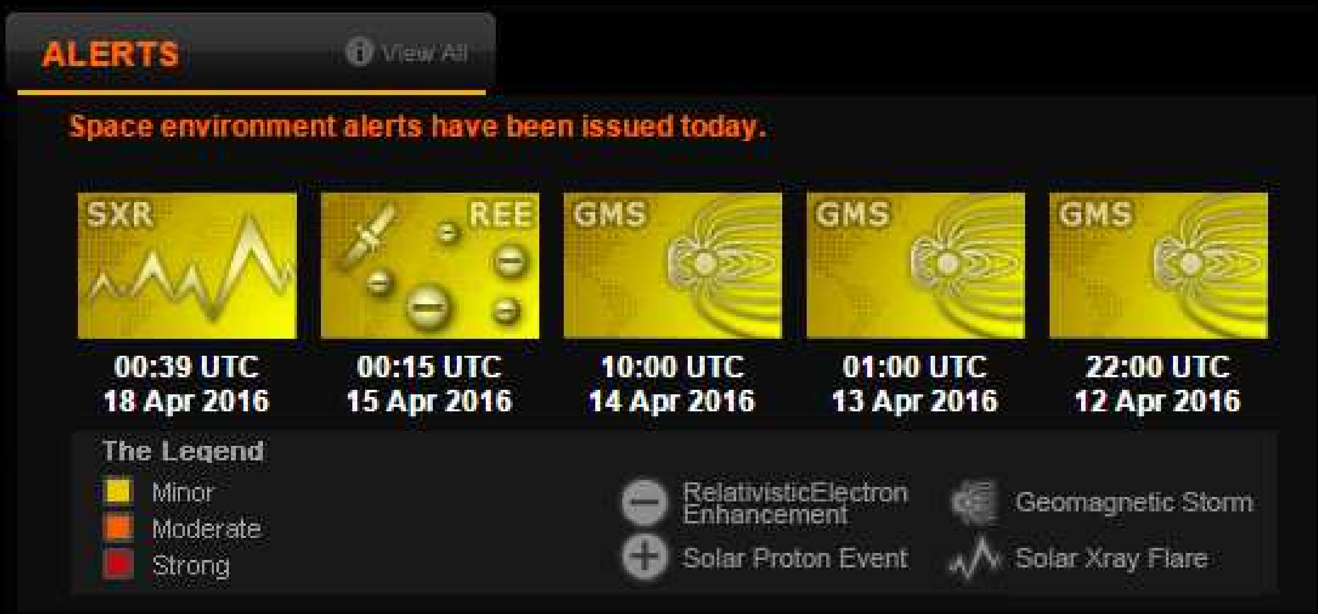
Relativisitic Electron Enhancement

Probabilities for GEO relativistic electrons enhancement event for the next 24/48/72 hours.

24HR	48HR	72HR
1%	1%	1%

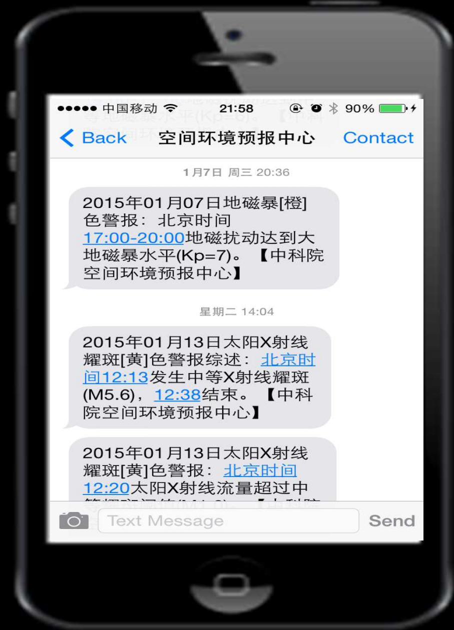
Space Weather Event Alerts

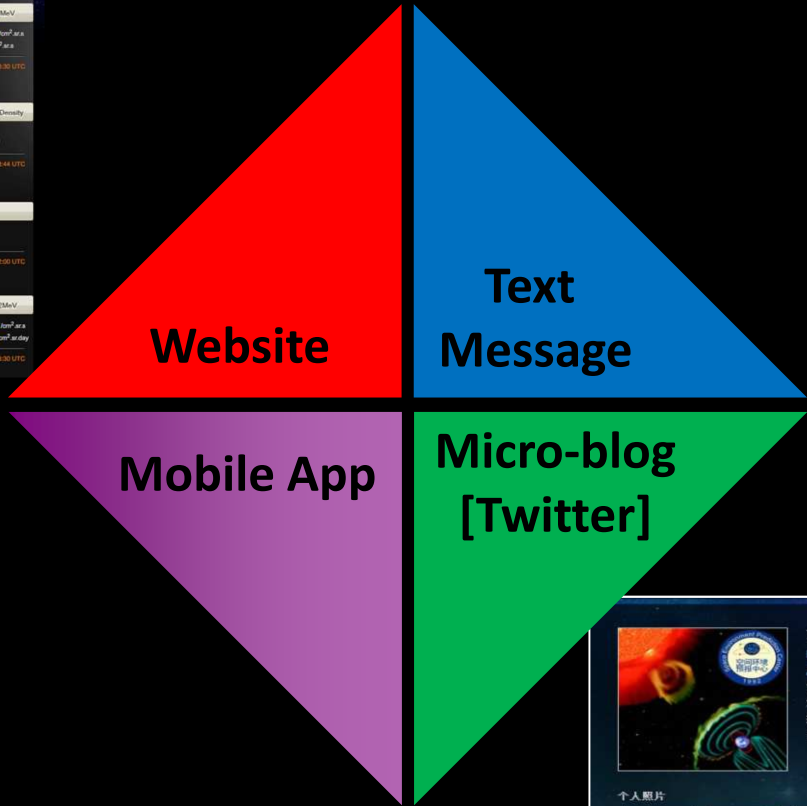
- **Space Weather Event Alerts**
  - Solar X-ray Flare
  - Solar Proton Event
  - Relativistic Electron Enhancement
  - Geomagnetic Storm



Delivery of Space Weather Services

http://eng.sepc.ac.cn





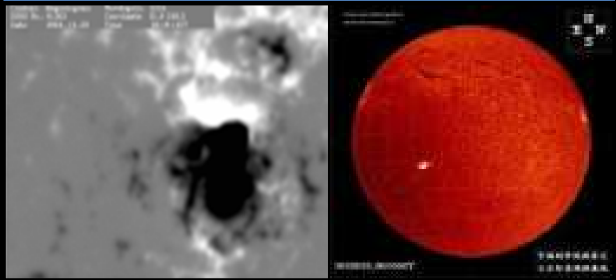
“e SpaceWx”

(>14k followers)

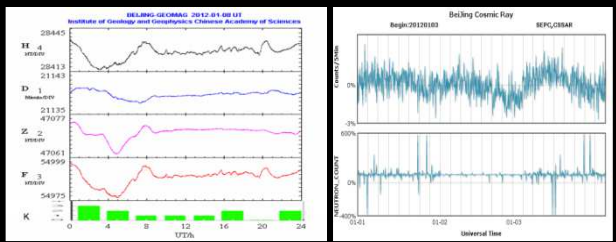
Space Environment Monitoring Networks: SEMnet

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.

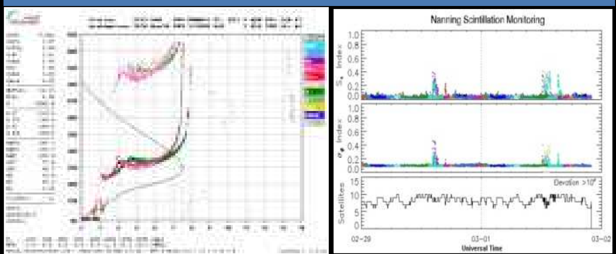
❶ Solar images



❷ Geomagnetic Field, Cosmic rays

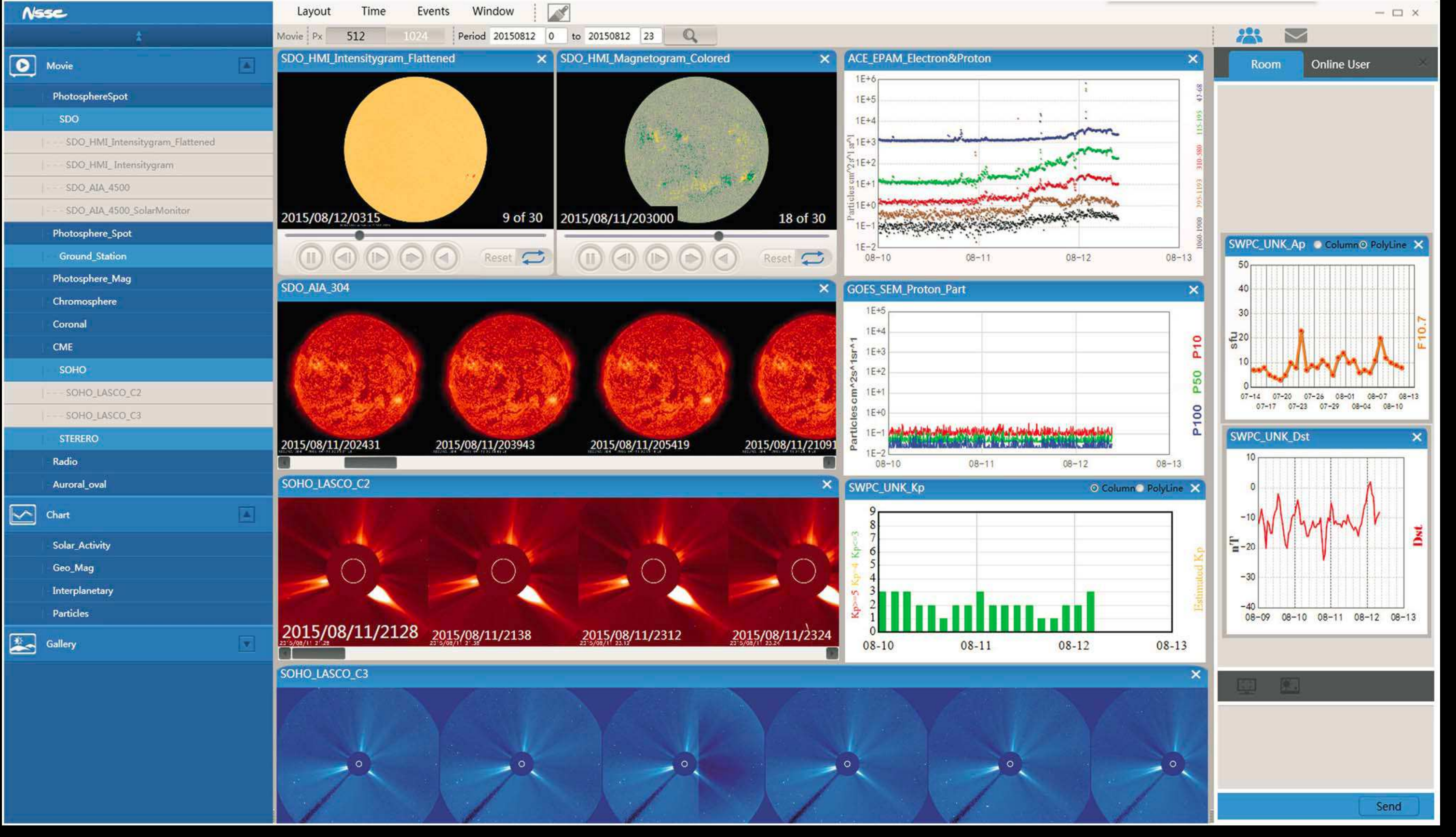


❸ Ionosphere profile/scintillation

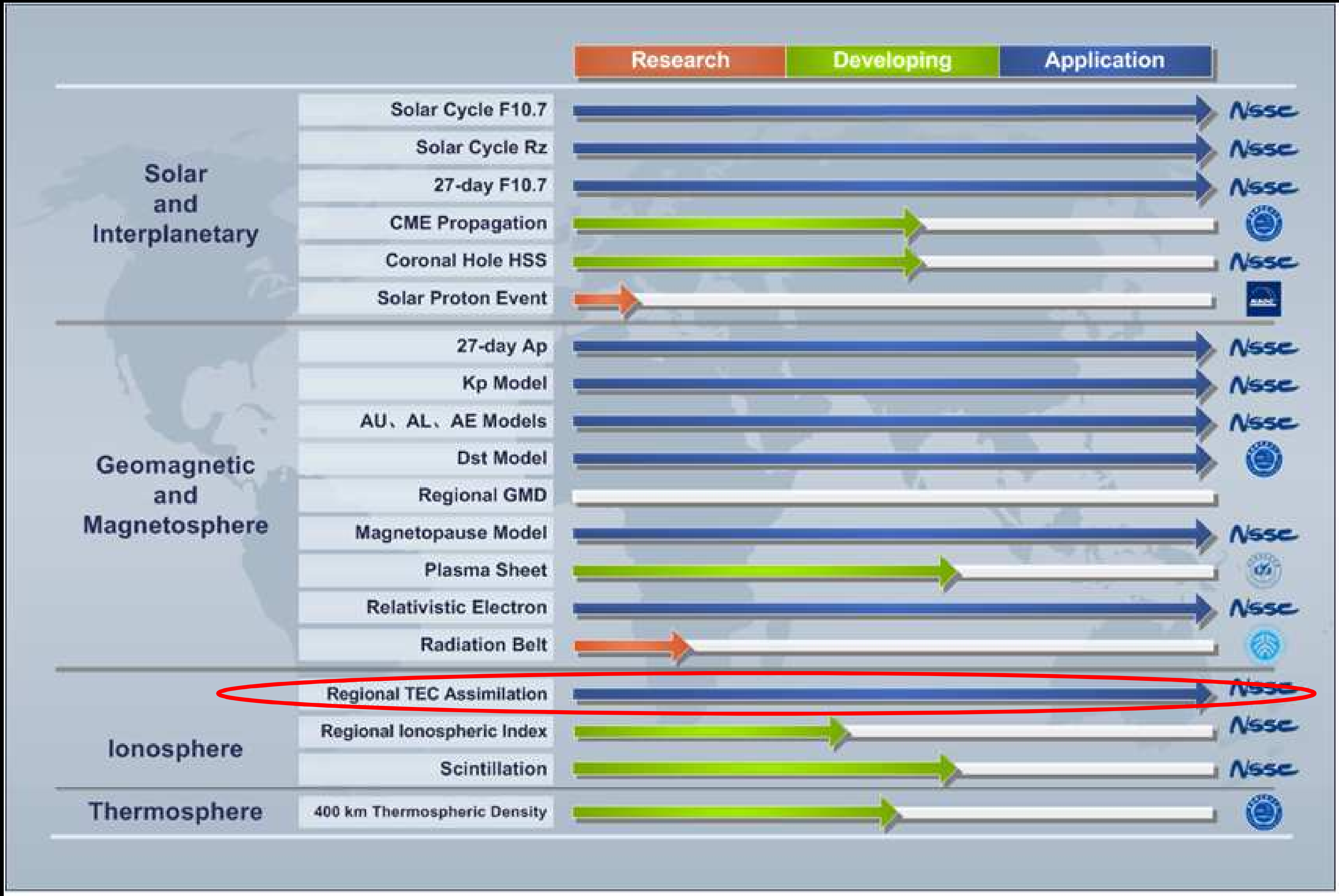


Space Weather Technology System: Analyzing Tool

- 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 website:http://eng.sepc.ac.cn



Space Weather Operational Models

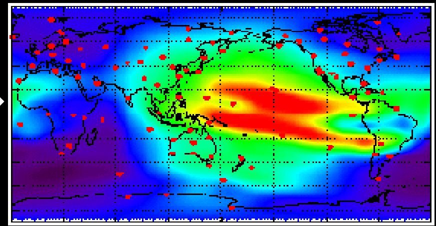


TEC GIM/RIMs

Who provides Global Ionospheric Maps?

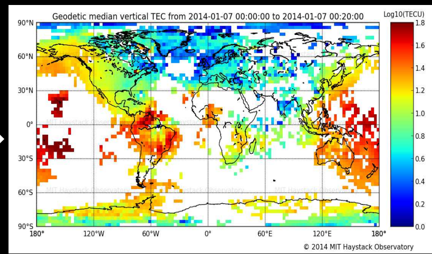
- Center for Orbit Determination of Europe **(CODE)**
- Jet Propulsion Laboratory **(JPL)**
- European Space Agency **(ESA)**
- Polytechnical University of Catalonia **(UPC)**

2.5° *5° *1 h

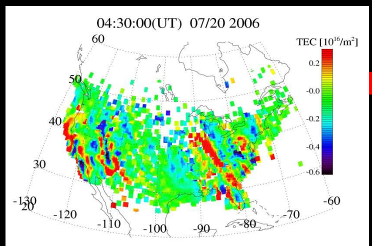


- MIT Automated Processing of GPS **(MAPGPS)**

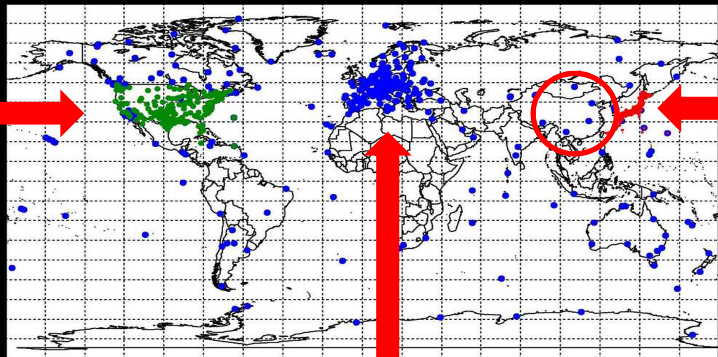
1° *1° *5 min



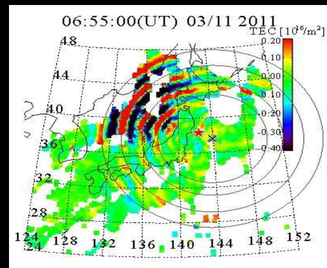
Regional Ionospheric Maps and real-time TEC product?



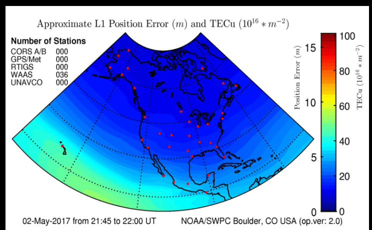
N. America
~2,700 Receivers
[Tsugawa et al., 2007]



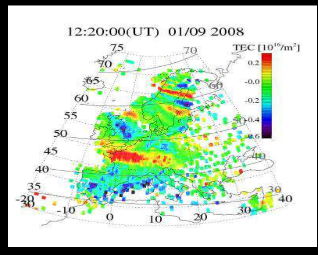
Europe
~1,200 Receivers
[Otsuka et al., 2012]



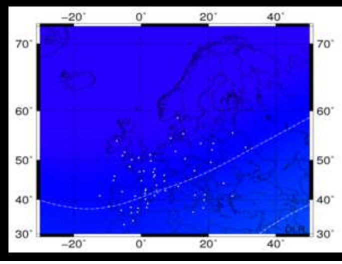
Japan
~1,200 Receivers
[Tsugawa et al., 2011]

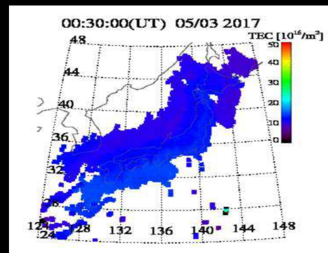


NATEC (NOAA/SWPC)



Europe TEC (DLR)





GEONET TEC (NICT)

Ionospheric modeling via data assimilation

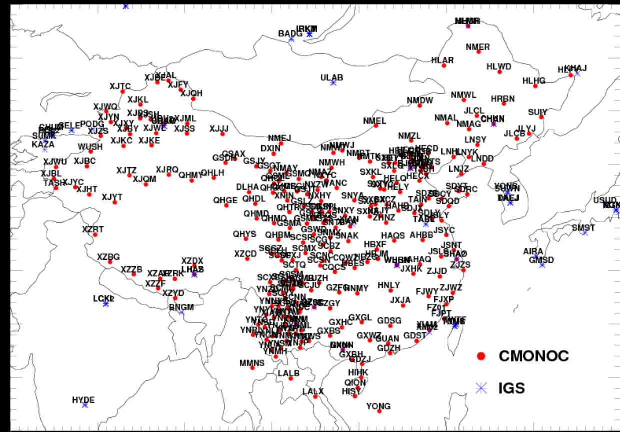
- **The data assimilation technique has been proved as an effective and efficient way of specifying ionosphere, which is implemented by using certain optimization schemes to incorporate measurements into background models.**
- **There are three essential elements in data assimilation techniques:**
  - **the background model (IRI) and observations (TEC data)**
  - **the optimization assimilation algorithm**
  - **the associated error covariance matrices**

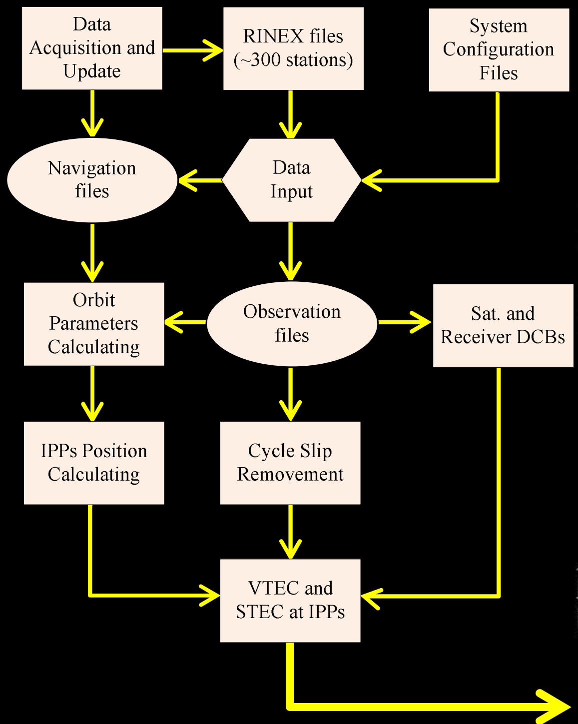
- **Typical Data Assimilation Models/Products**
  - **Utah State University: Global Assimilation of Ionospheric Measurements (USU GAIM)**
  - **University of Southern California and the Jet Propulsion Laboratory: Global Assimilative Ionospheric Model (USC/JPL GAIM)**
  - **University of Texas: Ionospheric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

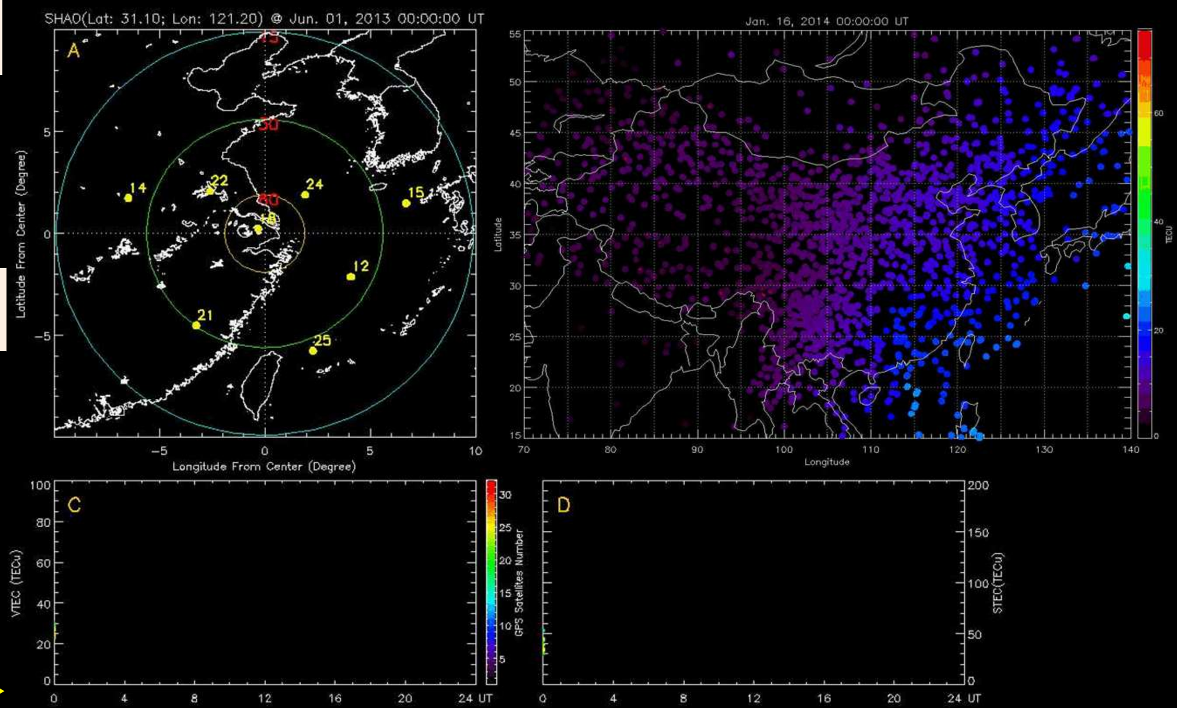
GNSS Data Processing & TEC Derivation

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

~300+ Receivers		
Crust Movement Observation Network of China (**CMONOC**)	International GNSS Service (**IGS**)	Space Environment Prediction Center (**SEPC**)
260+ Receivers	38 Receivers	9 receivers







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 Variationa (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.

- Format of cost function $J(x)$

$$J(x) = \frac{1}{2}(x - x_b)^T P^{-1}(x - x_b) + \frac{1}{2}(y - Hx)^T R^{-1}(y - Hx),$$

- 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)

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

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

$$P_{ij} = C_P x_b^i x_b^j e^{-(z_i - z_j)^2/(L_V^{ij})^2} e^{-d_{ij}^2/(L_H^{ij})^2},$$
$$R_{ij} = C_R \delta_{ij} y^2,$$

  - z: the altitude
  - d_{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
  - δ: the Dirac delta function

- Expression of ionosphere correlation length

$$(L_V^{ij})^2 = L_z^i L_z^j,$$
$$\frac{1}{(L_H^{ij})^2} = \frac{cos^2(\alpha)}{L_\theta^i L_\theta^j} + \frac{sin^2(\alpha)}{L_\phi^i L_\phi^j},$$

  - α: azimuth between two grid points
  - L_θ: ionospheric meridional correlation length
  - L_ϕ: ionospheric zonal correlation length
  - L_z: ionospheric altitudinal correlation length

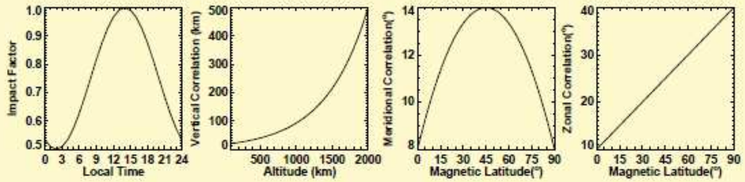
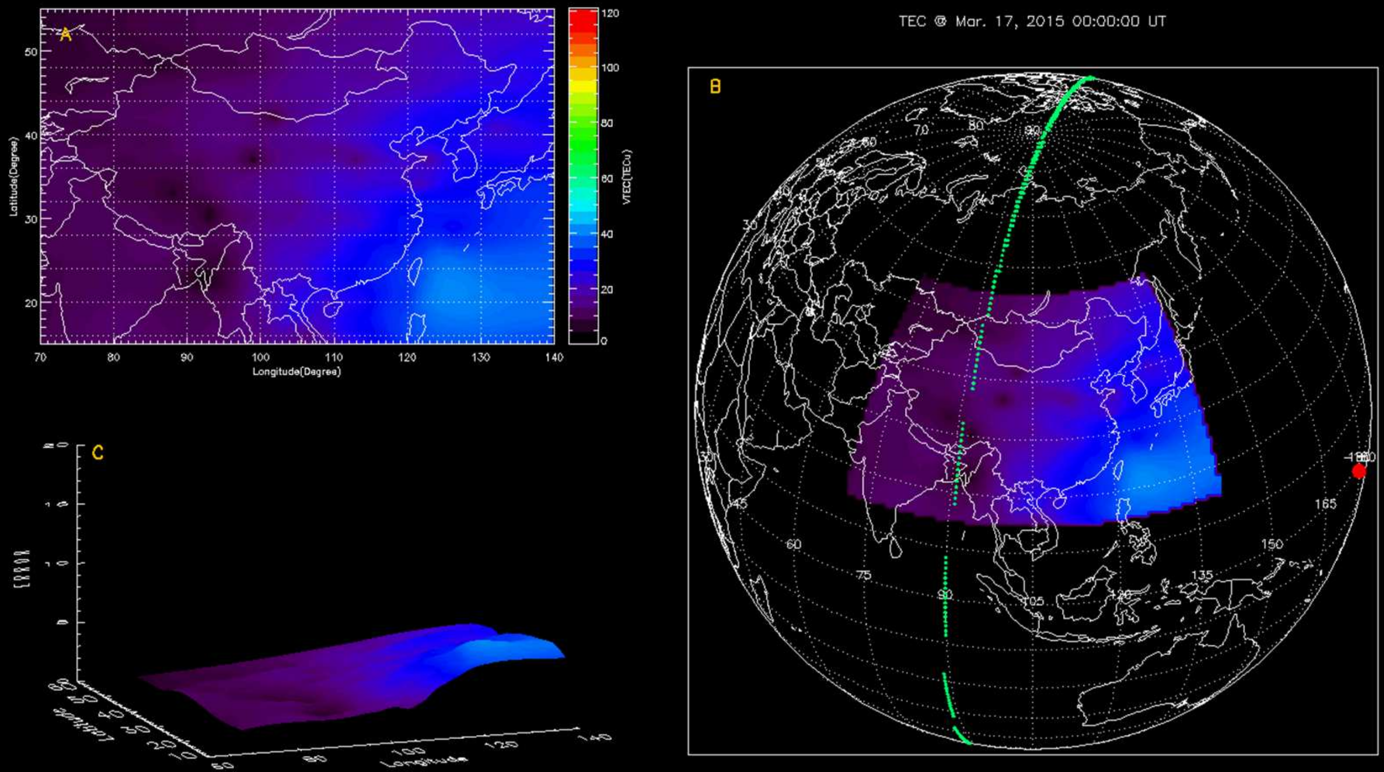
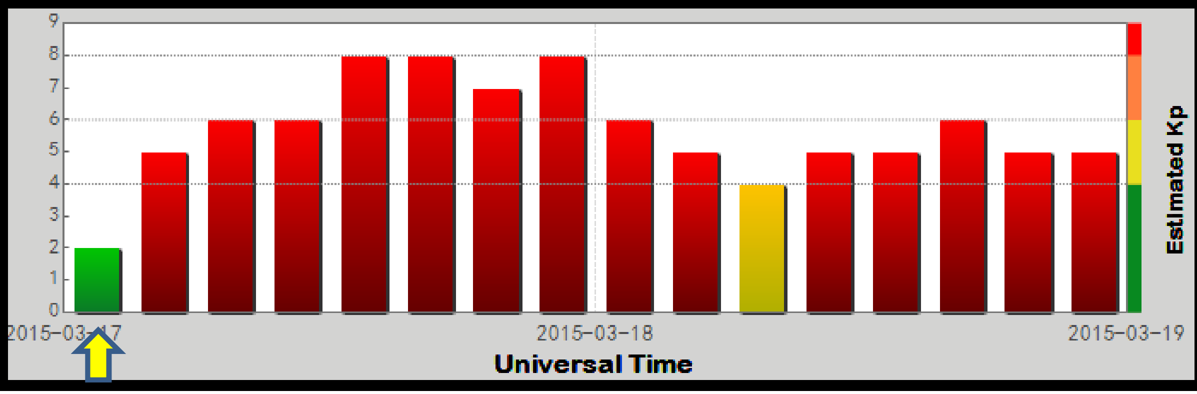


Figure 2: *Diurnal variation coefficients of ionosphere correlation length; vertical ionosphere correlation length with respect to altitude; meridional and zonal ionosphere correlation length with respect to magnetic latitude.*

Assimilation results: Geomagnetic storm and ionospheric storm on March 17-18, 2015

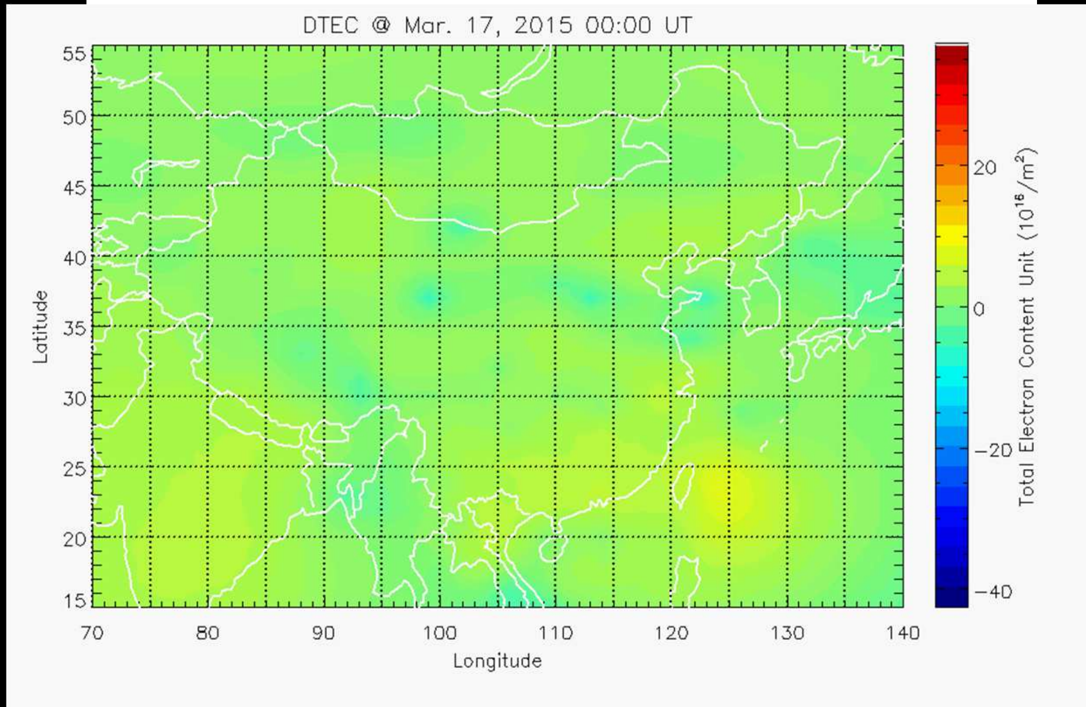




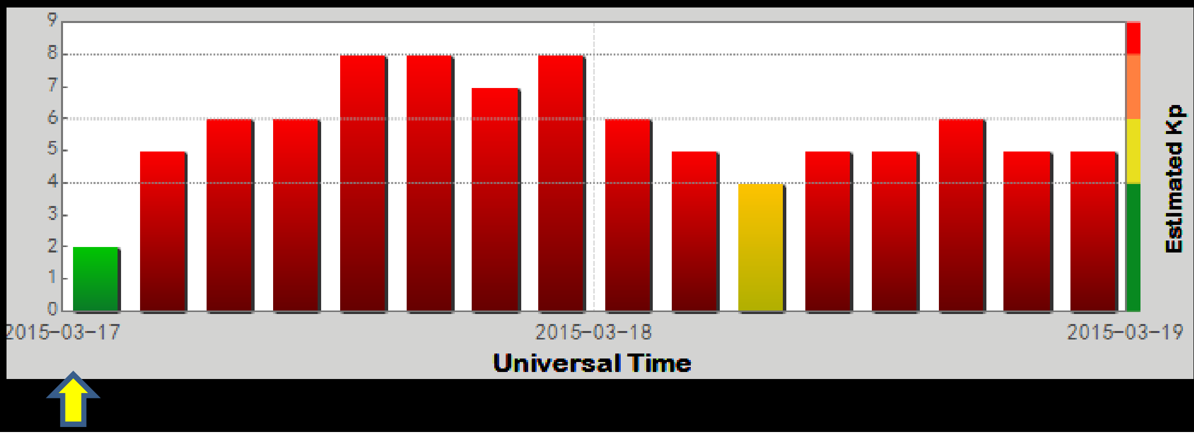
Kp index

Assimilation results: St. Patrick Storms, March 2015

$$DTEC = TEC - TEC_{Quiet\ time\ average}$$

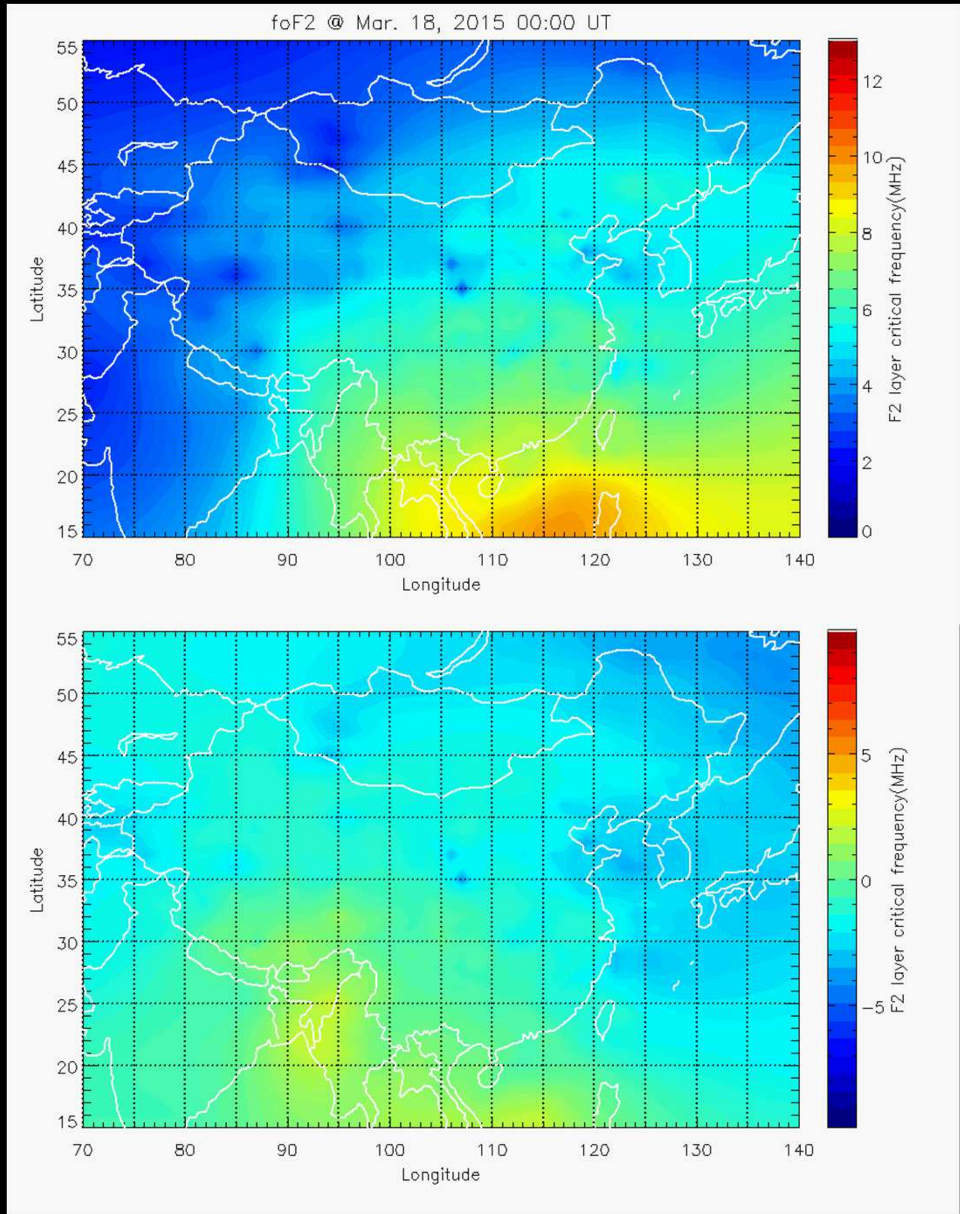


DTEC



Kp index

Assimilation results: St. Patrick Storms, March 2015

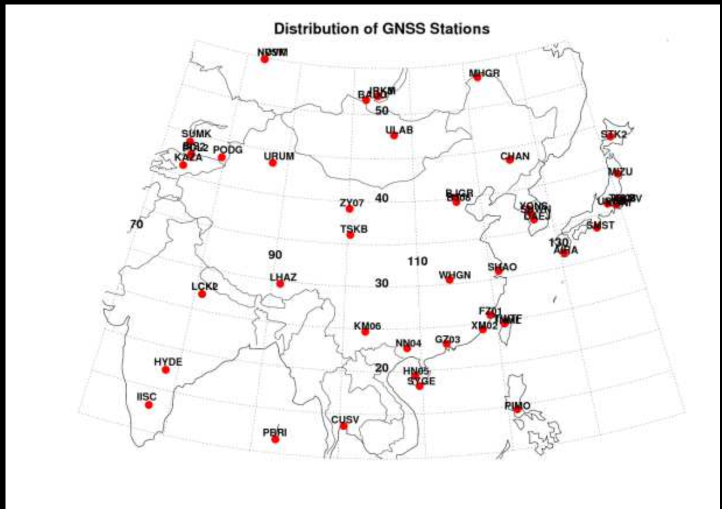


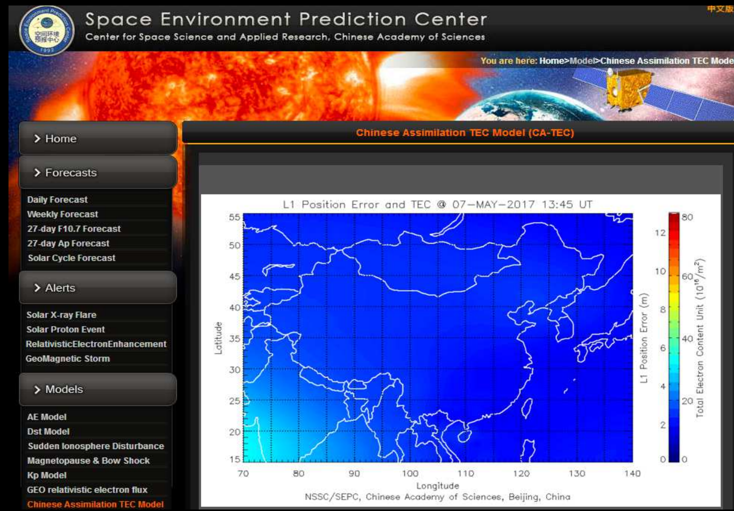
foF2

ΔfoF2

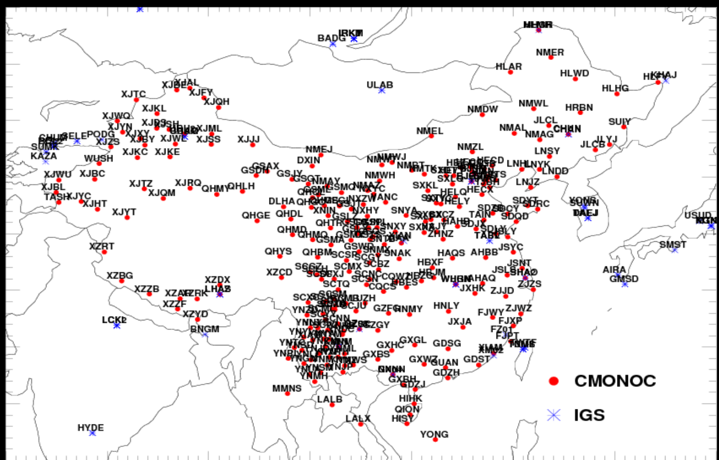
TEC maps: http://eng.sepc.ac.cn/TEC_eng.php

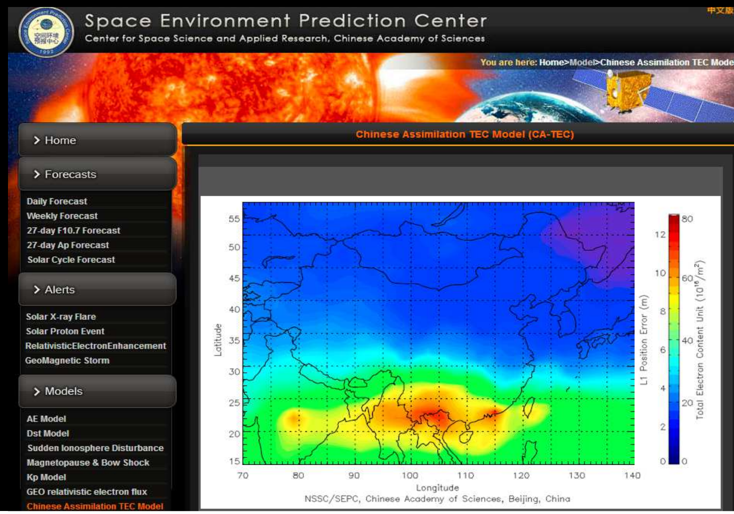
currently: driven by ~60 receivers





~ Oct 2017: driven by ~300+ receivers (1° × 1° × 15 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 $1^o \times 1^o \times 15$ 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

- Aa, E., W. Huang, S. Yu, S. Liu, L. Shi, J. Gong, Y. Chen, and H. Shen (2015), A regional ionospheric TEC mapping technique over China and adjacent areas on the basis of data assimilation, J. Geophys. Res. Space Physics, 120, 5049-5061, doi:10.1002/2015JA021140.

- Aa, E., S. Liu, W. Huang, et al. (2016), Regional 3-D ionospheric electron density specification on the basis of data assimilation of ground-based GNSS and radio occultation data (2016). Space Weather, 14, 1–16, doi:10.1002/2016SW001363.

Thank You !