Ionospheric space weather studies using high-resolution GNSS total electron content observations

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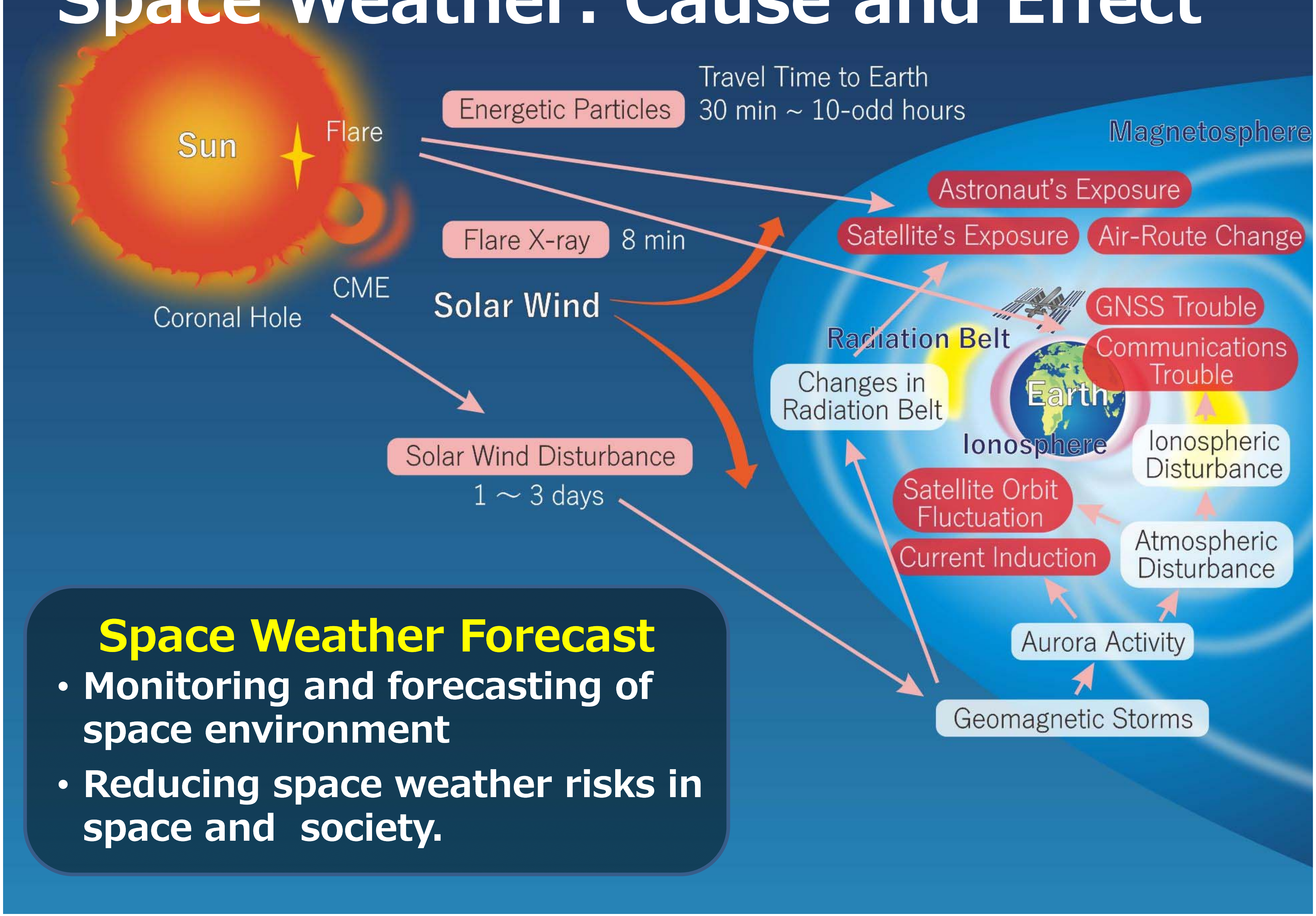
Space Weather: Cause and Effect



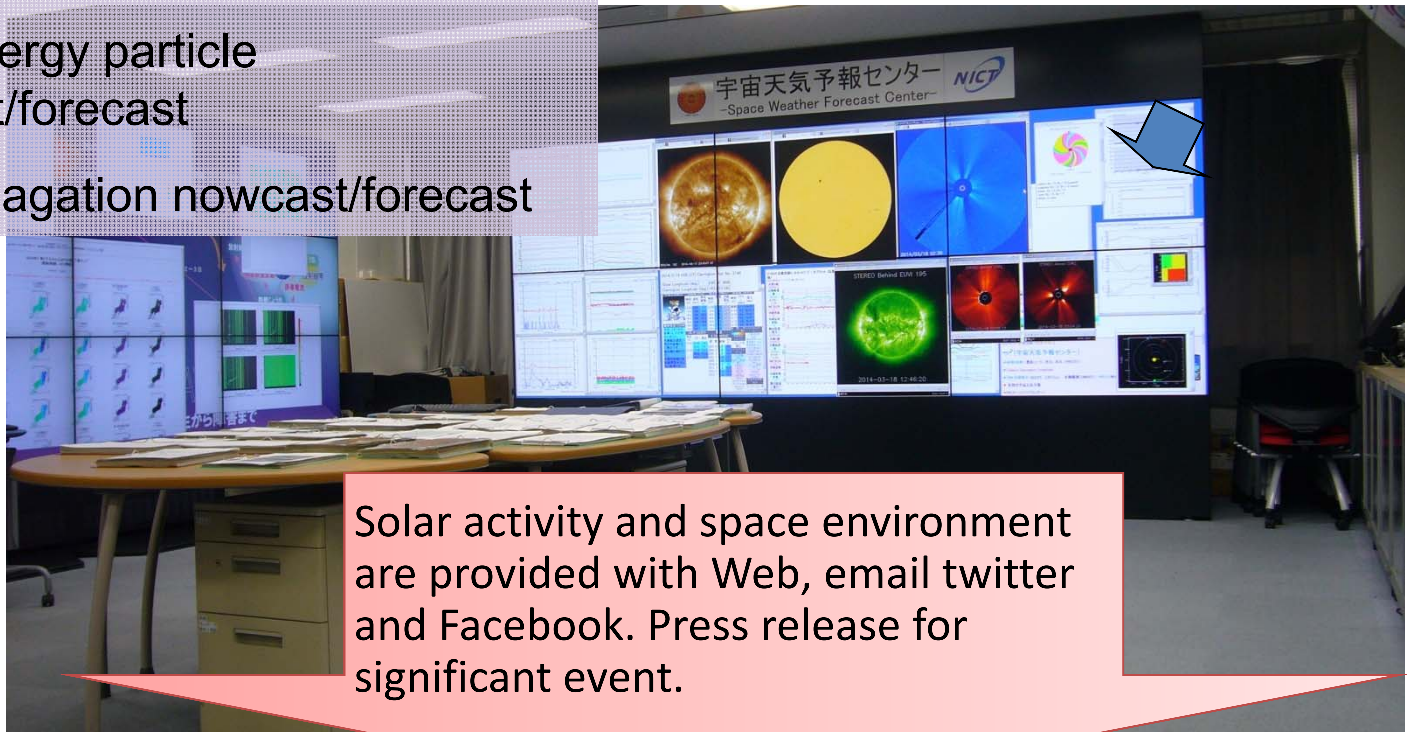
Space Weather Forecast

- Monitoring and forecasting of space environment
- Reducing space weather risks in space and society.

NICT Space Weather Forecast Center

- Flare nowcast/forecast
- Magnetic field nowcast/forecast
- High-energy particle nowcast/forecast
- HF propagation nowcast/forecast

Web access: ~160,000/month
E-mail subscribers: ~10,000



Solar activity and space environment are provided with Web, email twitter and Facebook. Press release for significant event.

Domestic users: satellite operator, aviation office and companies, power plant companies, HF telecommunicator /broadcaster, resource survey, Univ. and research institutes, amateur HF operators

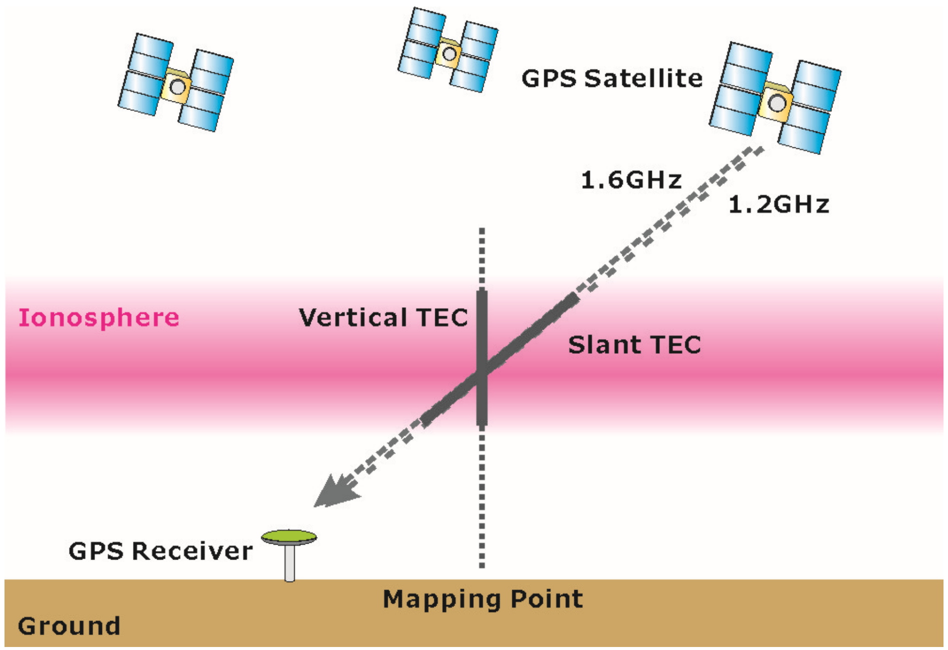
GNSS-TEC Observations

- Total electron content (TEC) can be derived by comparing the pseudorange/phase delays of the two GPS signals.

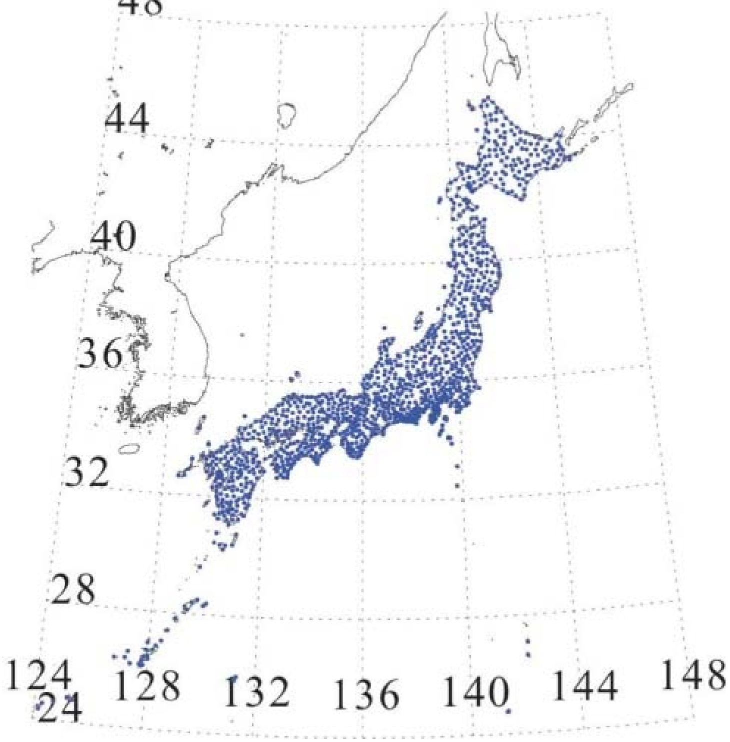
$$
\begin{aligned}
P_1 &= \rho + I/f_1^2 + \tau_1^r + \tau_1^s \\
P_2 &= \rho + I/f_2^2 + \tau_2^r + \tau_2^s \\
L_1 &= \rho - I/f_1^2 + \lambda_1 n_1 + \epsilon_1^r + \epsilon_1^s \\
L_2 &= \rho - I/f_2^2 + \lambda_2 n_2 + \epsilon_2^r + \epsilon_2^s
\end{aligned}
$$

P_1 P_2: Pseudorange
L_1 L_2: Carrier phase
I: Total electron content
f_1, f_2: Frequency
ρ: True range between the GPS satellite and receiver

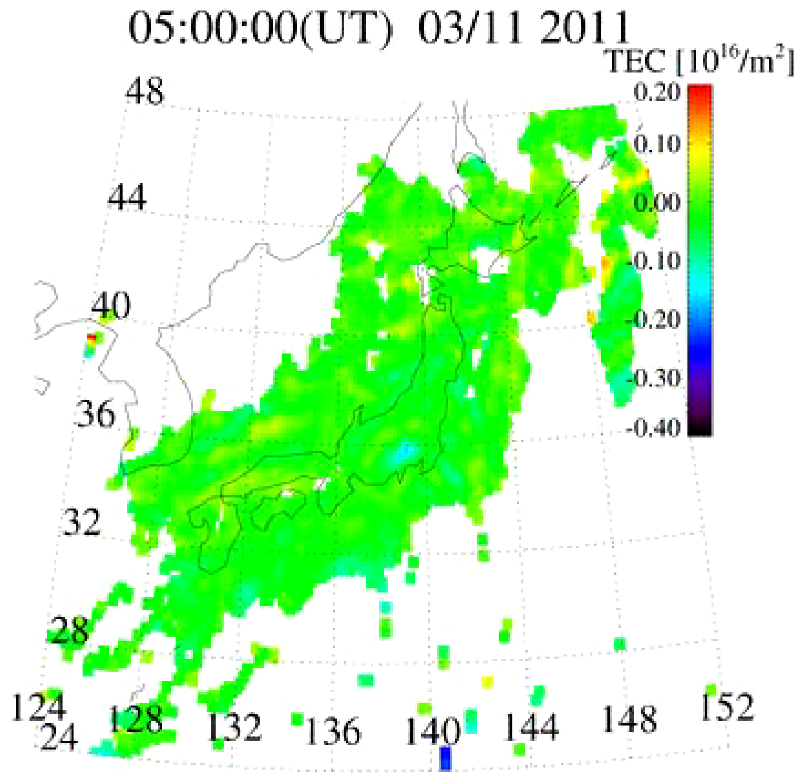
- TEC is a measure of integrated electron density in $1m^2$ column.
- Spatial resolution of TEC map depends on the number of GNSS satellites and GNSS receivers distribution.



2D High-Resolution GPS-TEC Observations



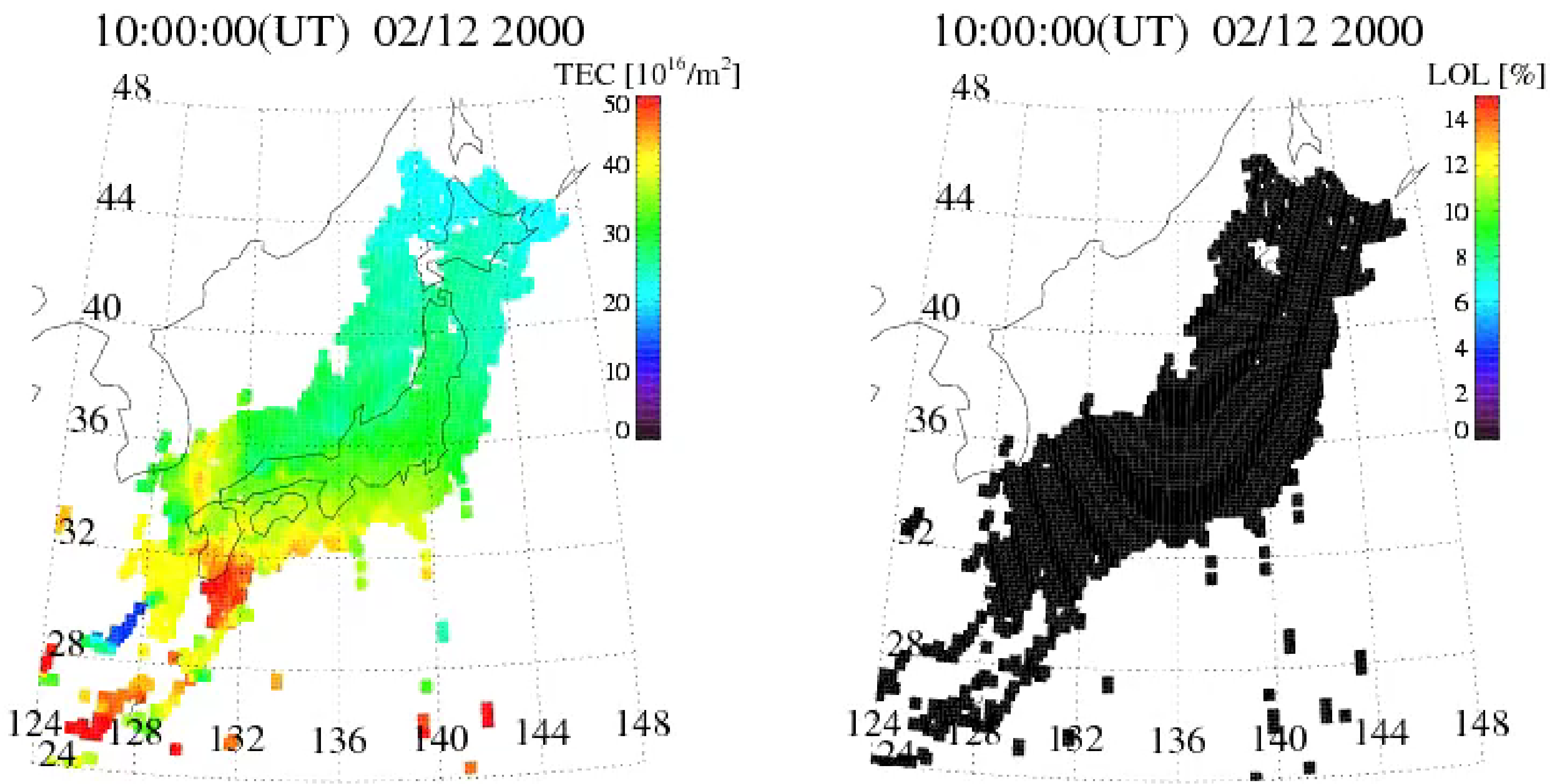
GEONET consisting of more than 1,200 GPS stations.



TEC variation map during 2011 Tohoku earthquake [Tsugawa et al., EPS, 2011]. The red star represents the epicenter.

- Using the dense GPS network in Japan, GEONET, we have developed quasi-realtime two-dimensional maps of absolute TEC, detrended TEC with 60, 30, 15-minute window, rate of TEC change index (ROTI), and loss-of-lock on GPS signal over Japan.

TEC observations for Space Weather



Absolute vertical TEC　　Loss-of-lock on GPS signal

- Using the dense GPS network in Japan, GEONET, we have developed quasi-realtime two-dimensional maps of absolute TEC, detrended TEC with 60, 30, 15-minute window, rate of TEC change index (ROTI), and loss-of-lock on GPS signal over Japan.

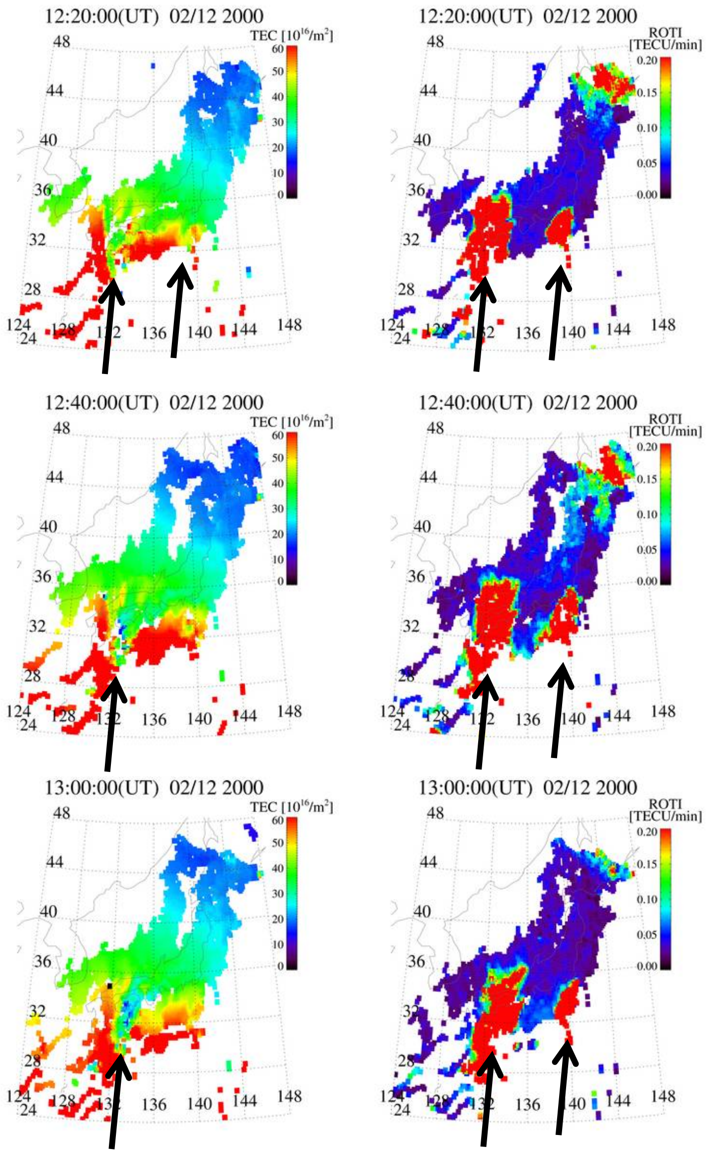
GPS Loss-of-Lock Caused by Plasma Bubble

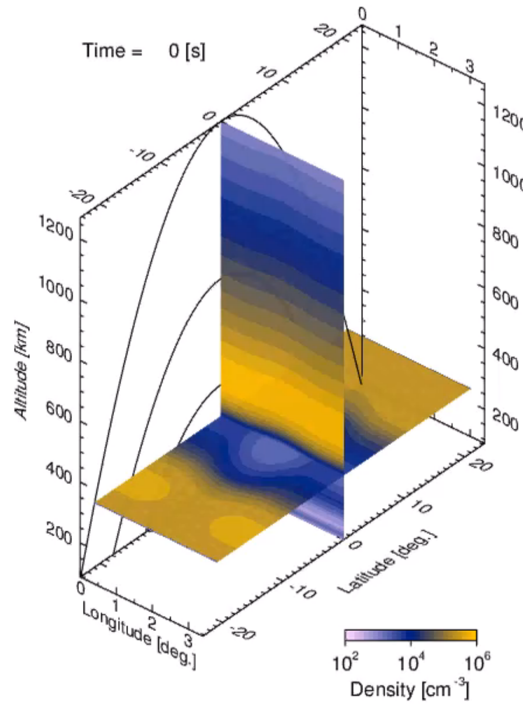
Absolute TEC | ROTI (~10km scale irregularity) | Loss-of-Lock (~100m scale irregularity)

12:20 UT (21:20 JST)

12:40 UT (21:40 JST)

13:00 UT (22:00 JST)

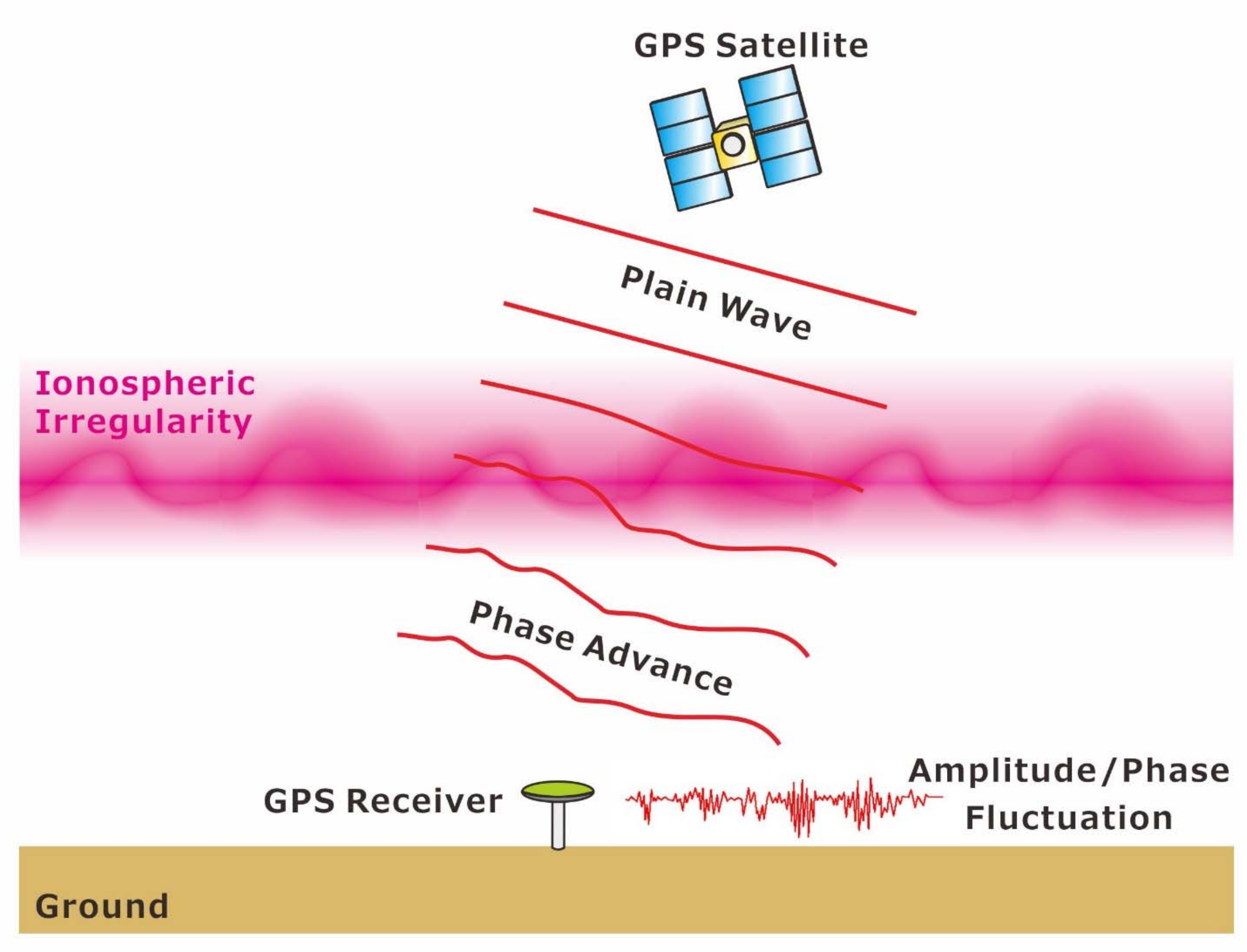




2D and 3D simulations of plasma bubble [Courtesy of Dr. T. Yokoyama (NICT)]

[Tsugawa et al., submitted to JDR, 2017]

Ionospheric scintillation



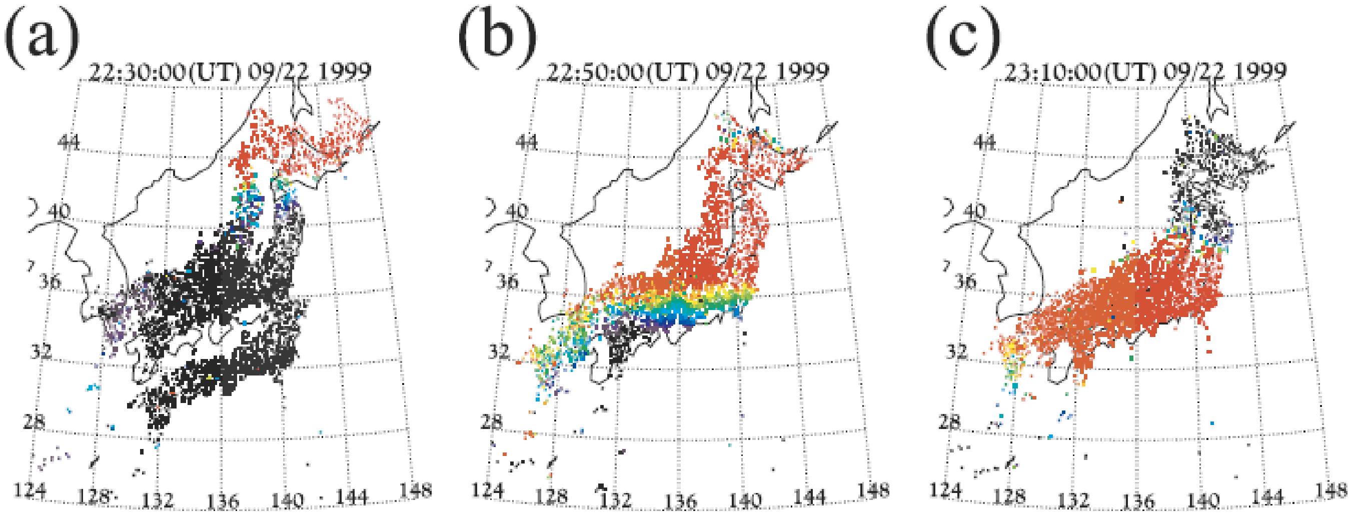
- Plasma bubbles include smaller scale (~100-m scale) ionospheric irregularities.
- These ionospheric irregularities causes ionospheric scintillation, that is, amplitude and phase fluctuations on GNSS signals.

Characteristics of EPB and their effect on GNSS

Amplitude	several 10 to 100TECU depletion in TEC
Time scale	Several 10 minutes to several hours
Spatial structure	Steep horizontal TEC gradient Narrow in zonal direction Extending along the magnetic field line
Other characteristics	Often observed mid- to low latitudes after the sunset. Almost always accompanied with ionospheric irregularity
Effect on GNSS	Differential GPS Augmented GPS (due to TEC model correction error) Loss-of-lock on GPS signals

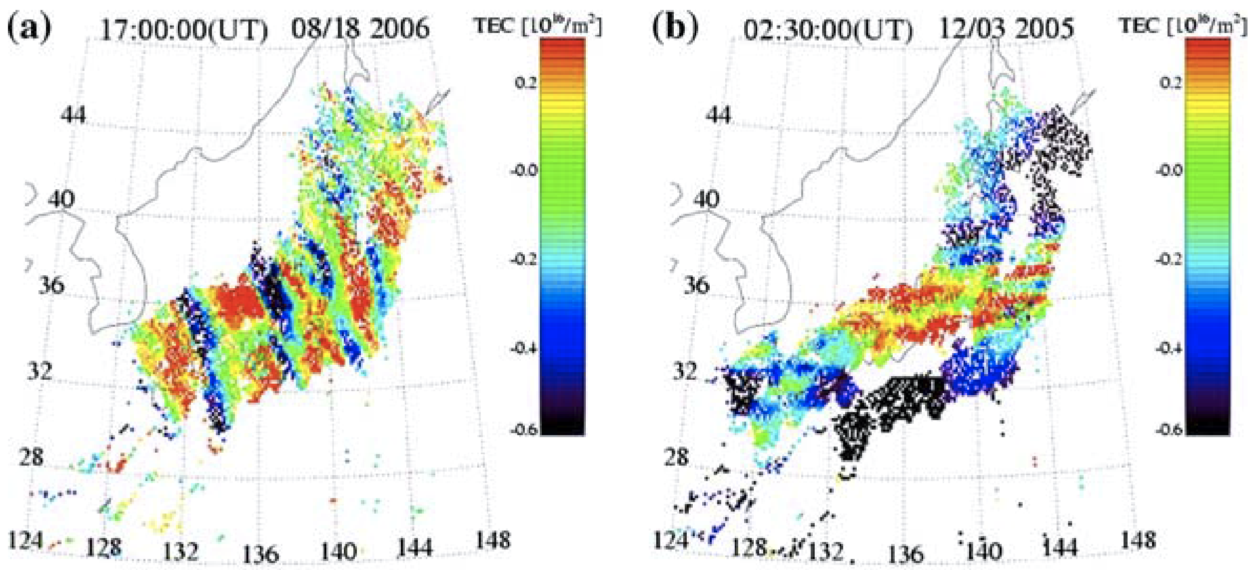
Traveling Ionospheric Disturbances (TID)

Large -scale TID (LSTID)



[*Tsugawa et al., JGR., 2003*]

Medium -scale TID (MSTID)

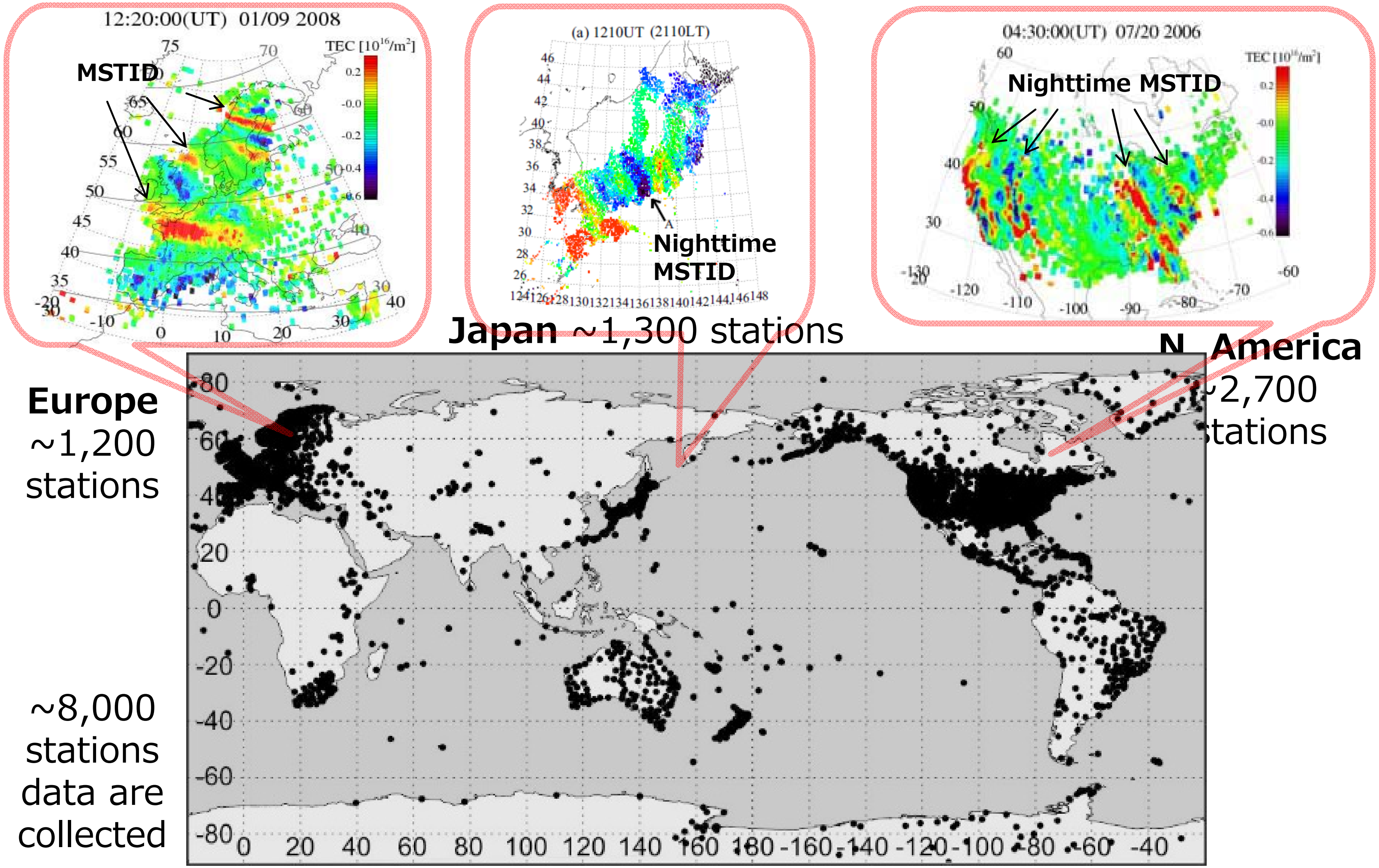


[*Tsugawa et al., GPS solut., 2007*]

Traveling Ionospheric Disturbances (TID)

Amplitude	A few TECU
Time scale	MS: Several 10 minutes LS: Several hours
Spatial structure	MS: Wavelengths of several 100 km LS: Wavelengths of 1,000 – 3,000 km, Zonally extended wavefront
Other characteristics	MS: Southwestward and Southeastward propagations in nighttime and daytime, respectively. LS: Related with magnetic storm
Effect on GNSS	Differential GPS PPP applications of GNSS

High-resolution GNSS-TEC observations



http://seg-web.nict.go.jp/GPS/DRAWING-TEC/

DRAWING-TEC project
(Dense Regional and Worldwide International GNSS-TEC observation)

1. Standardizing GNSS-TEC data for high-resolution TEC maps.
2. Developing a new high-resolution TEC mapping technique using the standardized TEC data.
3. Sharing the standardized TEC data and the data or the information of GNSS receiver network among the international ionosphere and GNSS researcher community.

DRAWING-TEC Website

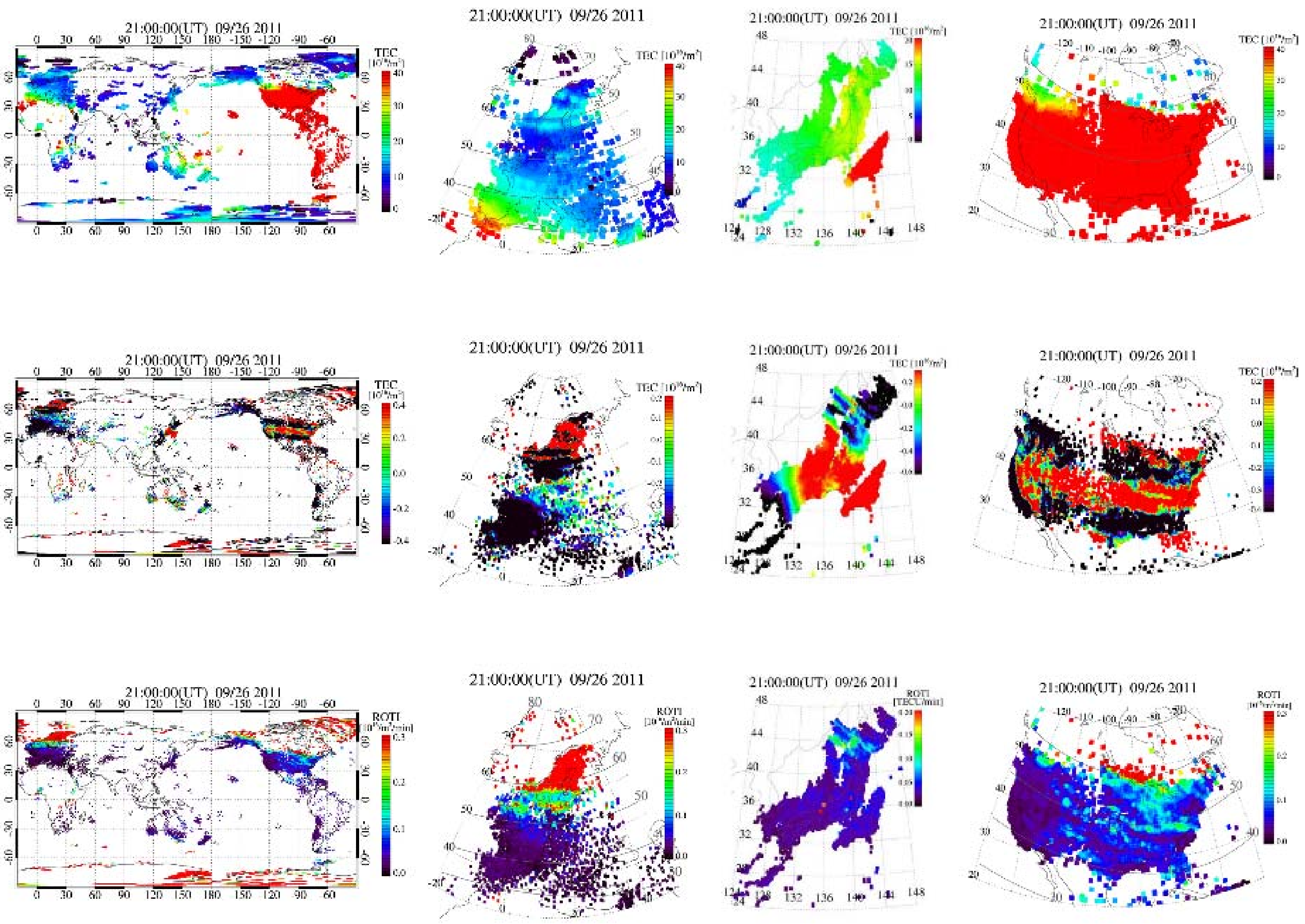
http://seg-web.nict.go.jp/GPS/DRAWING-TEC

Global | Europe | Japan | N. America

Absolute TEC

Detrended TEC

ROTI



GNSS-TEC exchange (GTEX) format (v1.0)

```
     1.0            GTEX DATA            GNSS               GTEX VERSION / TYPE
RNX2GTEX V1.0       NICT, JAPAN                             PGM / RUN BY
     0                                                      EXPONENT OF TECU
     TEC values in 10^16 el/m^2 (1 TEC Unit)                COMMENT
     TEC Status Flag = 0 : Normal data                      COMMENT
                     = 1 : Lack of observables (TEC=999.)   COMMENT
                     = 2 : Too large TEC (TEC=999.)         COMMENT
                     = 4 : Cycle slip (TEC discontinuity)   COMMENT
                     = 5 : Cycle slip (LLI)                 COMMENT
                     = 6 : Beginning of arc                 COMMENT
     TYPES OF DATA   = R1 : Raw slant TEC including bias    COMMENT
                       A1 : Absolute slant TEC              COMMENT
                            R1 or A1 is necessary           COMMENT
                       1F : TEC status flag                 COMMENT
                       1O : Observation data used for TEC   COMMENT
                       ZN : Satellite zenith angle          COMMENT
                       AZ : Satellite azimuth angle         COMMENT
                                                            BIAS ESTIMATION PGM
01321310.12o  01321320.12o  01321330.12o                    RINEX FILE NAME
0132                                                        MARKER NAME
00000               TPS NETG3          3.4 EG3 Jul,02,2010  REC # / TYPE / VERS
                    TRM29659.00     GSI                     ANT # / TYPE
 -3690821.3891  2897721.3097  4305504.4426                  APPROX POSITION XYZ
       42.7294       141.8640        0.0486                 POSITION LAT LON ALT
     6     L1     C1     L2     P2     S1     S2            # / TYPES OF OBSERV
     5     R1     1F     1O     ZN     AZ                   # / TYPES OF DATA
    30.000                                                  INTERVAL
  2012     5      11      0      0     0.0000000     GPS    TIME OF FIRST OBS
                                                            END OF HEADER
 12  5 11  0  0  0.0000000  0  9G21G 9G18G15G28G 5G27G 8G26
 -61.7242  0  L1L2C1P2  32.45  194.42
 -33.4733  0  L1L2C1P2   9.32   14.04
 -49.7988  0  L1L2C1P2  20.39    9.03
 -55.8391  0  L1L2C1P2  83.27   39.34
 -43.6837  0  L1L2C1P2  32.21   44.21
 -38.7060  0  L1L2C1P2   8.31    3.34
 -44.8228  0  L1L2C1P2  74.42  265.99
 -31.3004  0  L1L2C1P2  23.01  343.20
 -48.7904  0  L1L2C1P2  50.12  115.79
 12  5 11  0  0 30.0000000  0  9G21G 9G18G15G28G 5G27G 8G26
```

Filename: ssssdddh.yy_TEC
ssss: marker name
ddd: day of the year
h: file sequence number
yy: 2-digit year

Header Part

RINEX files used to derive slant TEC

Rec. Position in Lat, Lon, Alt

Types of obs. in RINEX

Types of data product

Interval according to RINEX

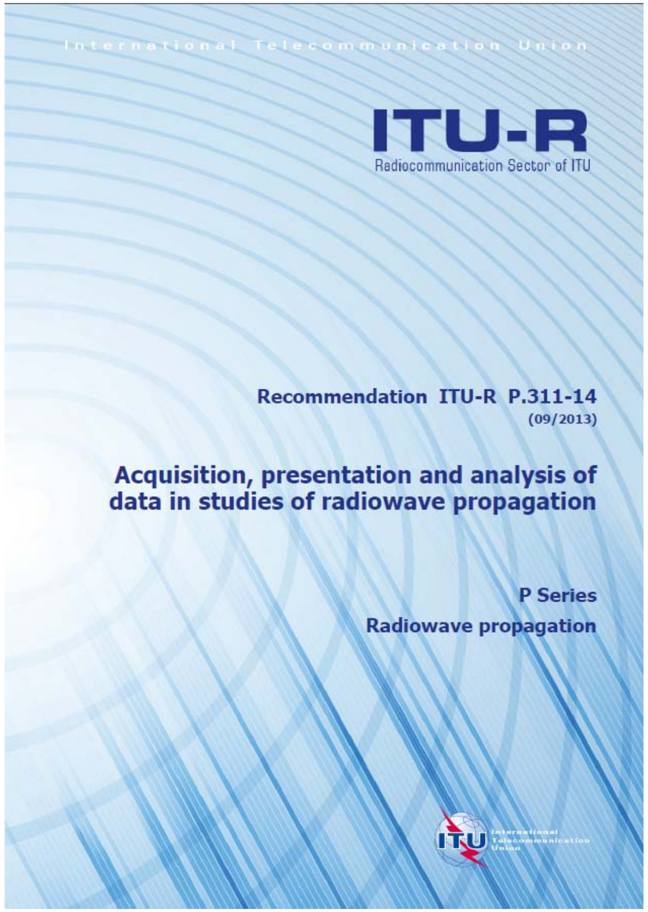
year, month, day, hour, min, sec, flag, # of PRNs, PRNs

sTEC, TEC flag, Used RINEX observation data, sat. zenith angle, azimuth angle for PRN21

1 epoch

International Telecommunication Union Radiocommunication Sector (ITU-R)

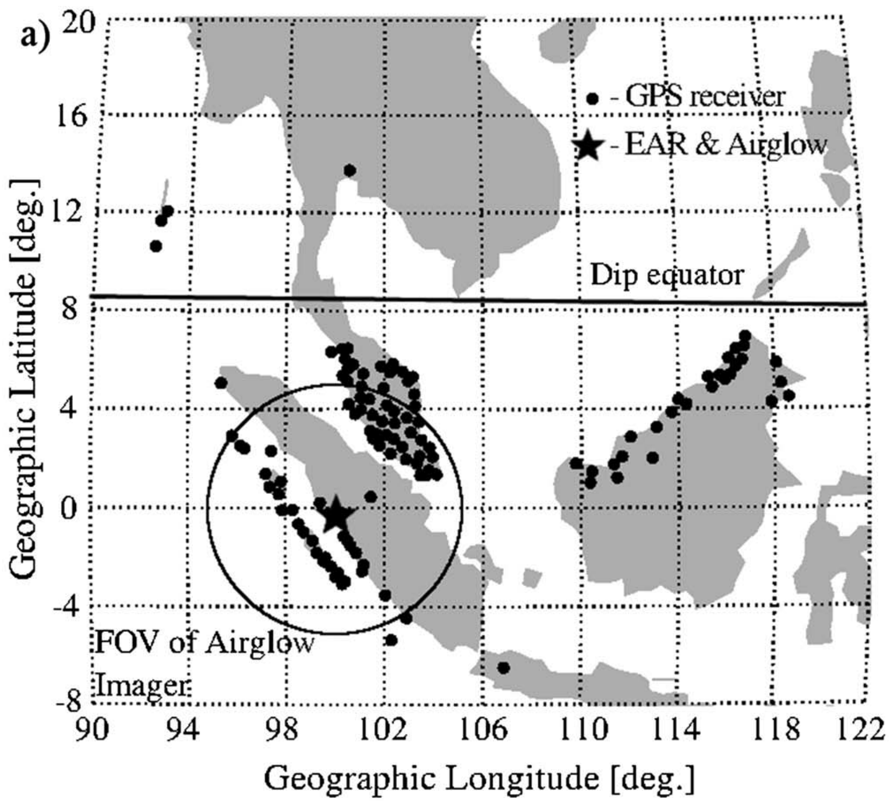
- NICT, as a delegate of Japan, first proposed "GTEX" as a format to promote international exchange and sharing of GNSS-TEC data in an input document to meetings of Working Party 3L (ionospheric propagation and radio noise), Study Group 3 (SG3, radiowave propagation) of ITU-R in June 2013 at Geneva, Switzerland.
- The GTEX format was approved as one of the standard data of trans-ionospheric data and included in Recommendation ITU-R P.311-16 Annex 1 in 2015

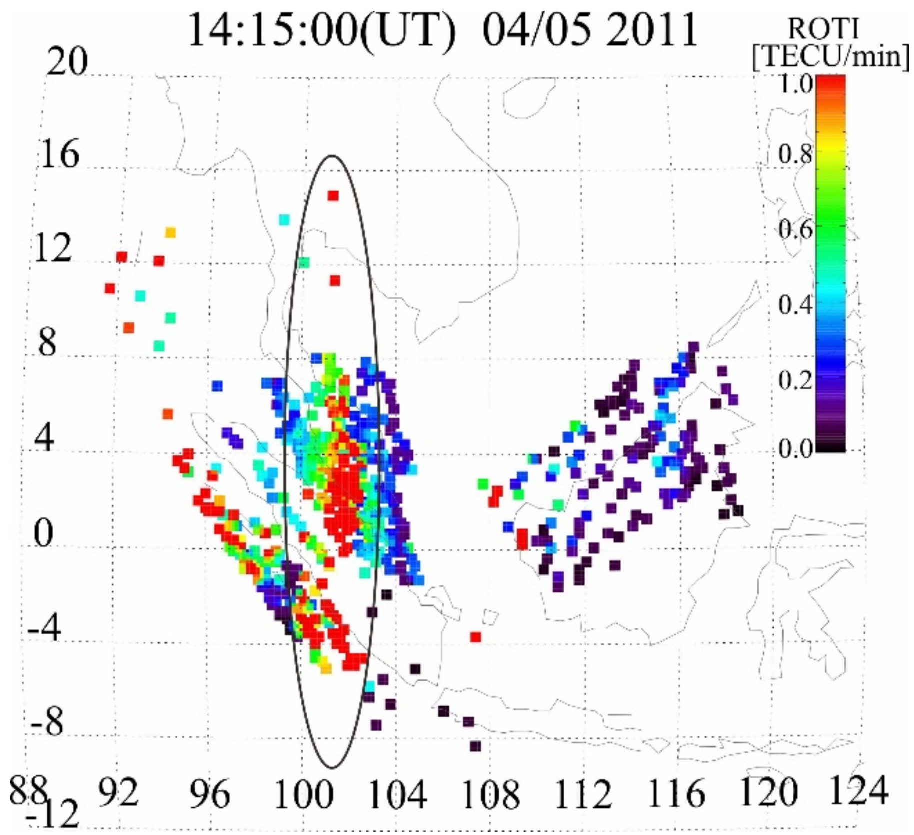


http://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/dtbank-form-tables.aspx

GNSS-TEC Data Sharing Based on GTEX

- Buhari et al. [2014] successfully captured plasma bubble structures using dense GNSS receiver network in Malaysia.



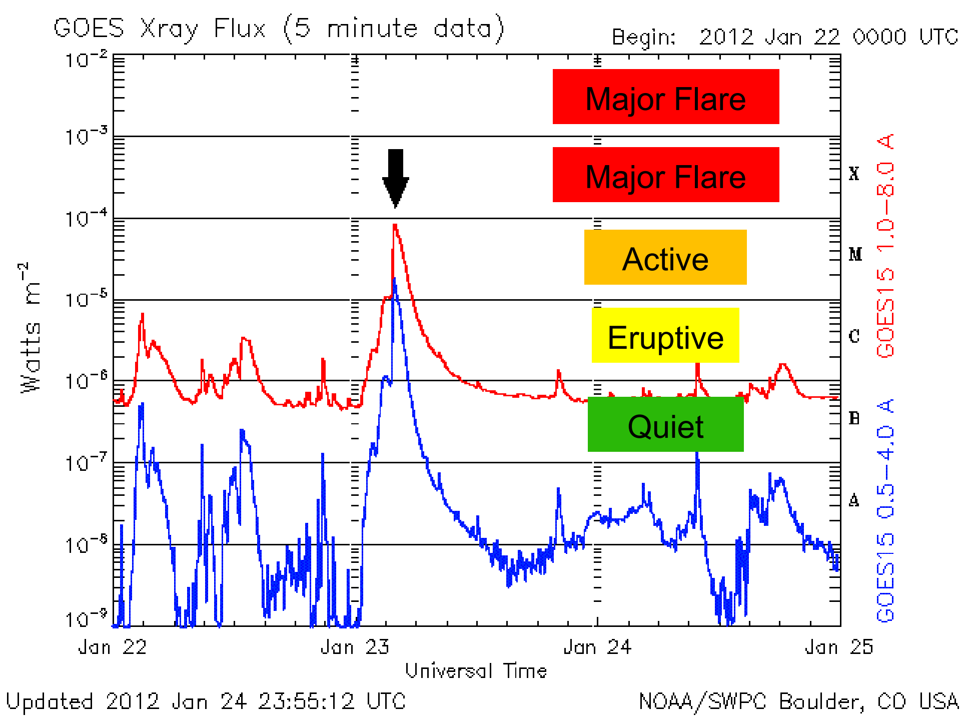


[Buhari+, JGR, 2014]

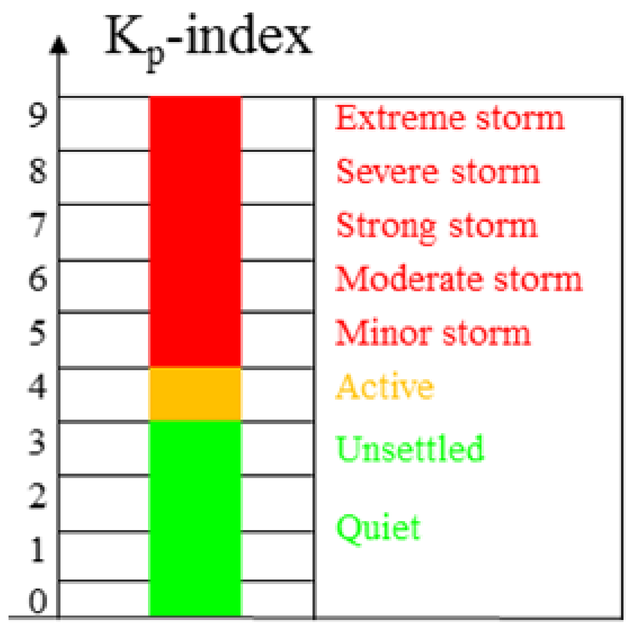
A new ionospheric storm scale

- Solar and geomagnetic activities have clear definitions based on physical measures.
- Ionospheric storms have no clear definition.

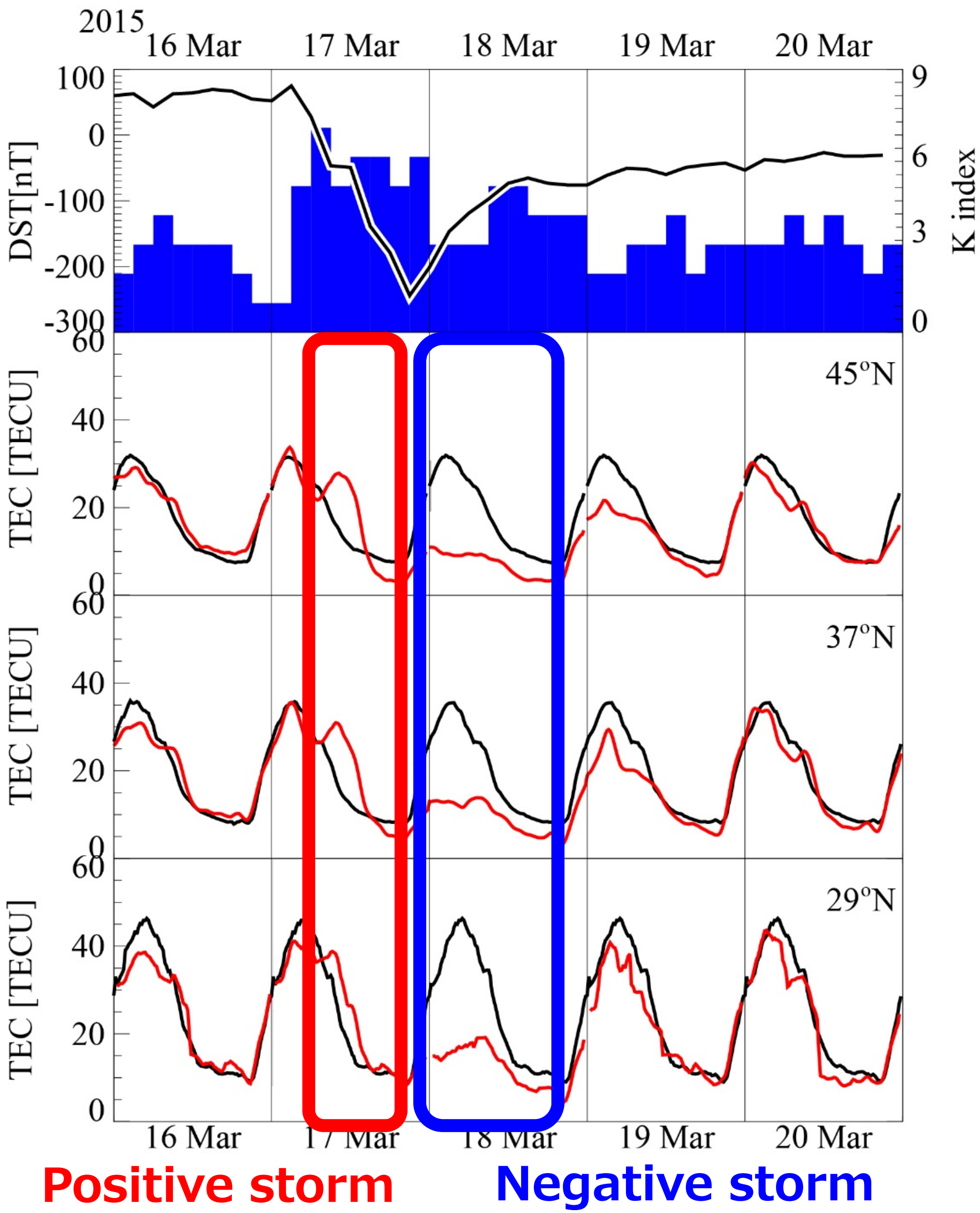
Solar flare: GOES X-ray Flux



Magnetic storm: K-index
(and Kp, Dst, AE, etc.)



A new ionospheric storm scale: I-scale

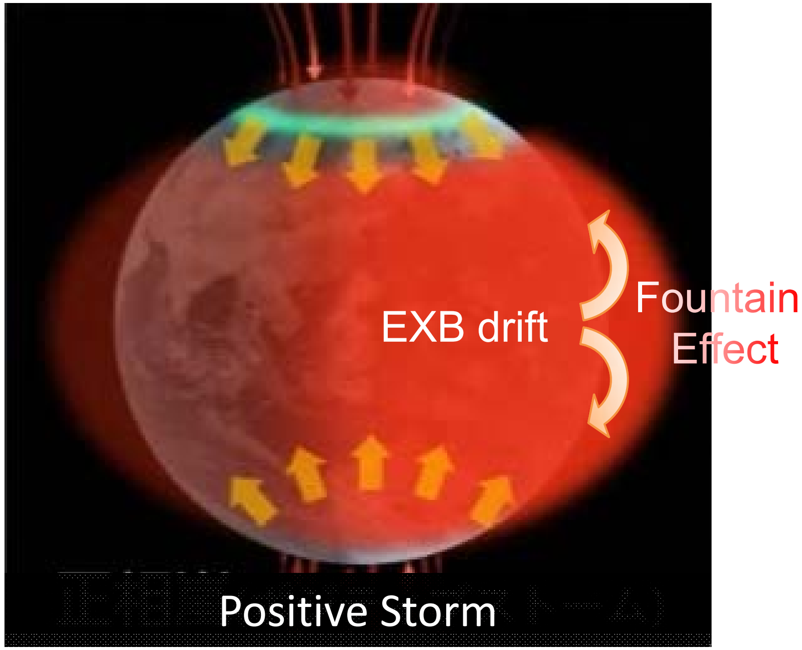


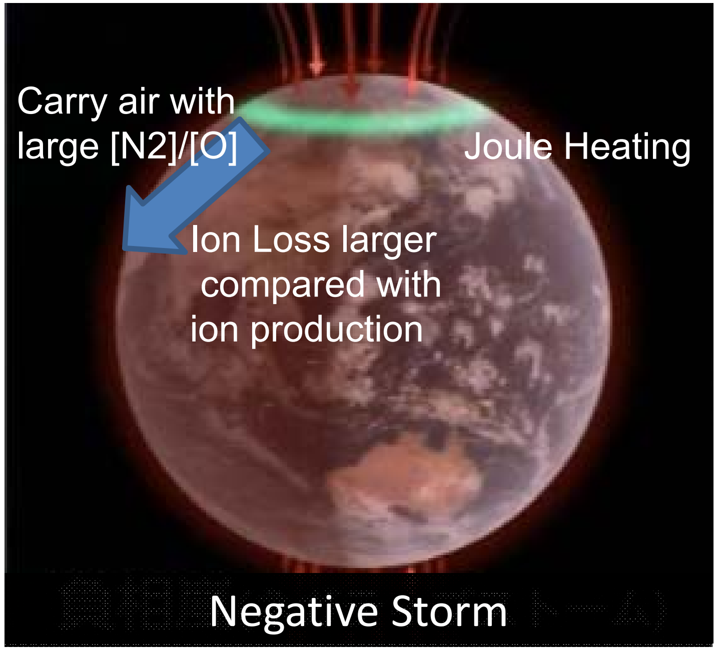
TEC in the Japanese sector during the St Patrick's day storm

- Observation (red)
- median of 27 days (black)

- Ionospheric parameters largely depend on local time, season, and latitude.
- It is necessary to investigate the ionospheric parameters statistically in order to define an universal ionospheric scale.

Basic mechanism of iono. storm





Positive Storm

- Larger F2-region plasma density than that for the quiet time
- Caused by disturbed electromagnetic force/ thermospheric wind
- Frequently occurs at the initial phase of magnetospheric storms
- Makes larger the GPS positioning error

Negative Storm

- Smaller F2-region plasma density than that for the quiet time
- Mainly caused by change in the thermospheric composition ([O]/[N2])
- Continues for one to several days frequently after positive storm
- Makes difficult the communication using higher frequency part of HF

Data set and methodology

【Data Set】

- 15-minute TEC for 18 years from 1997 to 2014 (TEC_{obs}).

【Methodology】

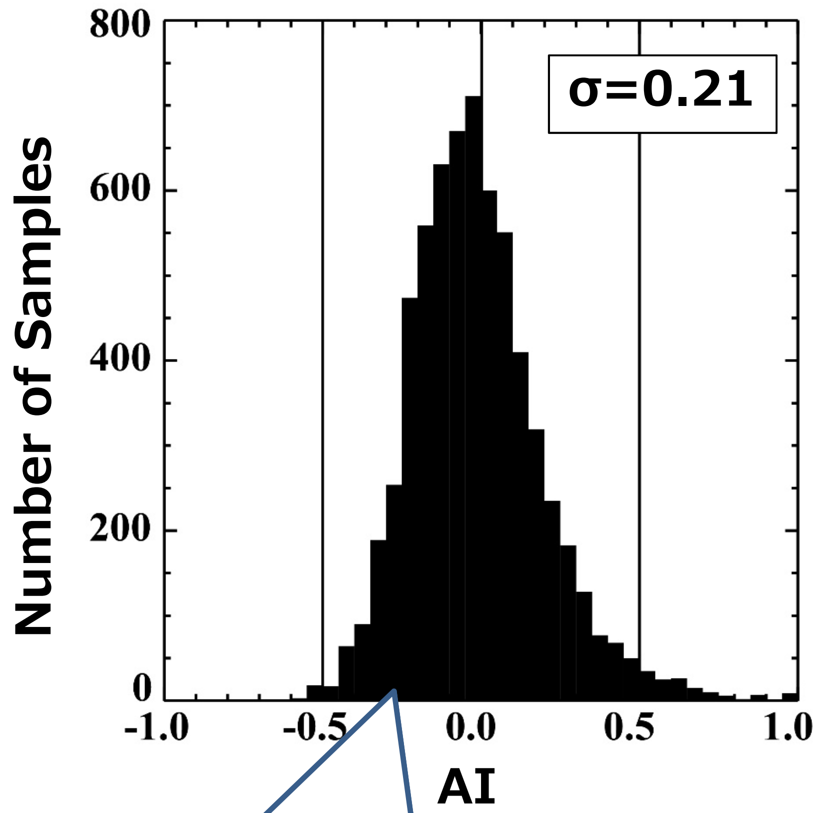
- Ionospheric activity index (AI) is used to describe ionospheric state [e.g. Bremer et al., 2006].

$$AI = \frac{TEC_{obs} - TEC_{ref}}{TEC_{ref}}$$

- The reference value, TEC_{ref} is defined as a median of TEC_{obs} at the same local time and latitude in the past 27 days.

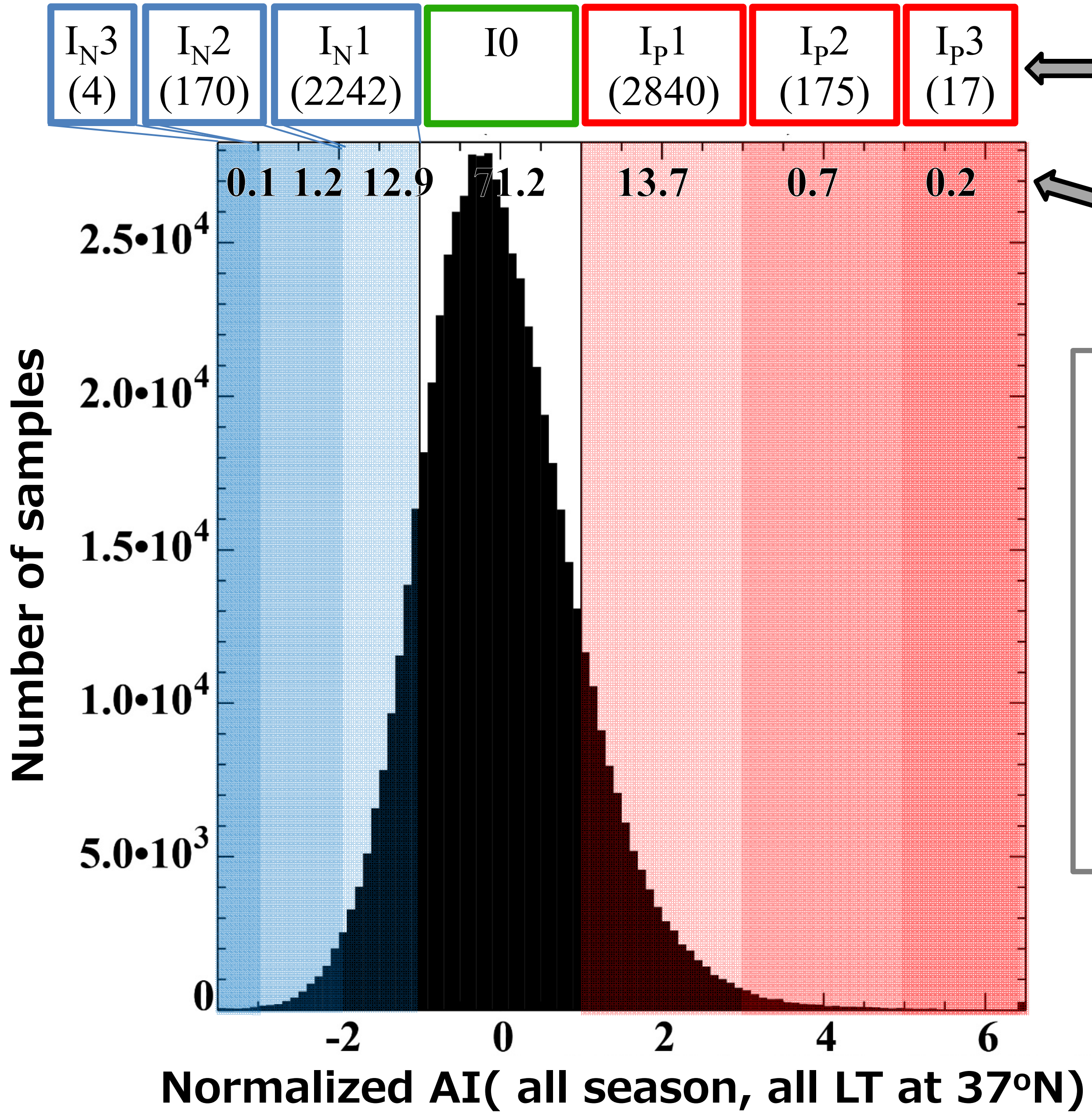
- Distribution of AI is investigated to determine an ionospheric storm scale.

Distribution of AI
(29°N, May-Jul, 20JST)



4 (samples/hour) x 90 (days) x 18 (years) =6480 samples

A new ionospheric scale: I-scale



I-scale
(Number of events with a duration of 2h or more)

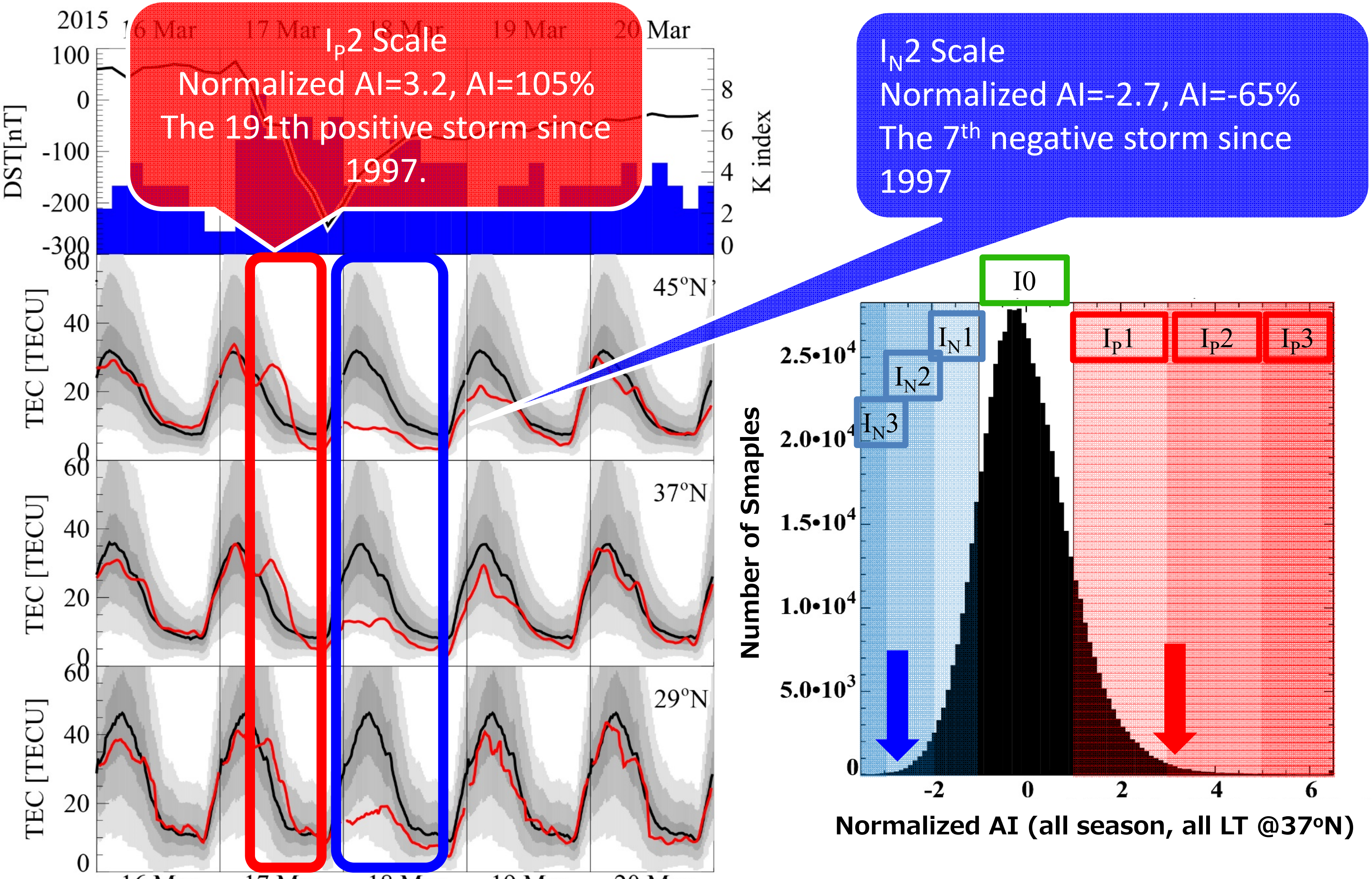
Occurrence rates
(every 15min) (%)

Positive storm scale
- I_P1: 1σ~3σ
- I_P2: 3σ~5σ
- I_P3: 5σ>

Negative storm scale
- I_N1: -1σ~-2σ
- I_N2: -2σ~-3σ
- I_N3: -3σ<

I-scale does not depend on season/LT/latitude.

St. Patrick’s event

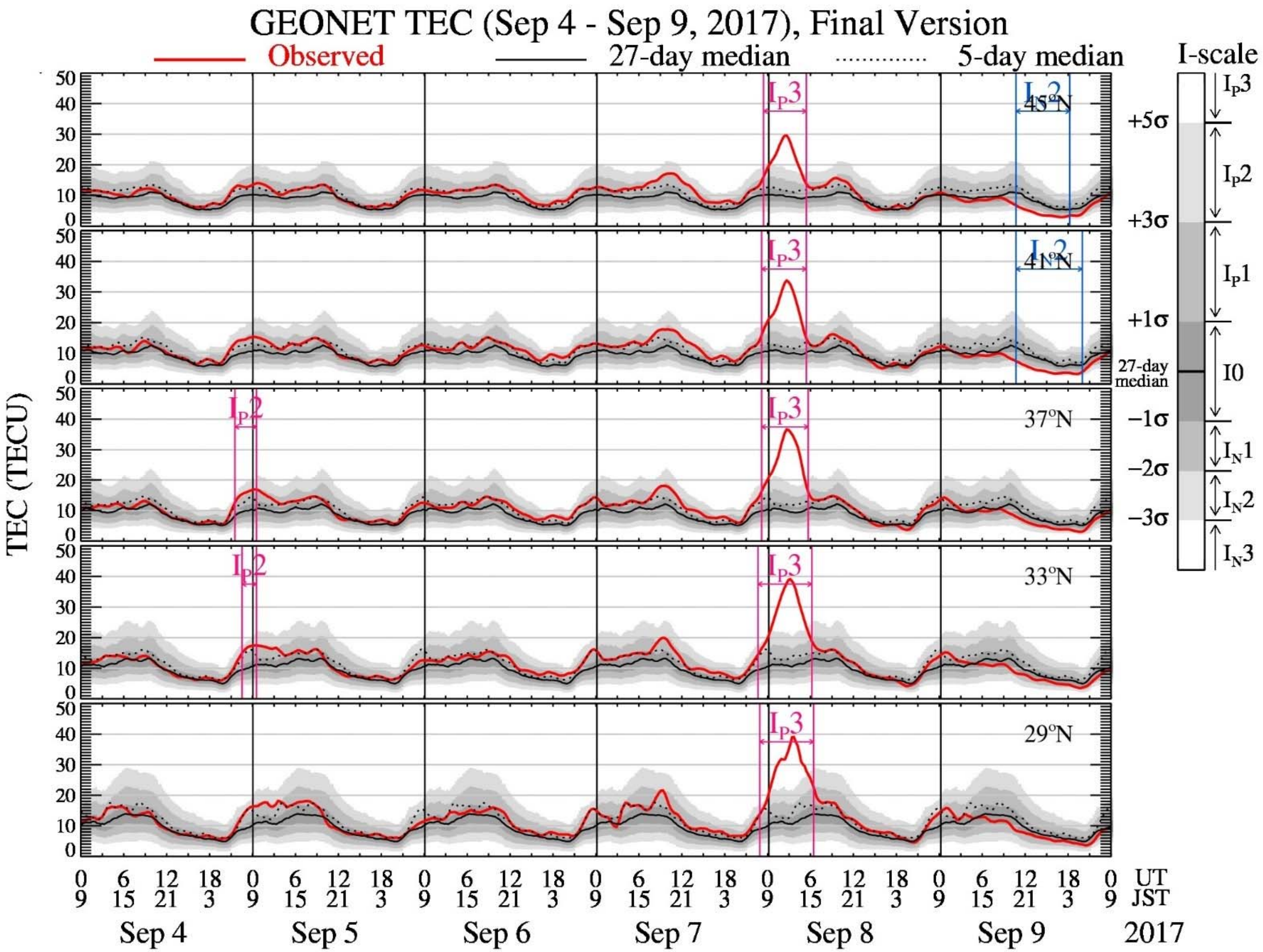


Positive storm **Negative storm**

[Nishioka et al., *Space Weather*, 2017]

Ionospheric storm monitoring system

http://seg-web.nict.go.jp/GPS/FC_GEONET/LAT-TEC



Ionospheric storm monitoring system

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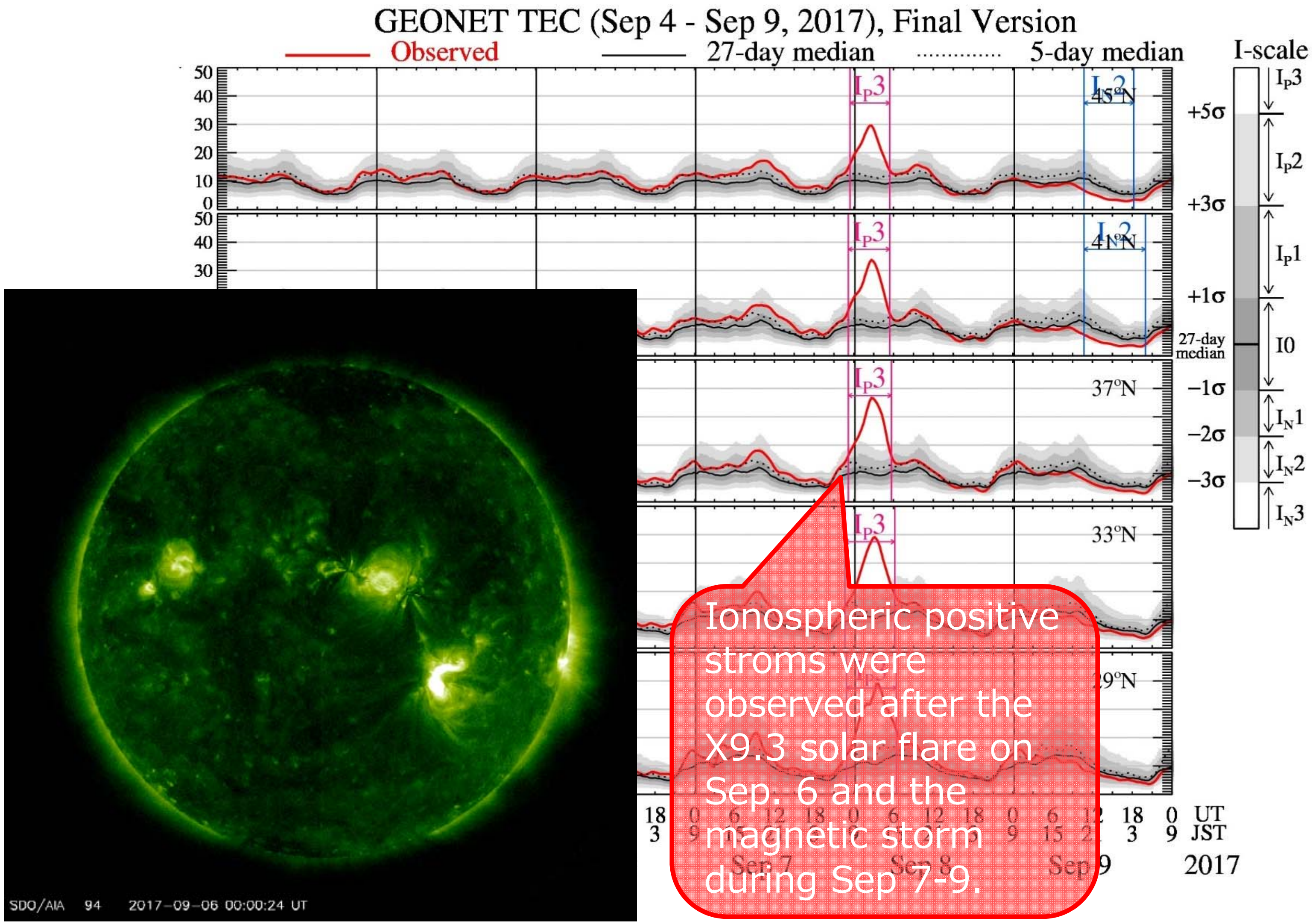


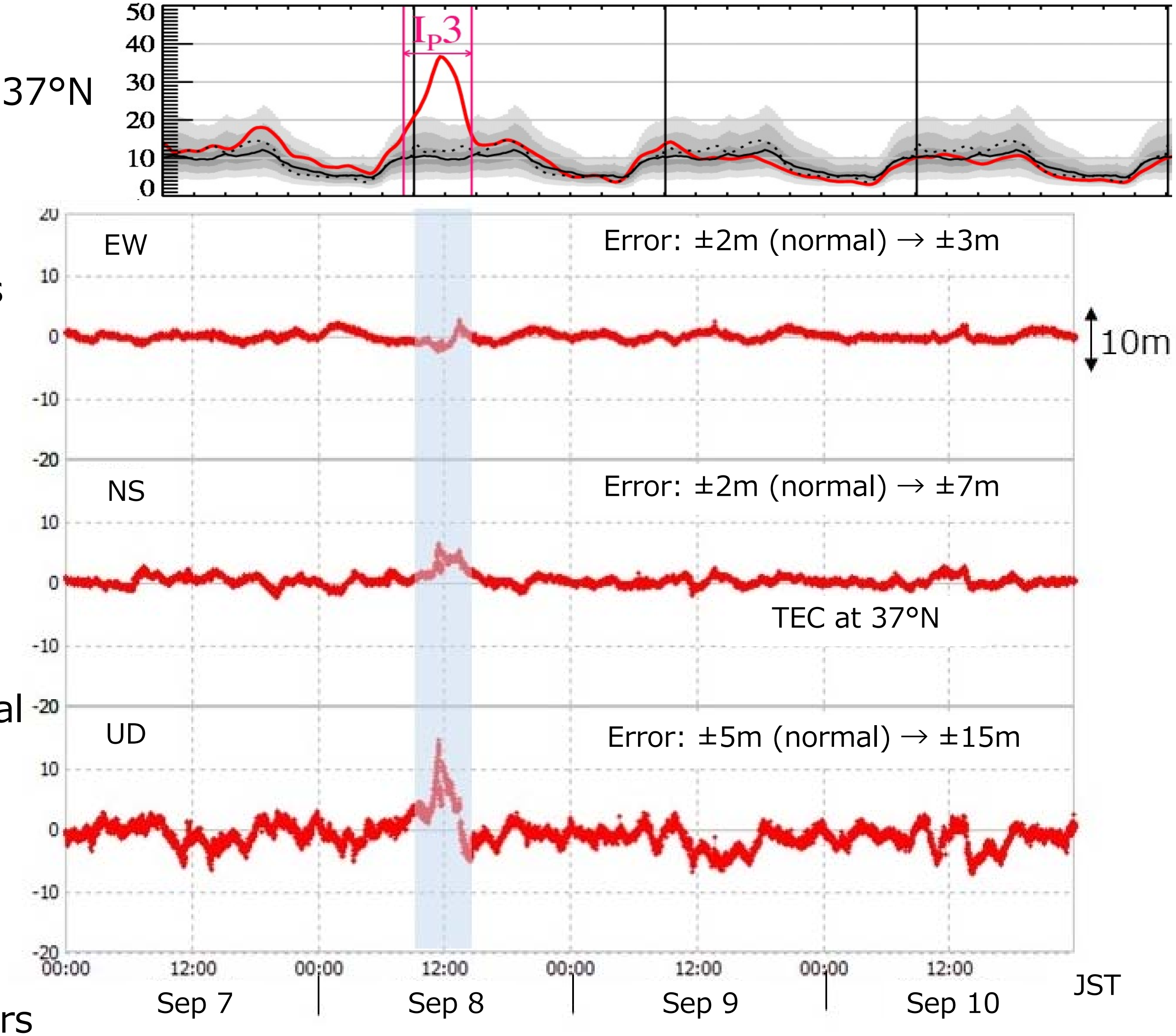
Ionospheric positive stroms were observed after the X9.3 solar flare on Sep. 6 and the magnetic storm during Sep 7-9.

Social impact: GPS positioning error

TEC at 37°N

Single-frequency positioning errors at Tsukuba station

- Ionospheric delay = TEC*40.3/cf²
- TEC became ~3.5 times larger than usual → ionospheric delay became ~3.5 times larger → comparable increase in positioning errors



from GSI, Japan (http://www.gsi.go.jp/denshi/denshi40001.html)

Ongoing study: Forecasting ionospheric storm using a machine learning technique

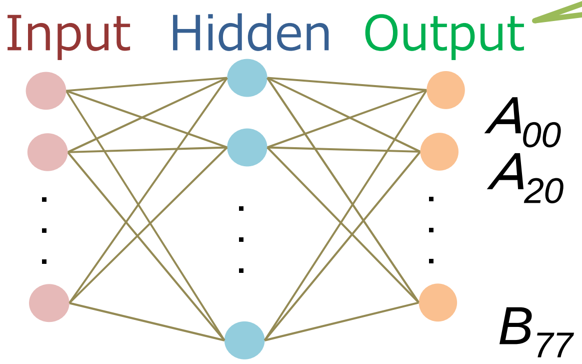
Data available on realtime bases

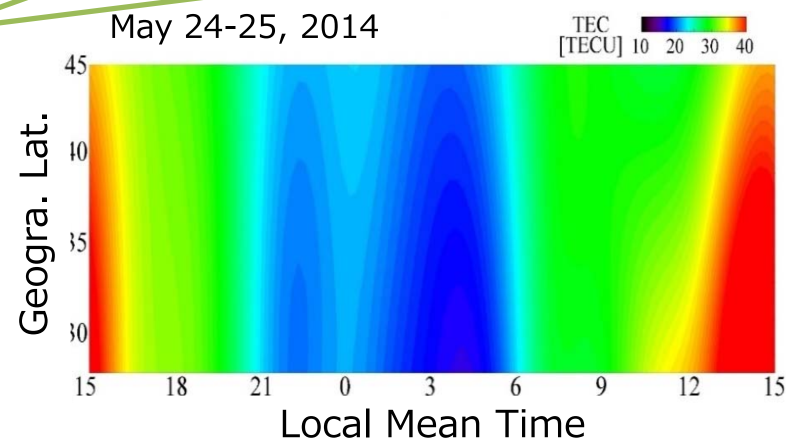
Quiet model
【Sun】F10.7, SSN、MgII
【Time】DOY
【Iono.】Previous-day TEC

Disturbed Model
【Iono.】Q-model output
【SW】IMF-Bt
【Mag.】K-index, Dst

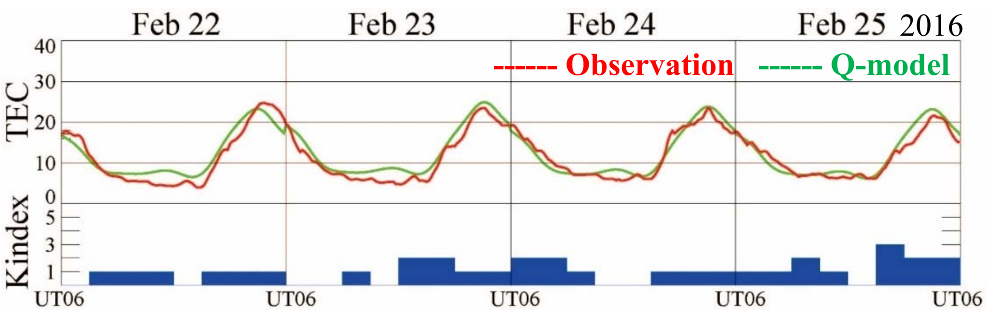
7000-day data from 1997年 were used

2D TEC map against latitude and local mean time, which is represented by 36 coefficients of the surface harmonics function.

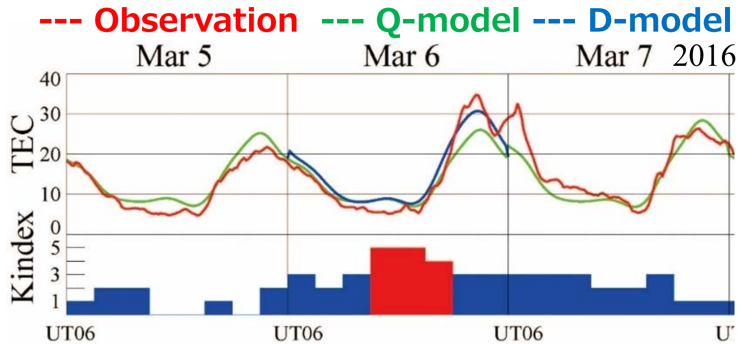




Quiet Model



Disturbed Model



Summary

- We have developed high-resolution TEC observations using dense GNSS receiver networks. The TEC observations can be a powerful tool to monitor and research ionospheric space weather phenomena such as ionospheric strom, plasma bubble, and traveling ionospheric disturbances.
- We conducted the DRAWING-TEC project to expand observation area of high-resolution TEC maps by the international exchange and sharing of GNSS and TEC data. A new TEC format, GTEX, was approved as one of the standard data of trans-ionospheric data in the Recommendation ITU-R P.311.
- A new universal ionospheric storm, I-scale, has been established based on statistical analysis of 18-year TEC data. Ionospheric storm monitoring system has been developed based on I-scale with realtime TEC observations in Japan.

Acknowledgement

TEC and ROTI maps in this paper were derived using GNSS receiver data provided by GSI, UNAVCO, IGS, SOPAC, CORS, EPN, BKGE, OLG, IGNE, DUT, ASI, ITACYL, ESEAS, SWEPOS, NMA, BIGF, MyRTKnet, and SuGAr. The GNSS data collection and processing were performed with the NICT Science Cloud. This work was partially supported by JSPS KAKENHI Grant Number JP16H06310, JP15H05813, and JP16H06286.

NICT