# High-resolution ionospheric total electron content observations using dense GNSS receiver networks

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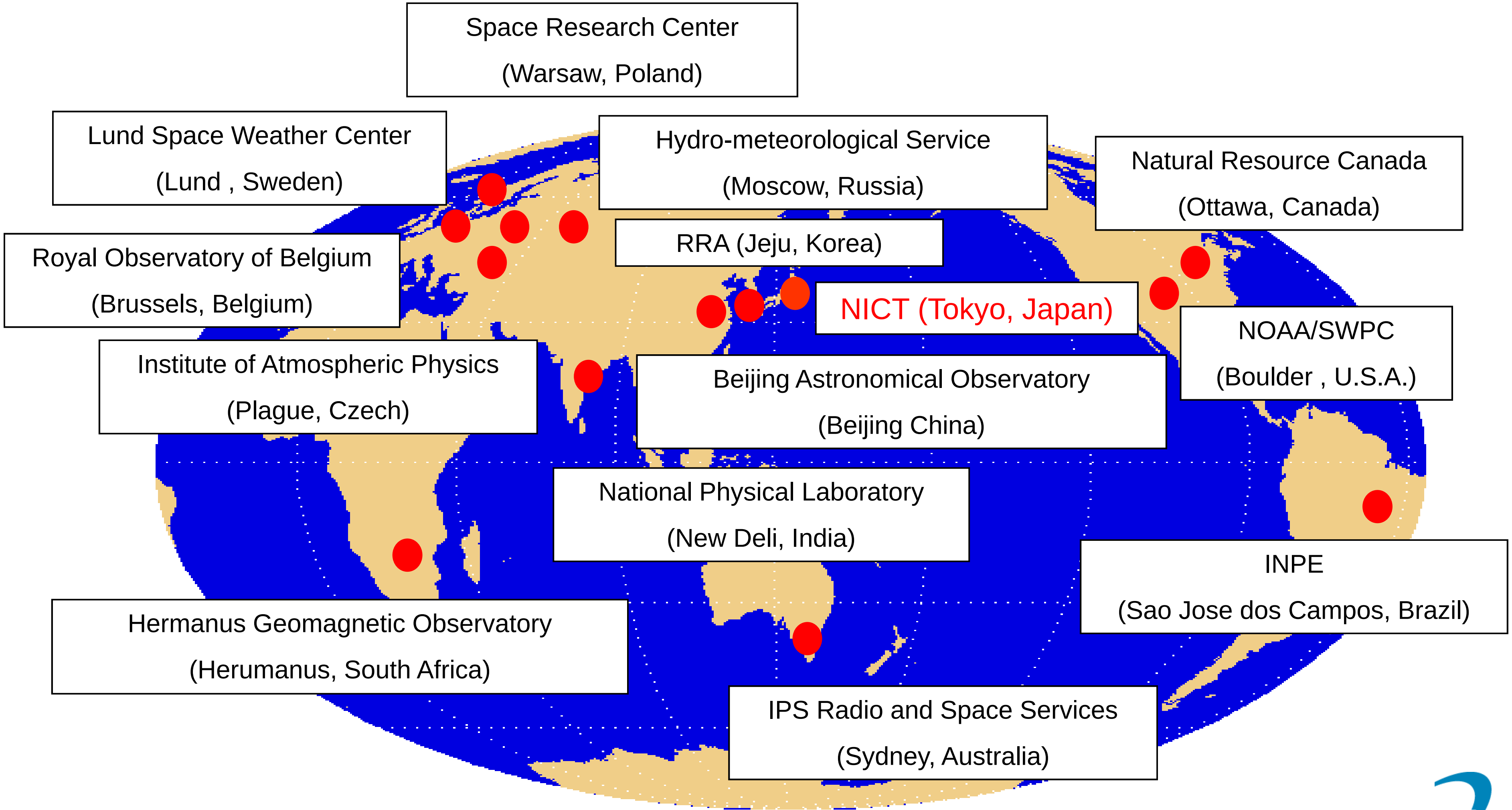
- Brief introduction of NICT's space weather activities
- High-resolution GNSS-TEC observations
- DRAWING-TEC project

NICT

# About NICT

- Headquarter: Koganei, Tokyo
- Staff: permanent researchers: 300, temporal researchers: 400, administrative: 200 (approximately).
- The “ONLY National Institute” of Information and Communications technology in Japan
- Our originality was in ionospheric observations for monitoring short wave propagations
- Our study fields expand not only narrow meaning of ICT, but also wide areas.

# Forecast centers of International Space Environment Service (ISES)



# NICT Space Weather Forecast Center

**Exchanging forecast and data among ISES forecast centers**

**Real-time space weather monitoring**

**Result of simulation**

- Flare prediction
- Geomagnetic activity prediction
- High energy particle prediction


**NICT Space Weather Forecast Center**

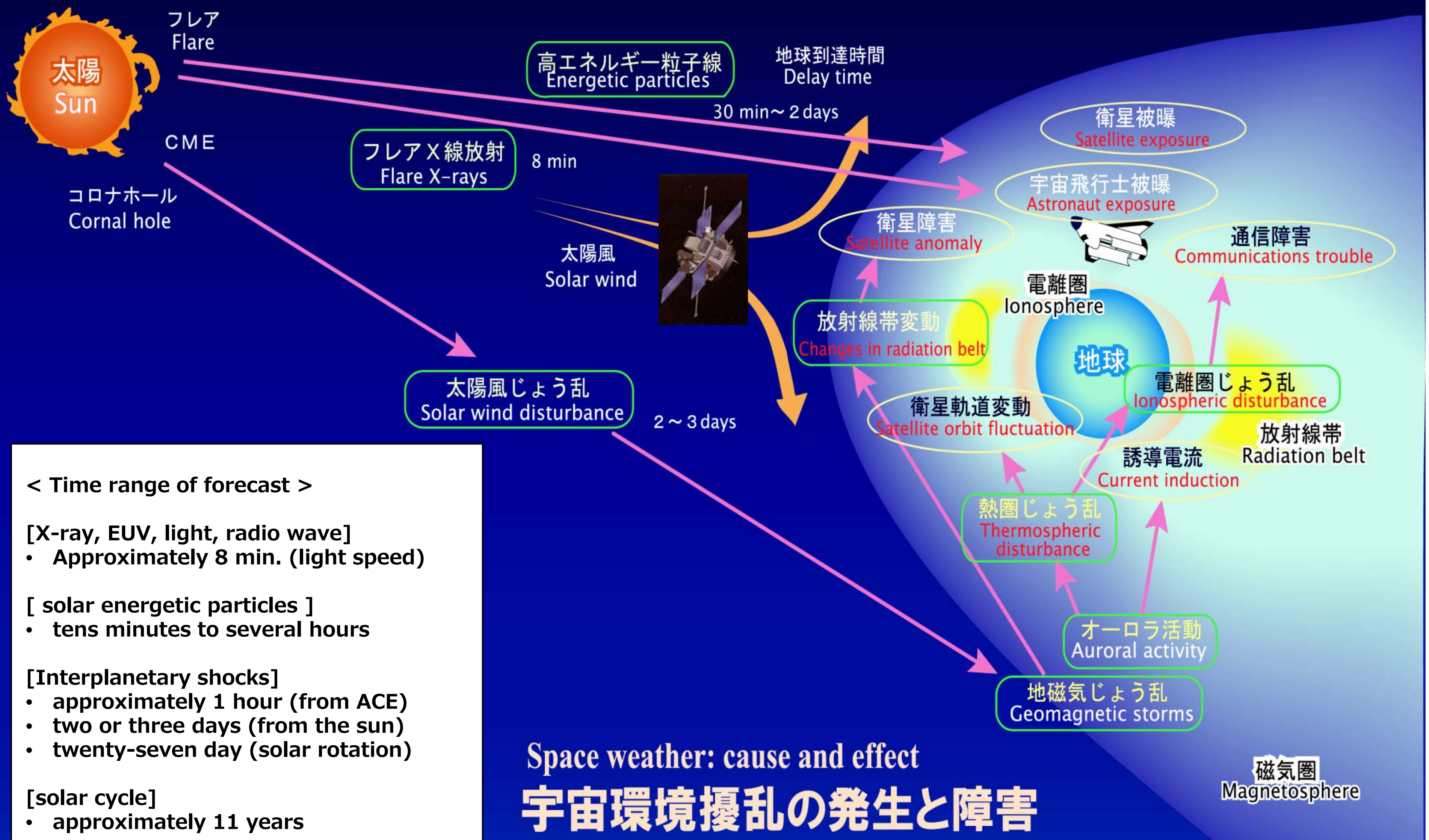
**Forecasts and current conditions of flare activities, geomagnetic activities, high-energy particle flux, HF propagation condition by web, e-mail, RSS, fax**

Domestic users: satellite operators, operators of power company, museum, operators of HF radio communication, etc.

# Space Weather Forecast Meeting


- We (forecasters and researchers) have a meeting to make a forecast every afternoon.

# Space weather: cause and effect




**< Time range of forecast >**

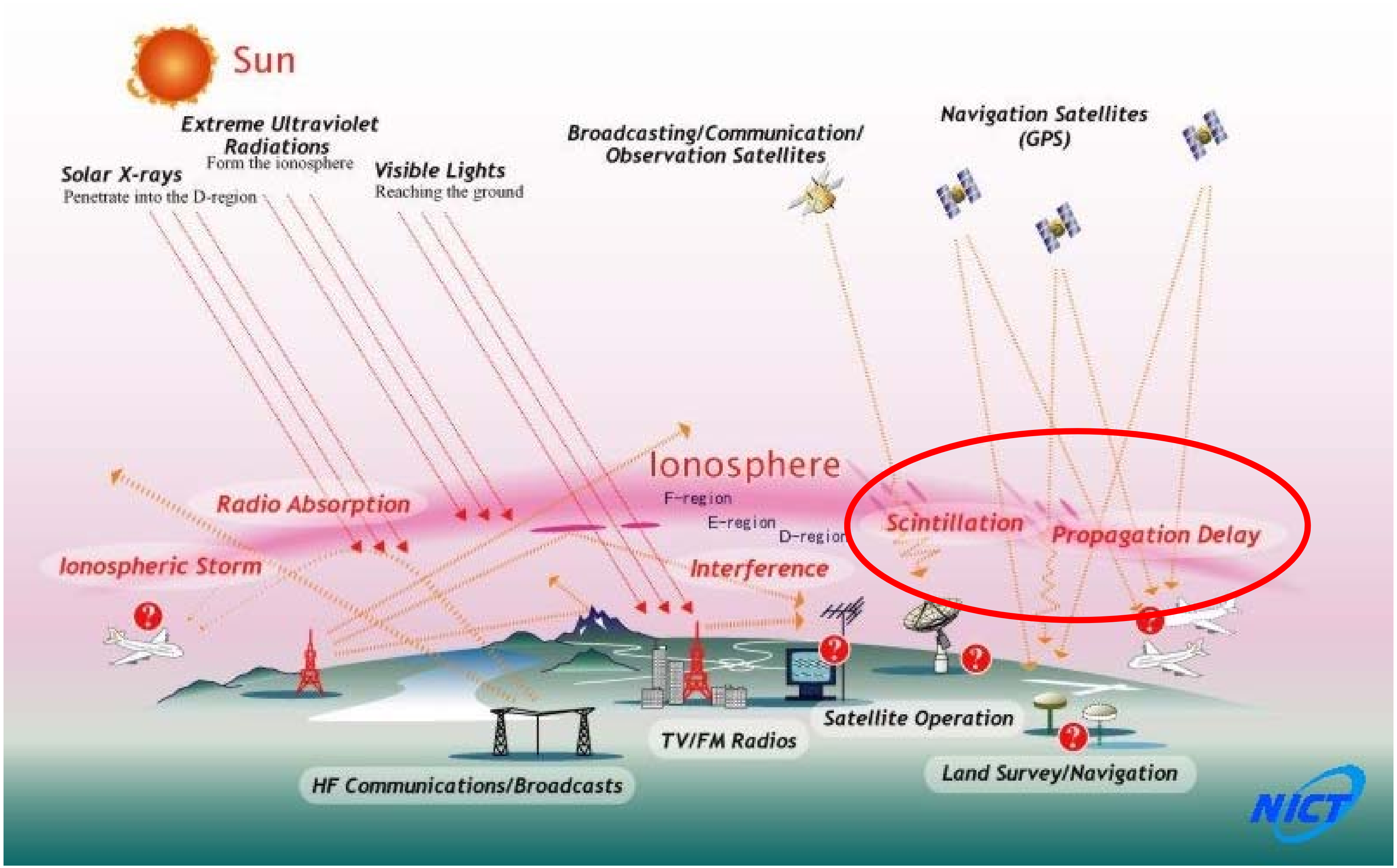
**[X-ray, EUV, light, radio wave]**
- **Approximately 8 min. (light speed)**

**[ solar energetic particles ]**
- **tens minutes to several hours**

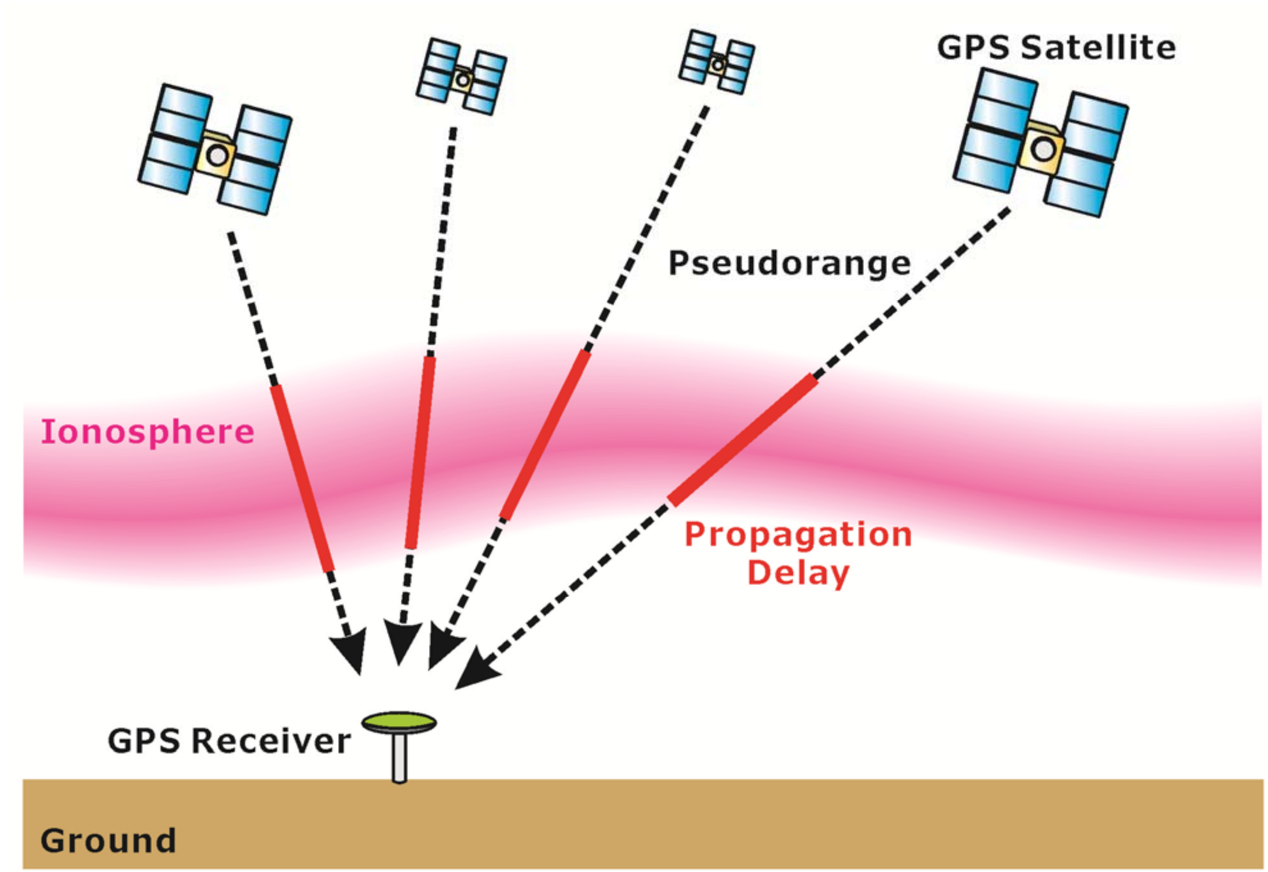
**[Interplanetary shocks]**
- **approximately 1 hour (from ACE)**
- **two or three days (from the sun)**
- **twenty-seven day (solar rotation)**

**[solar cycle]**
- **approximately 11 years**

# Ionospheric effects on radio applications

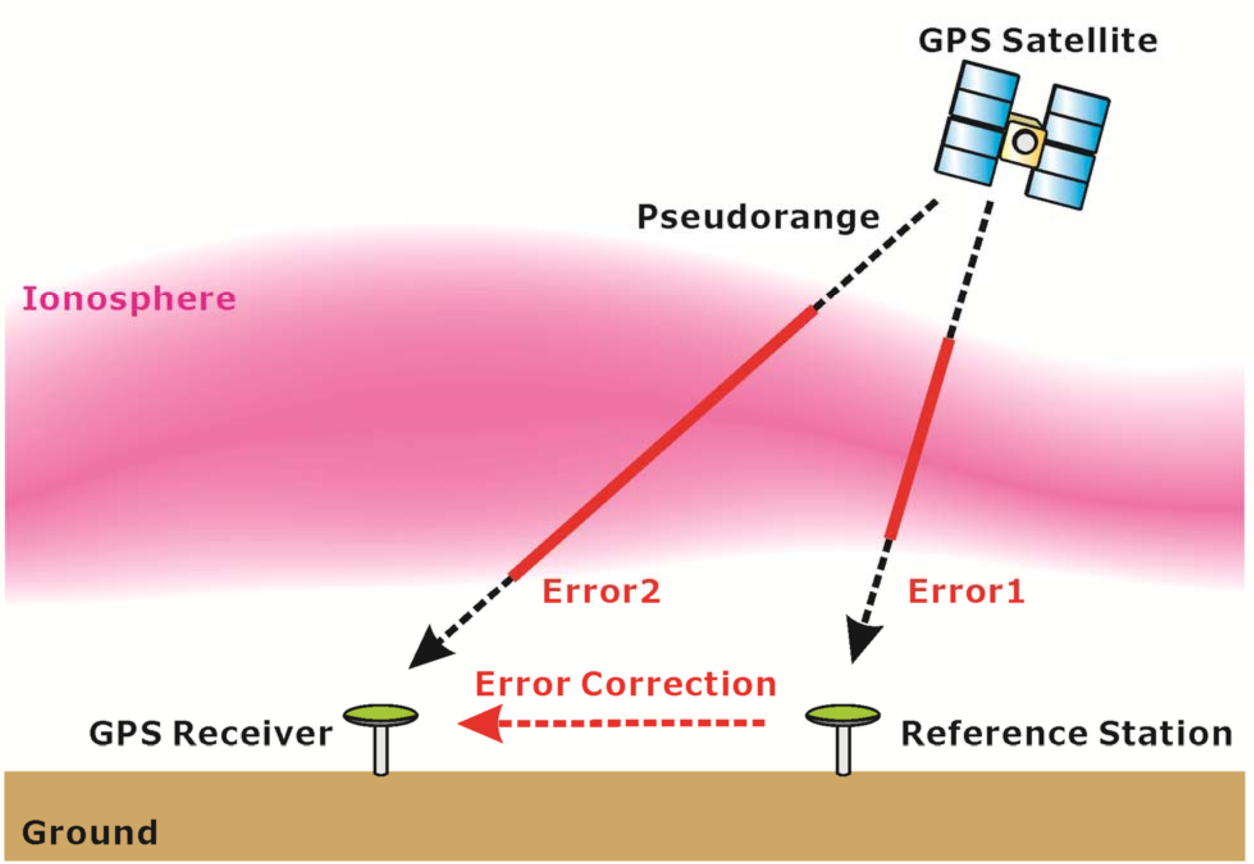


# GPS navigation and positioning



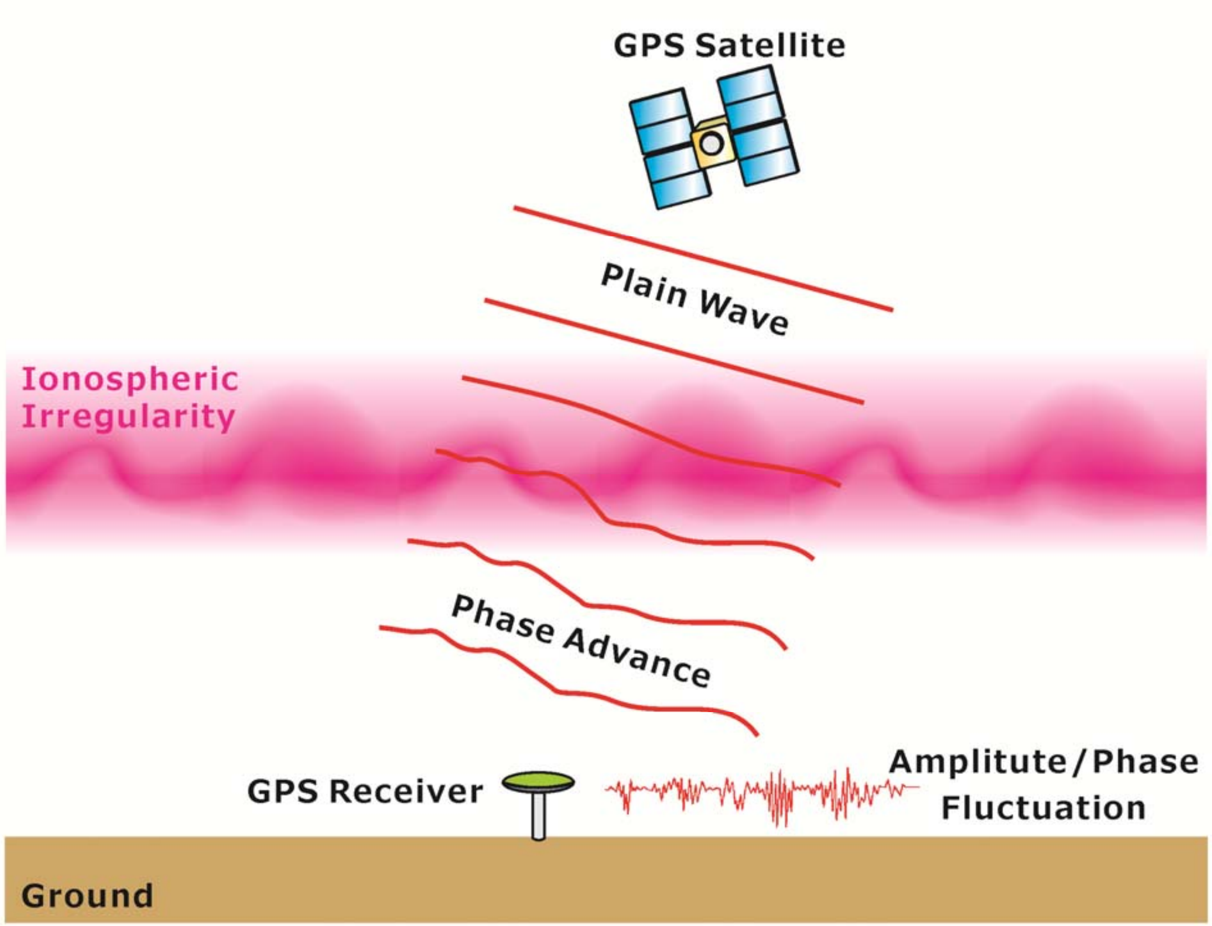

- Pseudorange includes ionospheric propagation delay which is the largest error of GPS positioning/navigation for general single-frequency GPS receivers.

# Differential GPS positioning




- Steep spatial gradient of ionospheric electron density causes differential GPS positioning errors.

# GPS scintillation




- Several 100m scale ionospheric irregularity causes GPS scintillation which results in loss-of-lock on GPS signals in the worst case.

# Derivation of TEC using GPS

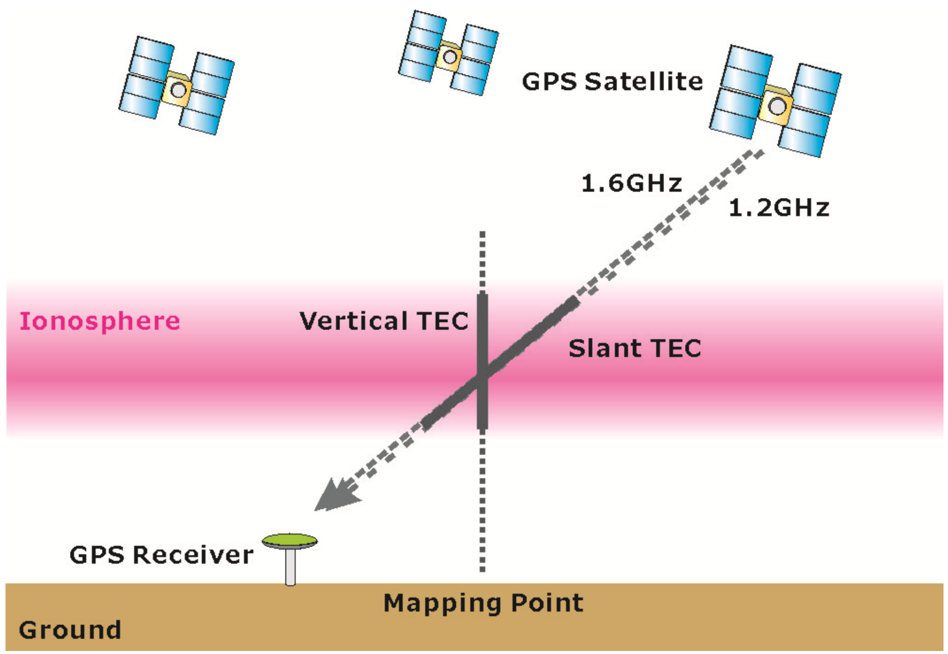
- Total electron content (TEC) can be derived by comparing the pseudorange/phase delays of the two GPS signals.

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

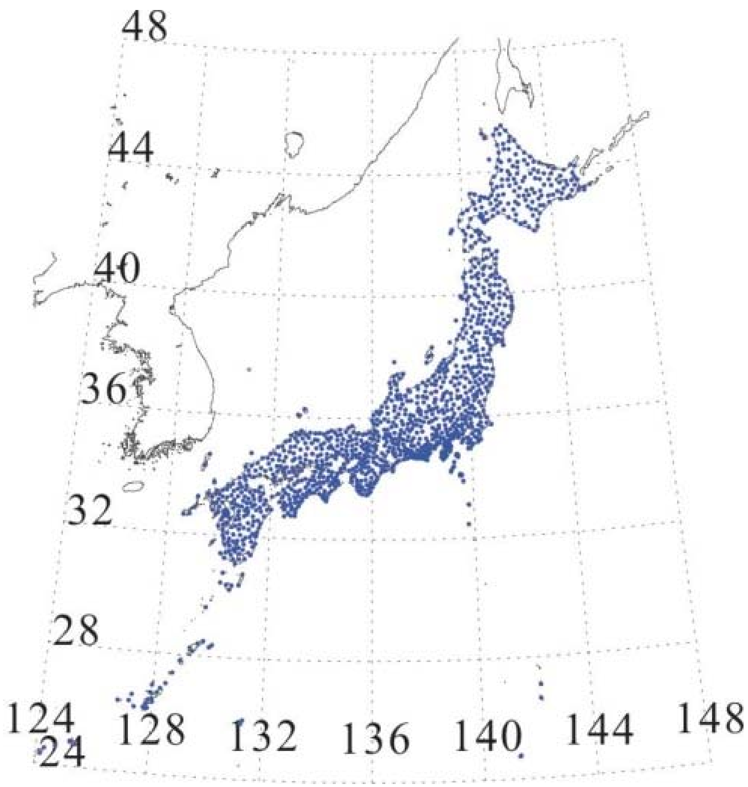
$P_1$ $P_2$: Pseudorange
$L_1$ $L_2$: Carrier phase
$I$: Total electron content
$f_1$, $f_2$: Frequency
$\rho$: True range between the GPS satellite and receiver

- TEC is a measure of integrated electron density in $1m^2$ column.

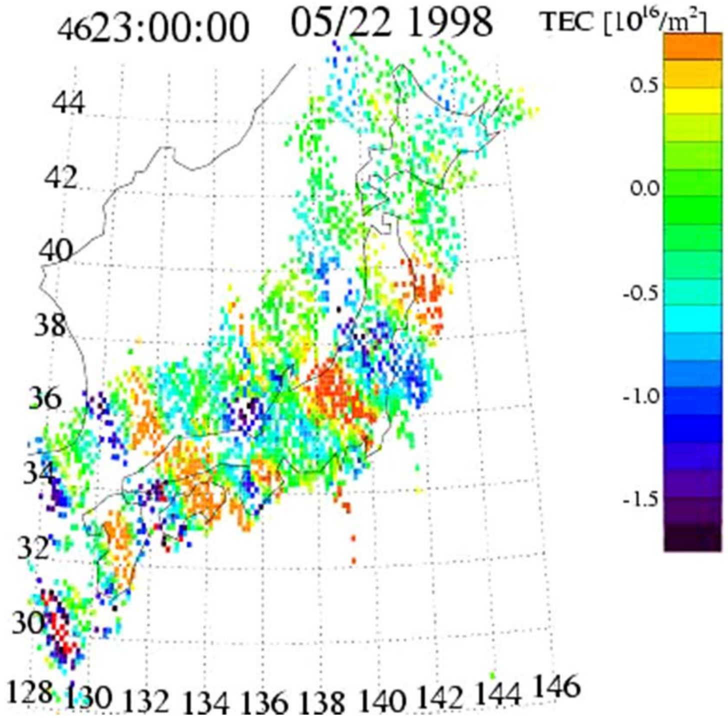
- 1 TECU($=10^{16}$electrons/$m^2$) is frequently used as a measuring unit of TEC.



# High-resolution TEC observation using a dense GPS receiver network




GEONET consisting of more than 1,200 GPS stations




Detrended TEC with 60-min window revealed medium-scale traveling ionospheric disturbances (MSTID) [Saito et al., GRL, 1998].

- A dense GPS receiver network makes it possible to observe high-resolution two-dimensional TEC variations.

# GPS-TEC maps in Japan

http://seg-web.nict.go.jp/GPS/GEONET

DRAWING-TEC: Home
GEONET GPS-TEC maps: Final | Quasi-Realtime | Realtime (β ver.)

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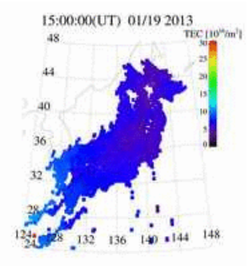
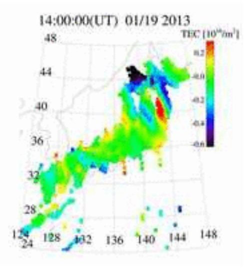
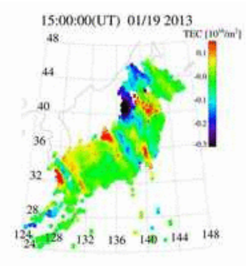
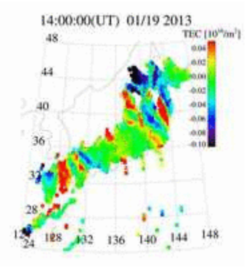
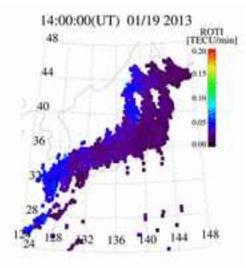
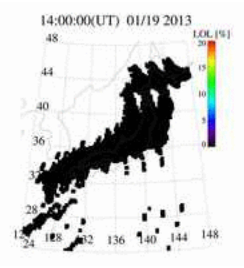
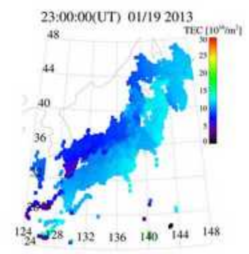
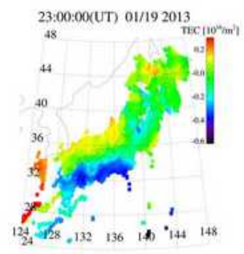
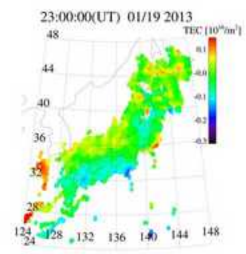
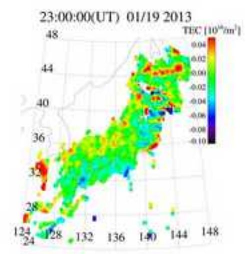
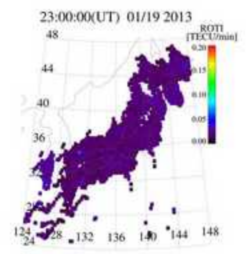
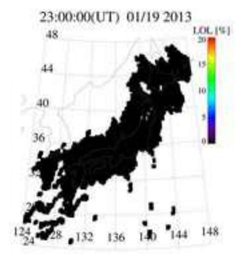
## GEONET GPS-TEC maps over Japan
## (latest 24 hours with 1-hour interval)

Japanese / English

The TEC (total electron content) data for TEC, detrended TEC, and ROTI maps are calculated by NICT under collaboration with Kyoto University and Nagoya University using GEONET GPS data provided by Geospatial Information Authority of Japan. If you have any questions or comments, please e-mail to iono@ml.nict.go.jp .

| Data Archive | TEC | Detrended with 60-min window | Detrended with 30-min window | Detrended with 15-min window | Rate of TEC change index | Rate of loss of lock on GPS |
|---|---|---|---|---|---|---|
| Latest 24 hours |   |   |   |   |   |   |
| **Time** | **TEC** | **Detrended with 60-min window** | **Detrended with 30-min window** | **Detrended with 15-min window** | **Rate of TEC change index** | **Rate of loss of lock on GPS** |
| 2013/01/19 23:00 UT<br>2013/01/20 08:00 JST |   |   |   |   |   |   |

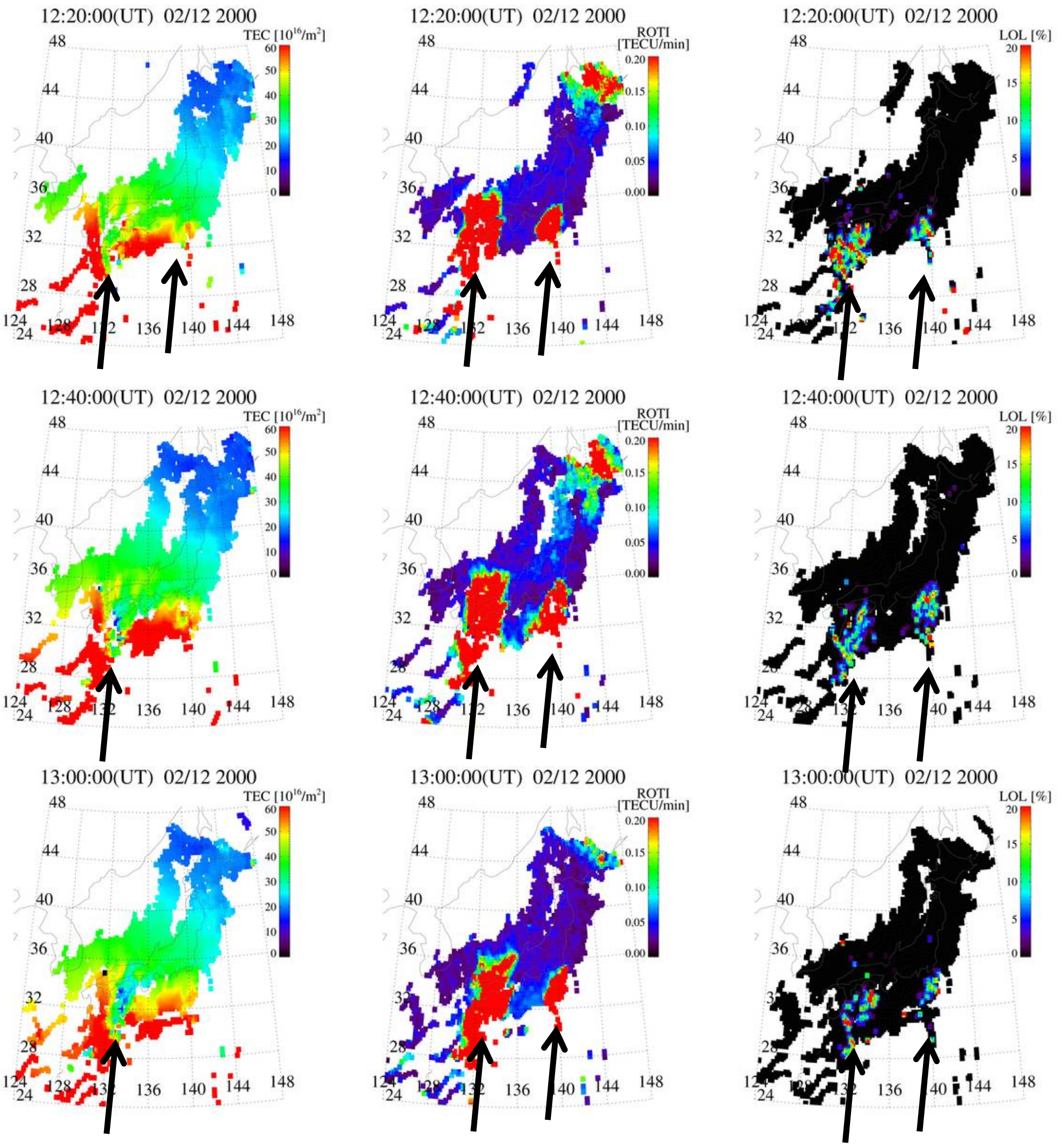
# High resolution GPS-TEC maps in Japan

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

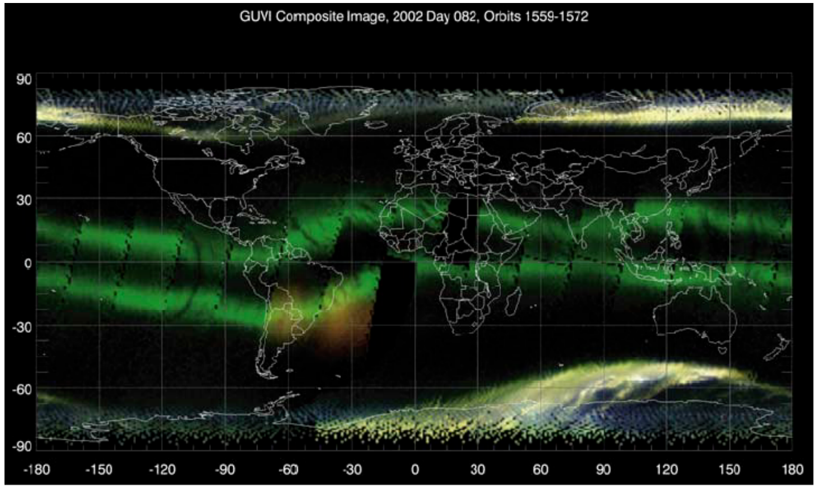
12:20 UT (21:20 JST)

12:40 UT (21:40 JST)

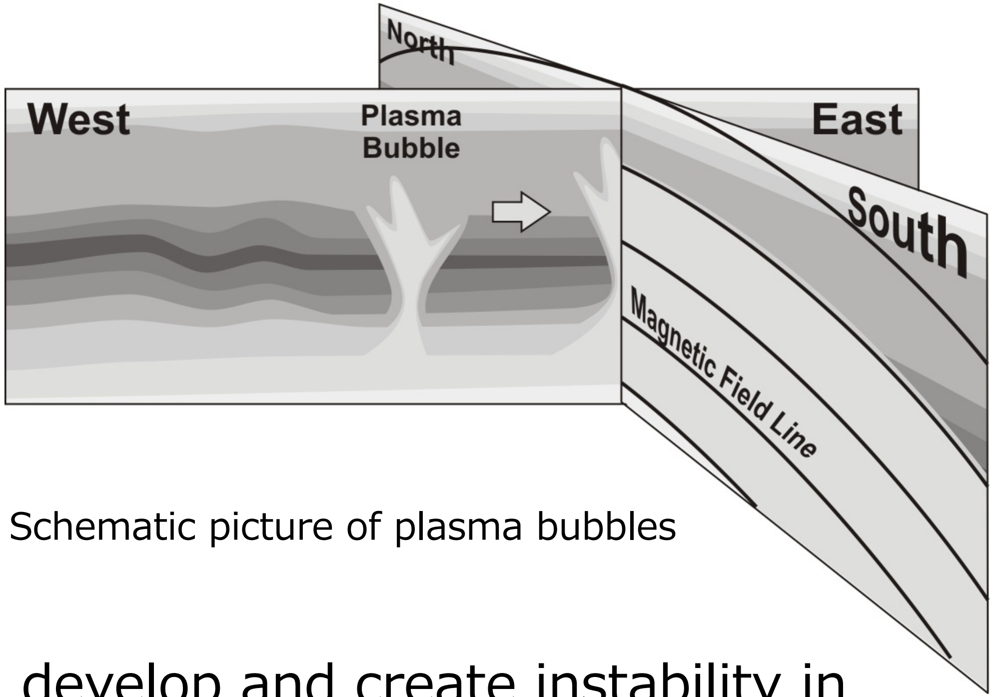
13:00 UT (22:00 JST)



# Equatorial plasma bubble (EPB)




135.6nm airglow images observed by TIMED/GUVI [Christensen et al., 2003]

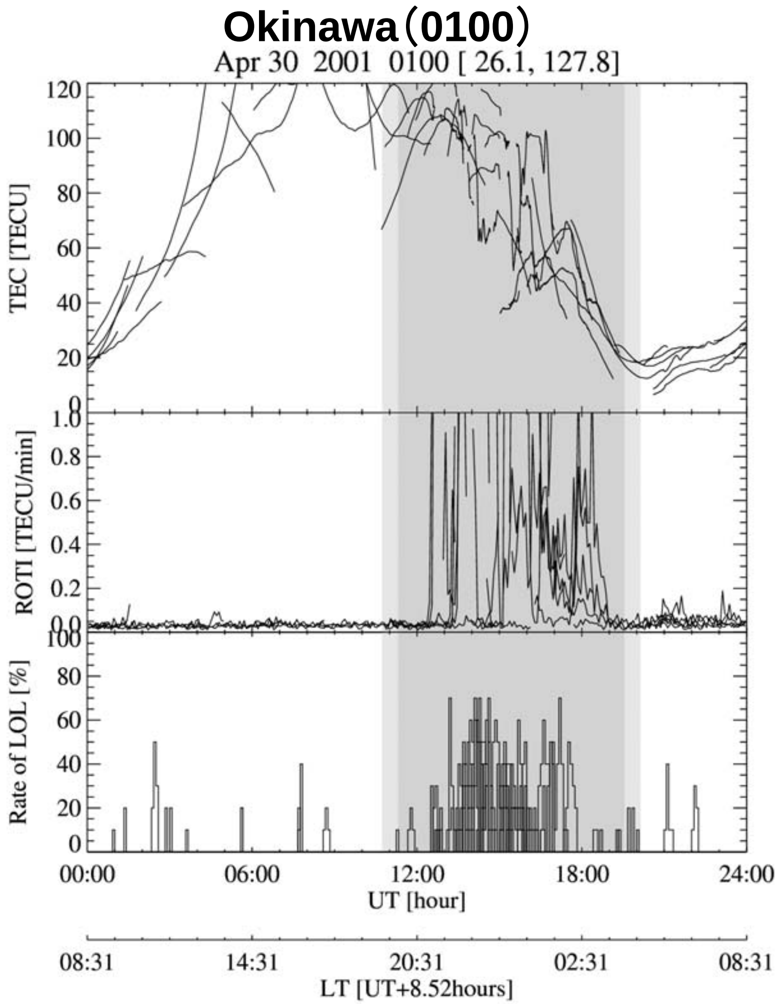


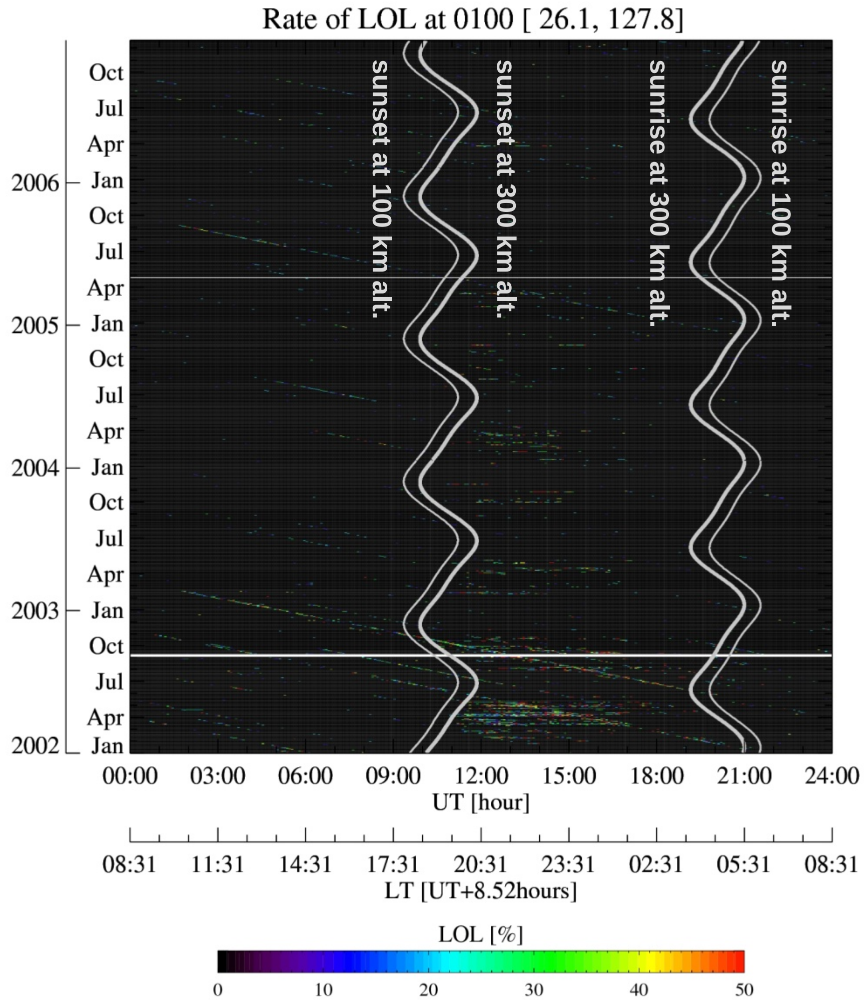

Schematic picture of plasma bubbles

- Plasma bubbles generally can develop and create instability in the low-latitude ionosphere after the sunset.
- Plasma bubbles generally move eastward and have the structure extending along the magnetic field line.
- A prompt penetrating magnetospheric electric field during the magnetic storm helped to trigger the super plasma bubble observed at mid-latitudes.

NICT

# ROTI and LOL at Okinawa, Japan

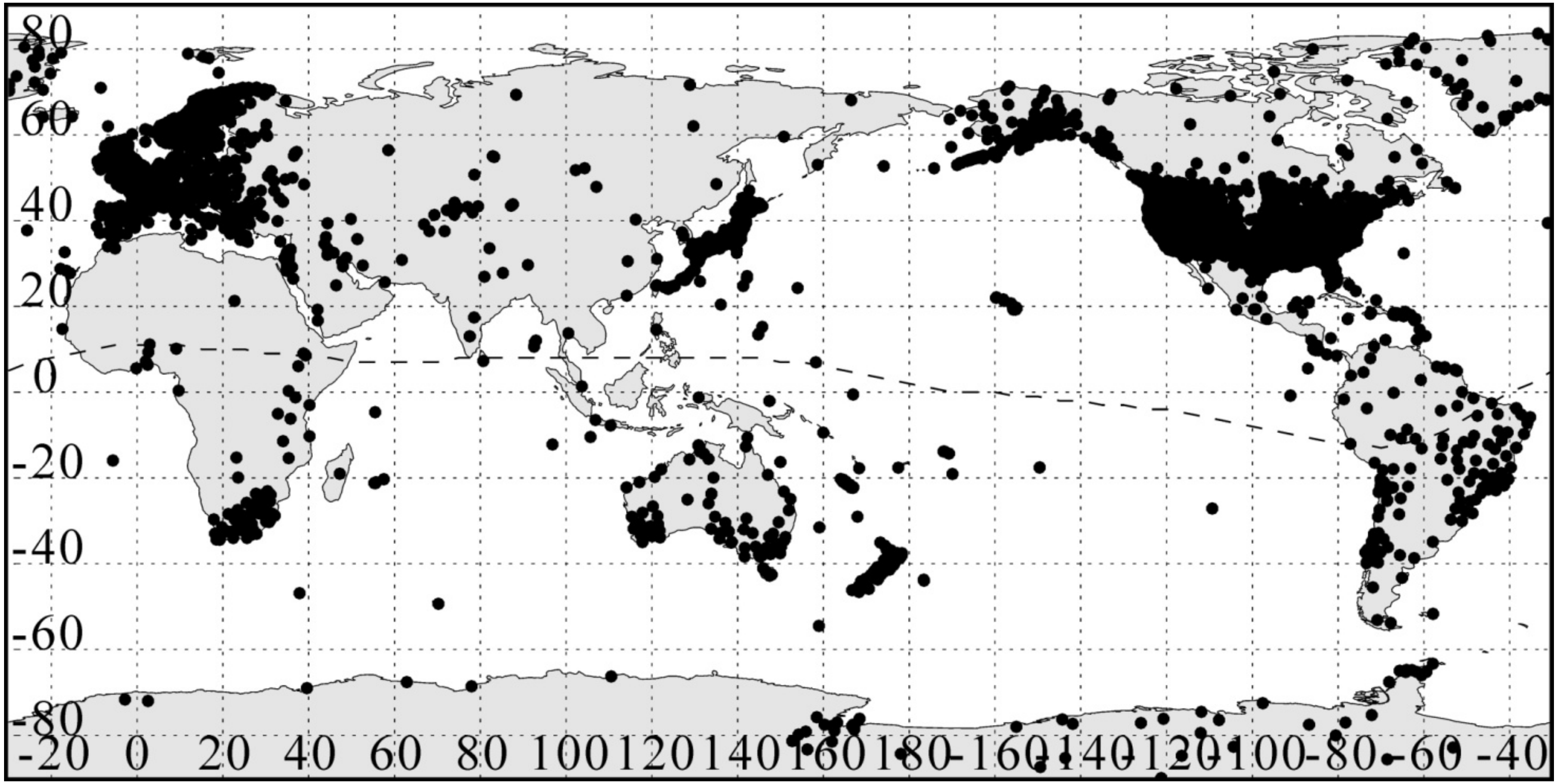



- Slant TEC, ROTI, and Rate of GPS-LOL (5-min window) on Apr 30, 2001.
- Sat. zenith angle: < 45 deg.

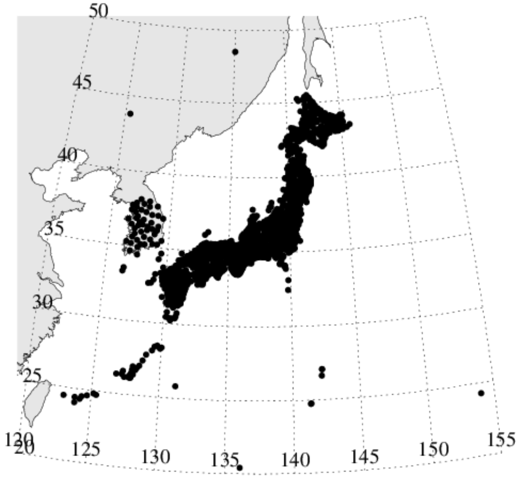
- Rate of LOL of 2 or more GPS satellites during 2002-2006.
- During Mar-Apr in 2002, the RLOL in the nighttime (21-24 JST) exceeds 30% (once per three days on the average).

# Global GNSS Receiver Networks



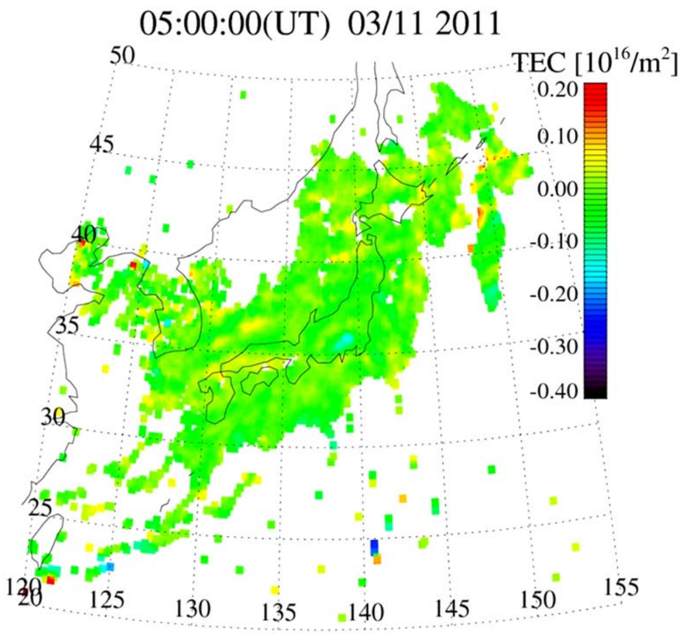

- We have collected all the available GPS receiver data (more than 6,000 receivers as of Jan. 2012) and made the database of TEC.

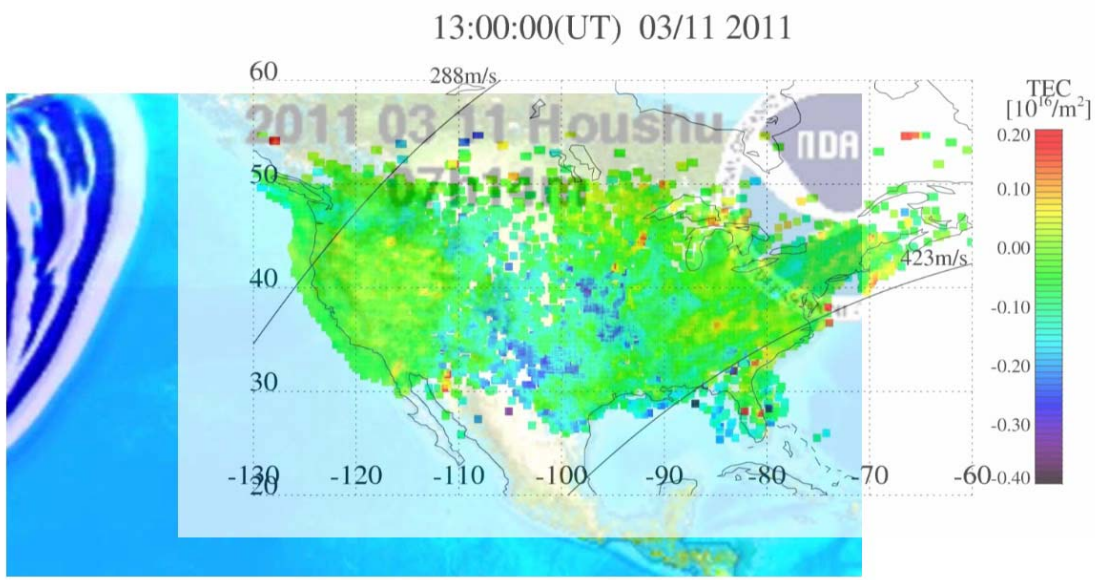
# Earthquake- and Tsunami-induced TEC variations



Japan (GEONET): ~1,200 receivers

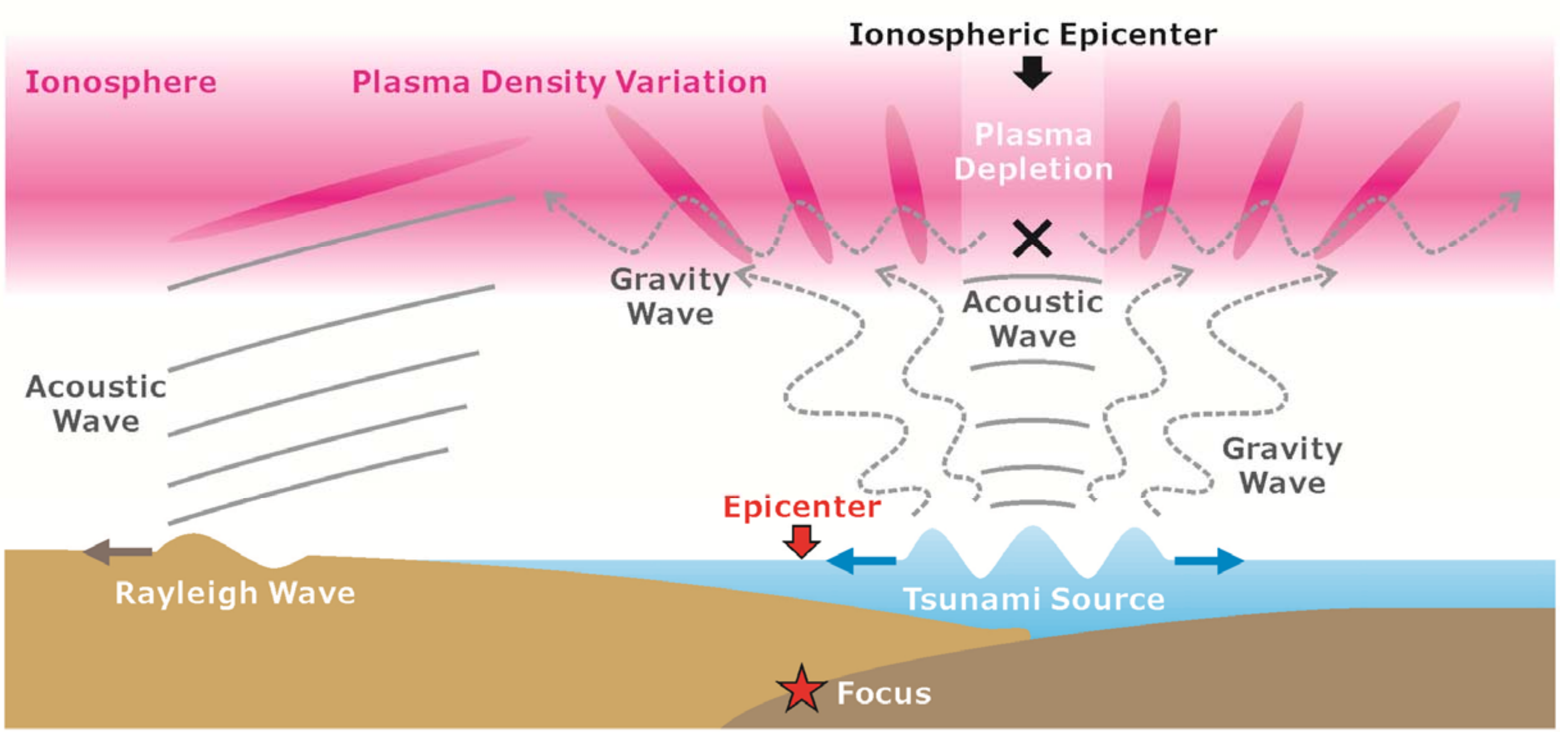
Korea (KMA): ~80 receivers
(KMA collects Korean GPS receiver data and
provides GTEX data)




[Tsugawa et al., EPS, 2011].

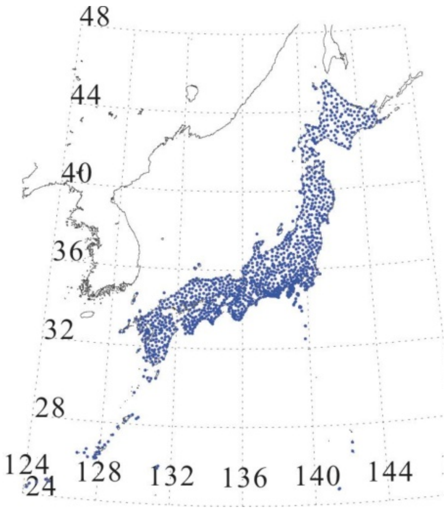
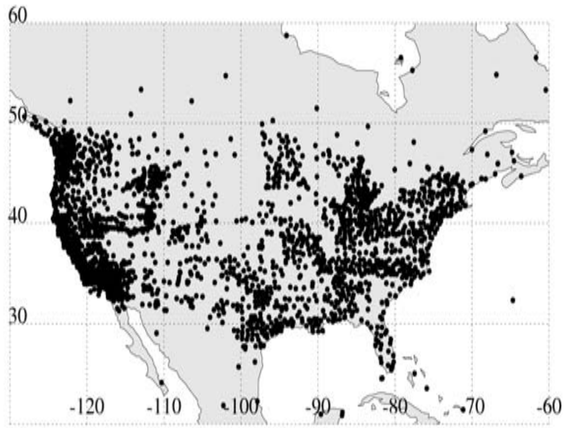
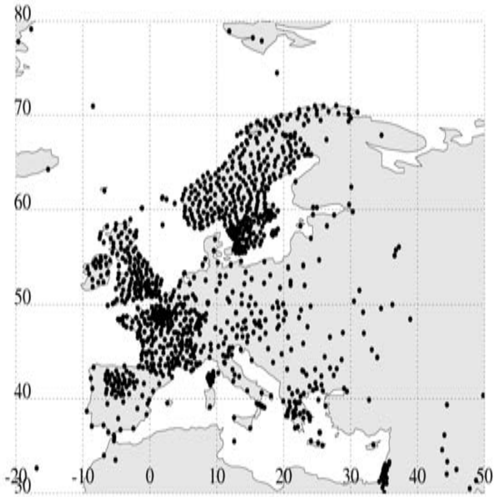
# Summary of earthquake/tsunami-induced ionospheric variations



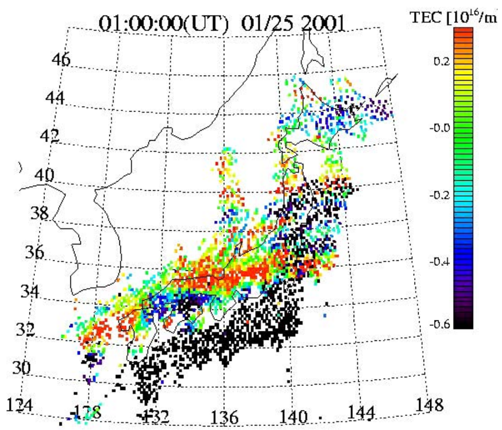

- Concentric waves propagating away from the ionospheric epicenter:
  the 1st fast wave → acoustic waves generated from the propagating Rayleigh wave.
  the 2nd and 3rd waves → atmospheric gravity waves generated in the lower ionosphere.
  the 4th and following waves → atmospheric gravity waves generated by tsunami wavefronts.
- Plasma depletion near the epicenter → plasma displacement due to neutral winds.
- Short-period TEC oscillation → acoustic wave resonance.

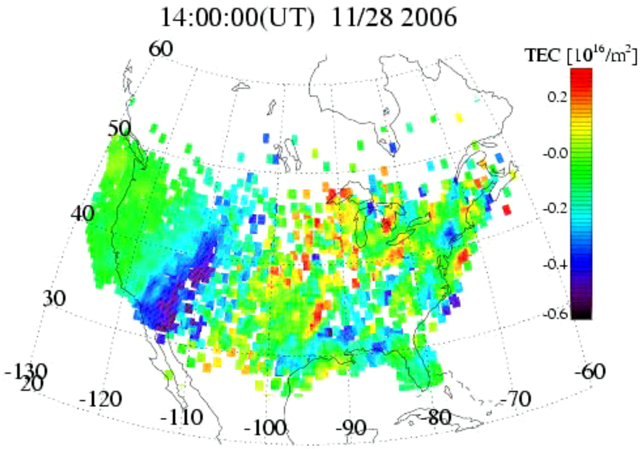
# High resolution GPS-TEC maps

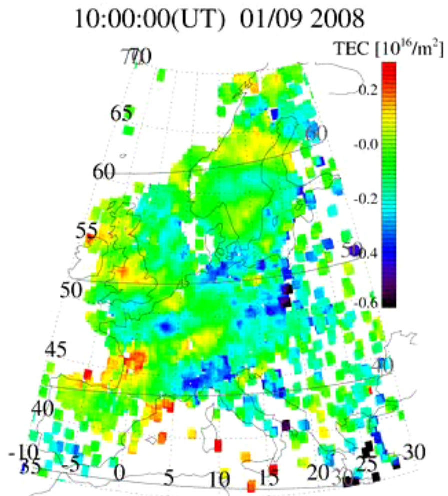
| **Region** | **JAPAN** | **N. America** | **Europe** |
|---|---|---|---|
| # of GPS Rec. | ~1,200 receivers | ~2,700 receivers | ~1,200 receivers |

Detrended TEC Map (60-min Window)







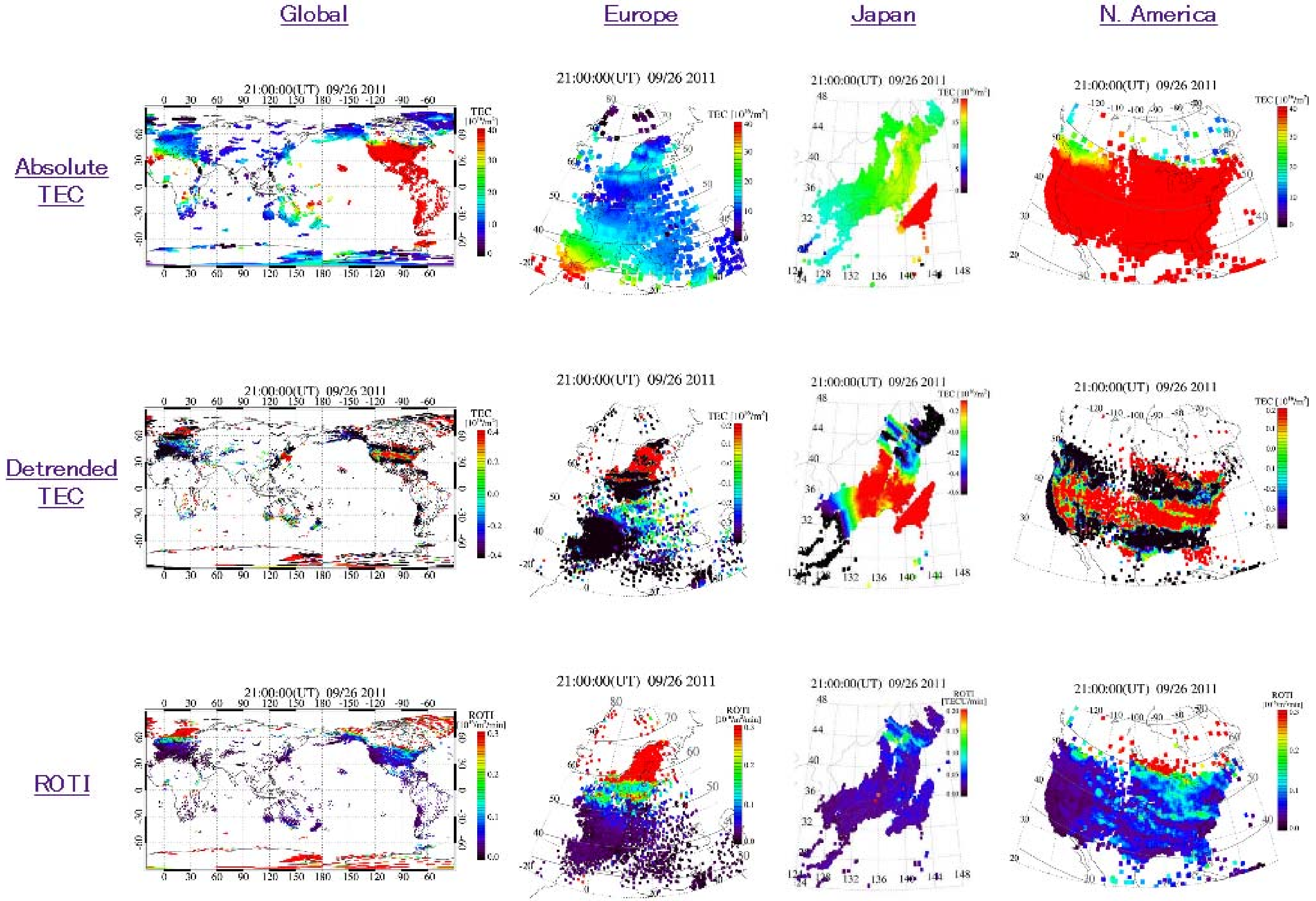

[Tsugawa et al., 2007].

[Otsuka et al., 2012].

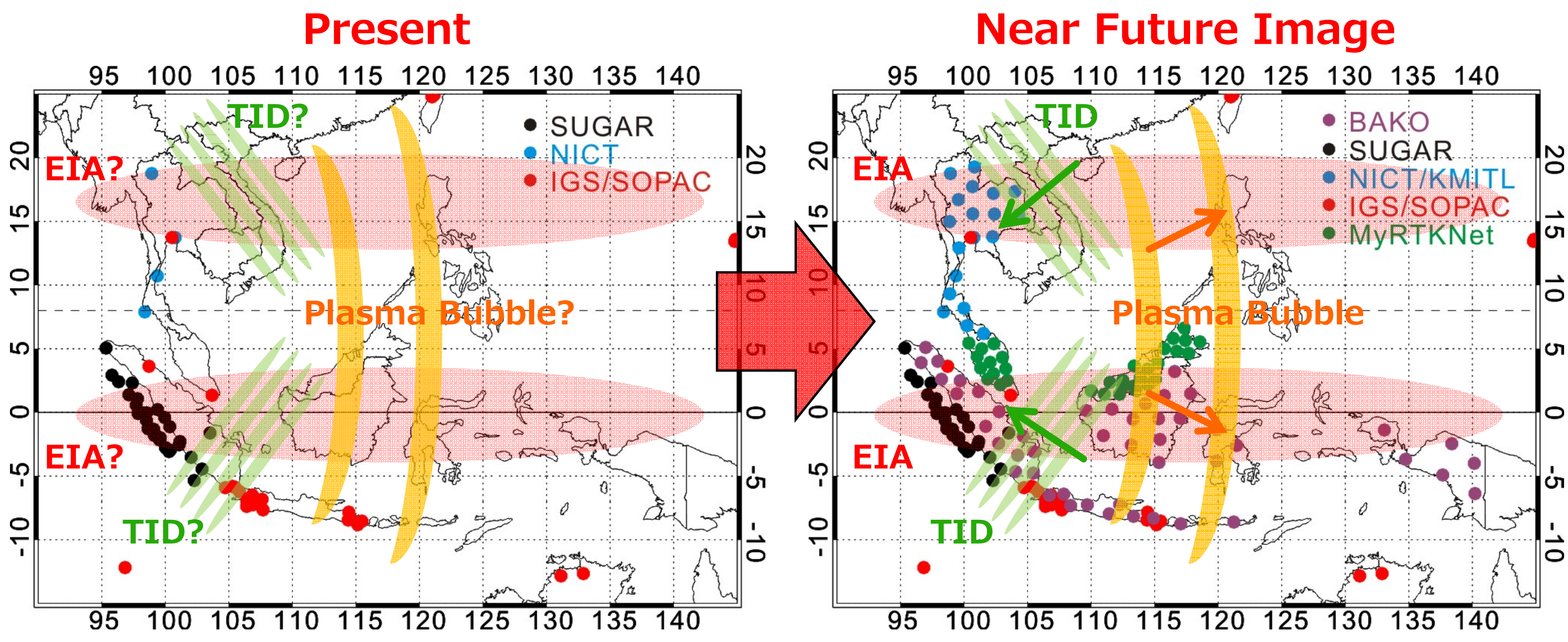
# Dense Regional And Worldwide INternational GNSS-TEC observation （DRAWING-TEC)

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

Quicklook



# Southeast Asian GNSS Networks Available for Ionospheric Researches




- Dense and wide-coverage GPS receiver network can reveal their spatial structures, propagation directions, and temporal evolutions.
- The GPS-TEC maps greatly contribute to the ionospheric researches and the nowcast/forecast of space weather.
- However, it is difficult to collect or share the GNSS data in some countries due to government or institute data policy.

# GPS Observation Data (RINEX format)

```
     2.00           OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE

DAT2RIN 2.35x       GSI, JAPAN          09MAR02 16:13:17 GMTPGM / RUN BY / DATE
GSI, JAPAN          GEOGRAPHICAL SURVEY INSTITUTE, JAPAN    OBSERVER / AGENCY
440101351           TRIMBLE 5700        Nav 1.05 Sig 0.00   REC # / TYPE / VERS
                    TRM41249.00                             ANT # / TYPE
0001                                                        MARKER NAME
                                                            MARKER NUMBER
 -3522845.0167  2777141.5661  4518959.0276                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N

     1     1                                                WAVELENGTH FACT L1/2

     4    L1    C1    L2    P2                              # / TYPES OF OBSERV
    30.0000                                                 INTERVAL
  2002     3     9     0     0    0.0000000      GPS        TIME OF FIRST OBS
HP-UX 10.20|PA-RISC|cc A.10.32.03|=+|=|                     COMMENT
***** RINEX HEADER SPECIFICATION 1.00 *****                 COMMENT
                                                            END OF HEADER
 02  3  9  0  0  0.0000000  0  9G 1G 2G 3G13G15G17G22G25G31
 -19012371.666    23282028.969   -14792202.9624    23282034.2034
 -20059488.864    22333773.945   -15610299.0404    22333776.2234
 -29405637.893    20488342.148   -22886235.5684    20488343.6844
 -10611214.715    23501437.734    -8249844.7244    23501441.9304
 -21574253.491    21813118.625   -16787240.0654    21813121.3794
 -19466956.219    22672753.922   -15147494.2964    22672757.9924
 -38120076.083    20147969.977   -29678594.7674    20147970.2814
 -34642202.746    23479338.891   -26972367.3494    23479343.8204
  -8256352.111    22876974.961    -6407292.0364    22876978.9264
 02  3  9  0  0 30.0000000  0  9G 1G 2G 3G13G15G17G22G25G31
 -18996599.842    23285030.305   -14779913.4304    23285036.4574
 -20169633.218    22312814.289   -15696125.7734    22312816.5204
```

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

**Header Part**

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

**1 epoch**

# GNSS-TEC exchange (GTEX) format (v0.3)

```
     0.3              GTEX DATA            GNSS                GTEX VERSION / TYPE
RNX2GTEX V0.3         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
                       1F : TEC status flag                    COMMENT
                       1O : Observation data used for TEC      COMMENT
                       ZN : Satellite zenith angle             COMMENT
                       AZ : Satellite azimuth angle            COMMENT
TEC2BIAS V0.3                                                  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**

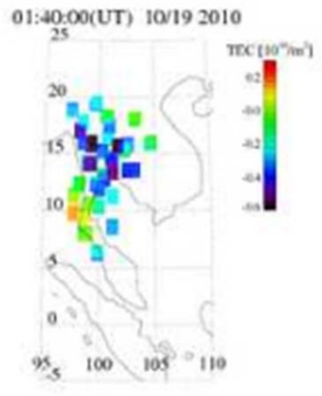
**Interval according to RINEX**

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

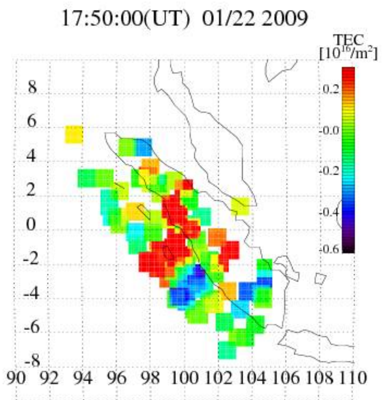
**1 epoch**

# GNSS-TEC data sharing based on GTEX

- NICT have developed the database of "GTEX" data for more than 6,000 GNSS receivers in the world. These data are available via the NICT science cloud, OneSpaceNet (OSN).
- Since the 1st AOSWA workshop held in Chiang Mai, Thailand in February 2012, we are now developing the GTEX data of Thailand, Indonesia, South Korea, and China collaborated with KMA, KMITL, LAPAN, and CMA, respectively.

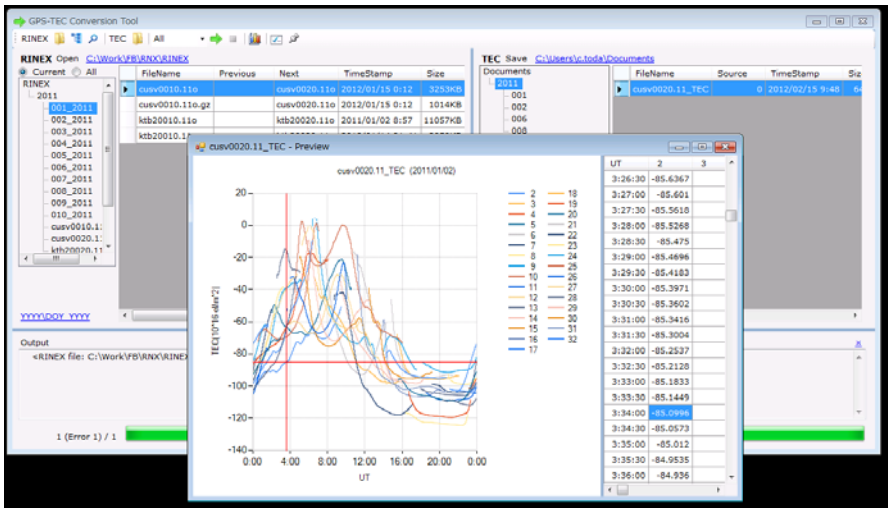



Detrended TEC over Thailand. [Courtesy of K. Watthanasangmechai (KMITL)]




Detrended TEC over Indonesia by SUGAR network.

- We can provide software products to convert RINEX data to GTEX data (Fortran 77) , and to make high-resolution TEC grid data (Fortran 77) and map images (IDL).
- NICT recently released a Windows software "RNX2GTEX" which are available via the NICT website.




http://seg-web.nict.go.jp/e-sw/download/index_e.html

# Asia-Oceania Space Weather Alliance: AOSWA

http://aoswa.nict.go.jp

- Objective: make a regional linkage of information of space weather for operations and researches
- GTEX data sharing is one of important topics.


The 1st AOSWA workshop at Chiang Mai, Thailand during 22-24 February 2012.

- 10 countries, 30 organizations, 76 participants
- 41 oral presentations, 21 poster presentations, 1 tutorial lecture
- an excursion
- business meeting

# ICAO Asia and Pacific Ionospheric studies task force (ISTF)

- ICAO plans to use aviation navigations based on GNSS, such as GBAS and SBAS. ICAO recognizes a necessity to evaluate the ionospheric effects on such navigations.
- ICAO Asia and Pacific have discussed about the effect of low-latitude ionospheric disturbances such as plasma bubble since 2009 and established the ionospheric studies task force (ISTF) in July 2011.


- In the 2nd meeting of ISTF held at Bangkok in Oct. 2012, the ionospheric data format for data sharing among countries were discussed.
- The GTEX format proposed by Japan (ENRI, NICT) were adopted as the sharing format in ISTF.
- GTEX format will be fixed by the next meeting (Jul. 2013).

NICT

# Summary

- High-resolution TEC observations using dense GNSS receiver networks can be a powerful tool to monitor and research medium-scale (~100-1,000 km) ionospheric disturbances such as plasma bubble.
- NICT started “DRAWING-TEC” project to expand the high-resolution TEC observation area with collaboration of ionosphere and GNSS researchers in the world.
- This project consists of (1) standardizing GNSS-TEC data (GTEX format), (2) developing dense TEC mapping technique, and (3) sharing the standardized TEC or GNSS data. The TEC-DRAWING project would promote studies of medium-scale ionospheric variations and their effect on GNSS.

# Acknowledgement

GNSS receiver data or GTEX-TEC data are provided by GSI, UNAVCO, IGS, SOPAC, CORS, WCDA, CHAIN, PANGA, KASI, KMA, EPN, BKGE, OLG, IGNE, DUT, ASI, ITACyL, ESEAS, SWEPOS, SATREF, BIGF, TrigNet, Geoscience Australia, IPS, RBMC, SUGAR, DPT, and KMITL.