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

T. Tsugawa¹, M. Nishioka¹, A. Saito², Y. Otsuka³, S. Saito⁴, T. Maruyama¹, T. Nagatsuma¹, K. T. Murata¹, and M. Ishii¹

¹ NICT, ² Kyoto University, ³ Nagoya University, ⁴ ENRI

• Brief introduction of NICT’s space weather activities
• High-resolution GNSS-TEC observations
• DRAWING-TEC project
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)
Forecasts and current conditions of flare activities, geomagnetic activities, high-energy particle flux, HF propagation condition by web, e-mail, RSS, fax

Real-time space weather monitoring

Exchanging forecast and data among ISES forecast centers

• Flare prediction
• Geomagnetic activity prediction
• High energy particle prediction

Result of simulation

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.
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
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.

\[
P_1 = \rho + I / f_1^2 + \tau_1^r + \tau_1^s \\
P_2 = \rho + I / f_2^2 + \tau_2^r + \tau_2^s \\
L_1 = \rho - I / f_1^2 + \lambda_1 n_1 + e_1^r + e_1^s \\
L_2 = \rho - I / f_2^2 + \lambda_2 n_2 + e_2^r + e_2^s
\]

- TEC is a measure of integrated electron density in 1m² column.

- 1 TECU (=10^{16} electrons/m²) 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

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

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 email to info@ml.nict.go.jp.

<table>
<thead>
<tr>
<th>Data Archive</th>
<th>TEC</th>
<th>Detrended with 80-min window</th>
<th>Detrended with 30-min window</th>
<th>Detrended with 15-min window</th>
<th>Rate of TEC change index</th>
<th>Rate of loss of lock on GPS</th>
</tr>
</thead>
</table>
| Latest 24 hours
| 2013/01/19 23:00 UT
| 2013/01/20 09:00 JST |
High resolution GPS-TEC maps in Japan

Absolute TEC

12:20 UT (21:20 JST)

12:40 UT (21:40 JST)

13:00 UT (22:00 JST)

ROTI (~10km scale irregularity)

Loss-of-Lock (~100m scale irregularity)
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.
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 $\rightarrow$ acoustic waves generated from the propagating Rayleigh wave.
  - the 2nd and 3rd waves $\rightarrow$ atmospheric gravity waves generated in the lower ionosphere.
  - the 4th and following waves $\rightarrow$ atmospheric gravity waves generated by tsunami wavefronts.

- Plasma depletion near the epicenter $\rightarrow$ plasma displacement due to neutral winds.

- Short-period TEC oscillation $\rightarrow$ 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

Global

Europe

Japan

N. America

Absolute TEC

Detrended TEC

ROTI
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)

Header Part

- GPS Observation Data G (GPS)
- RINEX Version / Type
- Header Part
- 1 epoch
- Year, month, day, hour, min, sec, flag, # of PRNs, PRNs
- 1 epoch
- Filename: sssdddhh.yyo
  - ssss: marker name
  - ddd: day of the year
  - h: file sequence number
  - yy: 2-digit year

Example:

```
02 3 9 0 0 0.0000000 0 96 1G 2G 3G13G15G17G22G25G31
-19012371.666 23282028.969 -1479220.9624 23282034.2034
-20094988.864 22333773.945 -15610299.0404 22333776.2234
-29405637.893 20488324.148 -22886235.5684 20488343.6844
-10611214.715 23501437.734 -8249644.7244 23501441.9304
-21574253.491 21813118.625 -16787240.0654 21813121.3794
-19466956.219 22672753.922 -15147494.2964 22672757.9924
-38120076.083 20147969.977 -29678594.7674 20147970.2114
-34642202.746 23479336.891 -26972367.3494 23479343.8204
-8256352.111 22876974.961 -6407292.0364 22876978.9264
```

- Wavelength Fact L1/2
- # / Types of Observ
- Interval
- Time of First Obs
- Comment
- End of Header

---

GPS Observation Data (RINEX format)
# GNSS-TEC exchange (GTEX) format (v0.3)

## Header Part

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<td>TYPES OF DATA = R1: Raw slant TEC including bias</td>
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<td>2012</td>
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</table>

## RINEX files used to derive slant TEC

- **filename**: ssssdddh.yy_TEC
  - **ssss**: marker name
  - **ddd**: day of the year
  - **hh**: file sequence number
  - **yy**: 2-digit year

## 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.

• 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
Objective: make a regional linkage of information of space weather for operations and researches

GTEX data sharing is one of important topics.

Asia-Oceania Space Weather Alliance: AOSWA
http://aoswa.nict.go.jp

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 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).
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.