GNSS-Based Radio Tomographic Studies of the Ionosphere at Different Latitudes

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Outline

- Global Navigation Satellite Systems (**GNSS**) include:

- new-generation high orbiting (HO) navigation systems (GPS and GLONASS and under development (Galileo, BeiDou, QZSS systems));
- and old-generation low orbiting (LO) navigation systems (Tsikada, Transit, etc.).

The GNSS constellations and the networks of ground receivers are suitable for probing the ionosphere along different rays and processing the obtained data by tomographic inversion procedures. The results are obtained by the methods of low orbiting and high orbiting radio tomography (LORT and HORT, respectively).

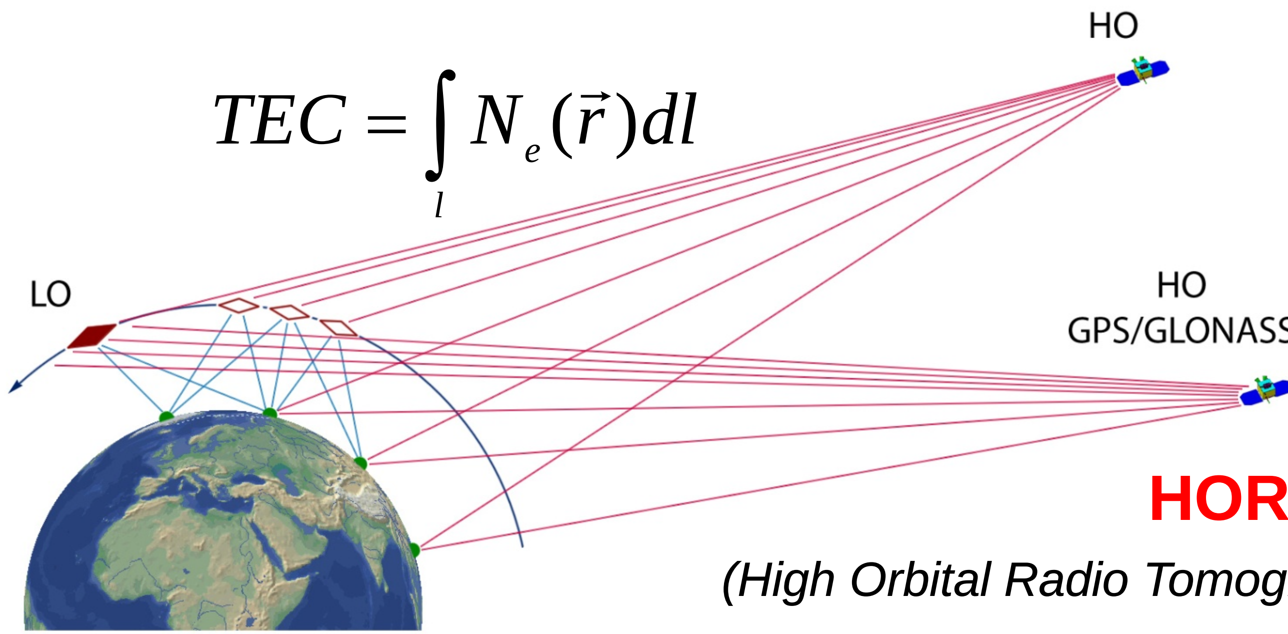
- We present the examples of tomographic images of the subequatorial, midlatitude, subauroral, and auroral ionosphere in different regions of the world.

- The GNSS RT methods are suitable for imaging the ionospheric disturbances, waves, TIDs caused by different phenomena including the tsunami wave propagation. We analyze the ionospheric disturbances after the strongest Tohoku earthquake in Japan (March 11, 2011).

- The RT reconstructions are compared to the measurements by the ionosondes and Global Ionospheric Maps (GIM).

Methods and Data

$$TEC = \int_l N_e(\vec{r})dl$$



LORT

(Low Orbital Radio Tomography)

"instantaneous" (~5-10 minutes) 2D RT images of the ionosphere above the receiving chains

{ the horizontal resolution is **20-30 km**, and the vertical, **30-40 km.** The resolution can be improved up to **20-10 km** using dense receiving system and nonlinear RT}

HORT

(High Orbital Radio Tomography)

4D RT images (3 spatial coordinates and time)
Typical resolution of HORT is about of **100-50 km** with a time step **60-20 min**.

resolution can be improved up to **30-50 km** with a time interval of **30-10 min** in the regions with dense receiving networks (West **Europe, USA, Alaska**) and up to **30-10 km & 2min** in regions with very dense networks (**Japan, S.California …**)

Ionospheric Ray Radio Tomography

$$\alpha \lambda r_e \int_L N d\sigma = \Phi = \varphi + \varphi_0,$$

- **Phase RT PT with estimation of initial phase** (RT using linear integrals, including unknows initial phase, определение которых является дополнительной задачей)
- **RT using relative phase**
- **Phase-difference RT - RT** using difference of linear integrals on close rays (it’s not necessary to determine the initial phase)

Ionospheric Ray Radio Tomograpghy

$$\alpha \lambda r_e \int_L N d\sigma = \Phi = \varphi + \varphi_0, \qquad \textbf{PN = Φ +ξ}$$

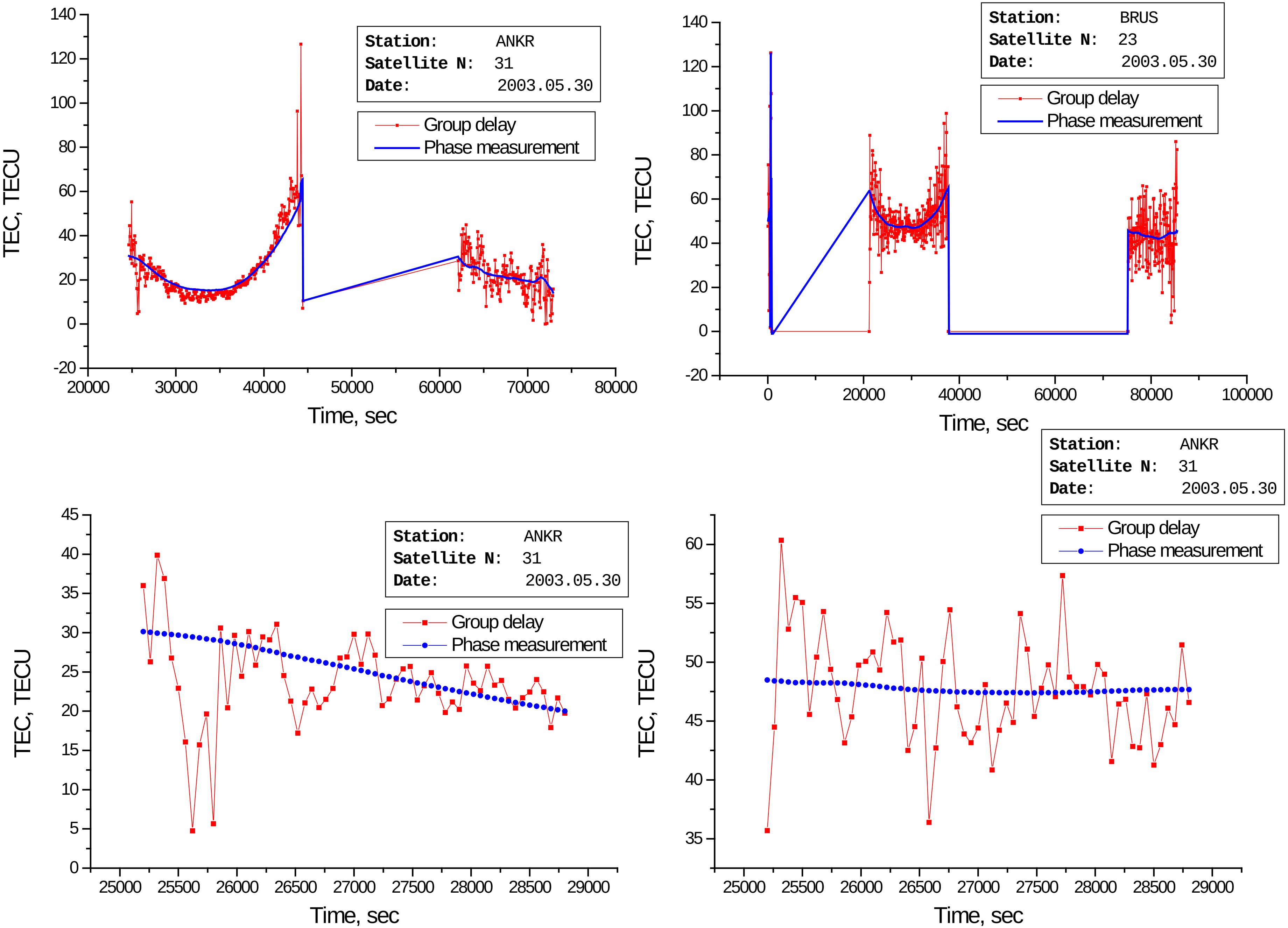
LN = Φ + ξ + E,   E = LN - PN

LN = Φ + ξ

$$-\left.\begin{array}{l} \textbf{LN = Φ} \\ \textbf{L´ N = Φ´} \end{array}\right\} \longrightarrow \textbf{AN = Φ – Φ´ = D}$$

20-40км – vertical resolution

10-30км – horizontal resolution


Station: ANKR
Satellite N: 31
Date: 2003.05.30
Group delay
Phase measurement
TEC, TECU
Time, sec
Station: BRUS
Satellite N: 23
Date: 2003.05.30
Group delay
Phase measurement
TEC, TECU
Time, sec
Station: ANKR
Satellite N: 31
Date: 2003.05.30
Group delay
Phase measurement
TEC, TECU
Time, sec
Station: ANKR
Satellite N: 31
Date: 2003.05.30
Group delay
Phase measurement
TEC, TECU
Time, sec

Solution with Smoothing

$$Af = \Psi \qquad \min \left\| f - f_0 \right\|^2_{W_n{}^2}$$

SIRT:

$$\vec{x}^{k+1} = \vec{x}^k + \sum_i \rho_i \frac{y_i - \left(\vec{a}_i, \vec{x}^k\right)}{\left(\vec{a}_i, \vec{a}_i\right)} \vec{a}_i$$

$$\min \left\| \vec{x} - \vec{x}_0 \right\|^2$$
$$A\vec{x} = \vec{y}$$

Modified SIRT:

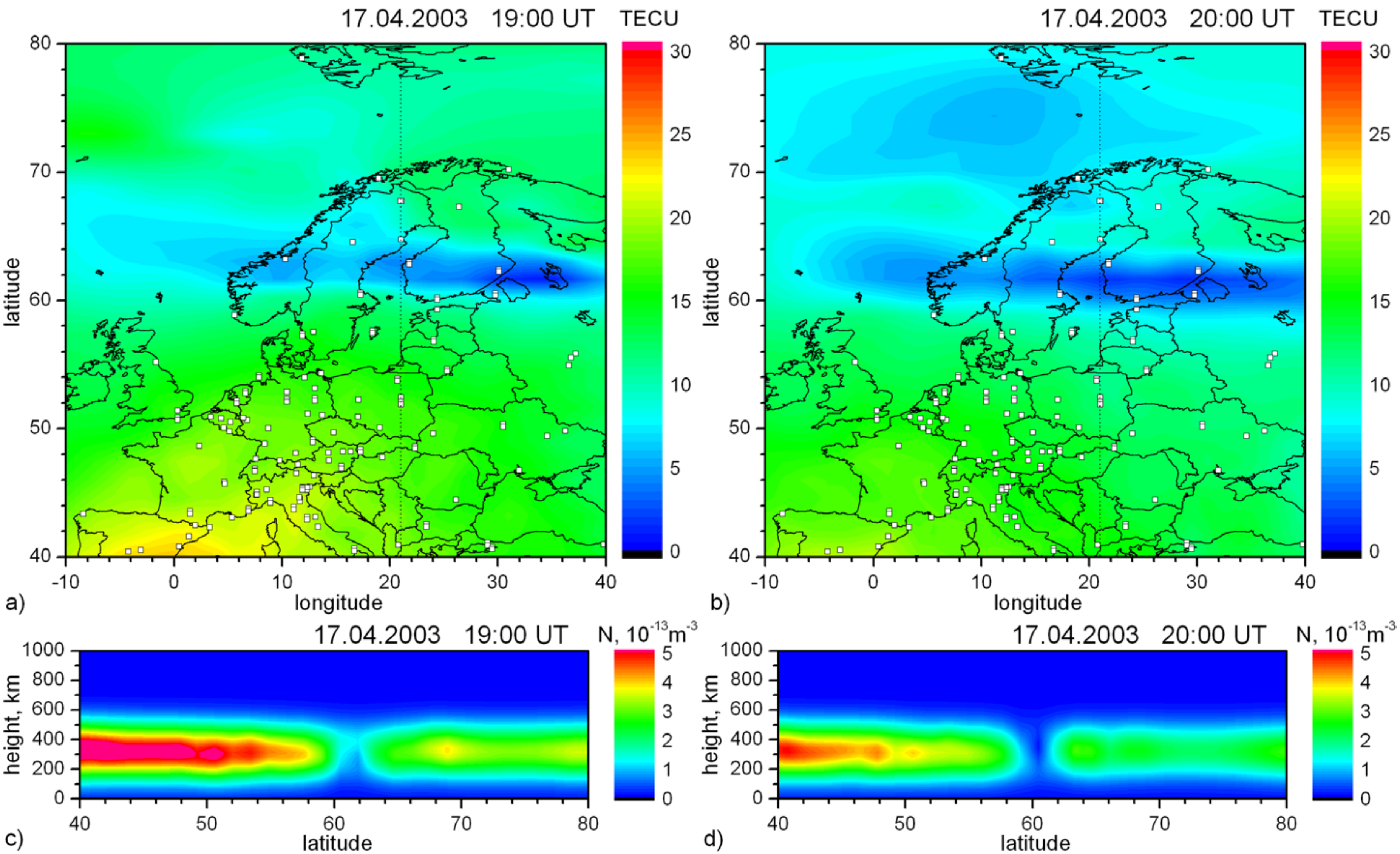
$$\vec{x}^{k+1} = \vec{x}^k + \sum_i \rho_i \frac{y_i - \left(\vec{a}_i', \vec{x}^k\right)_L}{\left(\vec{a}_i', \vec{a}_i'\right)_L} \vec{a}_i'$$

$$\min \left(\vec{x} - \vec{x}_0, \vec{x} - \vec{x}_0\right)_L$$
$$A\vec{x} = \vec{y}$$

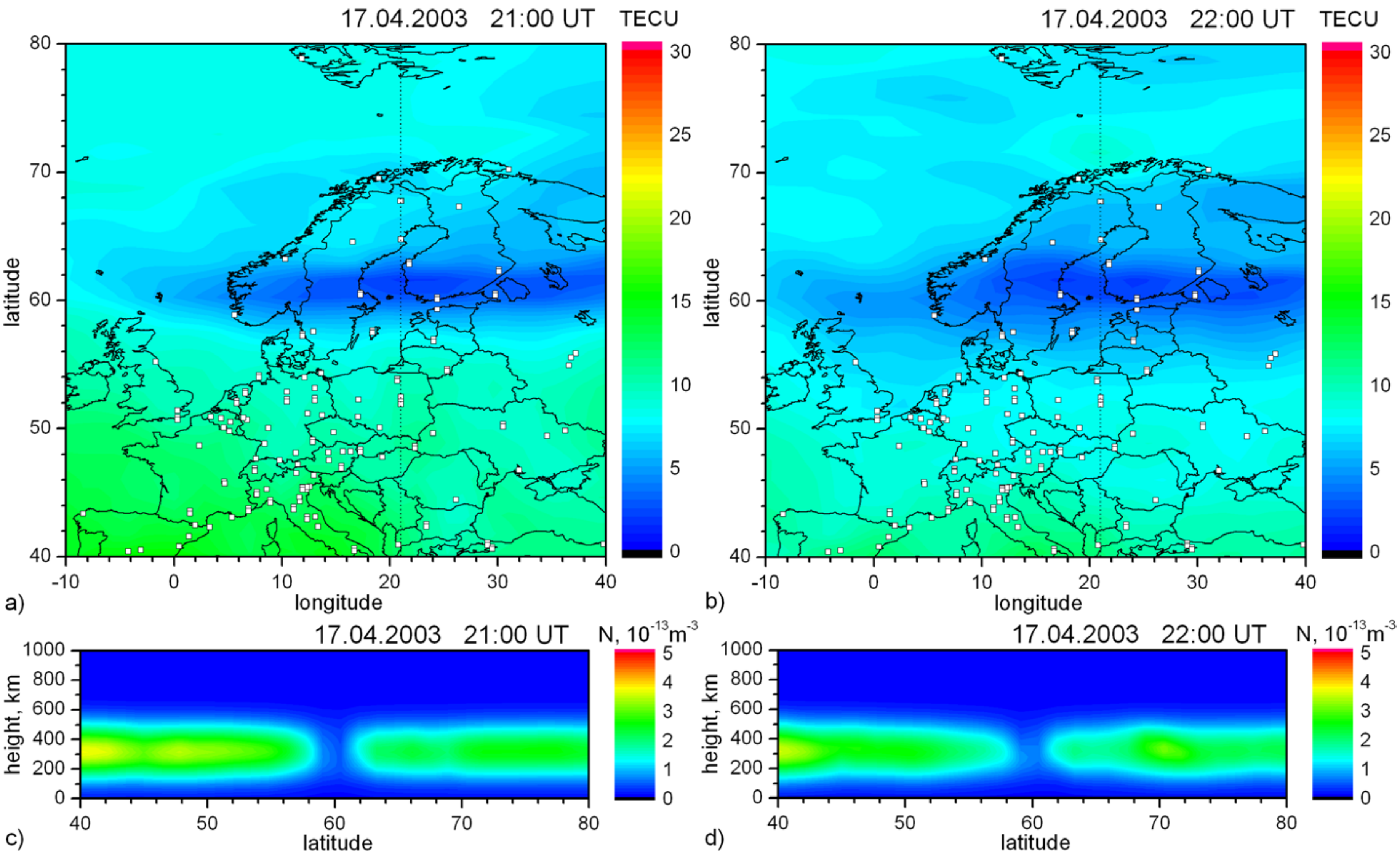
$$\vec{a}_i' = \left(L^* L\right)^{-1} \vec{a}_i$$

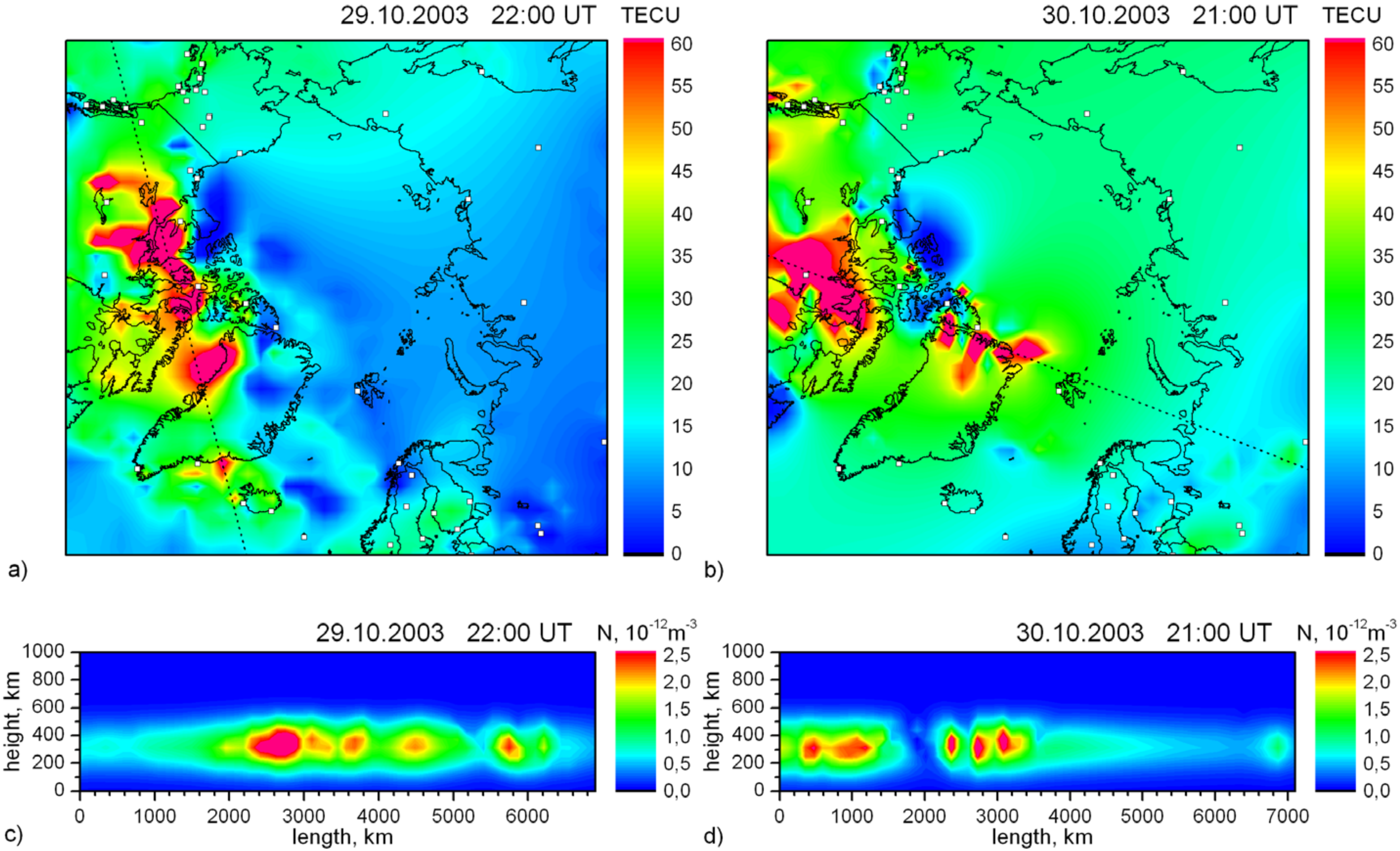
$$\vec{x}^{k+1} = \vec{x}^k + t\left(L^* L\right)^{-1} \sum_i \vec{a}_i \left(y_i - \left(\vec{a}_i, \vec{x}^k\right)\right)$$

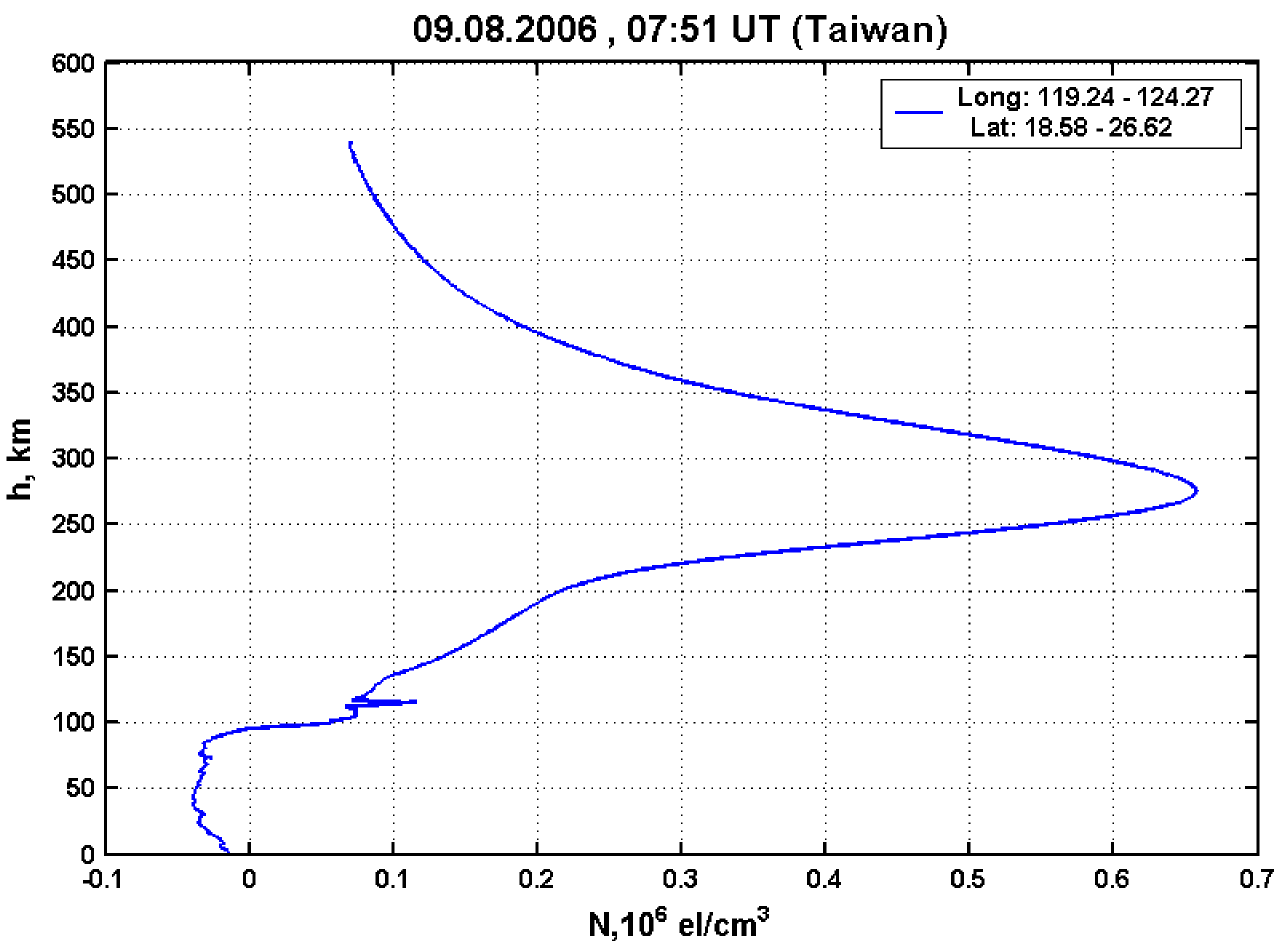
$$\left(\vec{z}, \vec{x}\right)_L = \left(L\vec{z}, L\vec{x}\right) = \left(\vec{z}, L^* L\,\vec{x}\right)$$



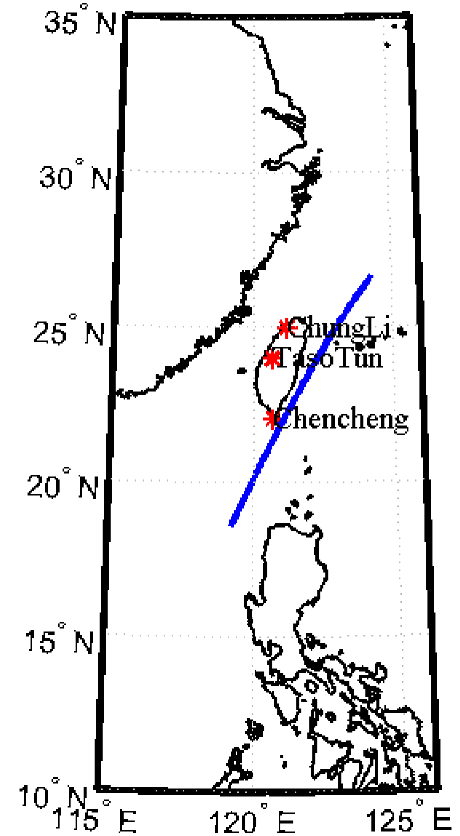
17.04.2003 19:00 UT
TECU
latitude
longitude
a)
17.04.2003 20:00 UT
TECU
latitude
longitude
b)
17.04.2003 19:00 UT
N, 10^-13 m^-3
height, km
latitude
c)
17.04.2003 20:00 UT
N, 10^-13 m^-3
height, km
latitude
d)


17.04.2003 21:00 UT
TECU
latitude
longitude
a)
17.04.2003 22:00 UT
TECU
latitude
longitude
b)
17.04.2003 21:00 UT
N, 10^-13 m^-3
height, km
latitude
c)
17.04.2003 22:00 UT
N, 10^-13 m^-3
height, km
latitude
d)

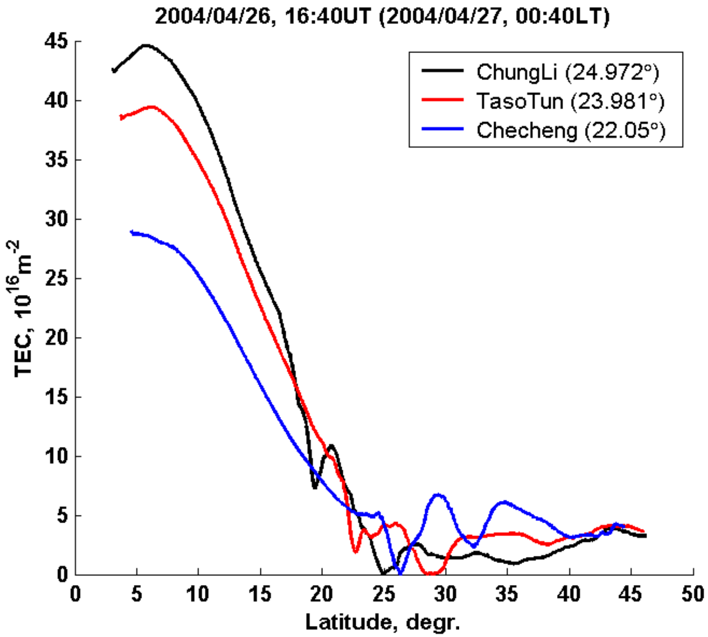

29.10.2003 22:00 UT
TECU
60
55
50
45
40
35
30
25
20
15
10
5
0
a)
30.10.2003 21:00 UT
TECU
b)
29.10.2003 22:00 UT
N, 10^-12 m^-3
2,5
2,0
1,5
1,0
0,5
0,0
height, km
1000
800
600
400
200
0
length, km
0
1000
2000
3000
4000
5000
6000
7000
c)
30.10.2003 21:00 UT
d)

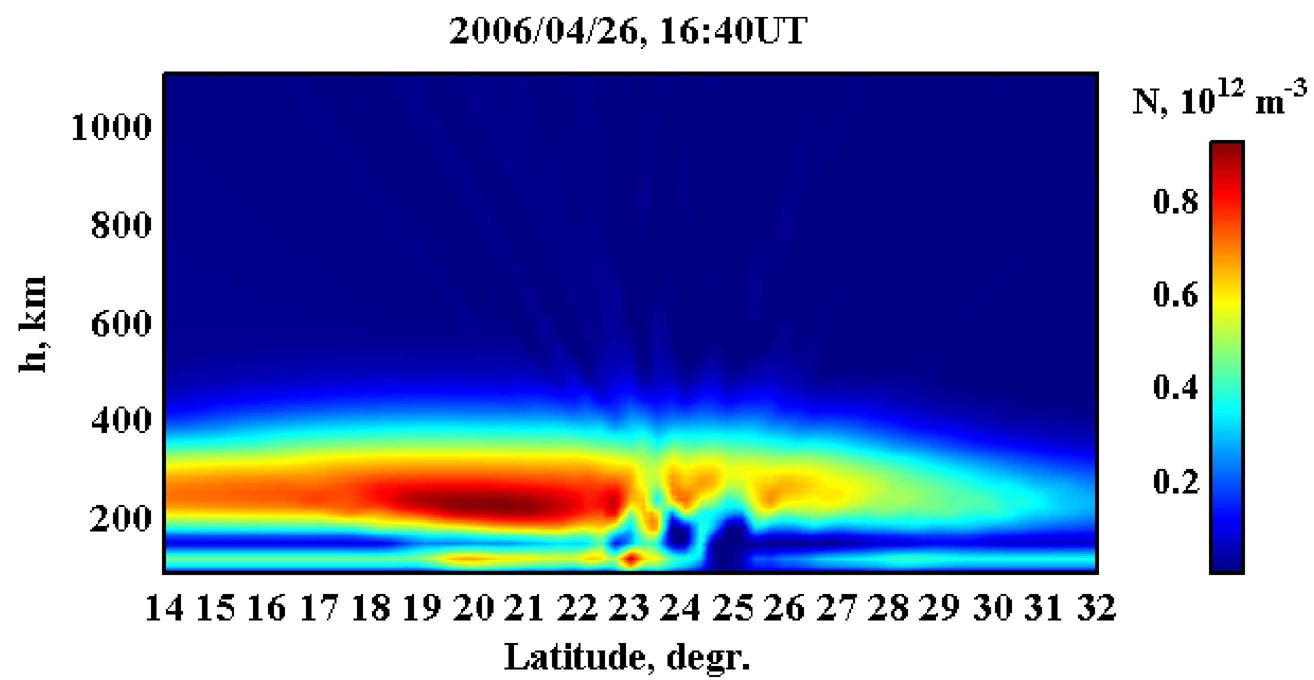


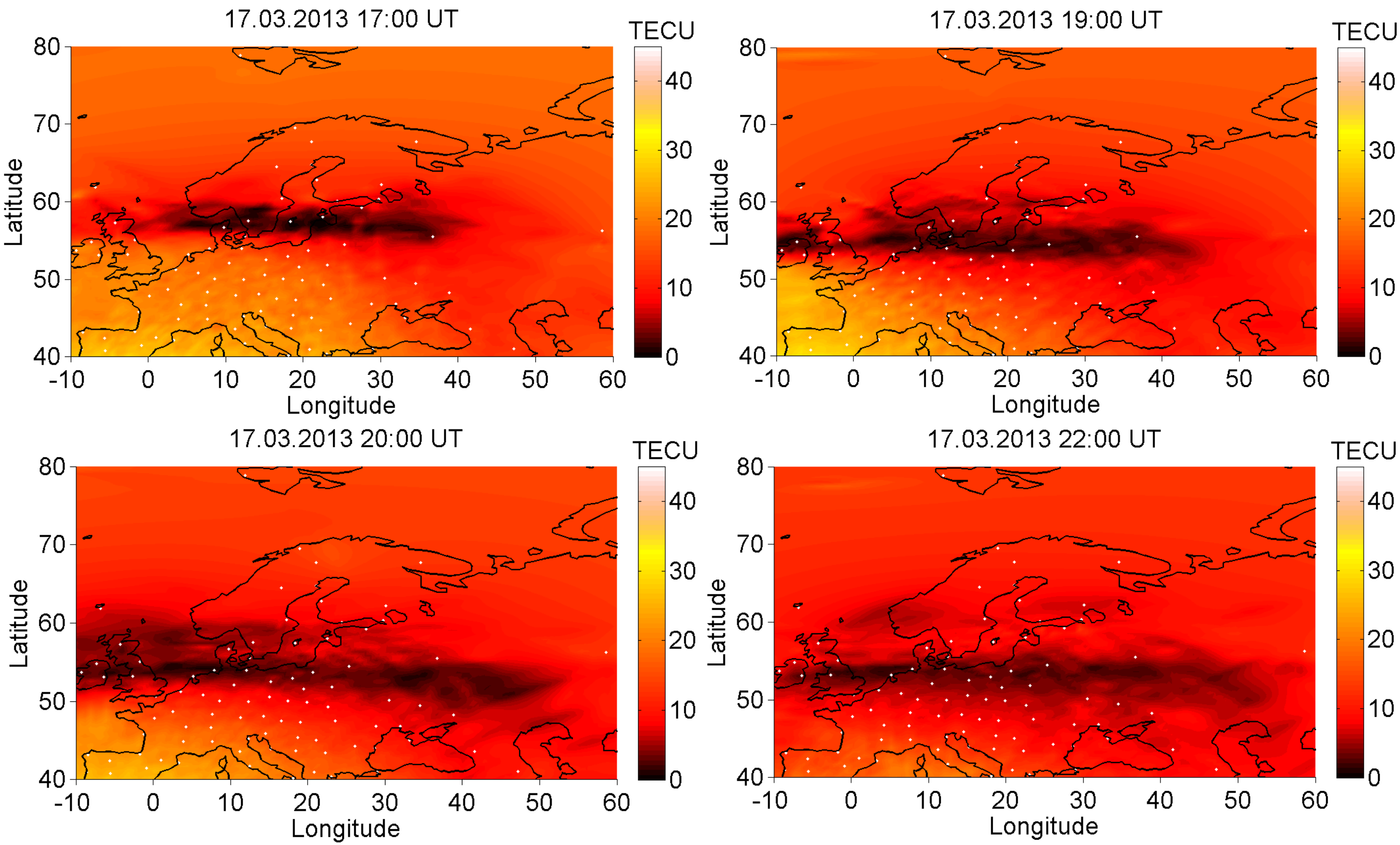
09.08.2006 , 07:51 UT (Taiwan)
Long: 119.24 - 124.27
Lat: 18.58 - 26.62
h, km
N,10^6 el/cm^3



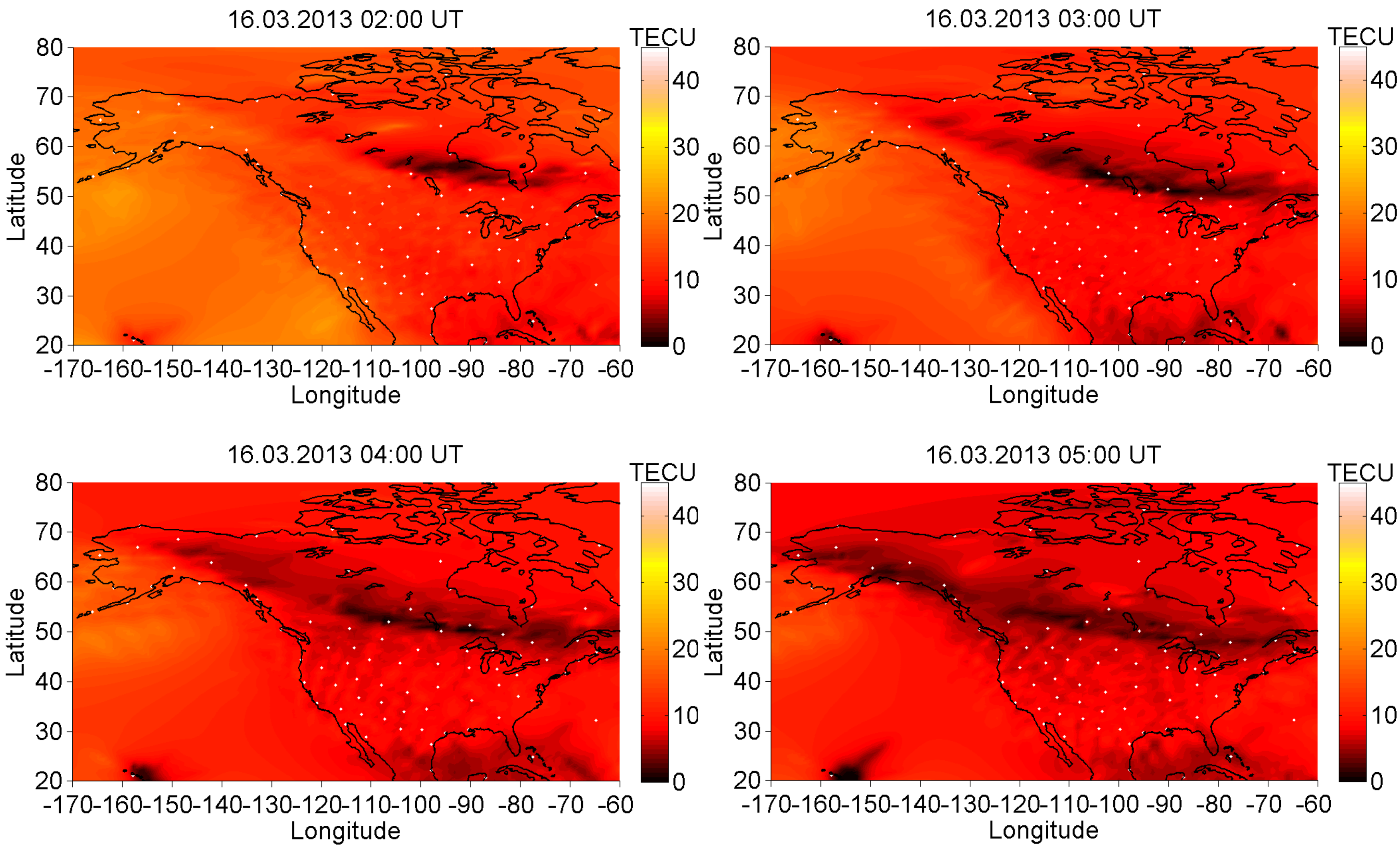
35° N
30° N
25° N
20° N
15° N
10° N
115° E
120° E
125° E
ChungLi
TasoTun
Chencheng


2004/04/26, 16:40UT (2004/04/27, 00:40LT)
ChungLi (24.972°)
TasoTun (23.981°)
Checheng (22.05°)
TEC, 10^16 m^-2
Latitude, degr.
0
5
10
15
20
25
30
35
40
45
50

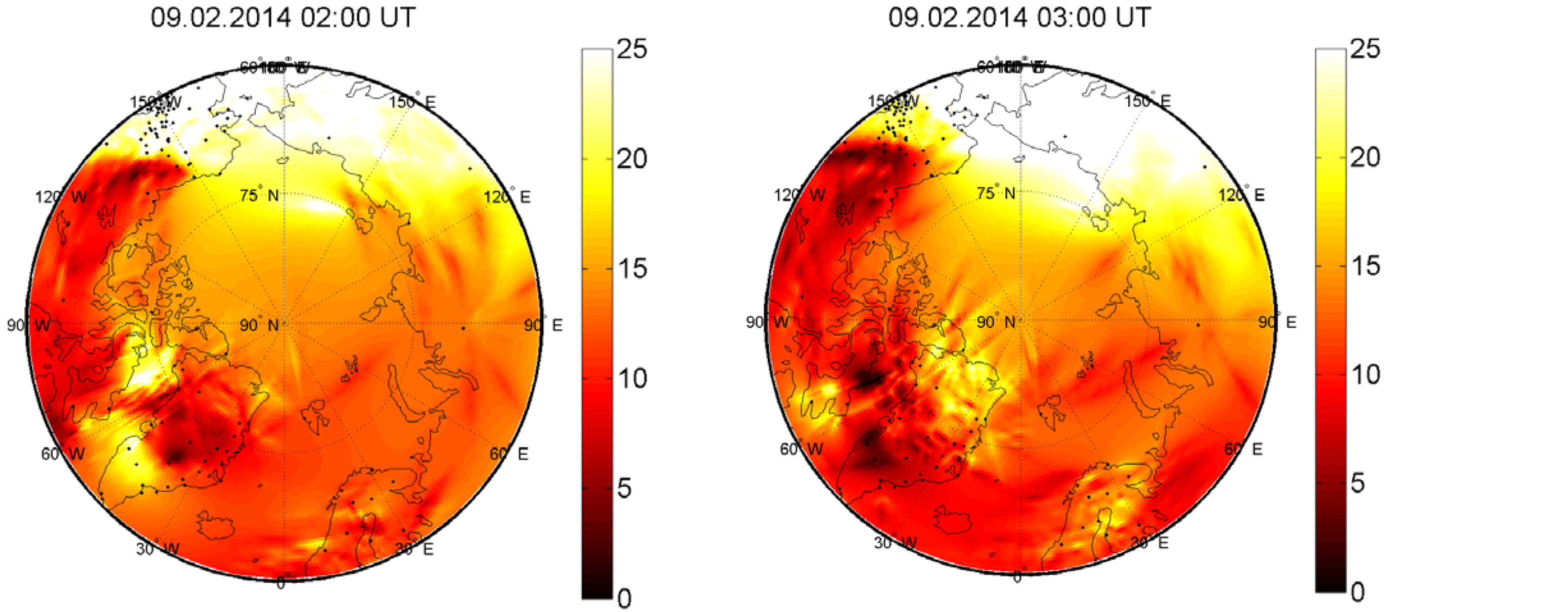

2006/04/26, 16:40UT
h, km
1000
800
600
400
200
N, 10^12 m^-3
0.8
0.6
0.4
0.2
14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
Latitude, degr.



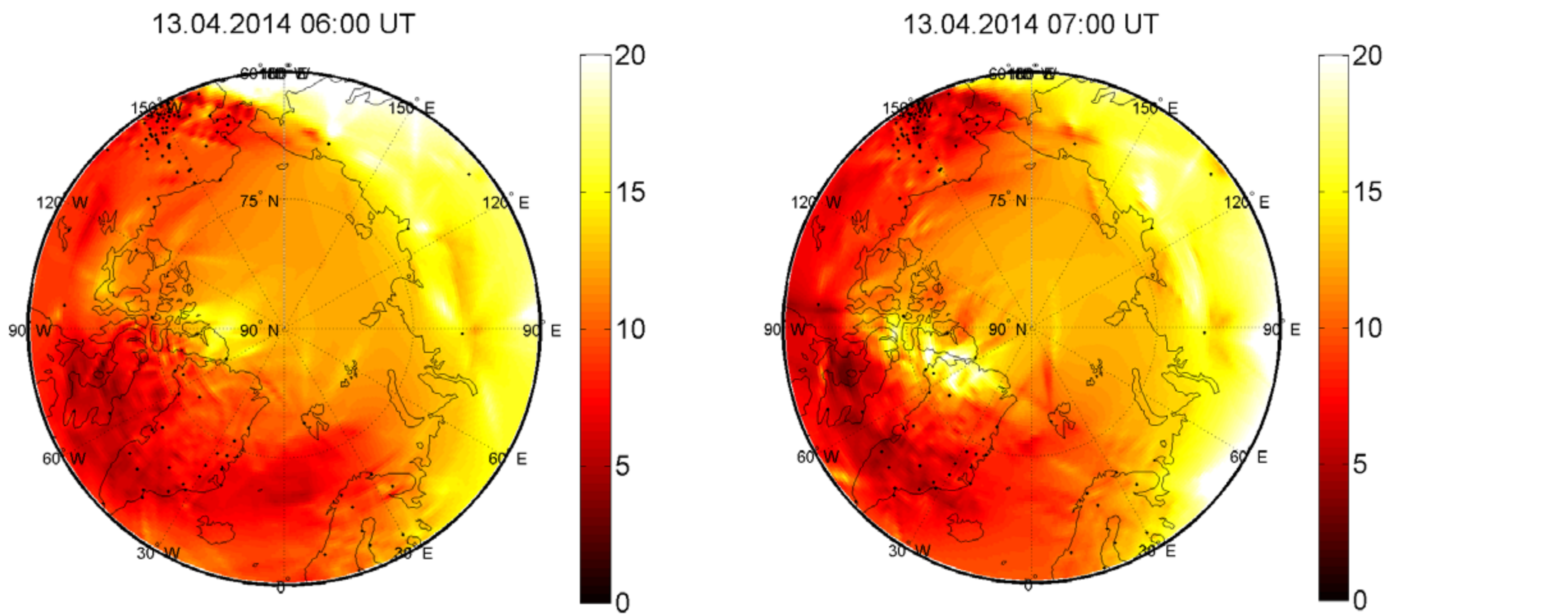
The example of evolution of the ionization trough above Europe
on March 17, 2013, 17:00-22:00 UT (Kp=6.7)



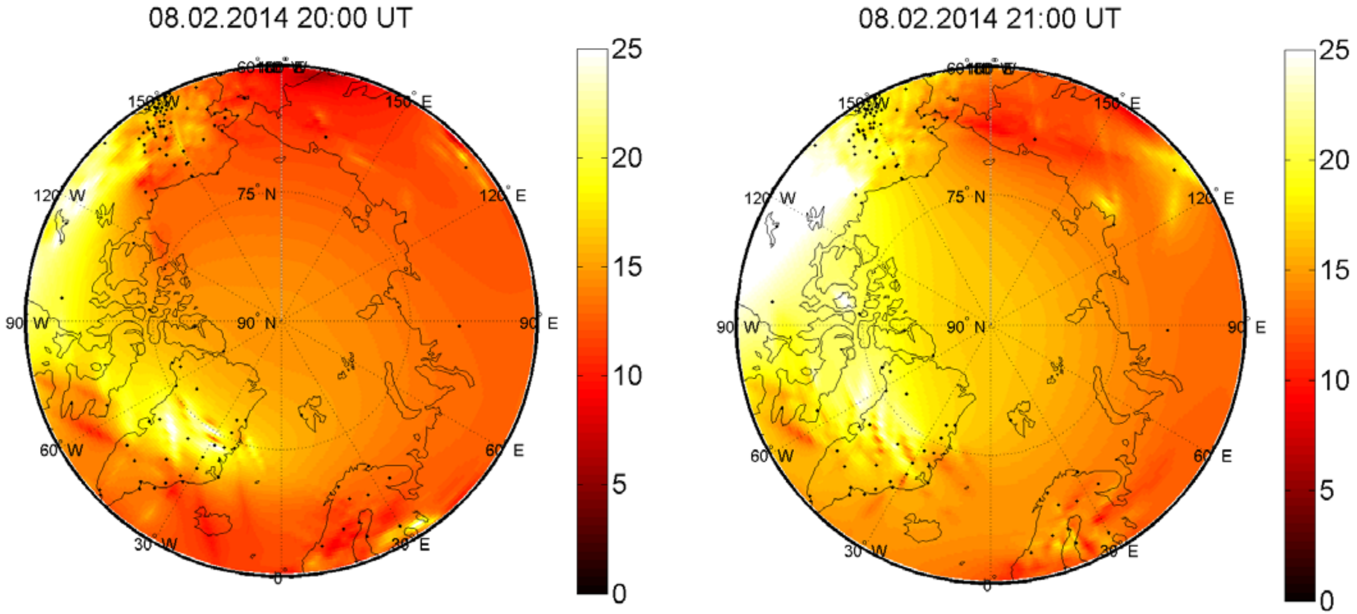
The example of evolution of the ionization trough above North America on March 16 , 2013, 02:00-05:00 UT (Kp=3.3)



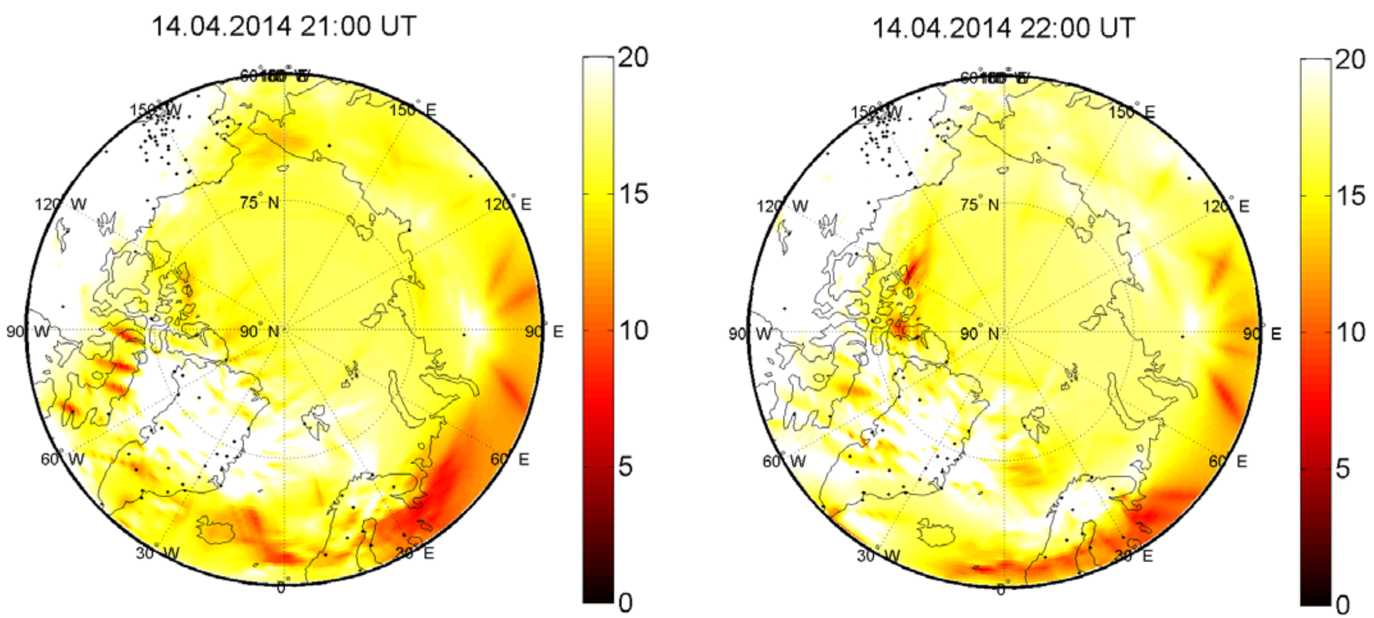
TEC maps above the Arctic region on February 9, 2014 (02:00 and 03:00 UT)



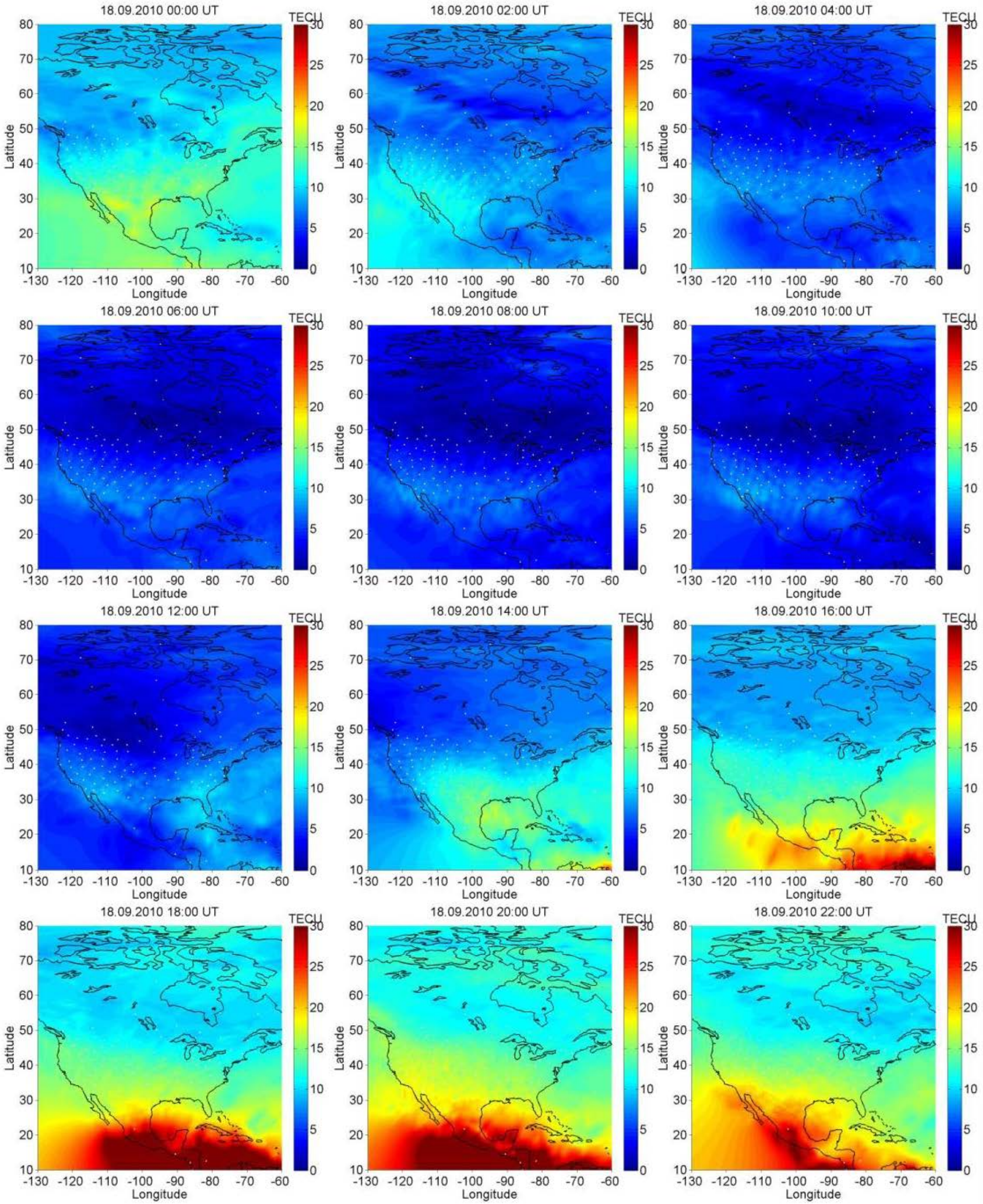
TEC maps above the Arctic region on April 13, 2014 (06:00 and 07:00 UT)



TEC maps above the Arctic region on February 8, 2014 (20:00 and 21:00 UT)

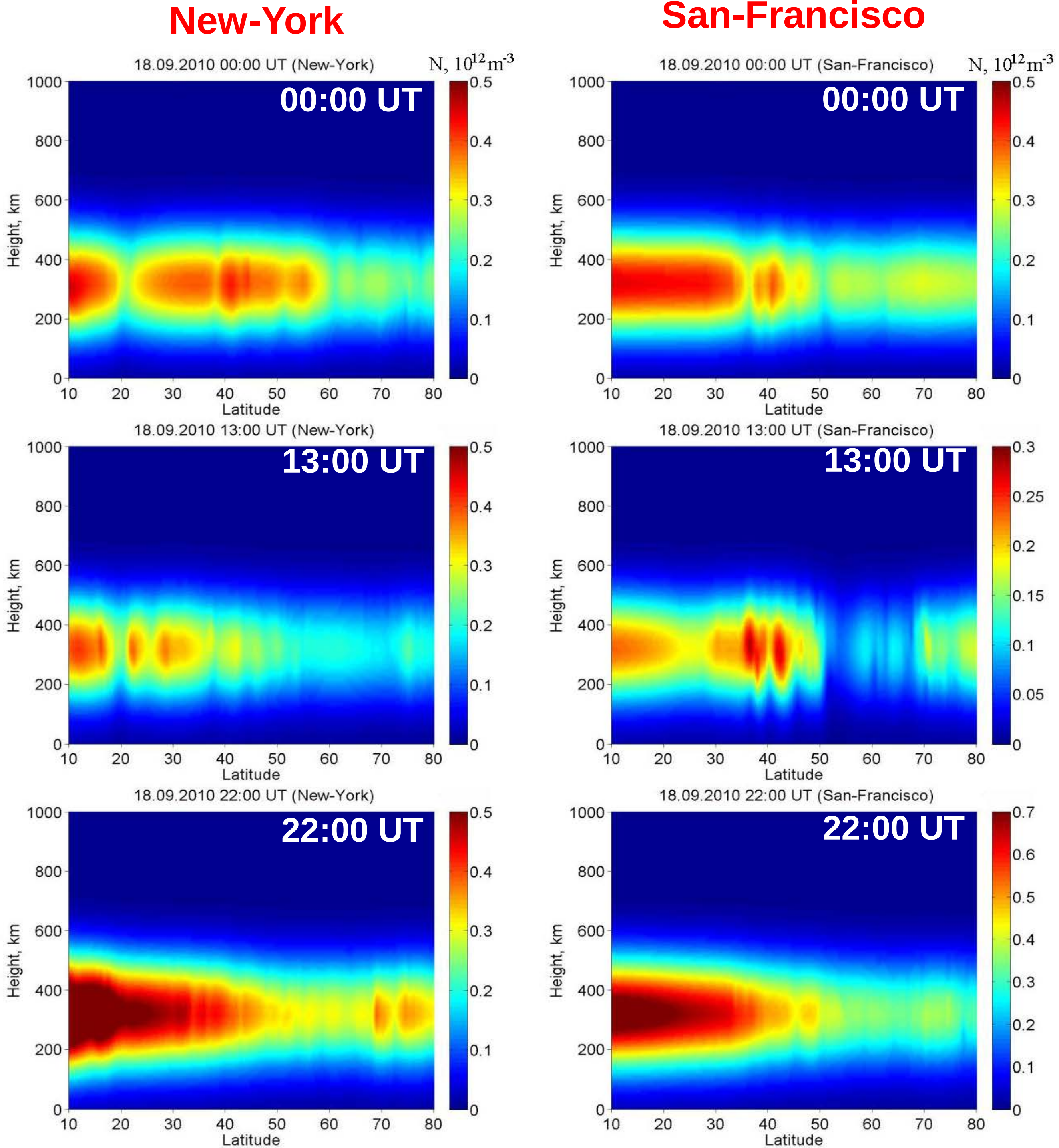


TEC maps above the Arctic region on April 14, 2014 (21:00 and 22:00 UT)

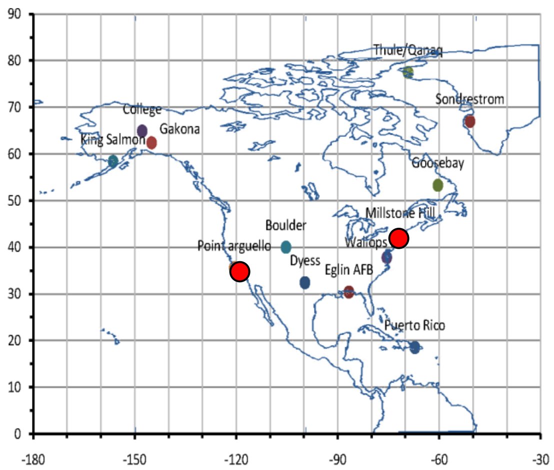


Vertical TEC above North America according to 4D HORT during 18.09.2010

(00:00 UT-22:00 UT)

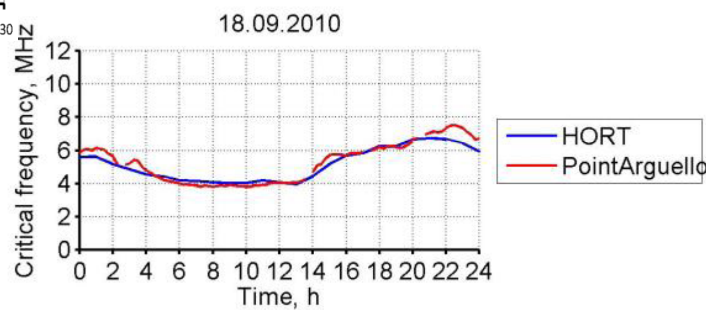


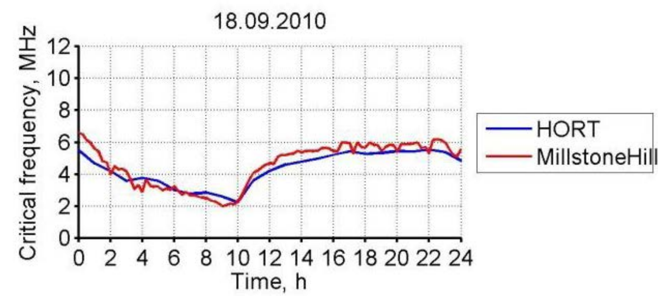
Vertical cross-sections of the ionosphere along meridians of New-York and San-Francisco according to 4D HORT during 18.09.2010

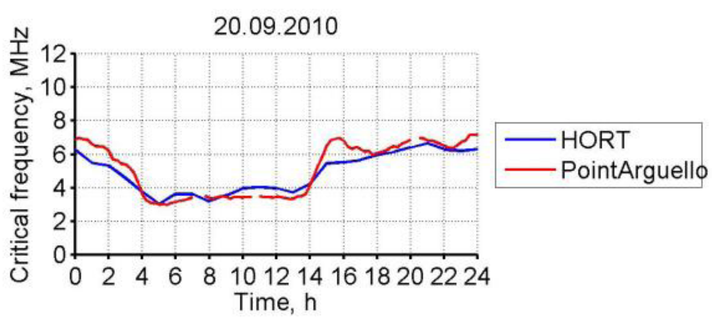


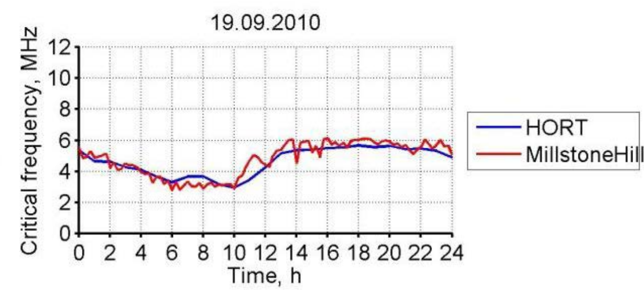
Comparison of HORT and ionosonde data

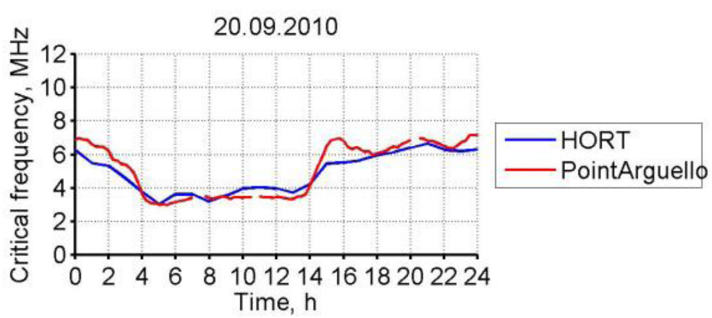
Sept. 18–20, 2010: f_oF2 as obtained from HORT-images and f_oF2 as obtained from Point Arguello ionosonde & Millstone Hill ionosonde.

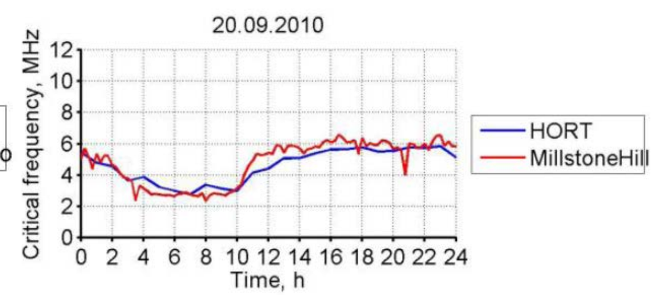




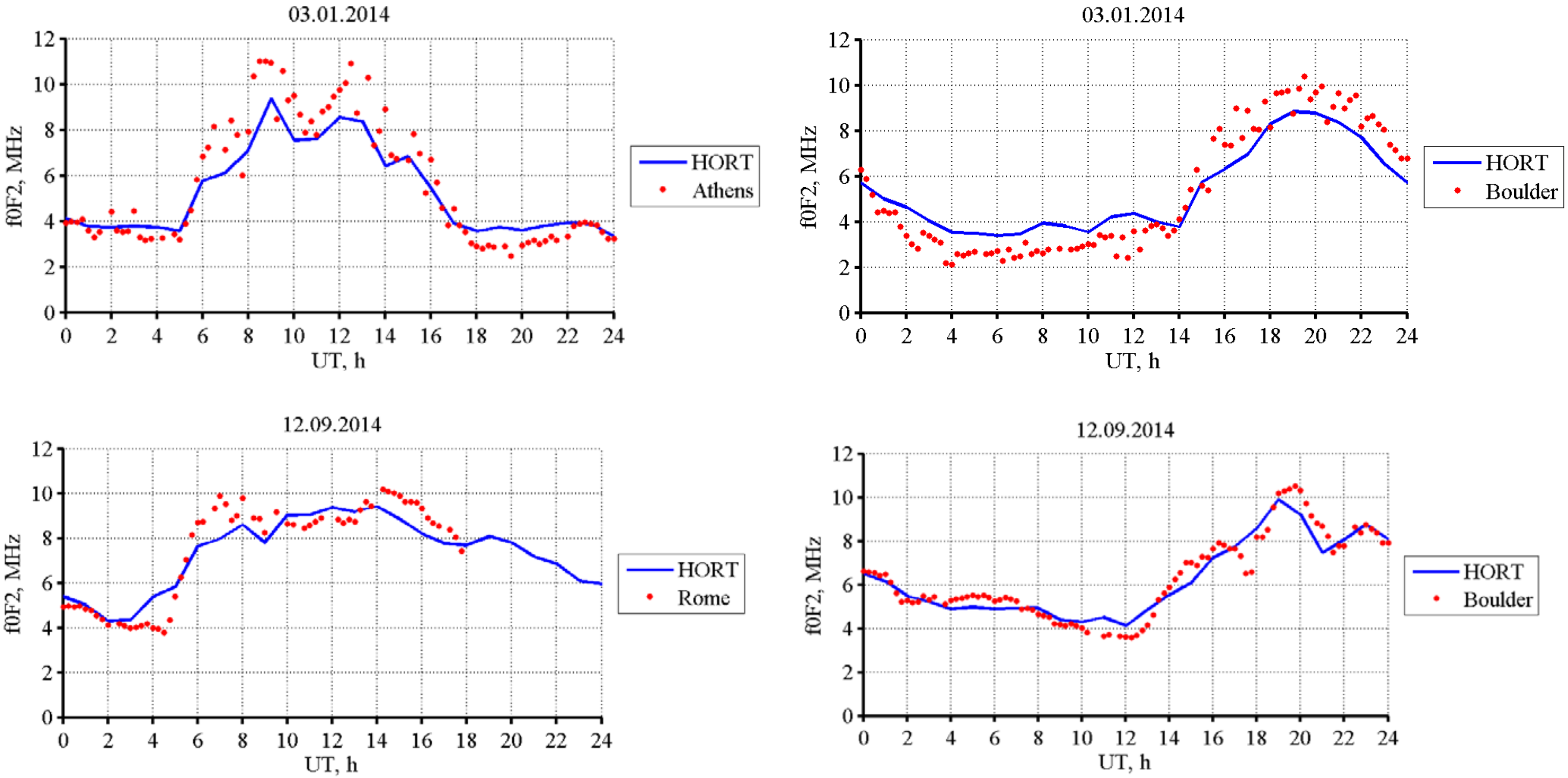






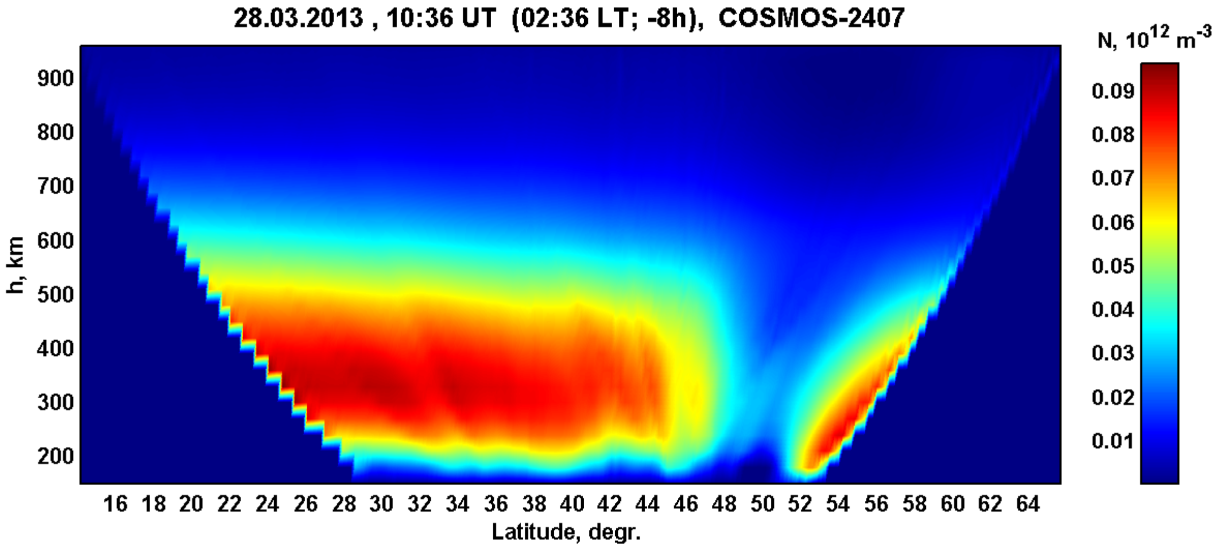


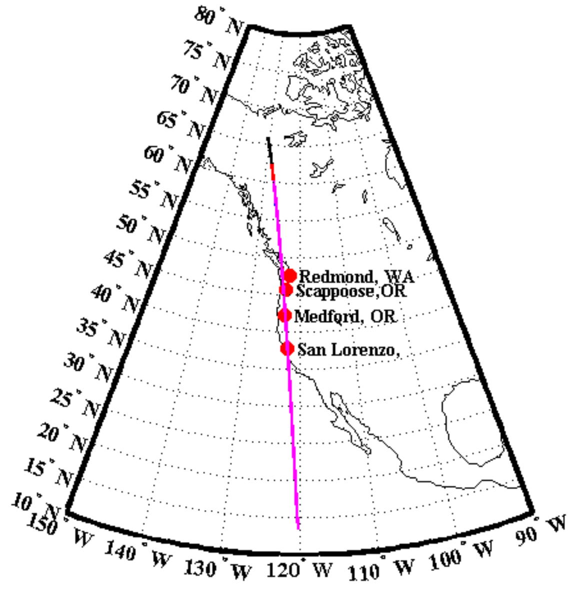
Comparison of HORT and ionosonde data

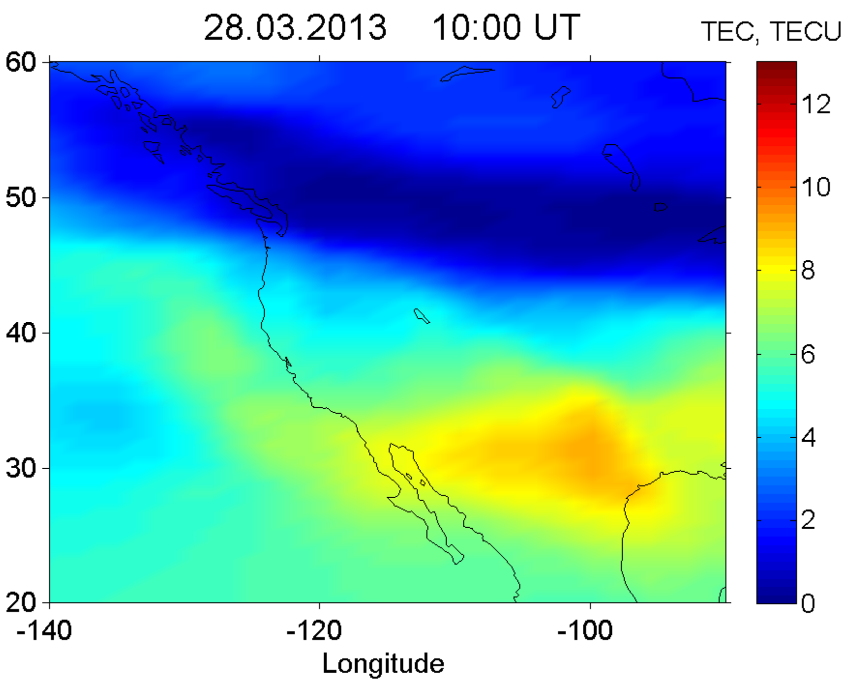


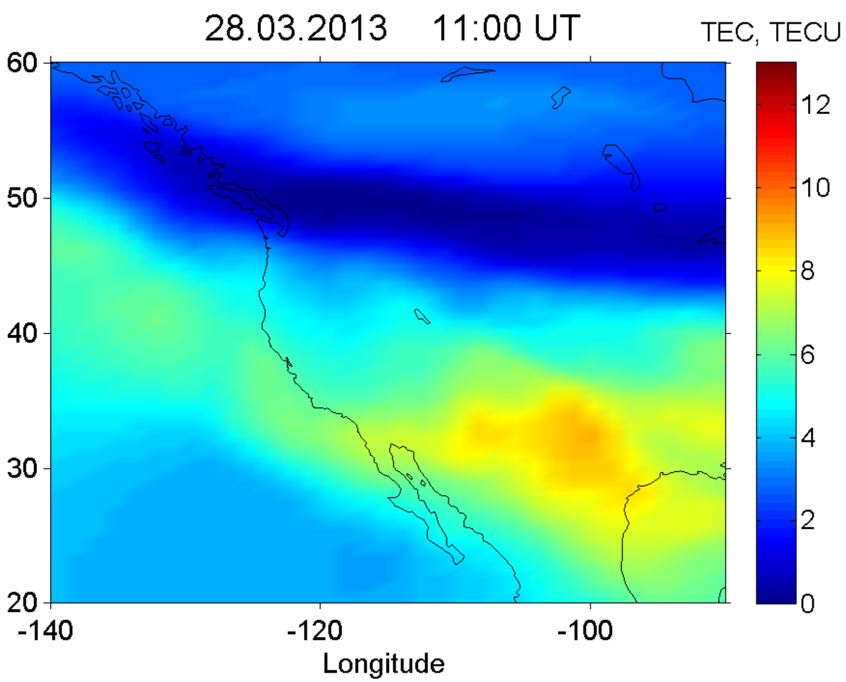
The analysis based on thousands of comparisons indicates that the diurnal behavior of *f0F2* retrieved from HORT quite closely agrees with the ionosonde data. The discrepancies in critical frequencies are far below **0.5 MHz** during the geomagnetically quiet periods and above **1 MHz** during the disturbances**.**

U.S. West Coast

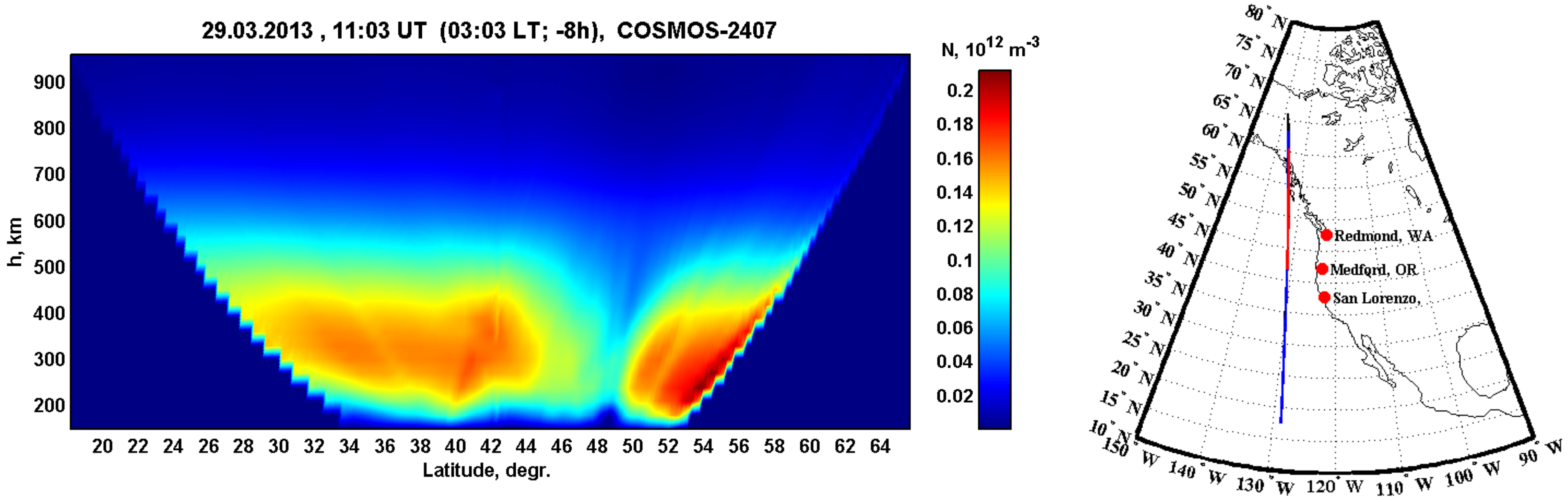


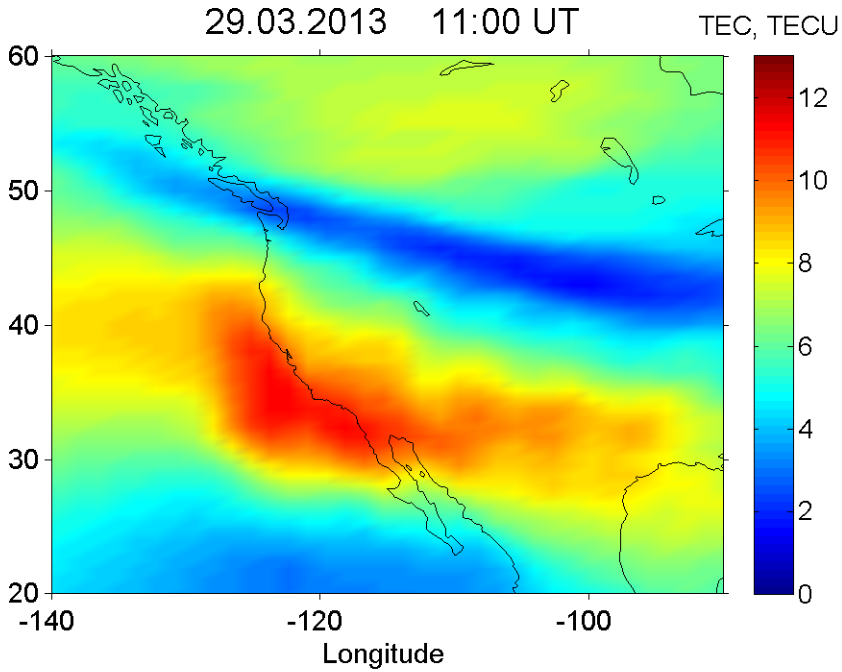


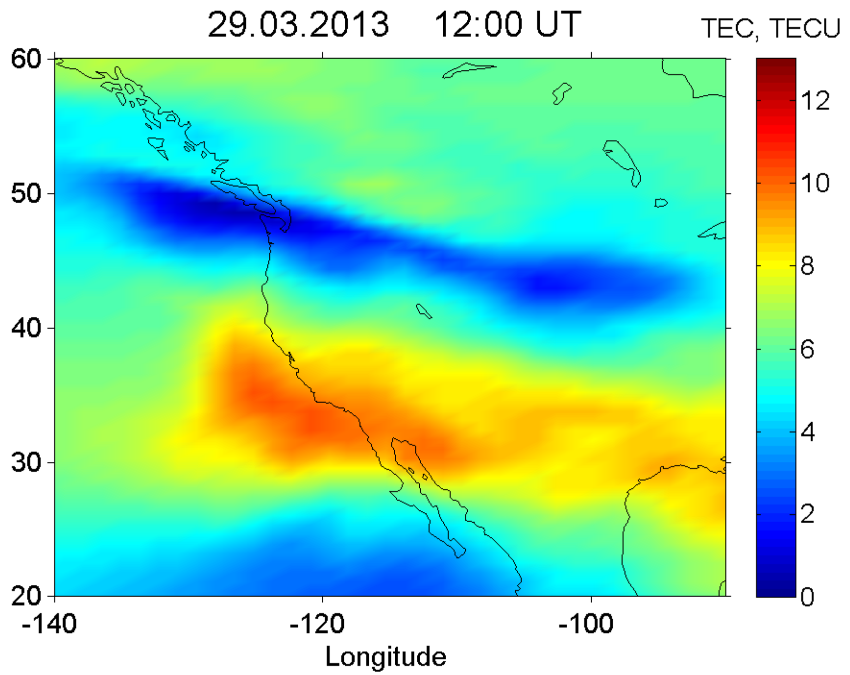




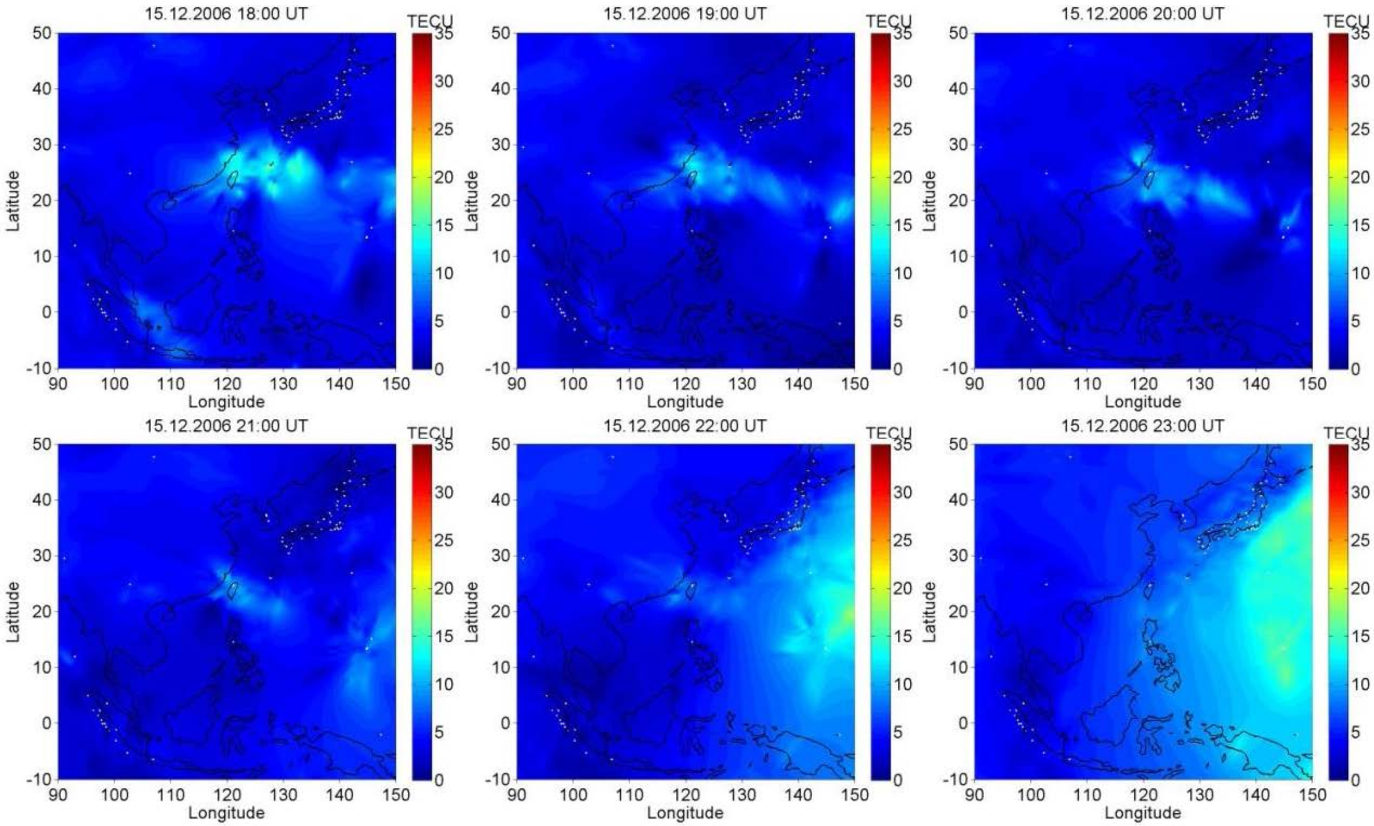
U.S. West Coast



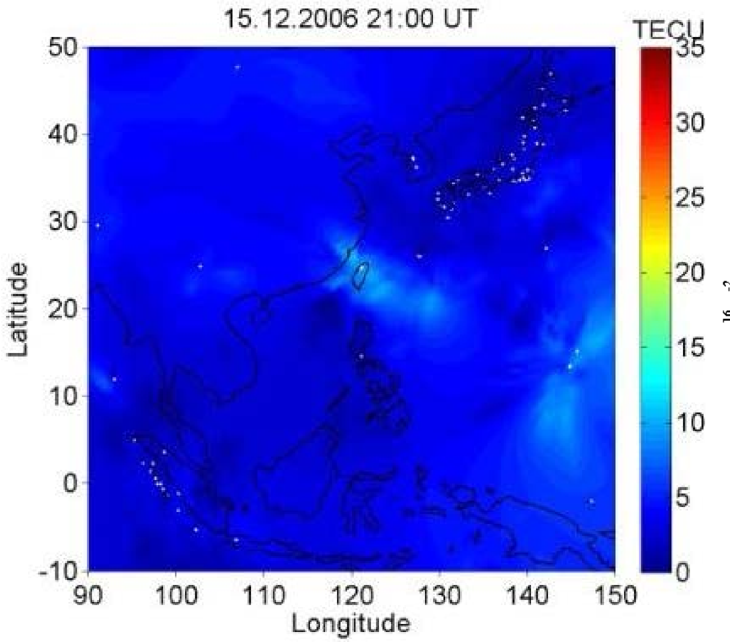


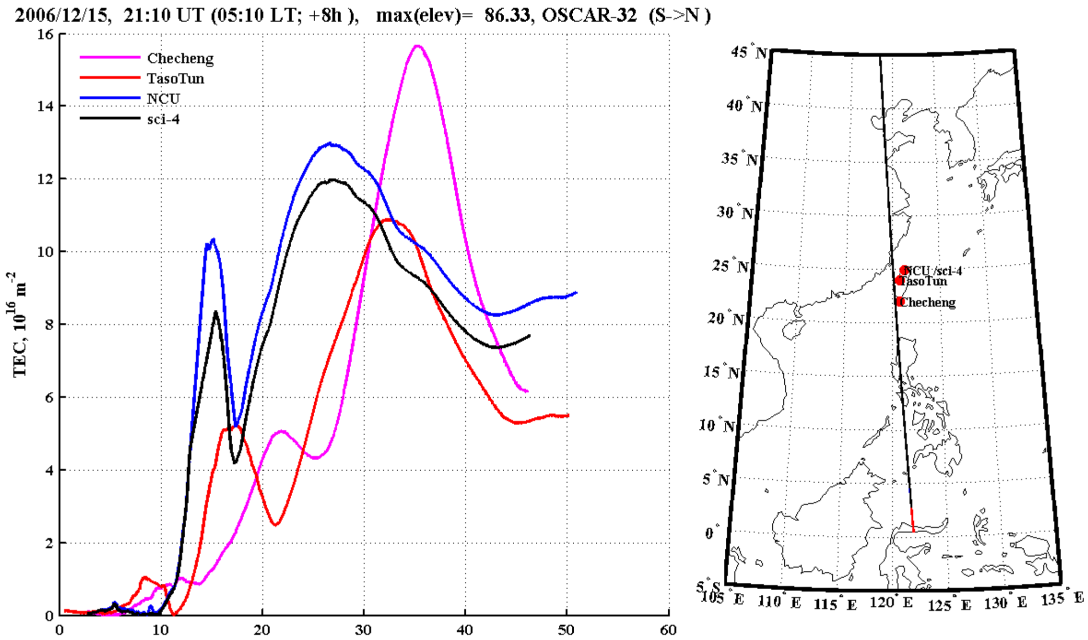


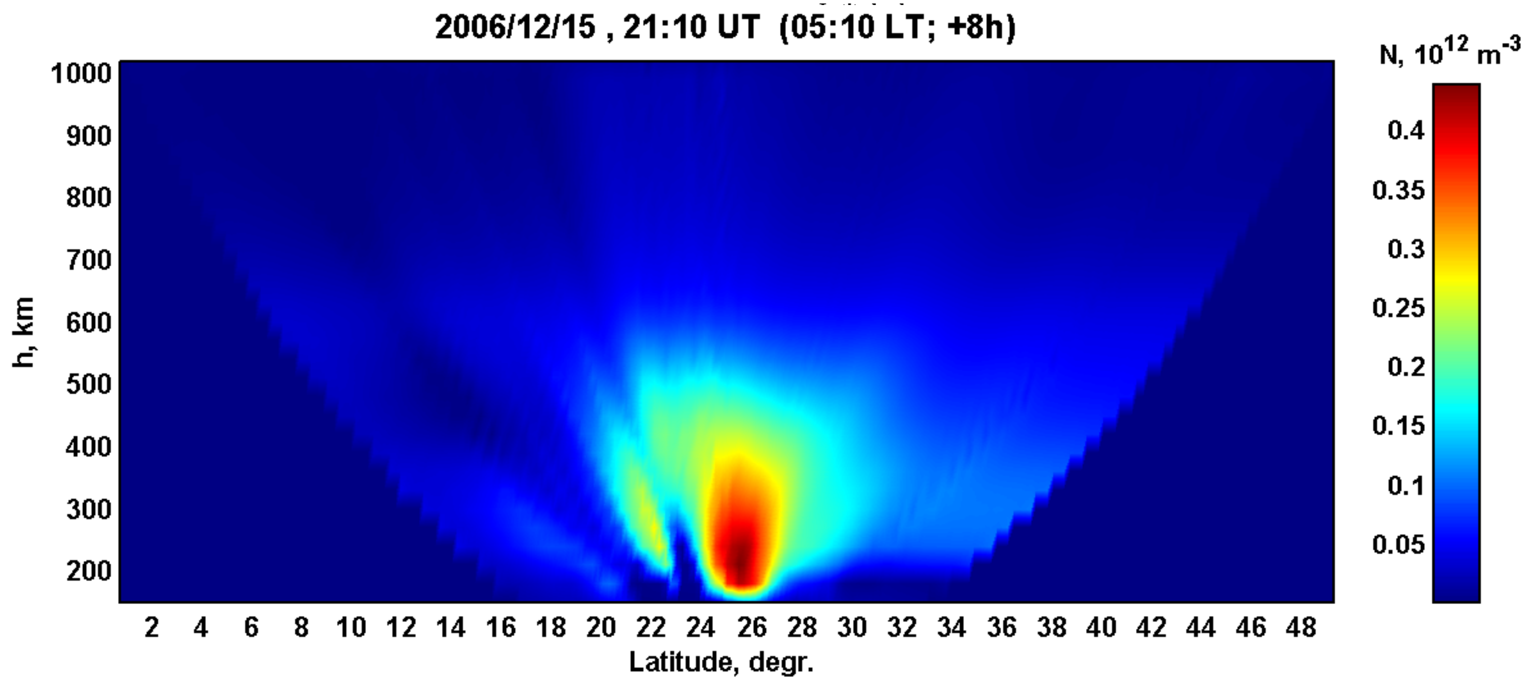
Vertical TEC above South-East Asia according to 4D HORT during geomagnetic storm 15.12.2006 (18:00 UT-23:00 UT)

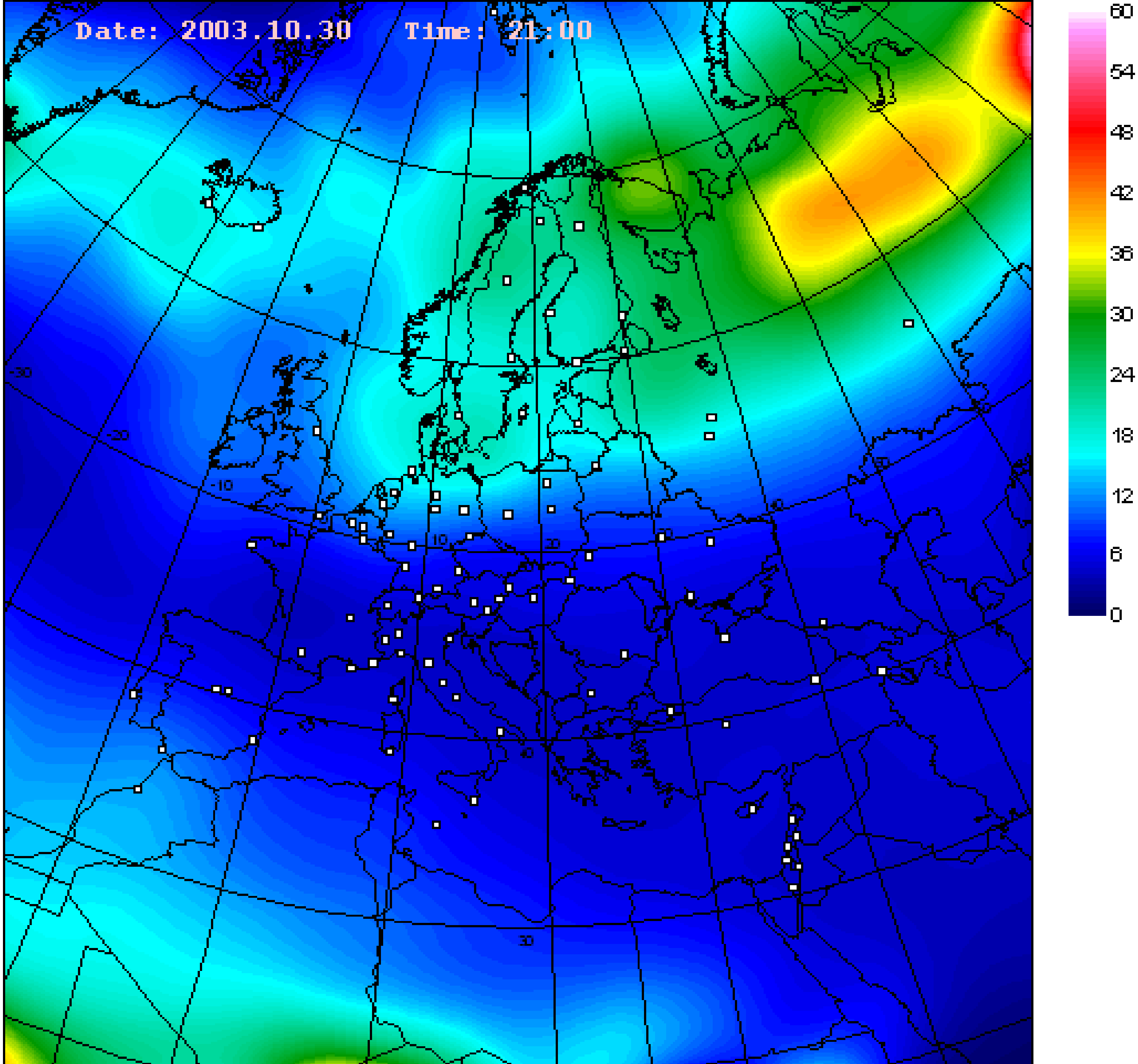


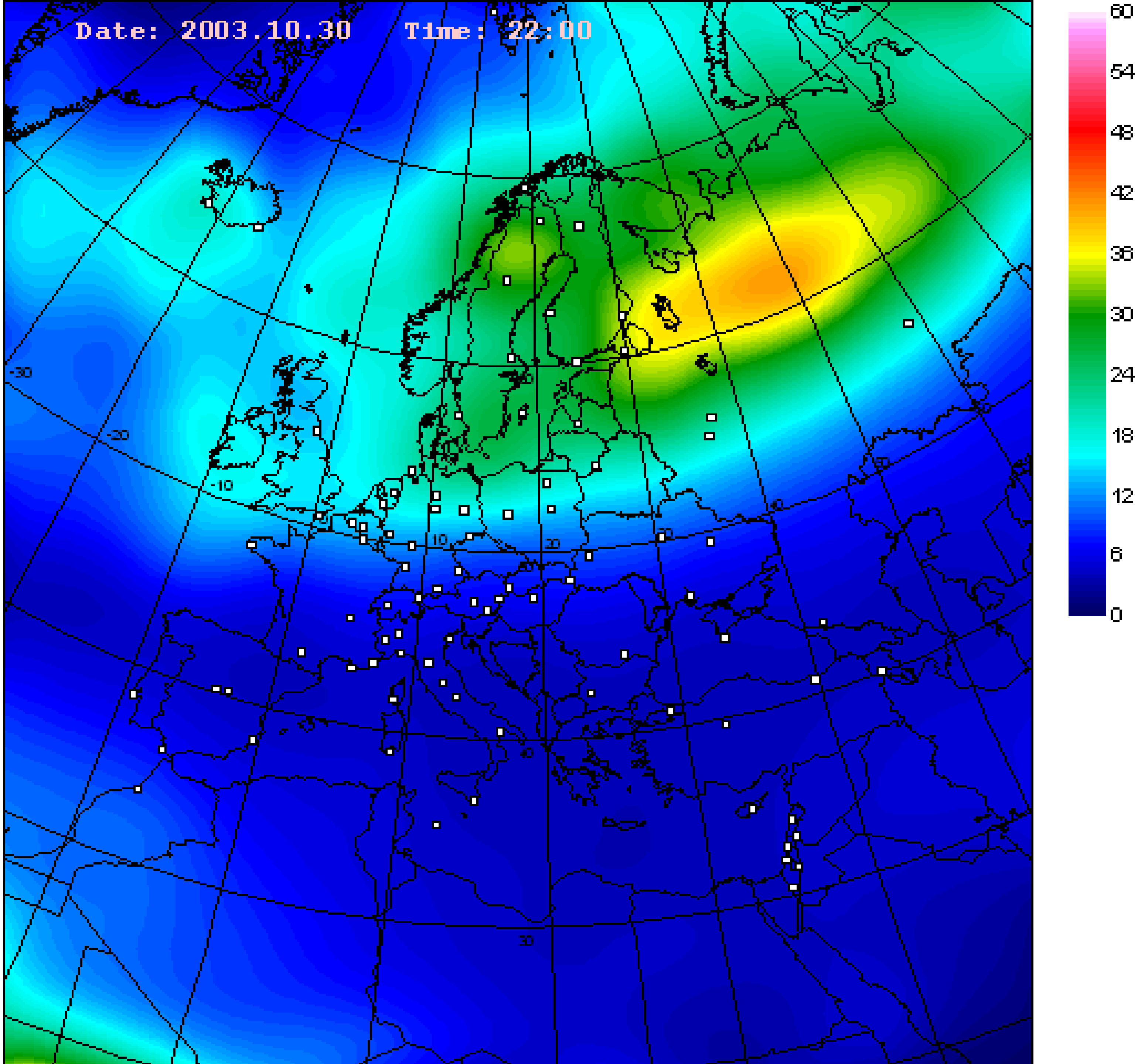
HORT **LORT**

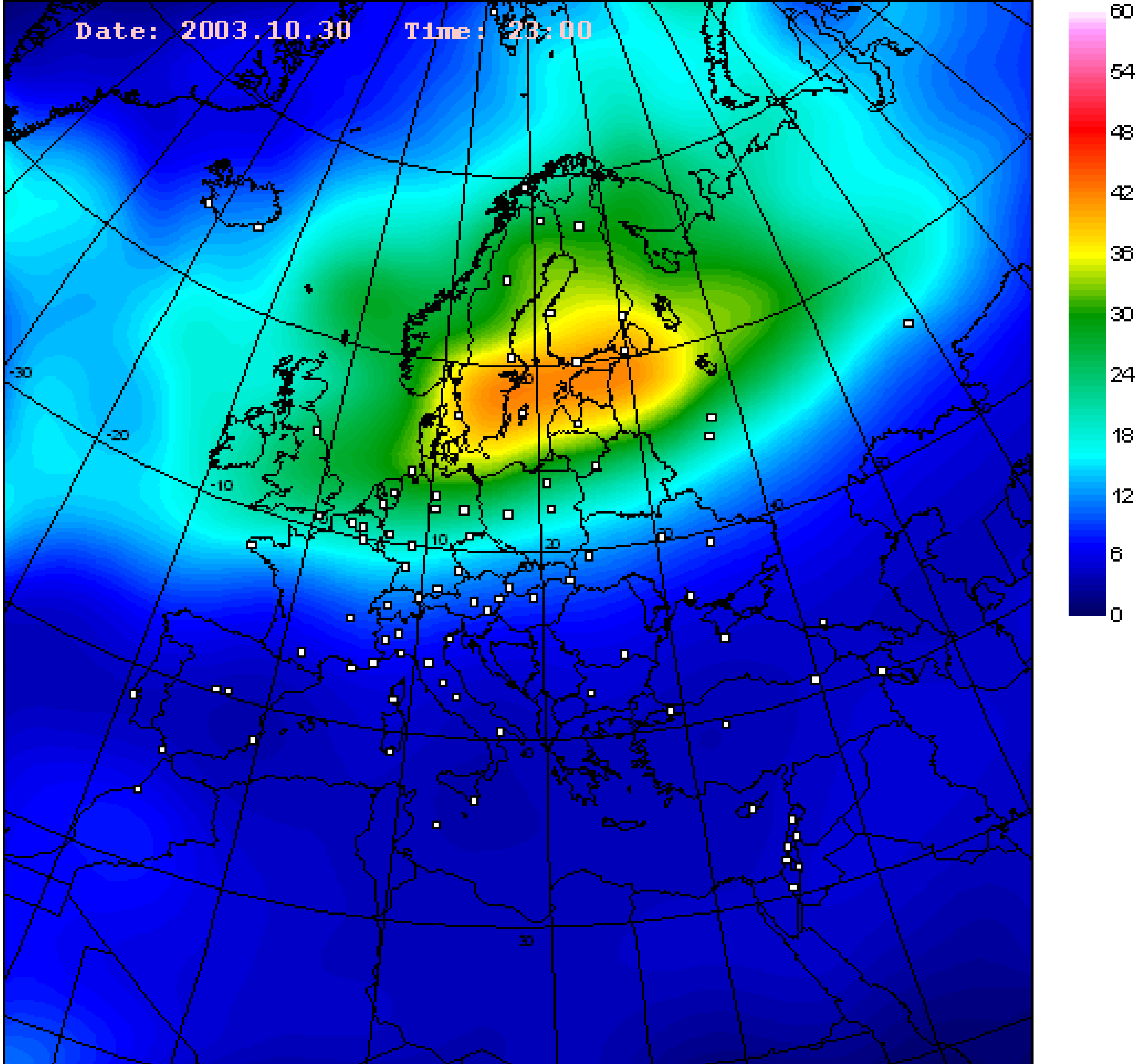

15.12.2006 21:00 UT
TECU
Latitude
Longitude


2006/12/15, 21:10 UT (05:10 LT; +8h), max(elev)= 86.33, OSCAR-32 (S->N)
Checheng
TasoTun
NCU
sci-4
TEC, 10^{16} m^{-2}
NCU /sci-4
TasoTun
Checheng

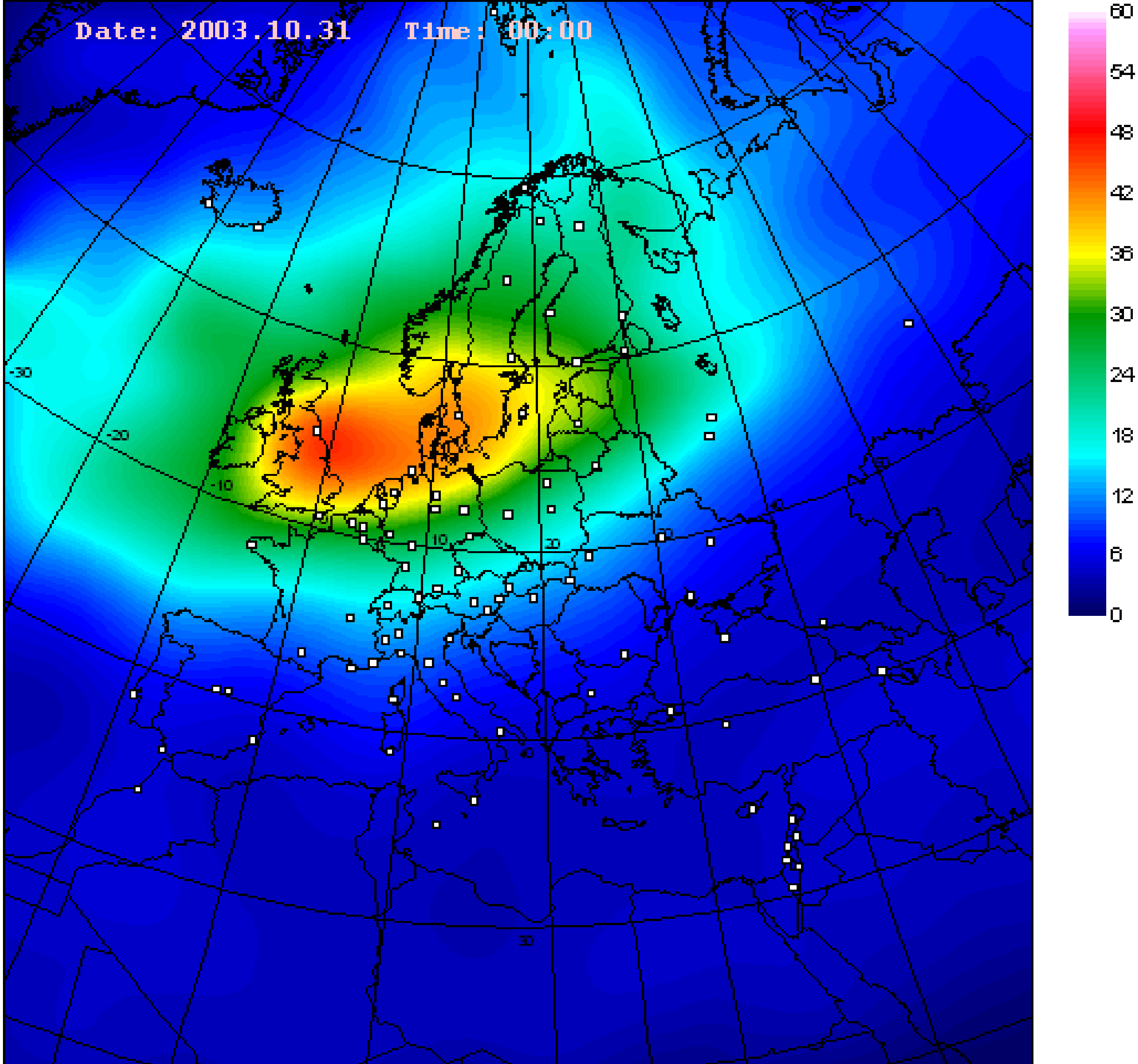

2006/12/15 , 21:10 UT (05:10 LT; +8h)
N, 10^{12} m^{-3}
h, km
Latitude, degr.


Date: 2003.10.30 Time: 21:00
60
54
48
42
36
30
24
18
12
6
0

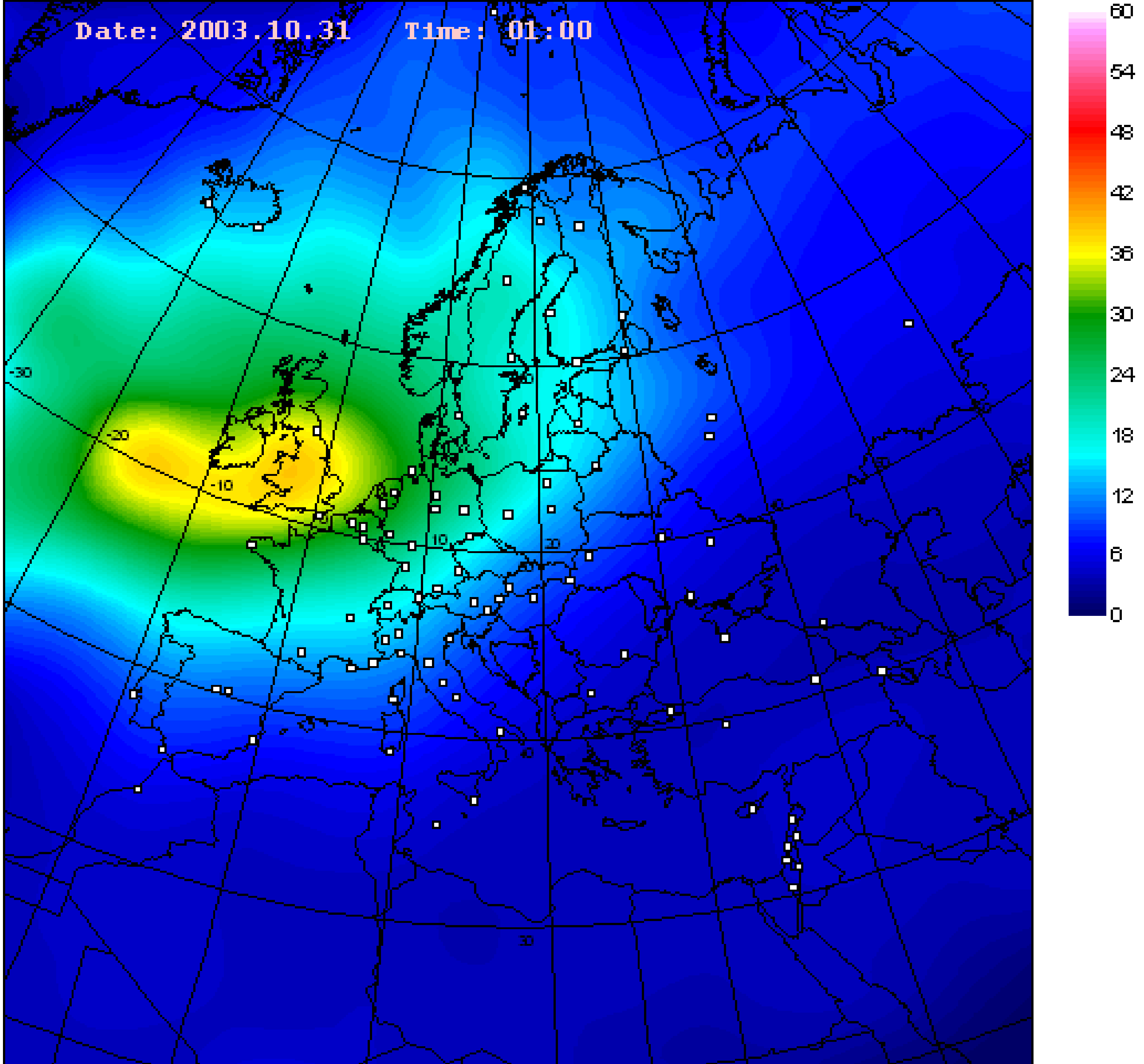

Date: 2003.10.30 Time: 22:00
60
54
48
42
36
30
24
18
12
6
0



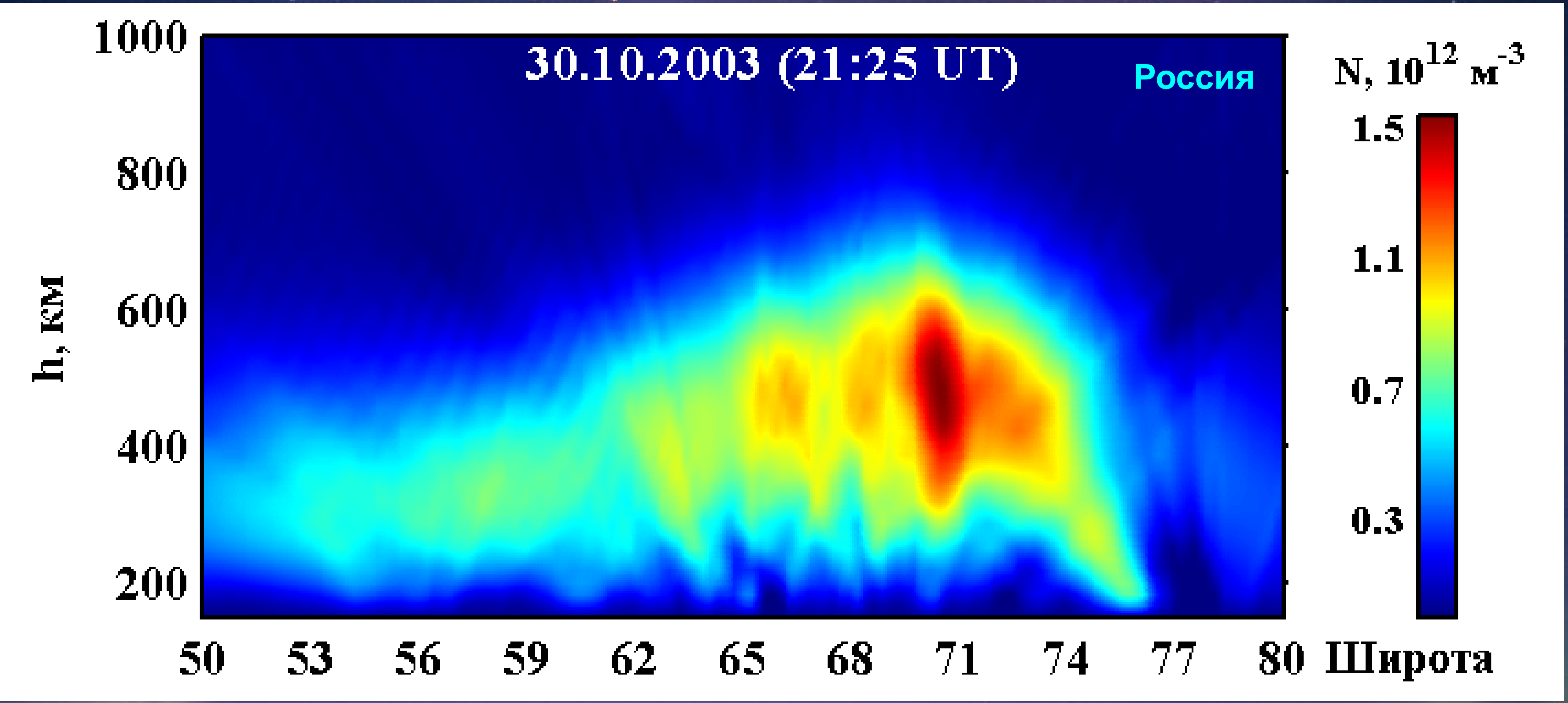
Date: 2003.10.30 Time: 23:00
60
54
48
42
36
30
24
18
12
6
0

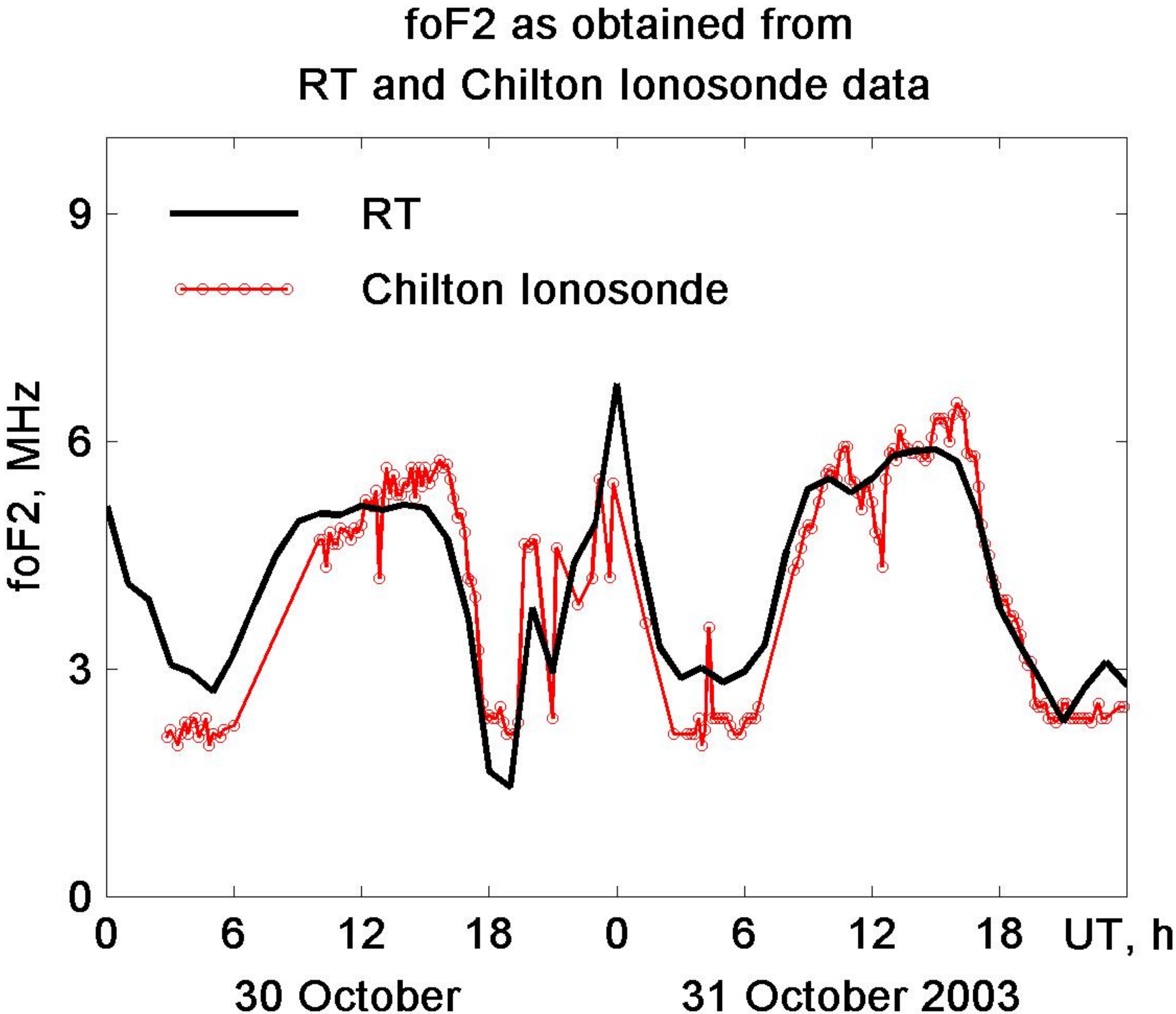


Date: 2003.10.31 Time: 00:00
60
54
48
42
36
30
24
18
12
6
0
-30
-20
-10
10
20
30
40

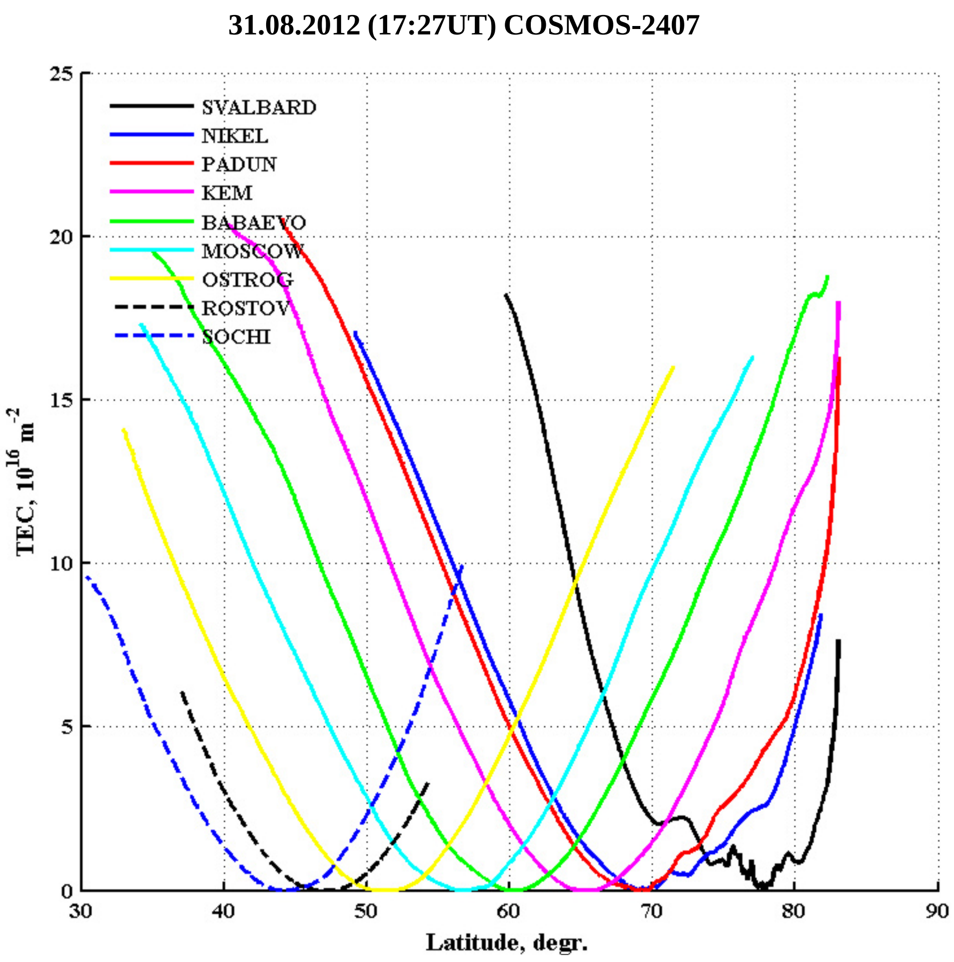

Date: 2003.10.31 Time: 01:00
60
54
48
42
36
30
24
18
12
6
0
-30
-20
-10
10
20
30

Solar Extreme Events of 2003

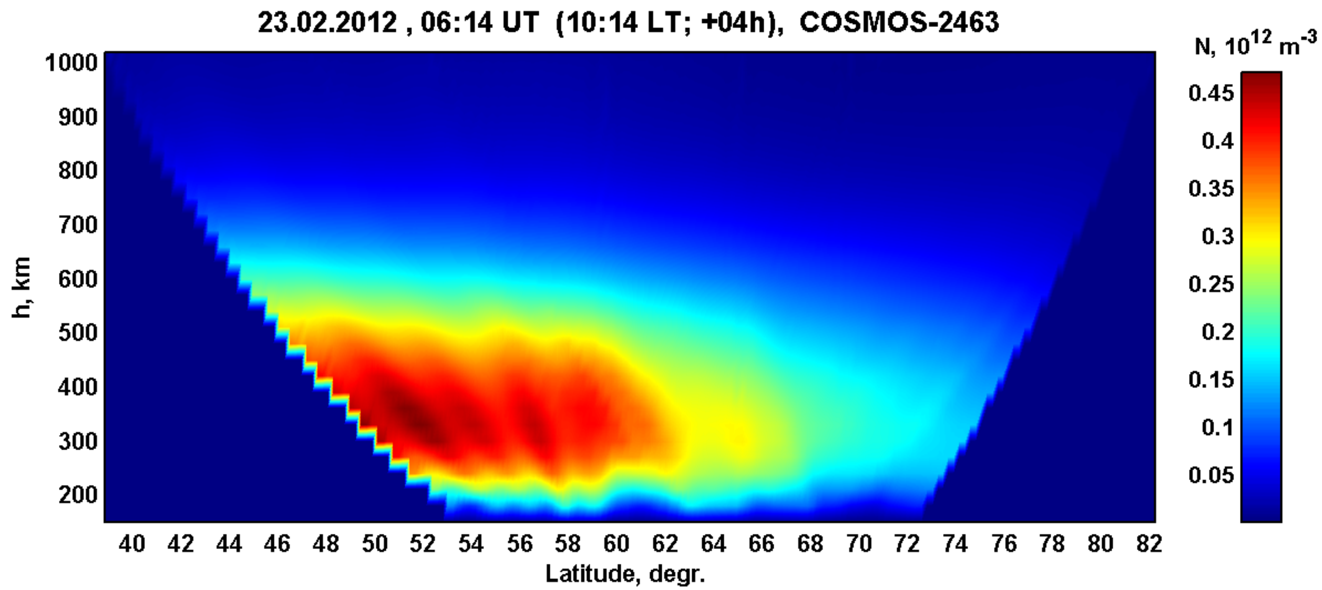



foF2 as obtained from
RT and Chilton Ionosonde data
RT
Chilton Ionosonde
foF2, MHz
9
6
3
0
0
6
12
18
0
6
12
18
UT, h
30 October
31 October 2003

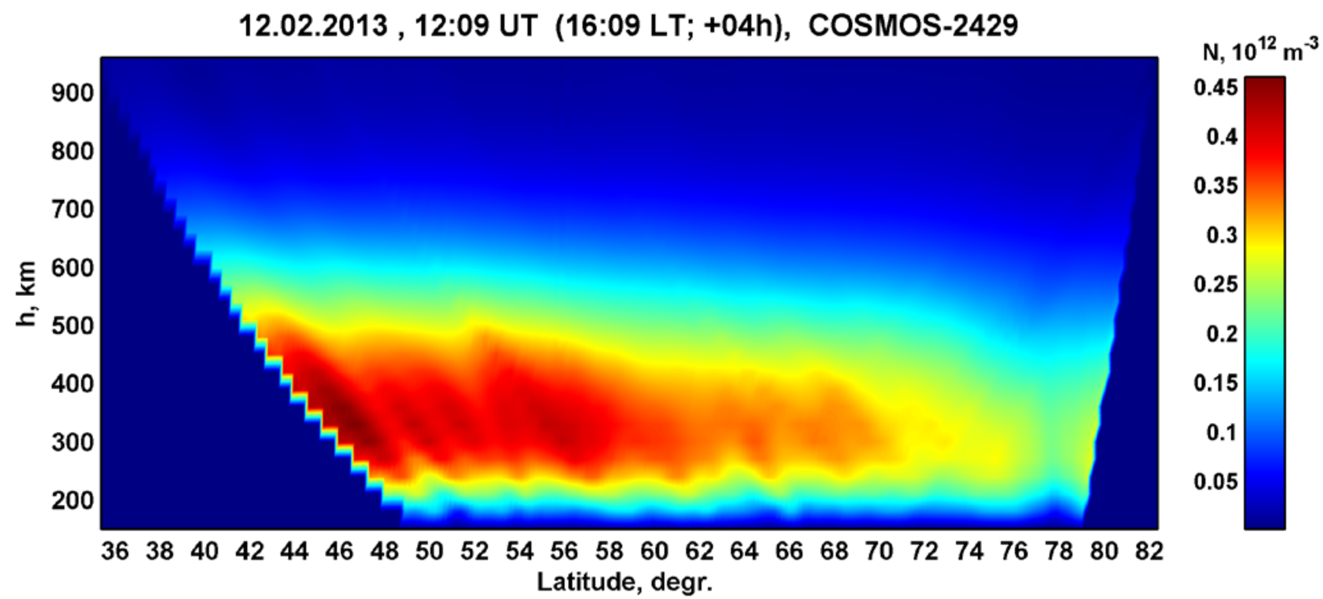
Russian LORT system (Svalbard – Moscow - Sochi)



TIDs (Nortwest of Russia)



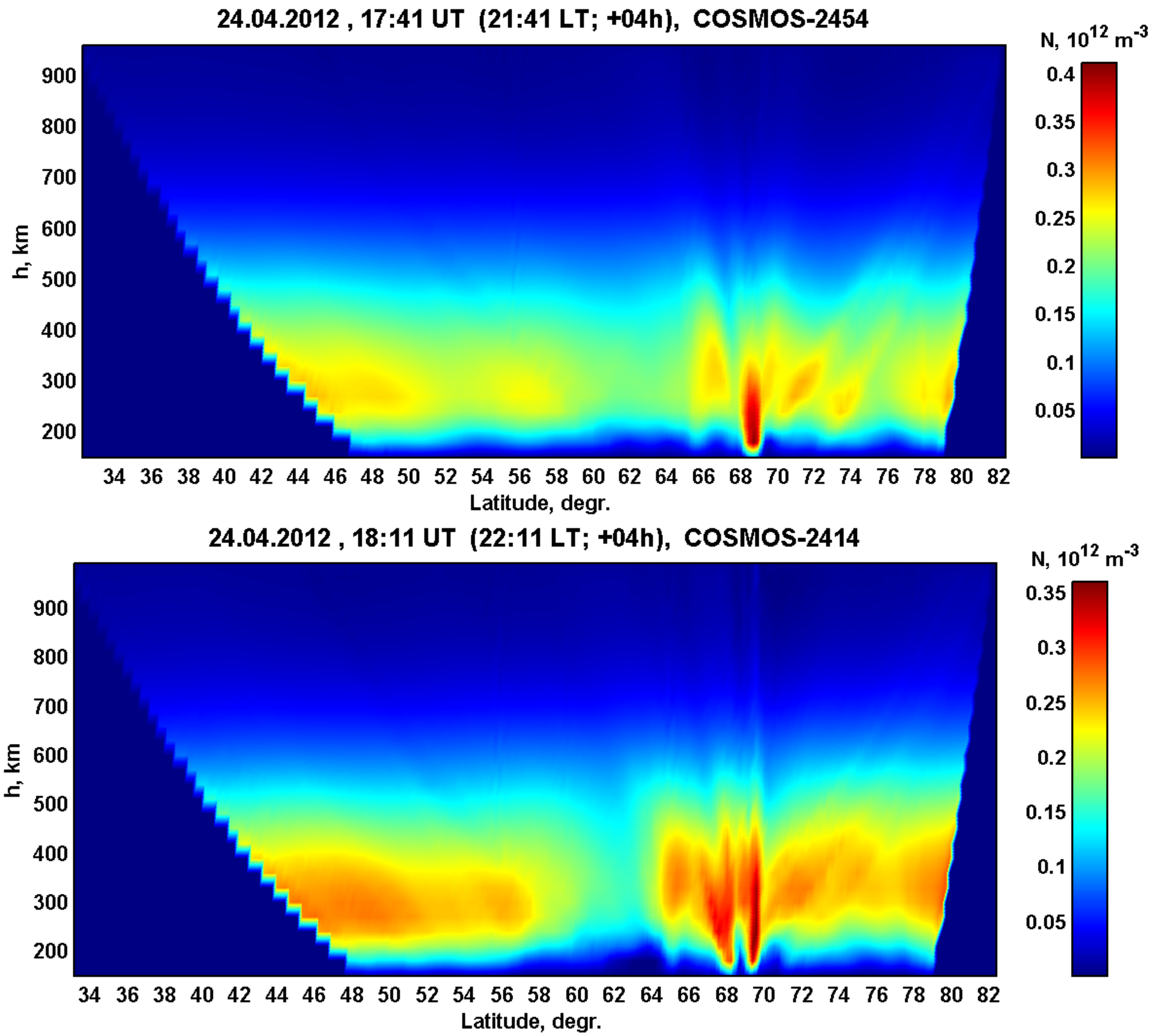
LORT image above Russian RT chain on February 23, 2012 , 06:14 UT



LORT image above Russian RT chain on February 12, 2013 , 12:09 UT

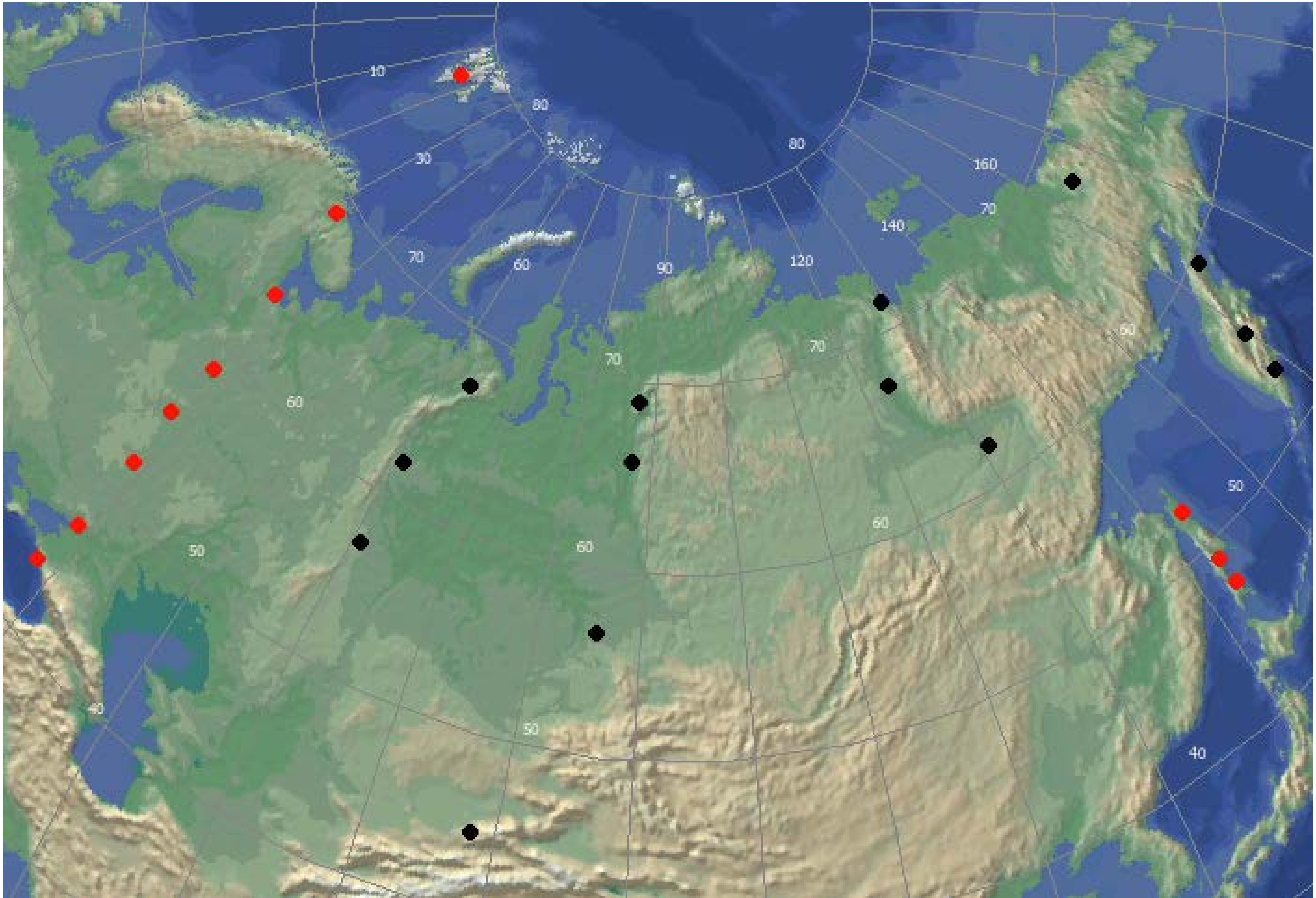
Region of Russian LORT system

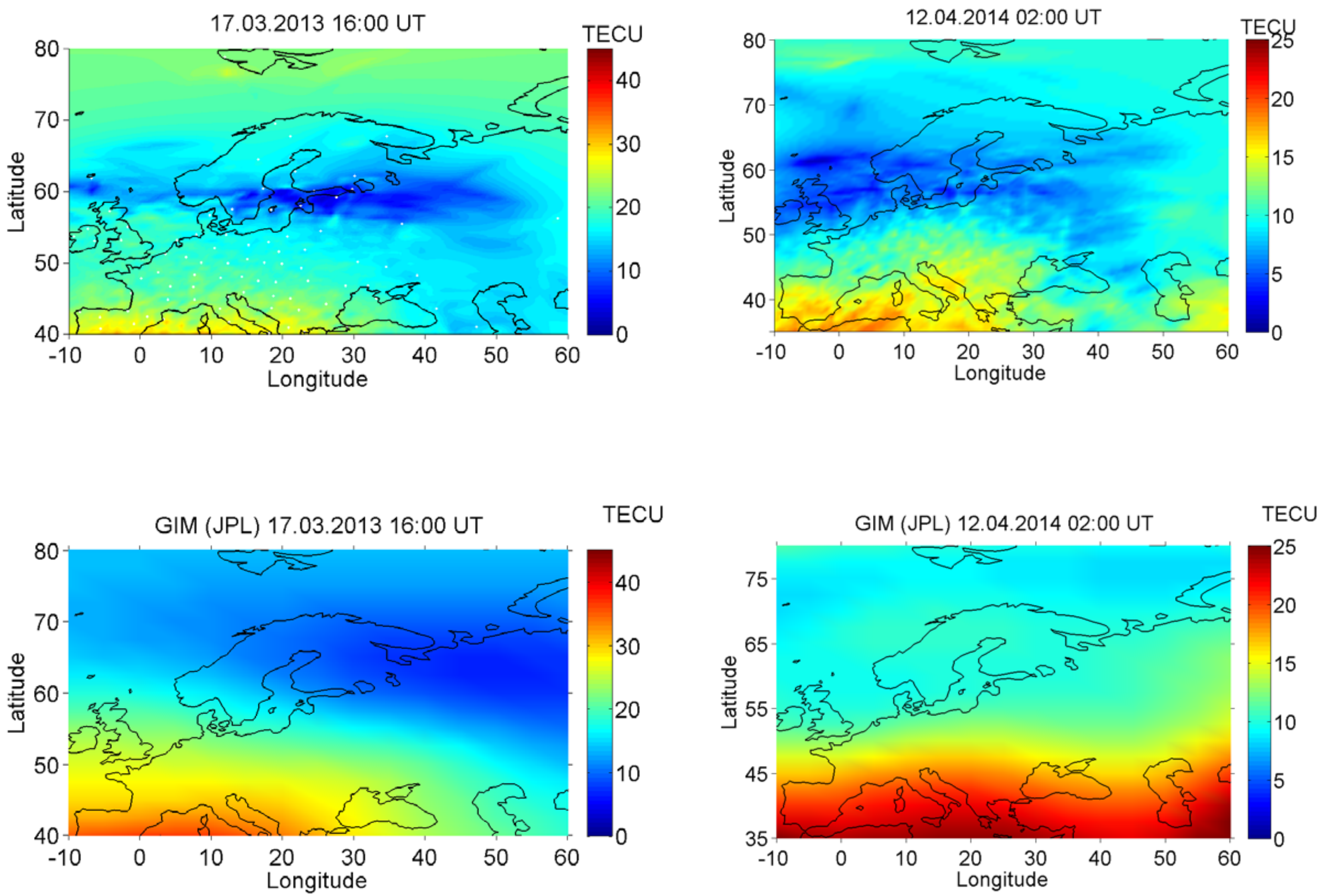
ionospheric features are probably associated with particle precipitation



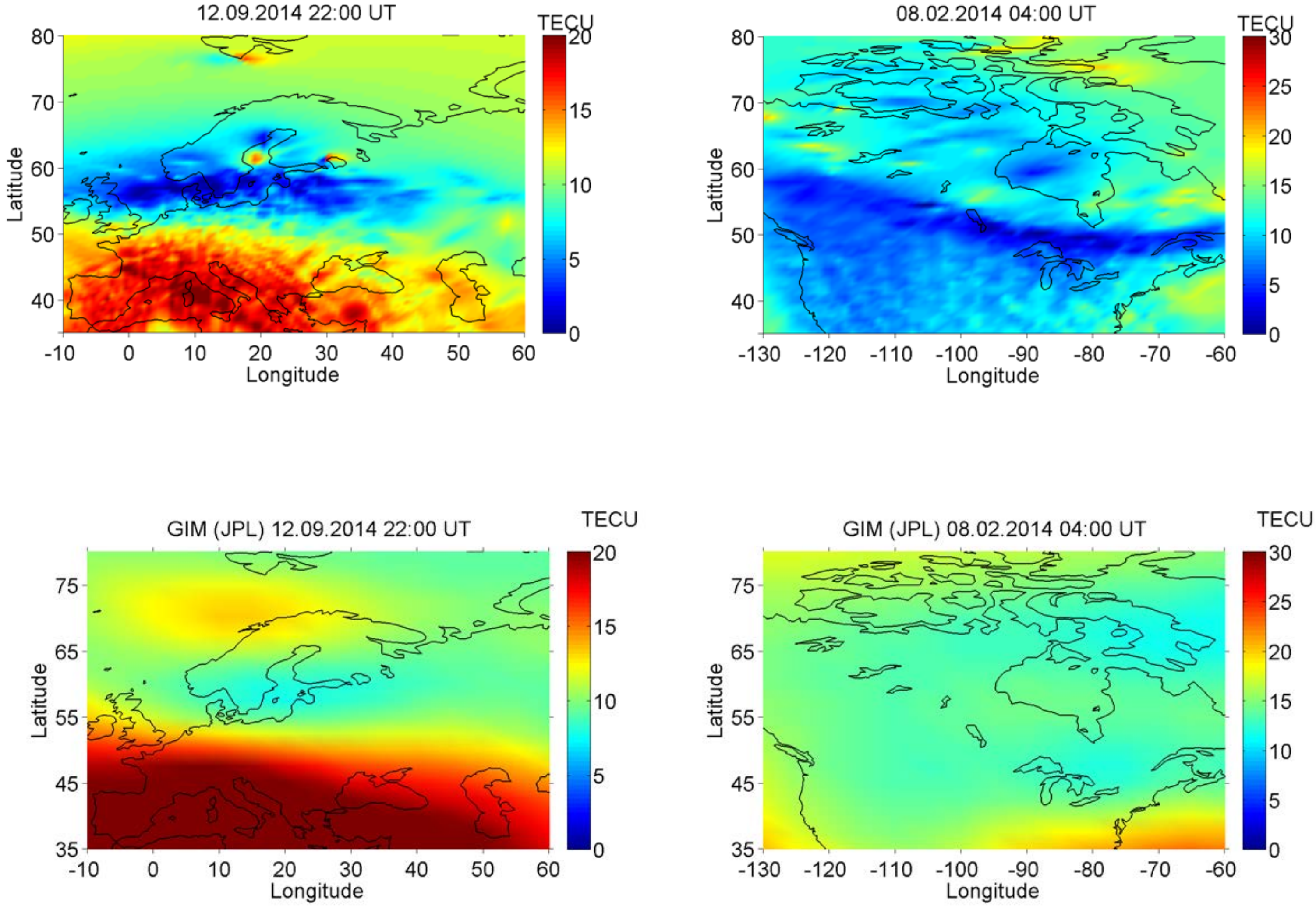
LORT images above Russian RT chain on April 24, 2012 , 17:41 and 18:11 UT

Система НОРТ. ФЦП “Создание системы мониторинга геофизической обстановки над территорией РФ на 2008-2015 годы”

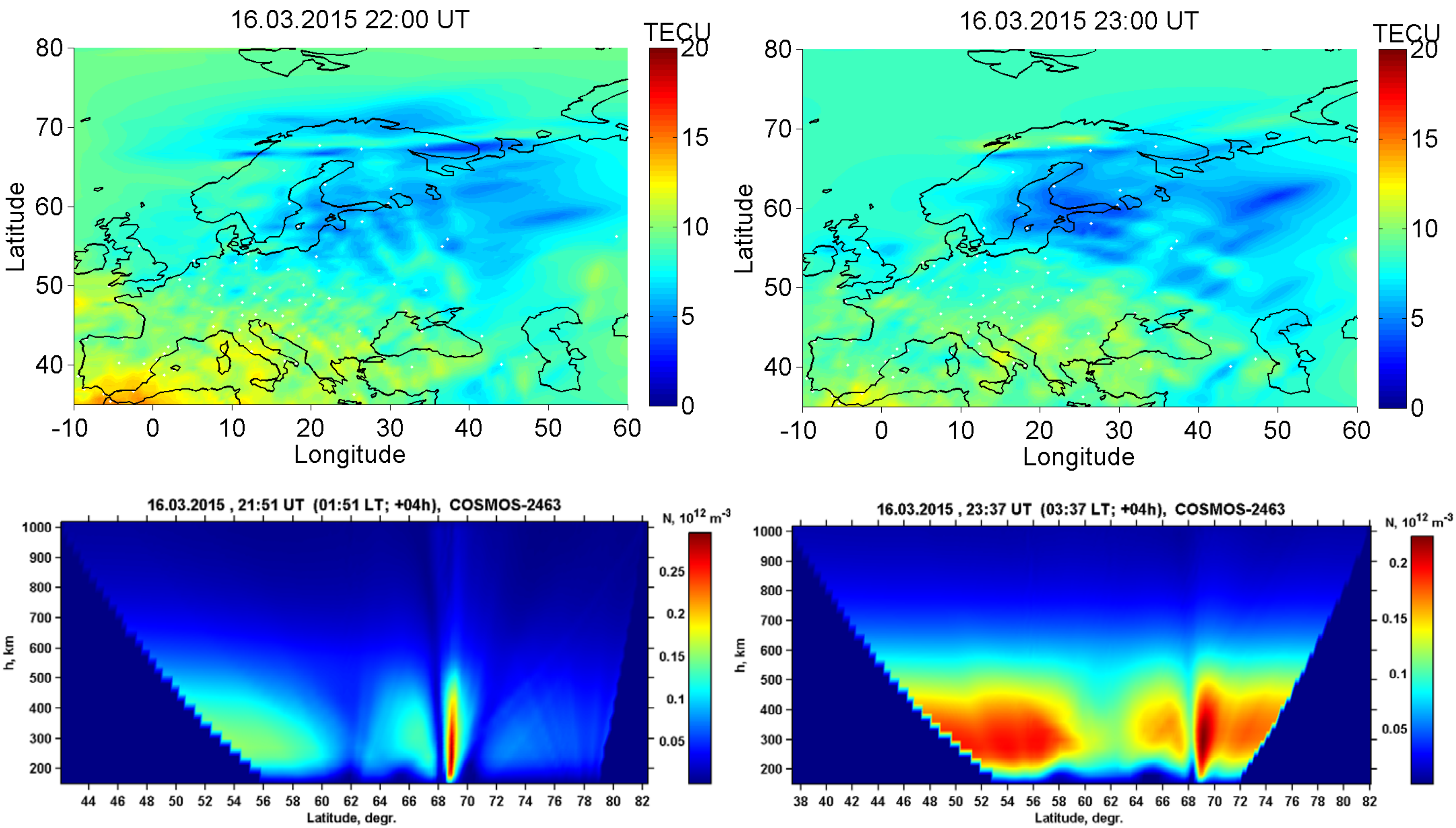


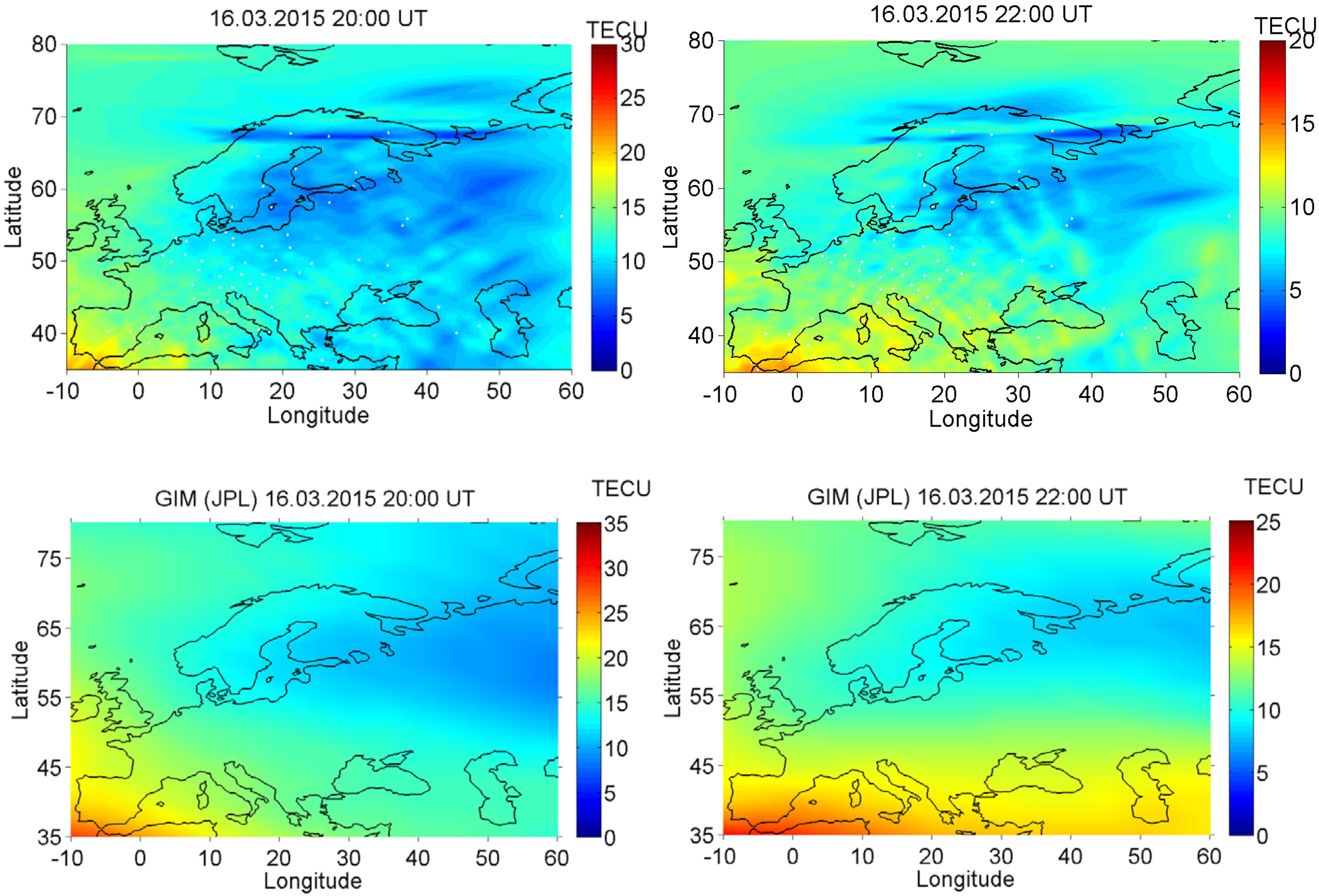


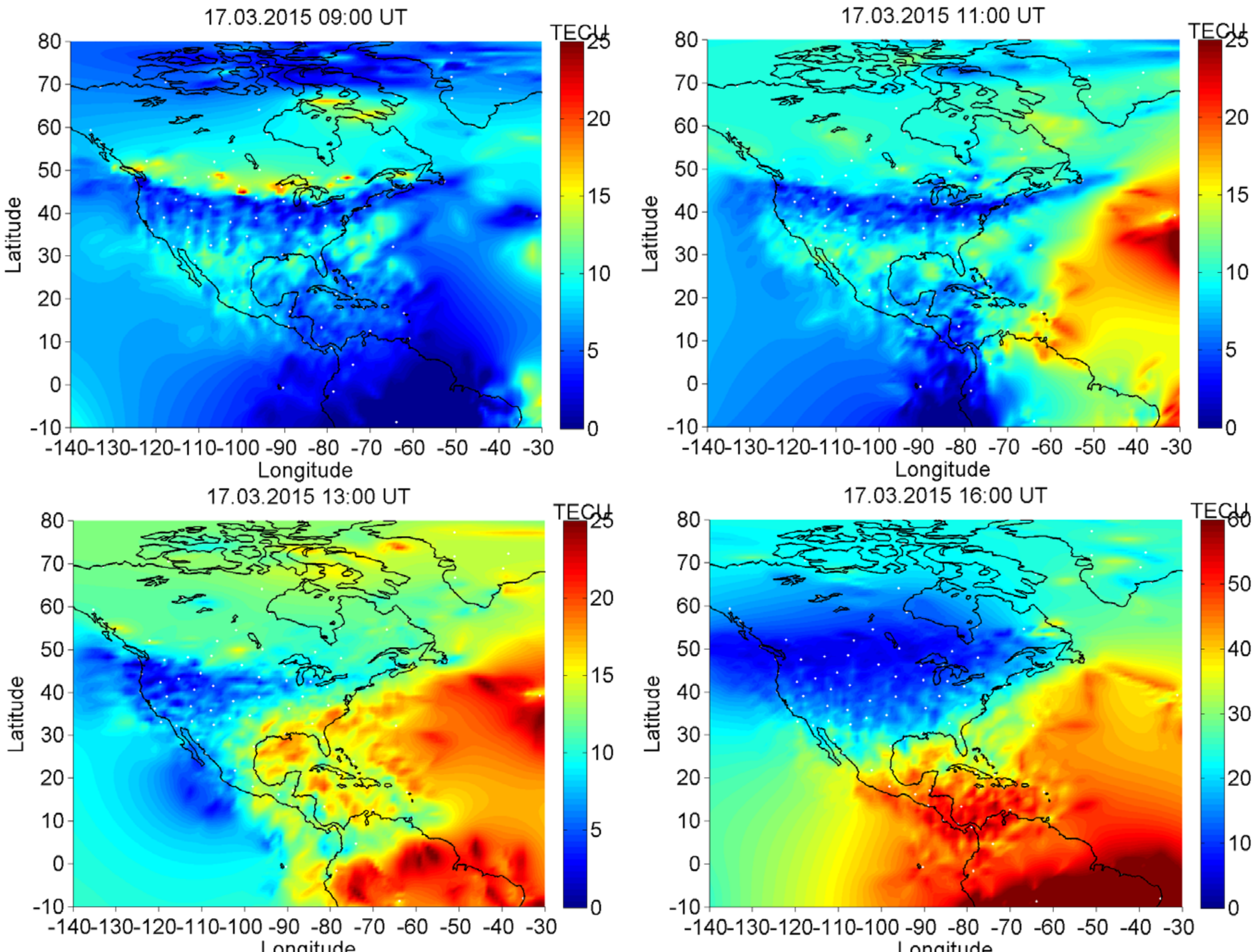
17.03.2013 16:00 UT
12.04.2014 02:00 UT
GIM (JPL) 17.03.2013 16:00 UT
GIM (JPL) 12.04.2014 02:00 UT
TECU
Latitude
Longitude



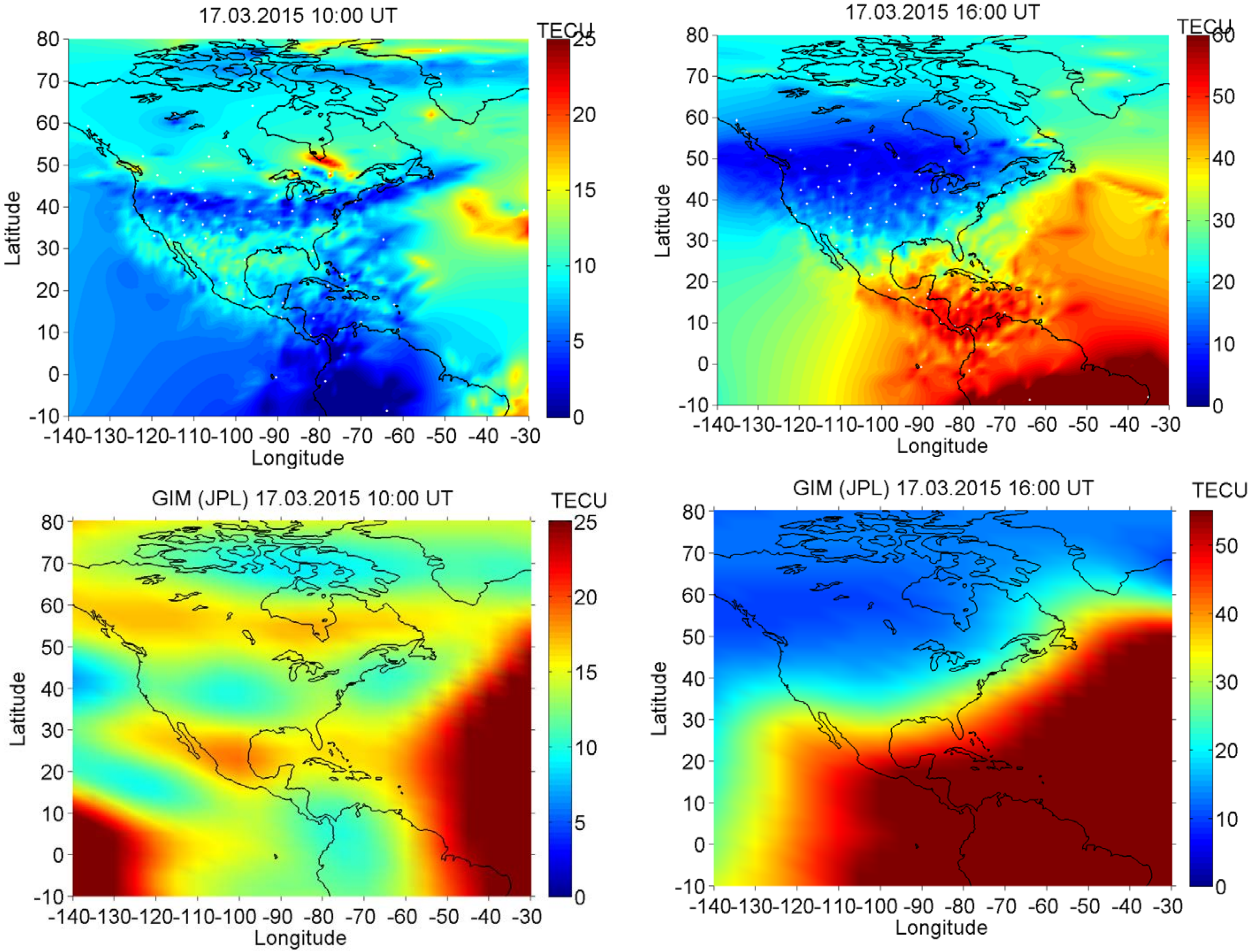
12.09.2014 22:00 UT
TECU
Latitude
Longitude
08.02.2014 04:00 UT
TECU
Latitude
Longitude
GIM (JPL) 12.09.2014 22:00 UT
TECU
Latitude
Longitude
GIM (JPL) 08.02.2014 04:00 UT
TECU
Latitude
Longitude


16.03.2015 22:00 UT
16.03.2015 23:00 UT
TECU
Latitude
Longitude
16.03.2015 , 21:51 UT (01:51 LT; +04h), COSMOS-2463
16.03.2015 , 23:37 UT (03:37 LT; +04h), COSMOS-2463
h, km
N, 10^{12} m^{-3}
Latitude, degr.


16.03.2015 20:00 UT
TECU
Latitude
Longitude
16.03.2015 22:00 UT
TECU
Latitude
Longitude
GIM (JPL) 16.03.2015 20:00 UT
TECU
Latitude
Longitude
GIM (JPL) 16.03.2015 22:00 UT
TECU
Latitude
Longitude

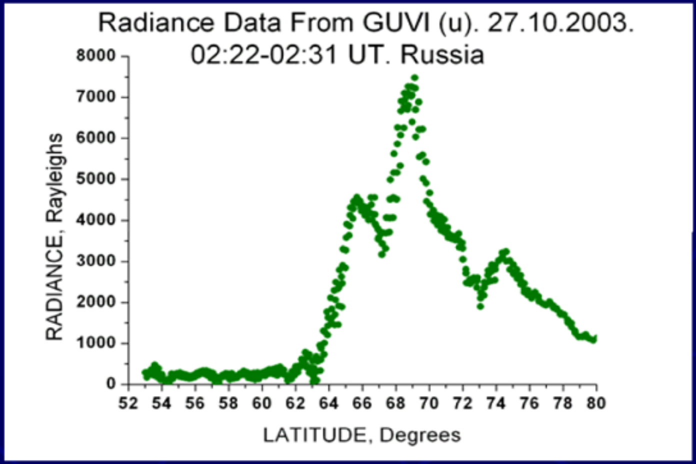


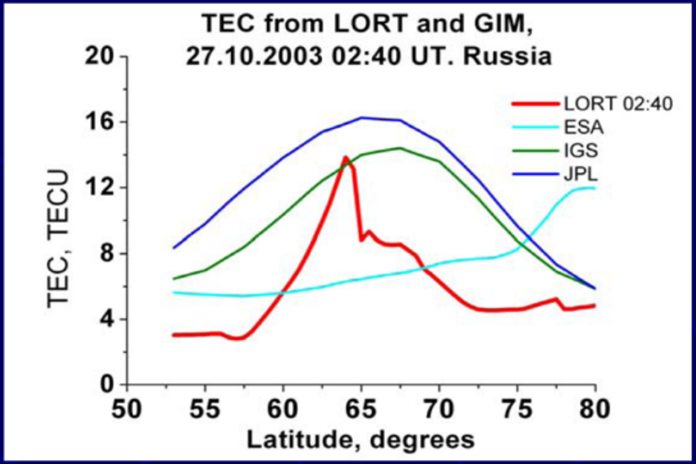
17.03.2015 09:00 UT
17.03.2015 11:00 UT
17.03.2015 13:00 UT
17.03.2015 16:00 UT
TECU
Latitude
Longitude



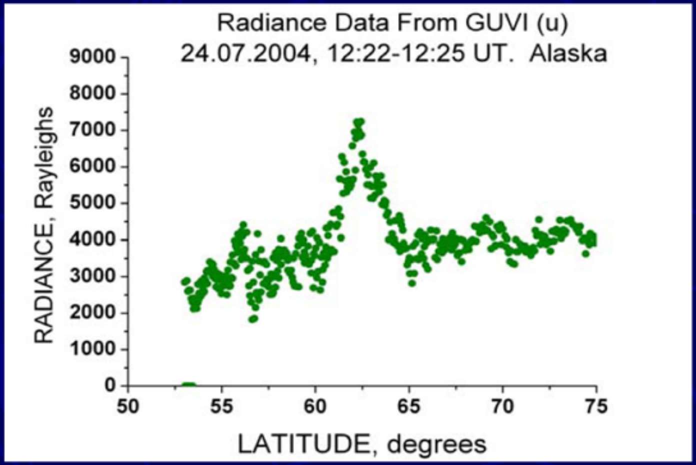
17.03.2015 10:00 UT
17.03.2015 16:00 UT
GIM (JPL) 17.03.2015 10:00 UT
GIM (JPL) 17.03.2015 16:00 UT
TECU
Latitude
Longitude

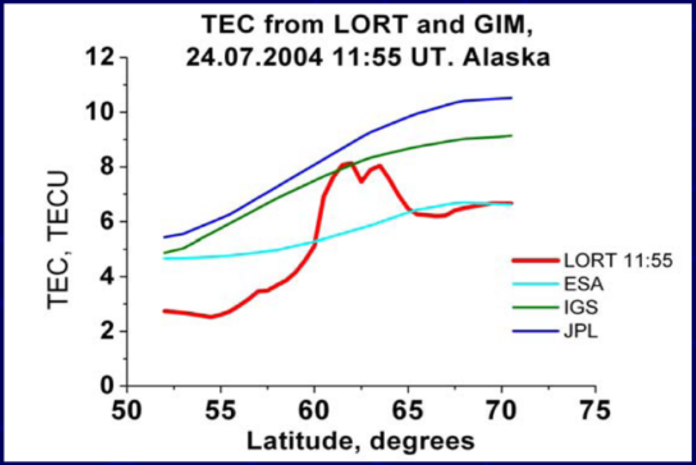
Comparison of GUVI Data and TEC by LORT and GIM



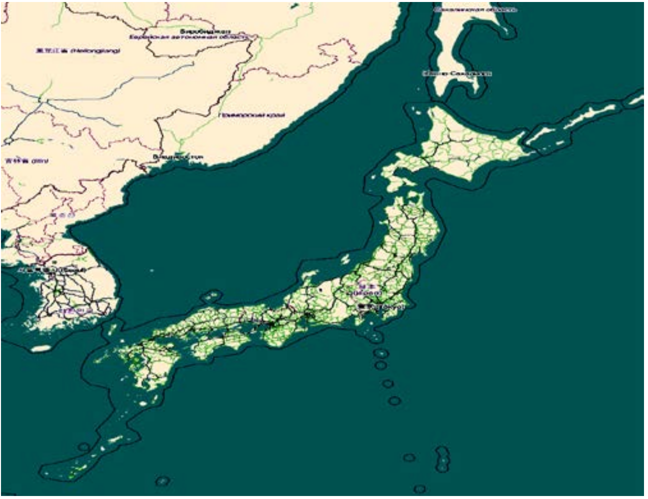


Dst=-47 Kp=3.3 Ap=20

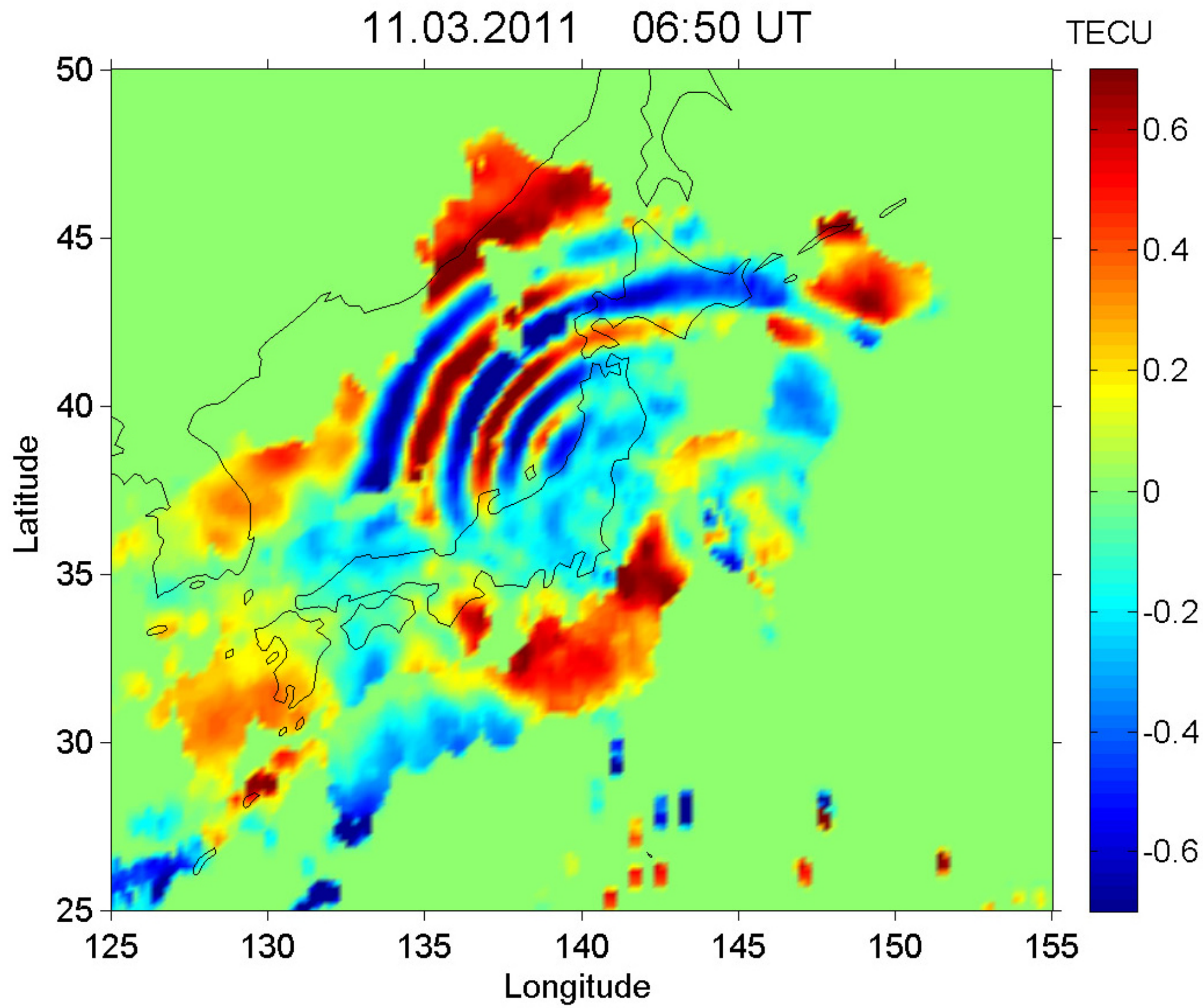




Dst=-18 Kp=6 Ap=80



Tohoku mega-earthquake



The TEC waves, caused by the AGW from the Tohoku mega-earthquake, diverging from the epicenter of the event.

SUMMARY

- The combination of LORT and HORT systems provides significant advantages: HORT yields 3D distributions of the ionospheric plasma over vast regions, and LORT provides significantly higher resolution.

- The existing systems implementing the radio occultation (RO) approach (FormoSat-3/COSMIC and other systems that record the signals from the GPS/GLONASS satellites at HO satellites) provide the quasi tangential projections of electron density *N*.

  The combination of the RT and RO methods, which supports the RT data by the probing data on the satellite-to-satellite paths (RO data), can significantly improve vertical resolution of RT reconstructions.

- The existing UV sounder systems (GUVI, SSULI) provide the integrals of *N* squared. In this case, the data from UV sounders can be incorporated into the common tomographic iterative scheme; however, the data should be consistent in terms of accuracy.

- GIM TEC data are generally smoother than the results provided by RT. The GIM TEC data during the severe geomagnetic disturbances should be used with caution.

ACKNOWLEDGEMENTS

We are grateful to the NWRA for providing the data from Alaska RT System and Taiwan National Central University for providing the data from Taiwan RT System and Radio-Hydro-Physics LLC for providing the data from West Coast US RT System . The GIM data were obtained through ftp://ftp.unibe.ch/aiub/ CODE/.