# Ionospheric New Findings and Space Weather by FORMOSAT-3/COSMIC Radio Occultation Sounding

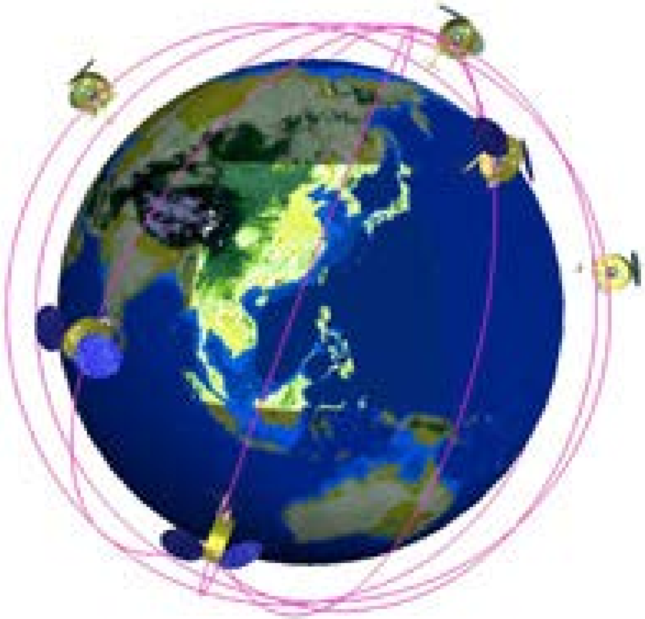
Tiger J.Y. Liu

TIGER (Taiwan Ionospheric Group for Education and Research)

National Central University, Chung-Li, TAIWAN
(E-mail: jyliu@jupiter.ss.ncu.edu.tw, tigerjyliu@gmail.com)

# Content

- Introduction
- New Finding
- Space Weather
- Conclusion



# FORMOSAT-3/COSMIC

Global Real-time
Weather (Meteorology)
Space Weather (Ionosphere)
Observation and Prediction

The FORMOSAT-3/COSMIC program is an international collaboration between Taiwan and the United States that will use a constellation of six remote sensing microsatellites to collect atmospheric data for weather prediction and for ionosphere, climate and gravity research. Data from the satellites will be made freely available to the international scientific community in near real-time.

# FORMOSAT-3/COSMIC

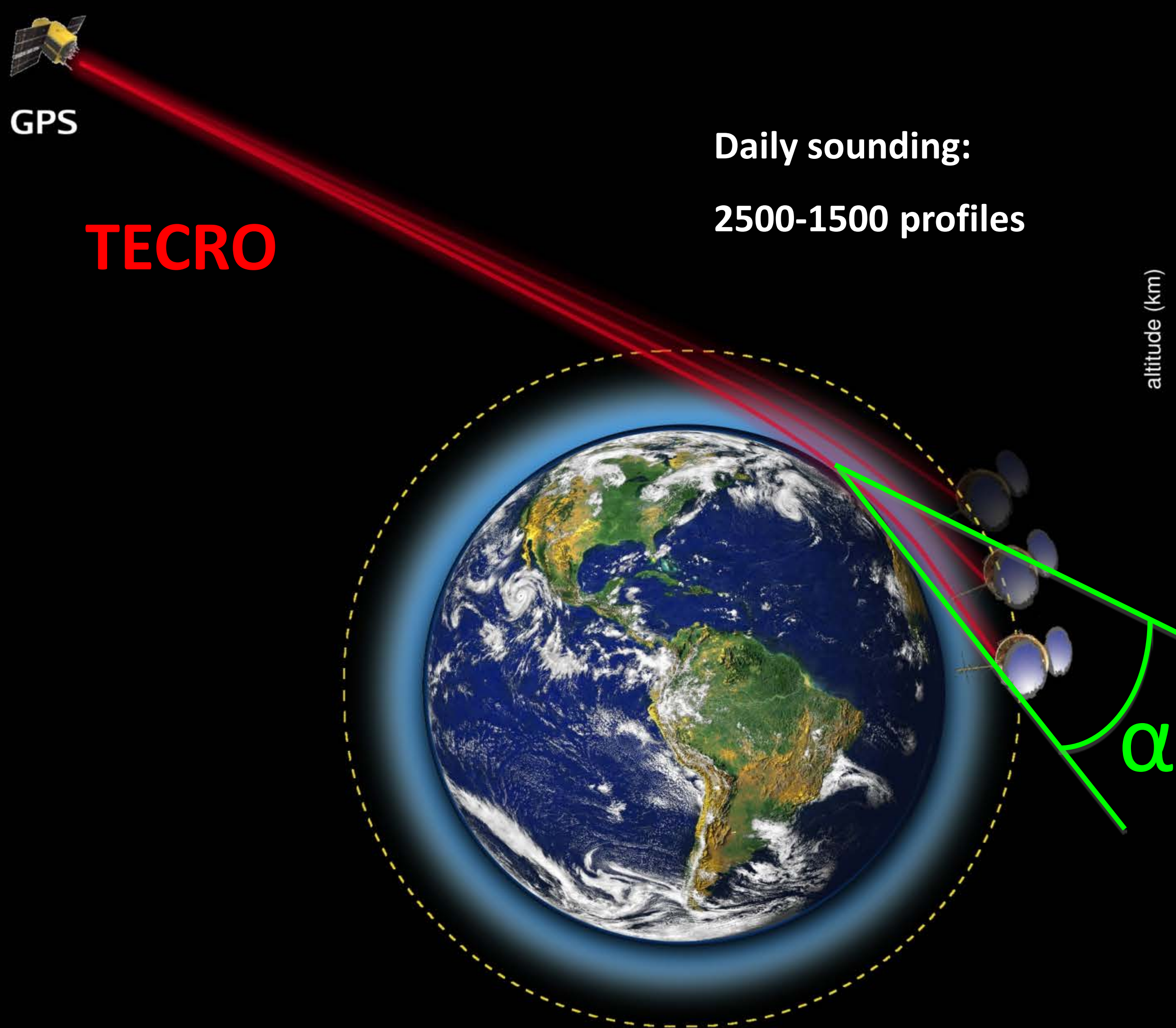
- ***FORMOSAT-3/COSMIC Constellation was launch at 01:40 UTC, April 14, 2006 (Taiwan Time: April 15 2006) at Vandenberg Air Force Base, CA.*** *Minotaur Launch*

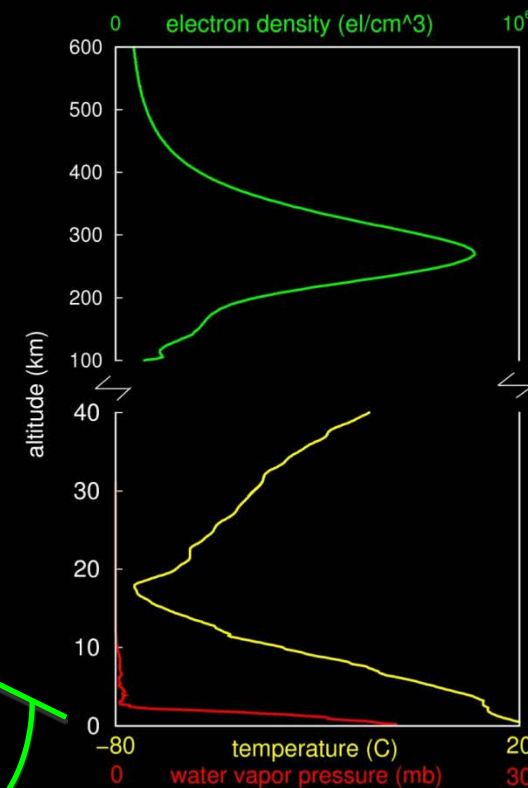
- ***Maneuvered into six different orbital planes (inclination ~72°) for optimal global coverage (at ~800 km altitude).***

- ***Five out of Six satellites are in good health and providing science data.***

# GPS Radio Occultation

**Total sounding: 4,000,000+ profiles**

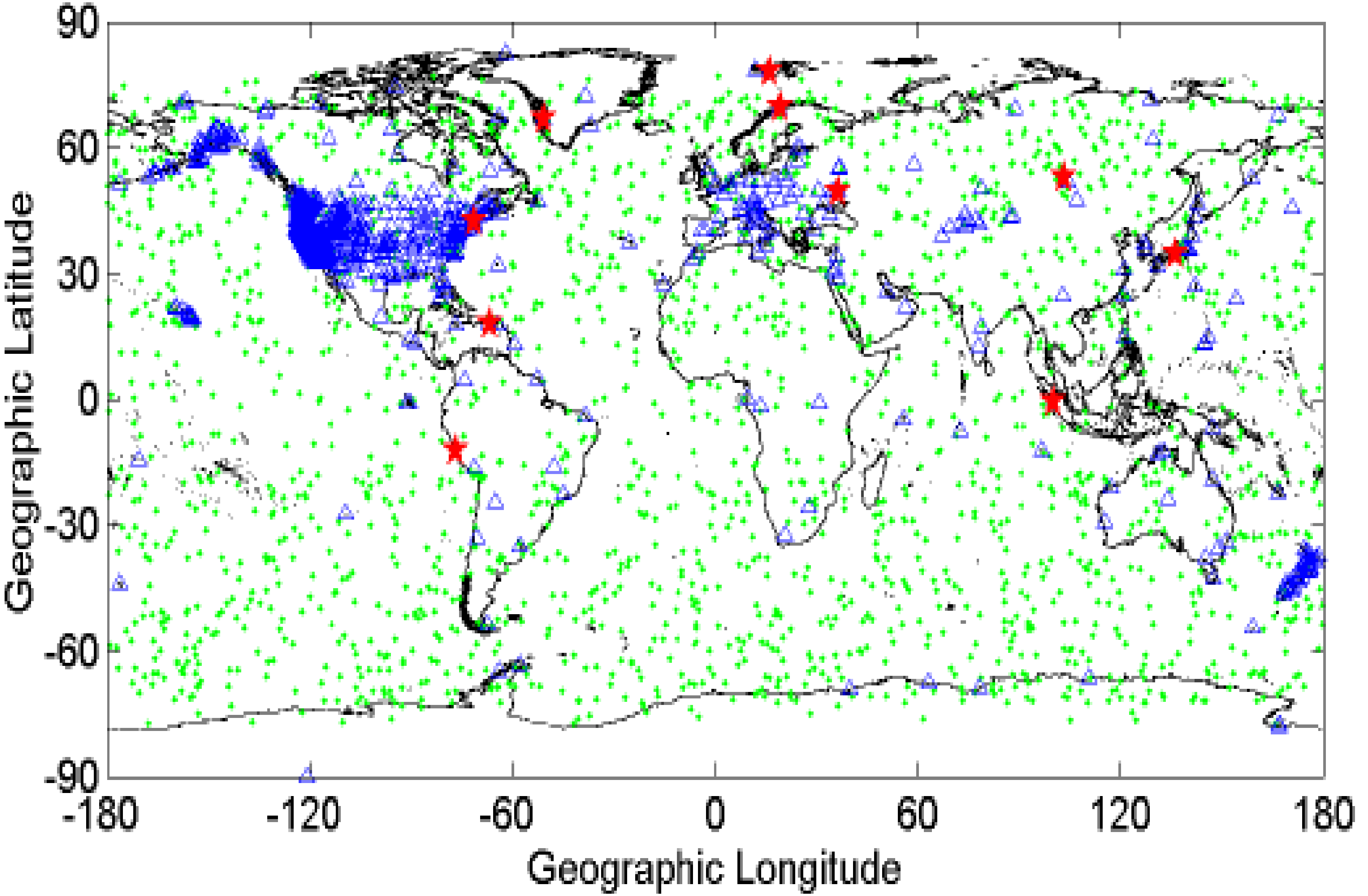


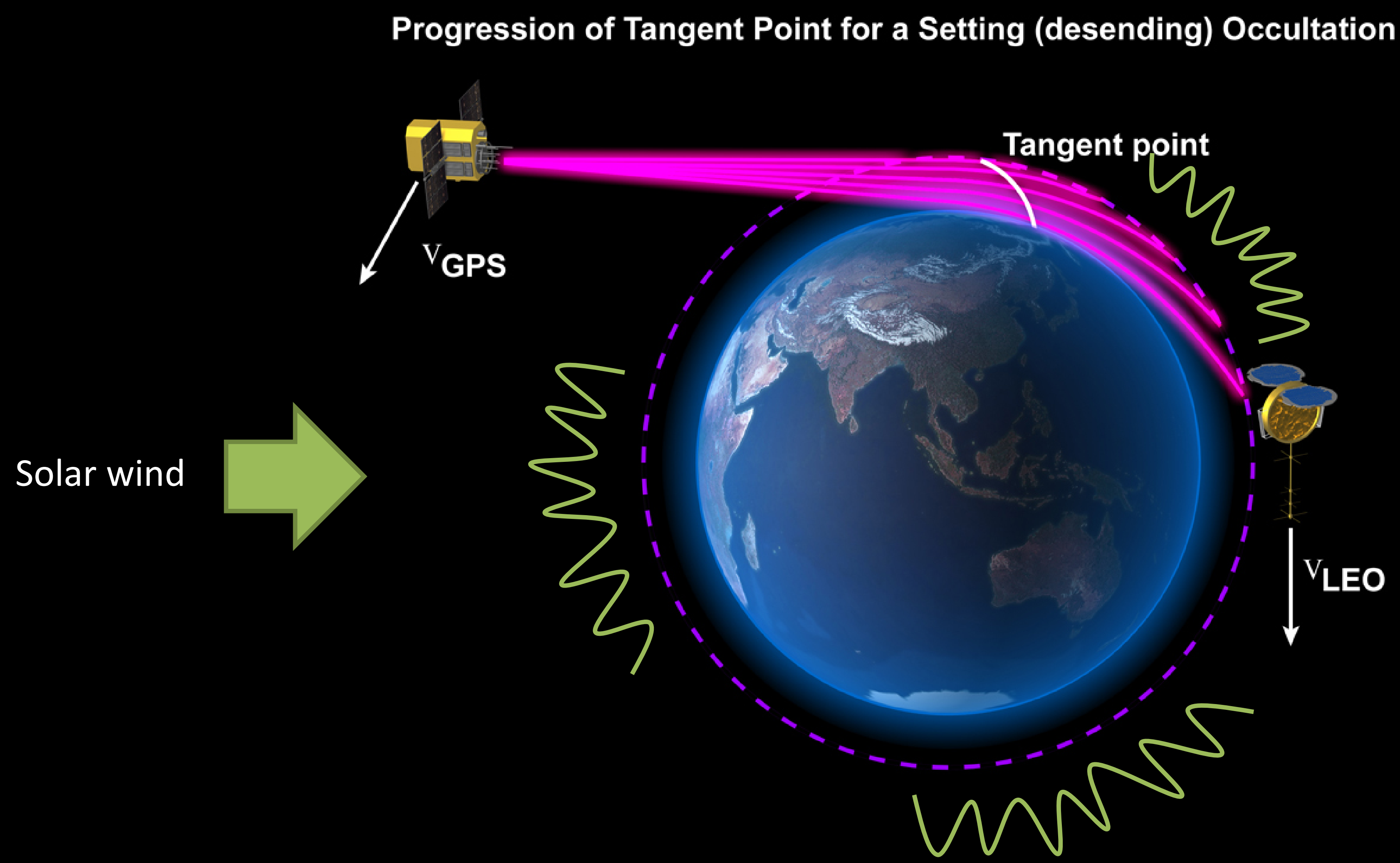

Wavelength and amplitude of in the vertical direction

Global 3D structure

# Ionospheric F3/C RO Sounding

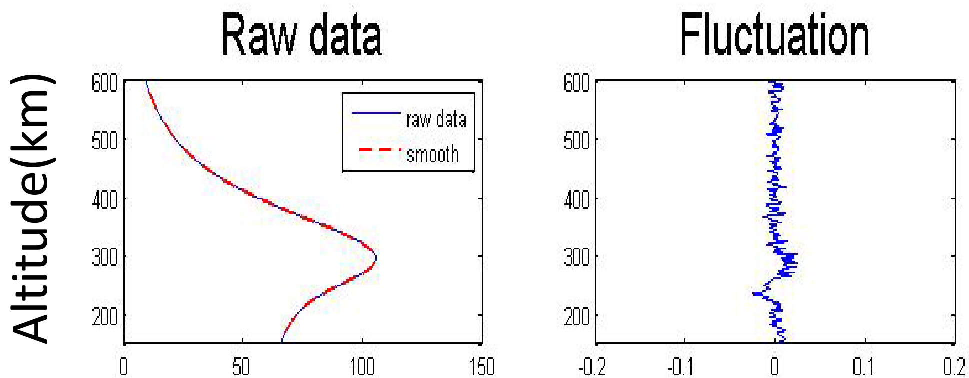


# Storm the Ionosphere

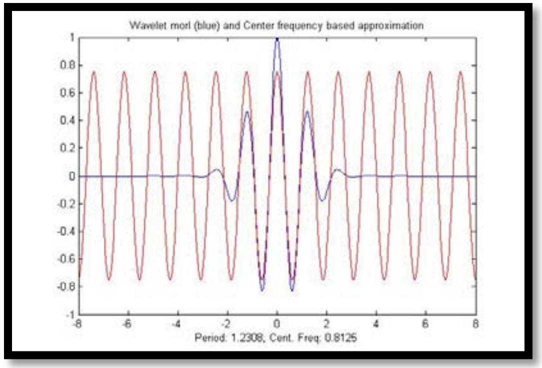


# Vertical fluctuation profile

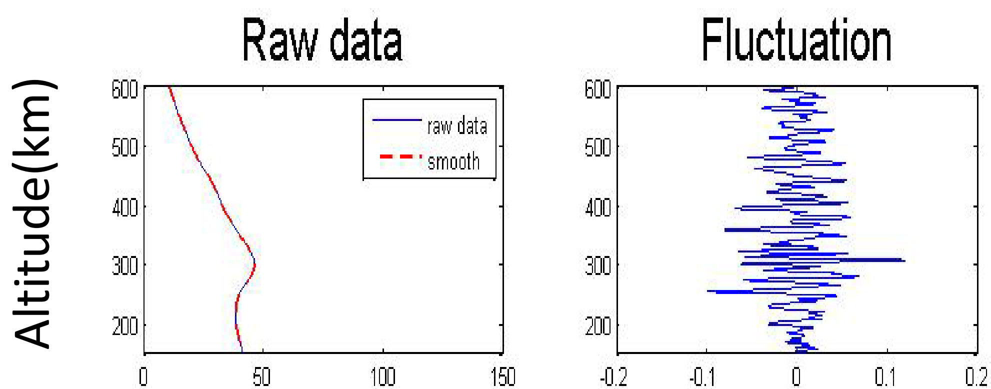
## Quiet time




**Mother wavelet- Morlet**

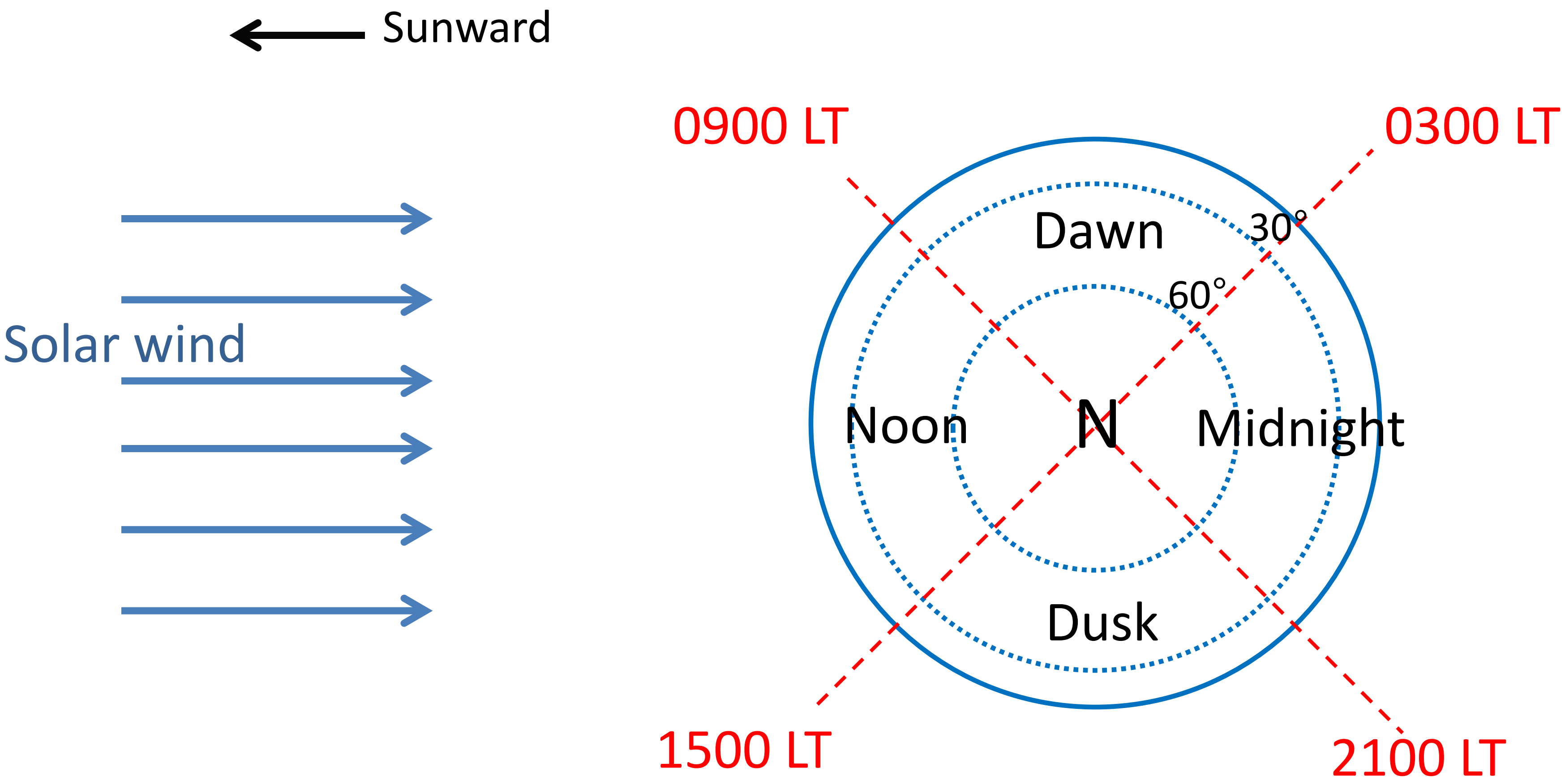



## Storm tme

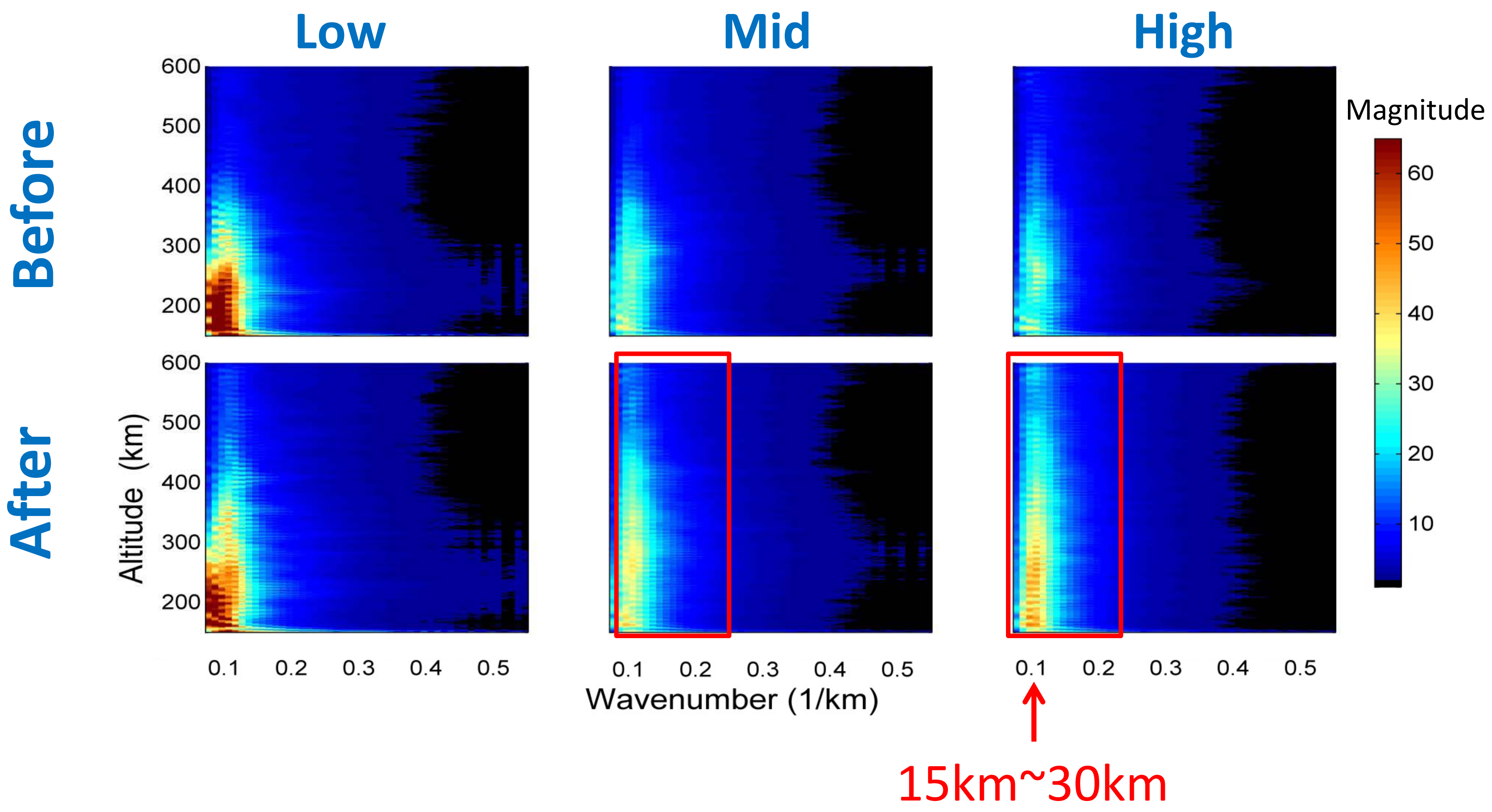



TEC (TECu)

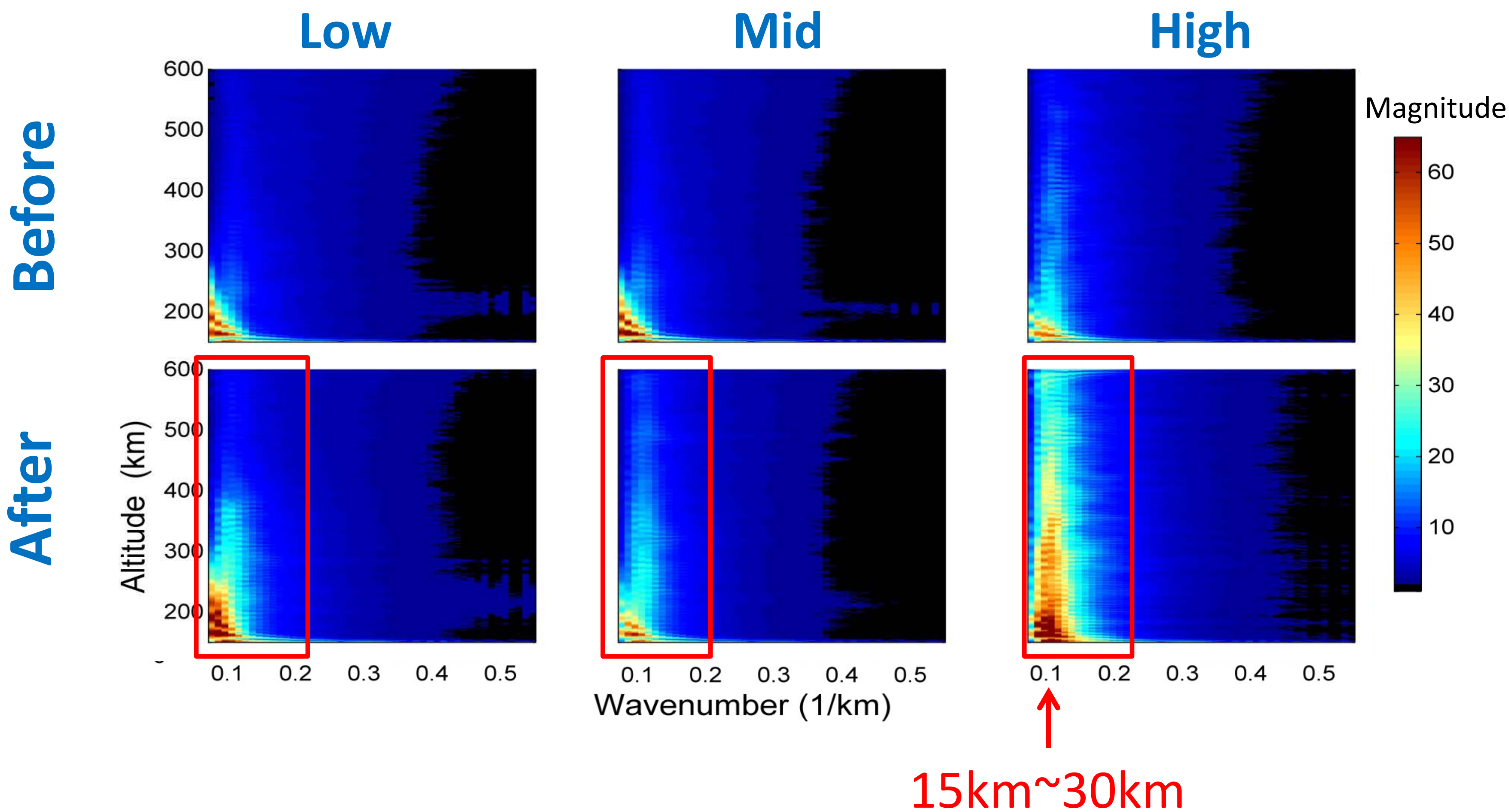
Wave number


Sunward
Solar wind
0900 LT
0300 LT
Dawn
30°
60°
Noon
N
Midnight
Dusk
1500 LT
2100 LT

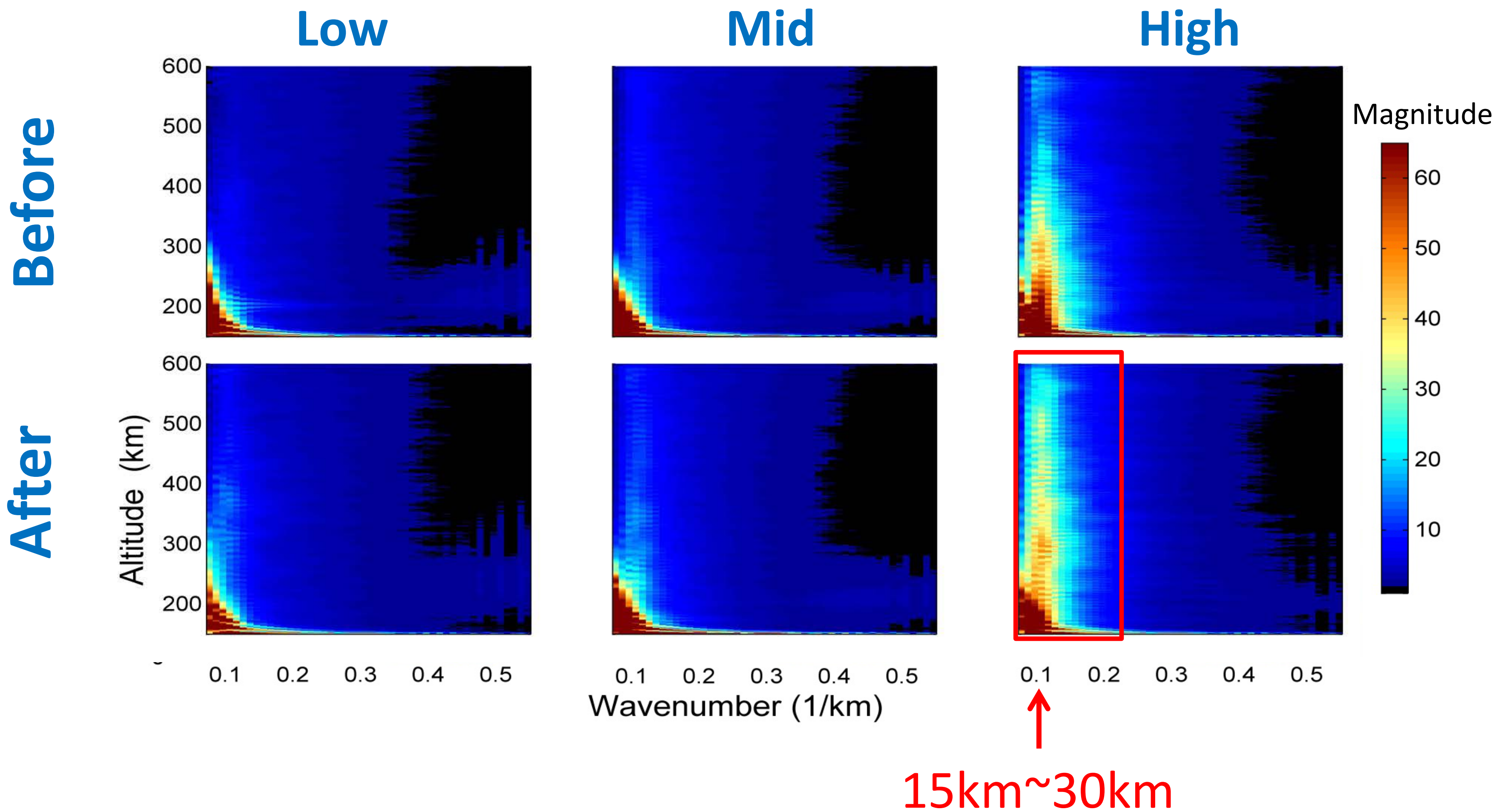
# 2010/05/02 TEC vertical fluctuation
# Midnight side



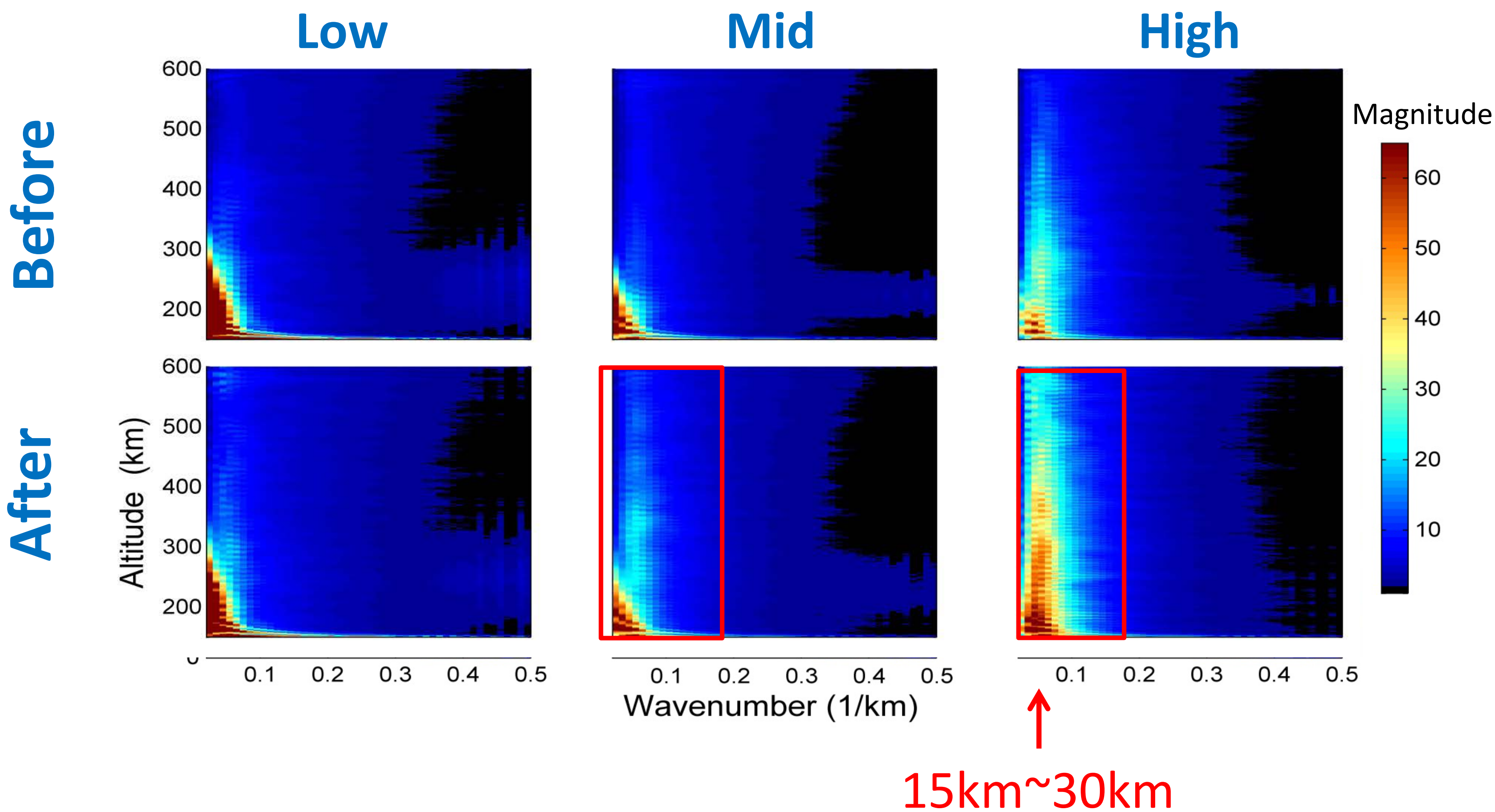
# 2010/05/02 TEC vertical fluctuation
# Dawn side



# 2010/05/02 TEC vertical fluctuation
## Noon side



# 2010/05/02 TEC vertical fluctuation
## Dusk side

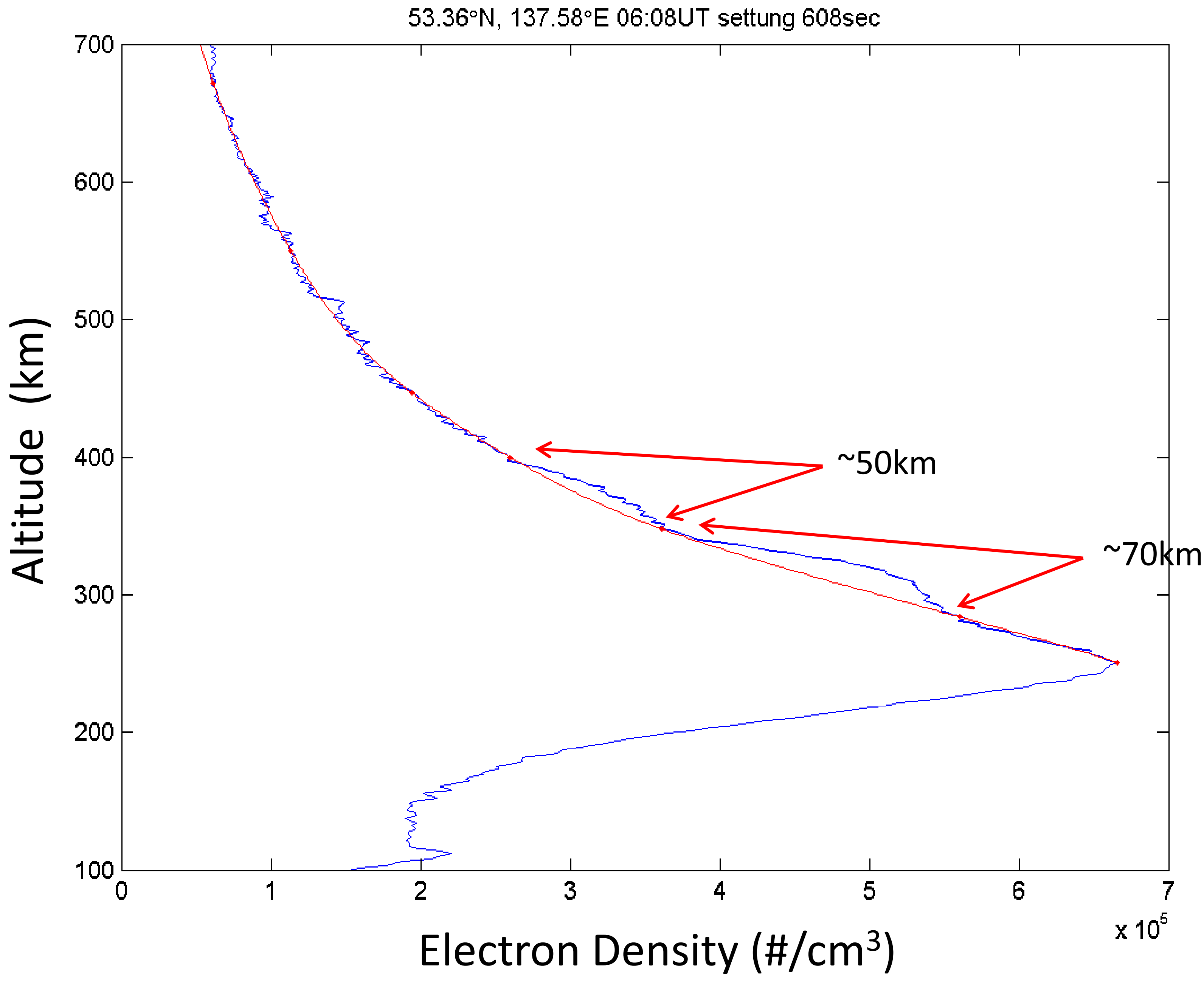


Earthquake Details

# Earthquakes slam the ionosphere

This is a computer-generated message -- this event has not yet been reviewed by a seismologist.

| | |
|---|---|
| **Magnitude** | 8.9 9.0 |
| **Date-Time** | **Friday, March 11, 2011 at 05:46:23 UTC**<br>Friday, March 11, 2011 at 02:46:23 PM at epicenter<br>Time of Earthquake in other Time Zones |
| **Location** | 38.322°N, 142.369°E |
| **Depth** | 24.4 km (15.2 miles) set by location program |
| **Region** | NEAR THE EAST COAST OF HONSHU, JAPAN |
| **Distances** | 130 km (80 miles) E of **Sendai, Honshu, Japan**<br>178 km (110 miles) E of **Yamagata, Honshu, Japan**<br>178 km (110 miles) ENE of **Fukushima, Honshu, Japan**<br>373 km (231 miles) NE of **TOKYO, Japan** |
| **Location Uncertainty** | horizontal +/- 13.5 km (8.4 miles); depth fixed by location program |
| **Parameters** | NST=350, Nph=351, Dmin=416.3 km, Rmss=1.46 sec, Gp= 29°,<br>M-type="moment" magnitude from initial P wave (tsuboi method) (Mi/Mwp), Version=A |
| **Source** | USGS NEIC (WDCS-D) |
| **Event ID** | usc0001xgp |

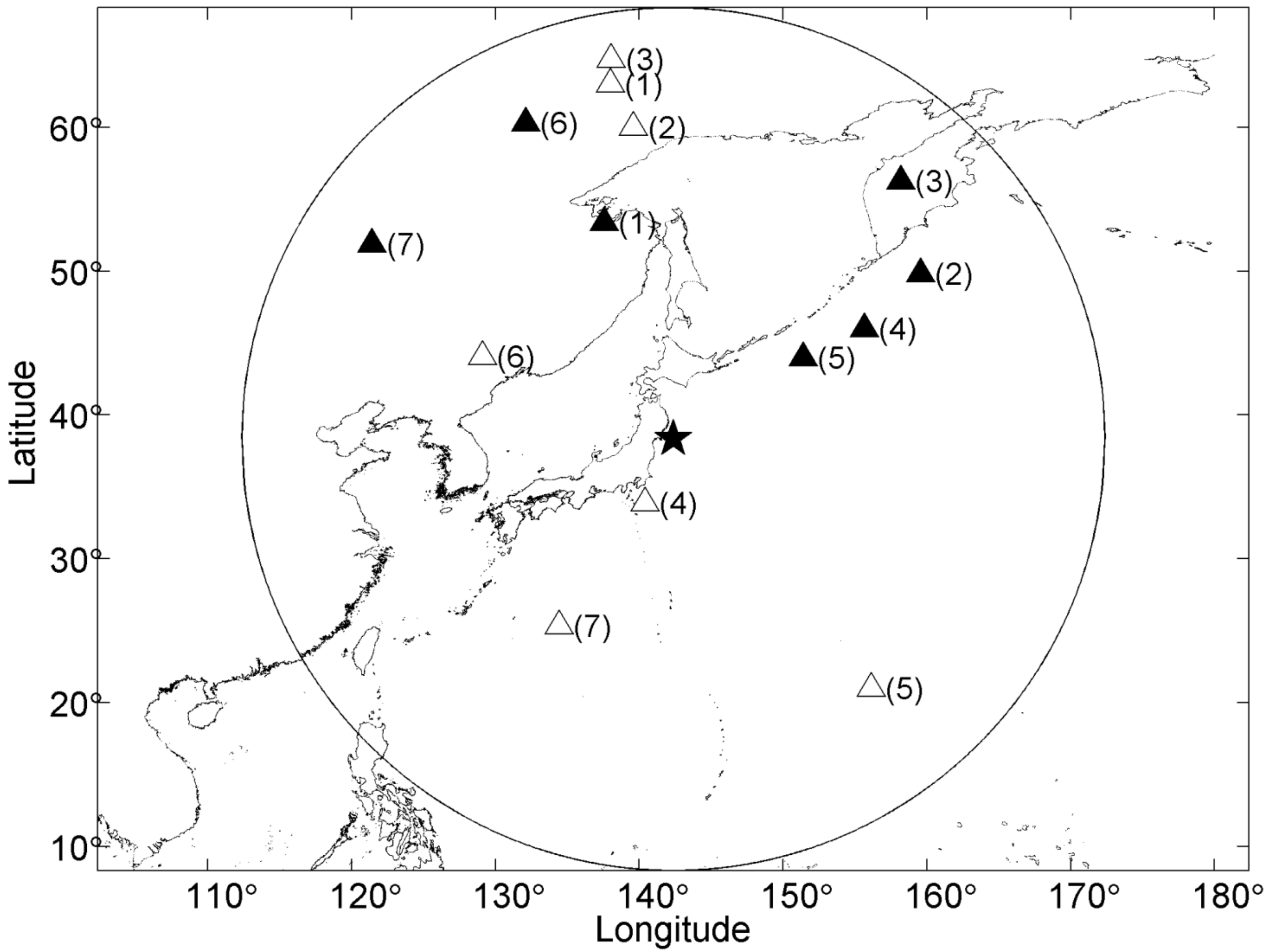



The electron density profile observed 22 minutes after earthquake.

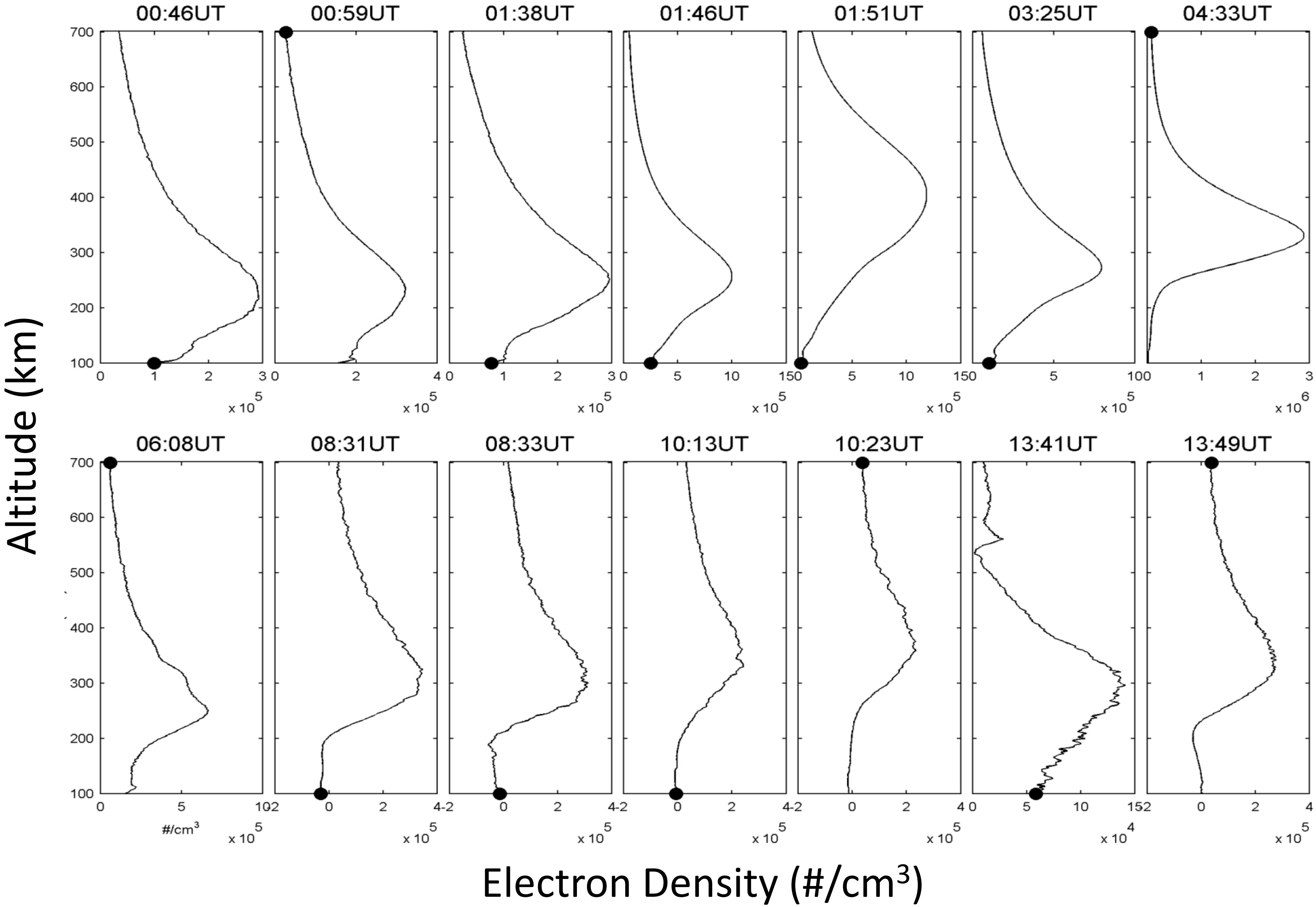
# Disturbances in F3/C electron density profiles during the 11 March 2013 Tohoku earthquake

**Table 1*:*** Observation Points Near the Epicenter 0-8 hr after the Tohoku Earthquake

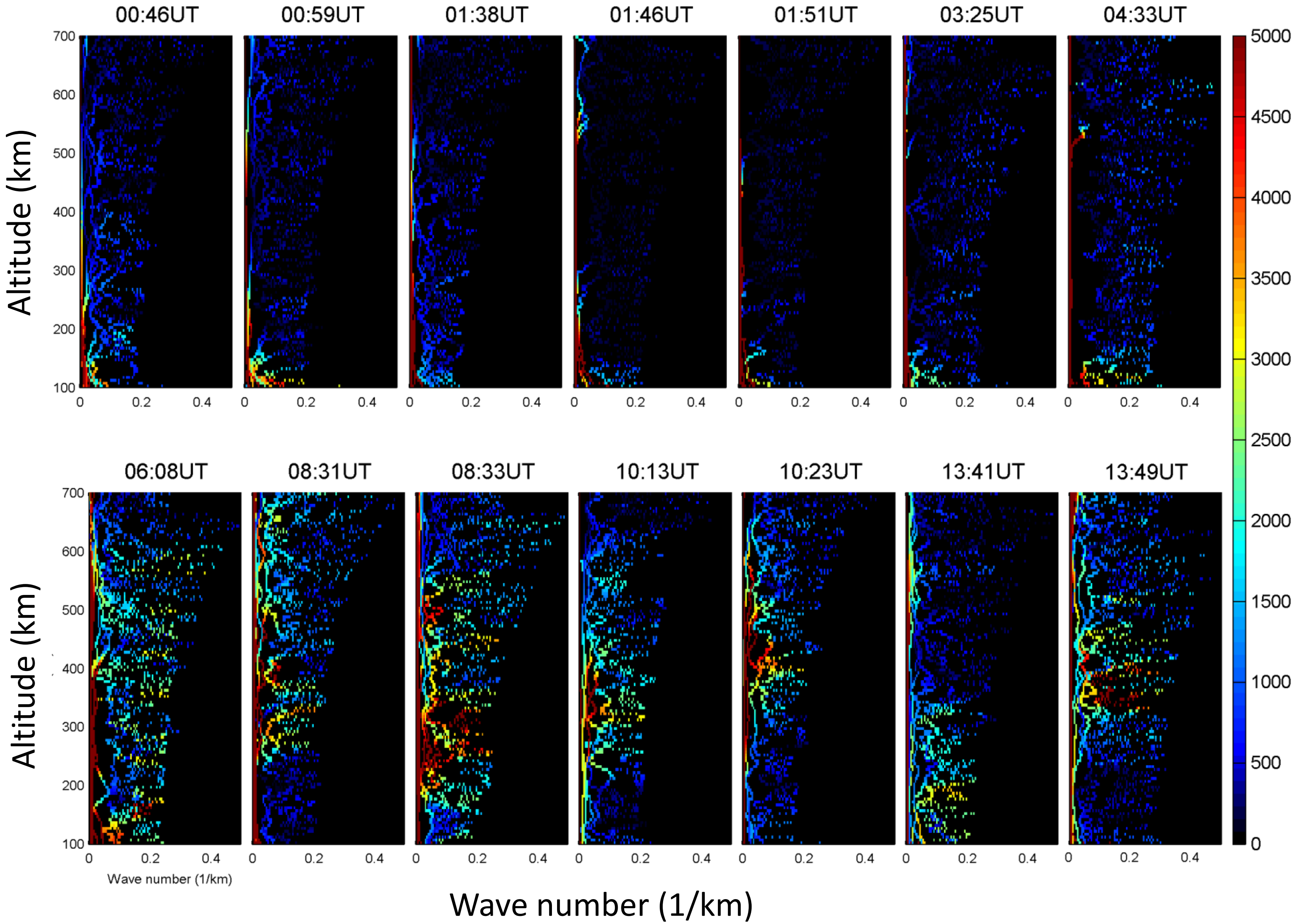
| No. | Location | Arrival (UT) | Travel (second) | Distance (km) | Speed (m/sec) |
|---|---|---|---|---|---|
| | 38.32°N, 142.37°E | 05:46 | | Epicenter | |
| 1 | 53.28°N, 137.36°E | 06:08 | 1320 | 1581 | 2196 |
| 2 | 49.83°N, 159.58°E | 08:31 | 9900 | 2072 | 223 |
| 3 | 56.26°N, 158.19°E | 08:33 | 10020 | 2394 | 239 |
| 4 | 45.98°N, 155.66°E | 10:13 | 16020 | 1535 | 100 |
| 5 | 43.99°N, 151.39°E | 10:23 | 16620 | 1067 | 67 |
| 6 | 60.28°N, 132.12°E | 13:41 | 27420 | 2425 | 87 |
| 7 | 51.86°N, 121.44°E | 13:49 | 28980 | 2494 | 88 |




Electron density profiles observed by F3/C RO within 3000 km from the epicenter. The black circle Indicates 3000km from the epicenter. The star and triangle symbols denote locations of the epicenter and the profiles 1-8hours after the earthquake . The open triangle symbols denote locations of the profiles 1-5 hours before the earthquake.



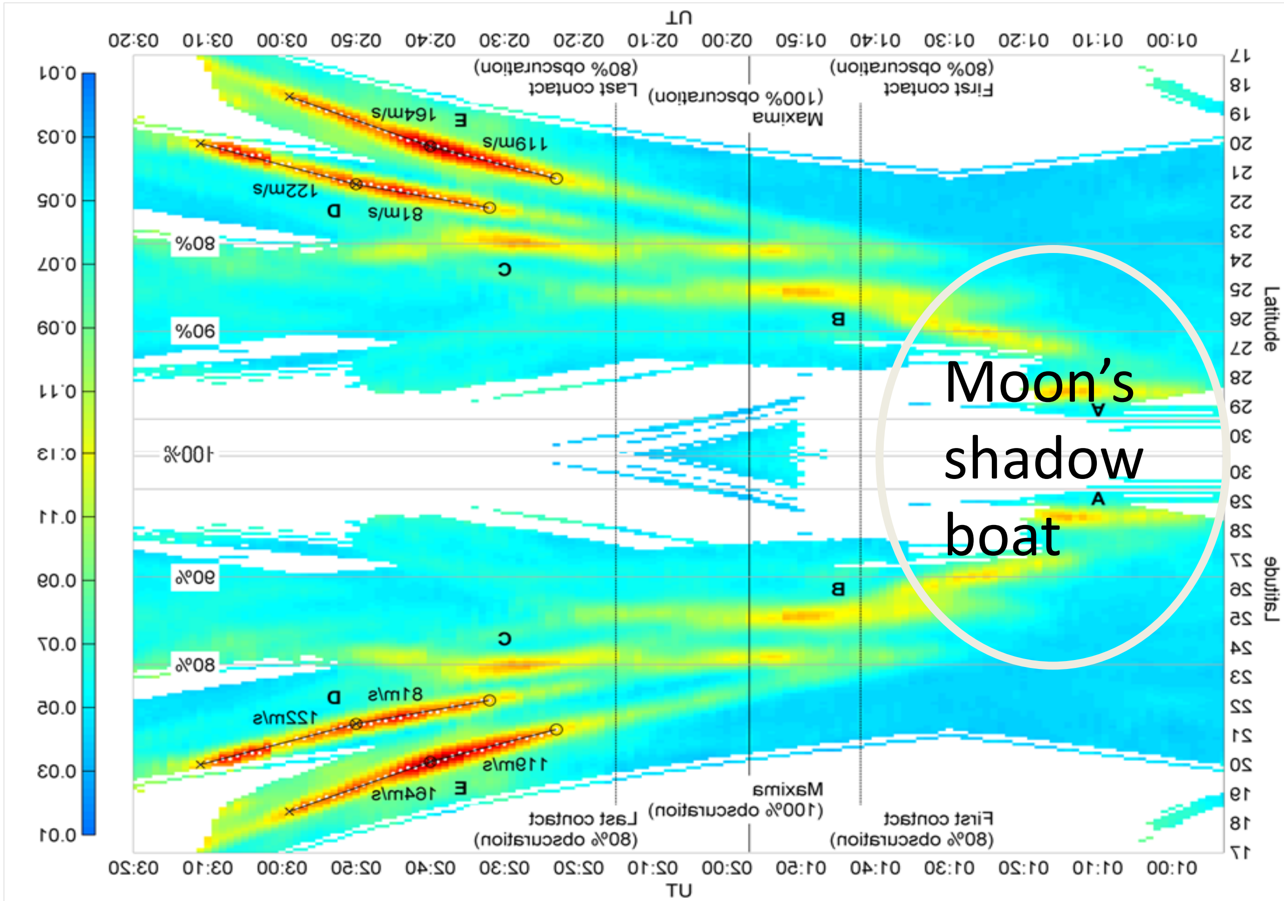

The electron density profiles 1-5hours before the earthquake (top panels), and those 1-8 hours after (bottom panels).



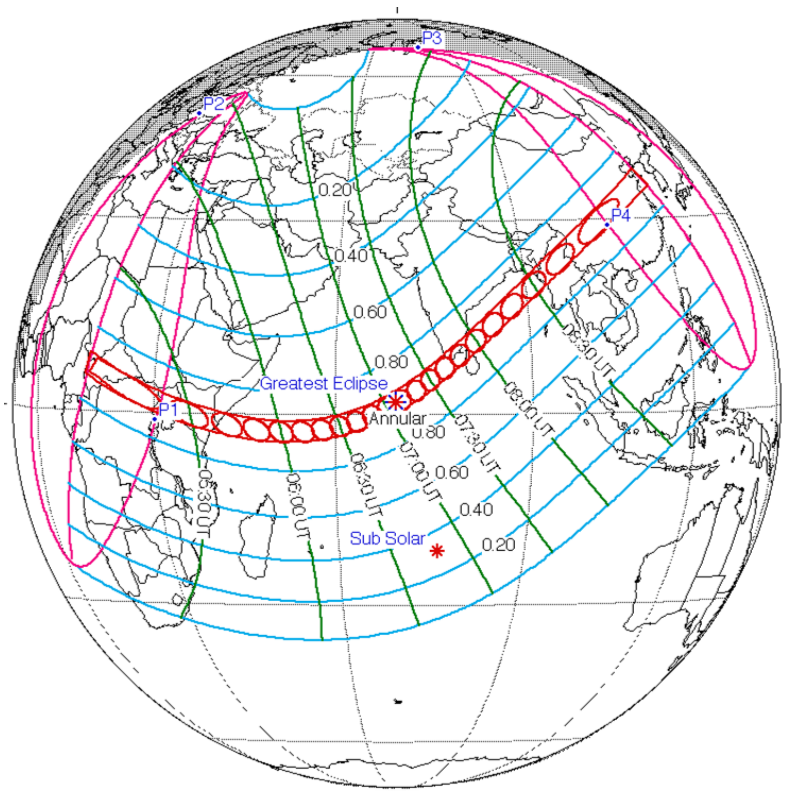

Spectra derived by using HHT.

Moon’s shadow boat

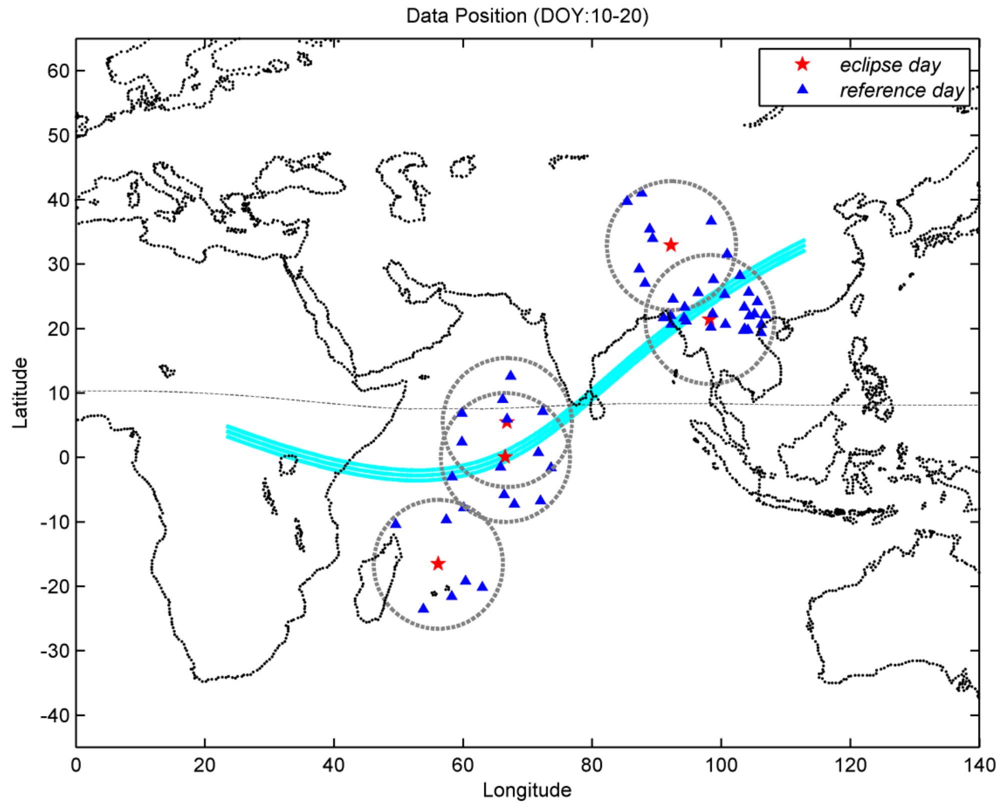
2010/01/15 Annual Solar Eclipse
(Ring of Fire)


Moon's
shadow
boat

# 2010/01/15 Annual Solar Eclipse (Ring of Fire)




(http://eclipse.gsfc.nasa.gov/eclipse.html, NASA)

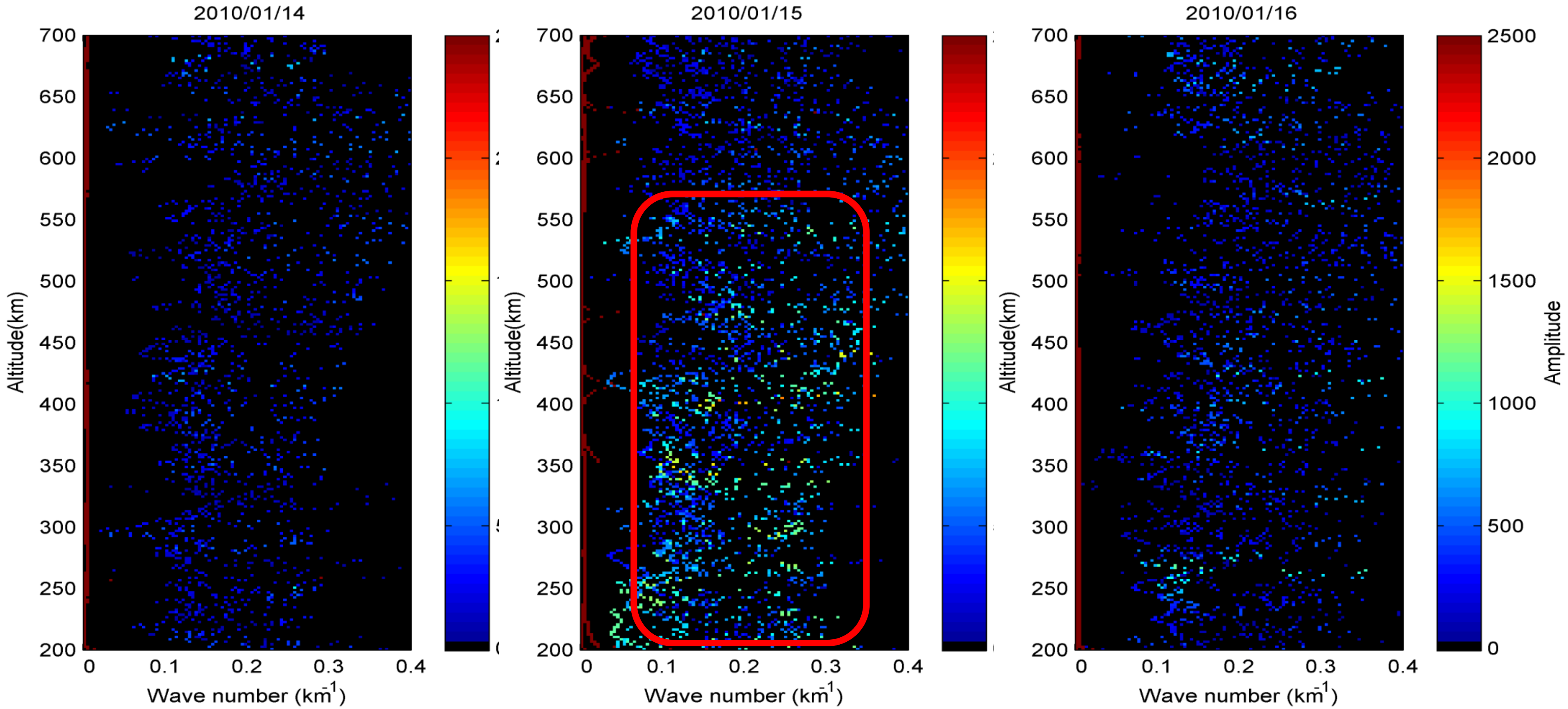



Eclipse period 05:18-08:55 UT

Observation zone: 5

Reference data point in each zone: 7/11/8/12/23

Day 1 Before Eclipse Day 2010/01/15 Day 1 After




Power spectra on day 1 before, eclipse day 2010/01/15, and day 1 after.

# Remark

- F3/C RO sounding shall be a powerful tool observing disturbances from the solar wind, atmosphere, and lithosphere, triggered by earthquakes, tsumani, volcano eruptions, typhoons, magnetic storms, solar eclipses, etc.
- The disturbances could significantly affect the satellite orbiting and in turn its positioning, navigation, communication, etc.

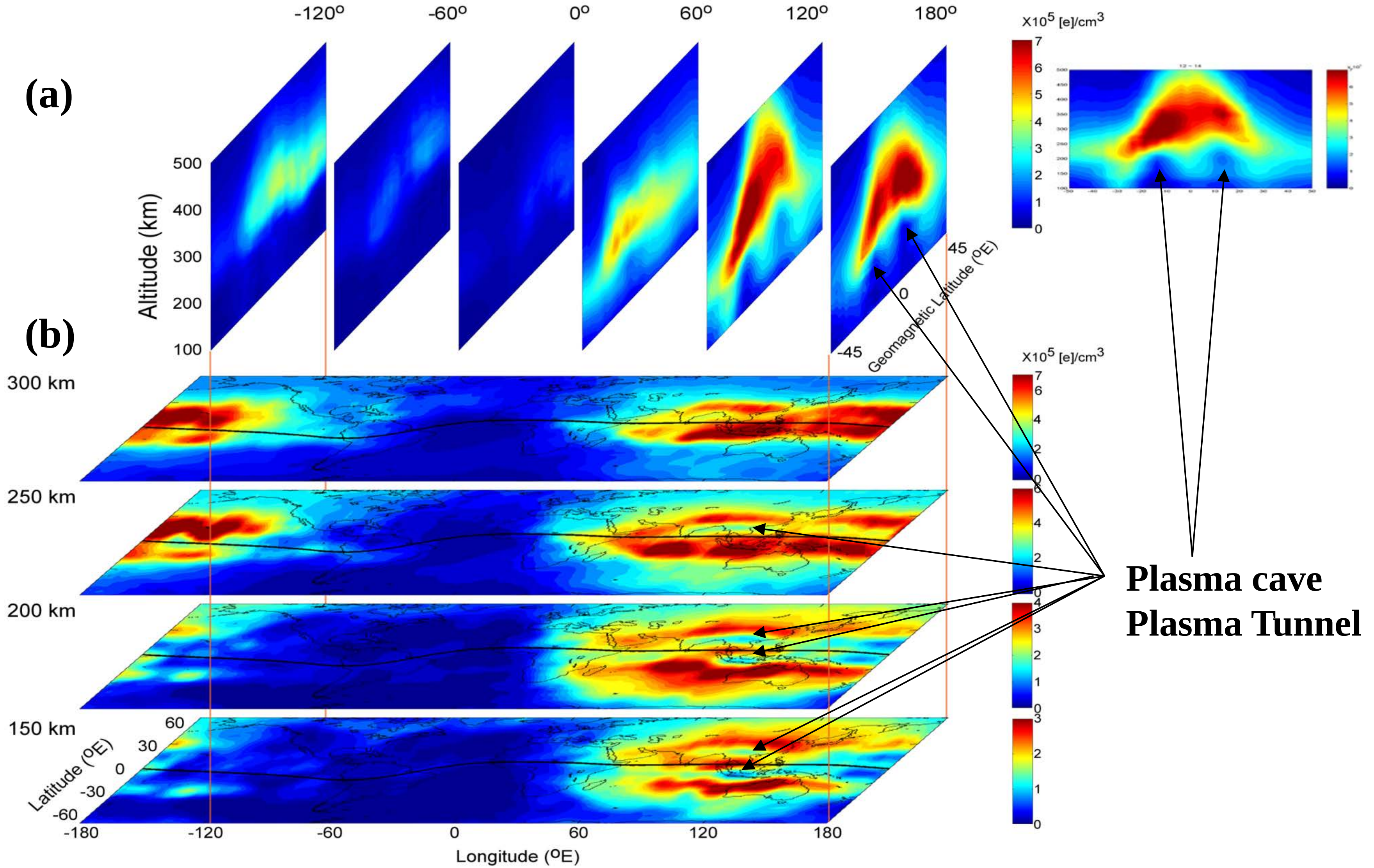
# Ionospheric Climate

Equatorial Ionization Anomaly (EIA)

Mid-latitude Trough

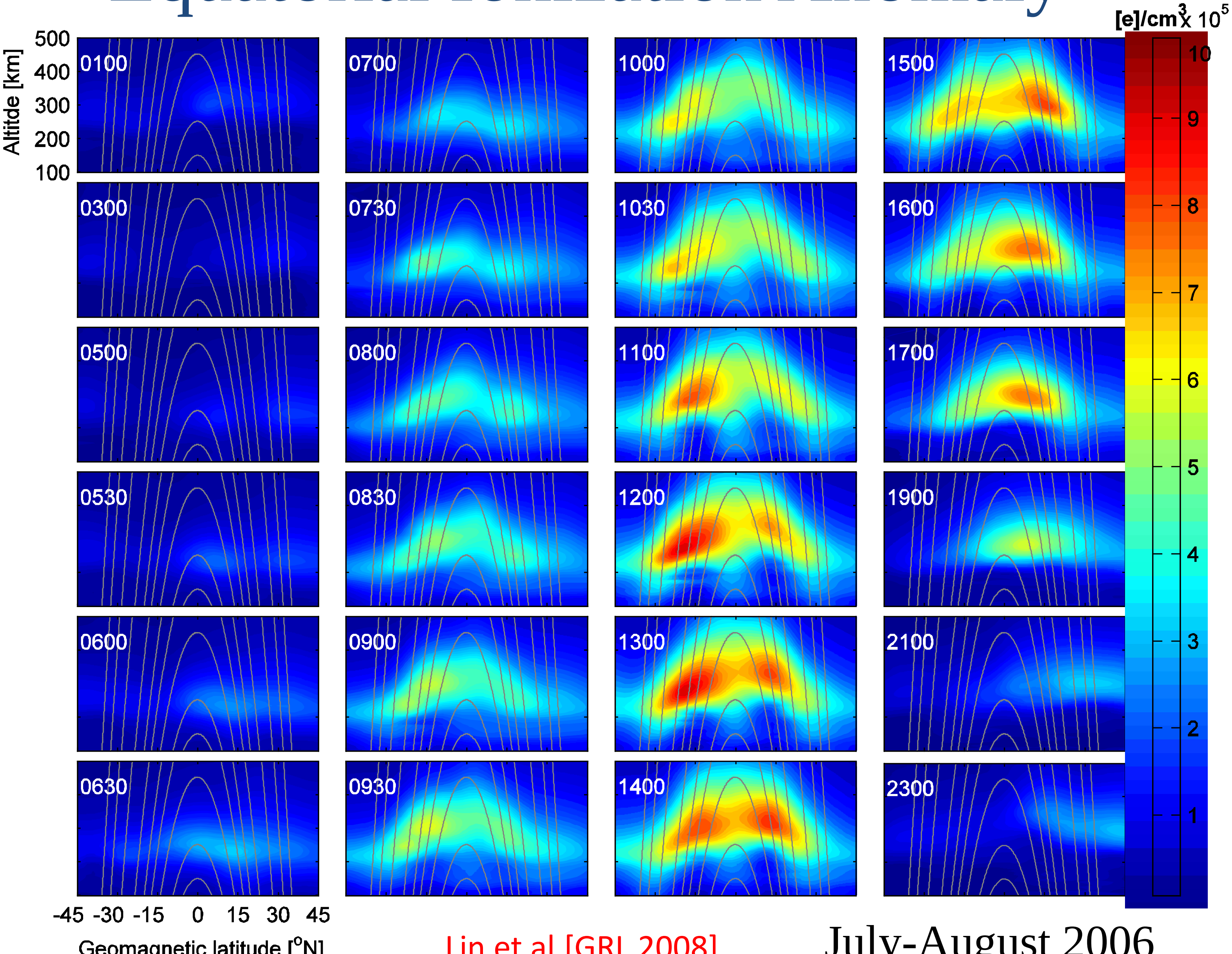
Ionospheric Weddell Sea Anomaly

# 3D Ionospheric plasma Structure




Liu et al. (JGR 2010)

# Equatorial Ionization Anomaly




Lin et al.[GRL 2008]

July-August 2006

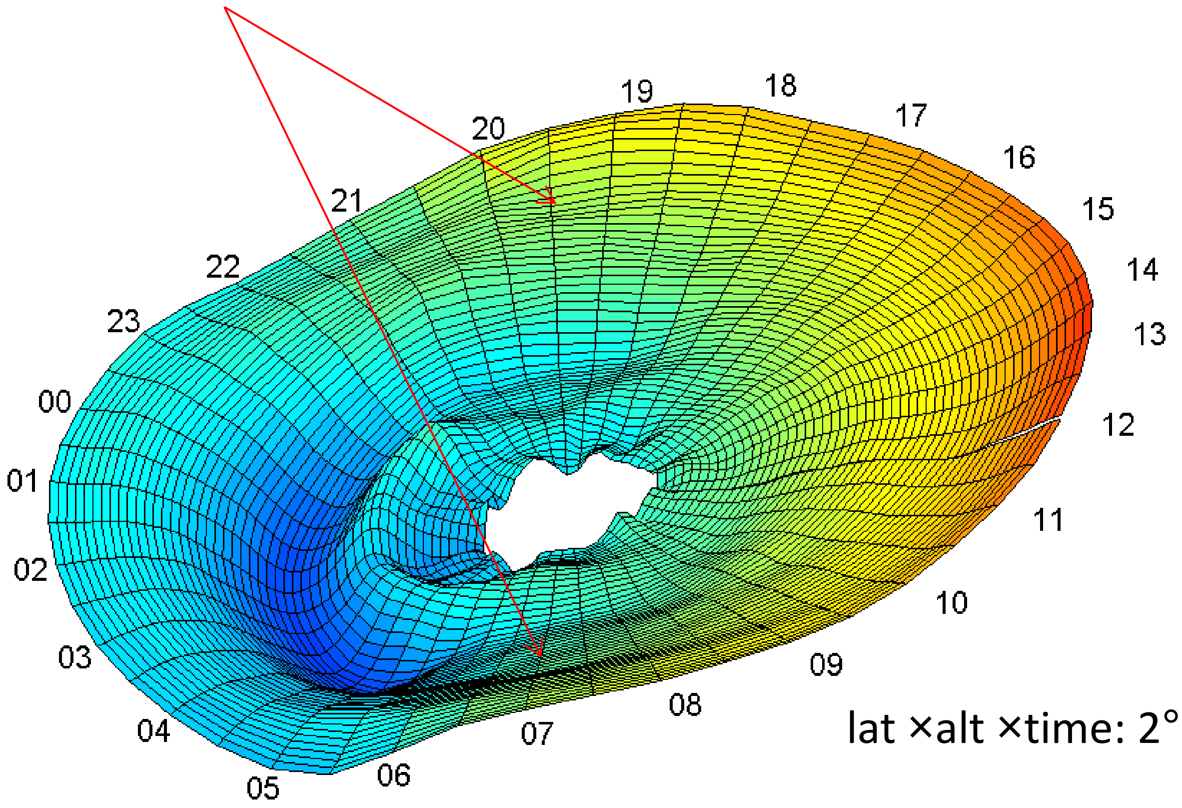
# Remark

- Results suggest that in addition to the asymmetric neutral composition effect, interactions between the summer-to-winter (transequatorial) neutral winds and strength of the equatorial plasma fountain effect play important roles in producing asymmetric development of the EIA crests as imaged by the F3/C.

# Mid-latitude Trough

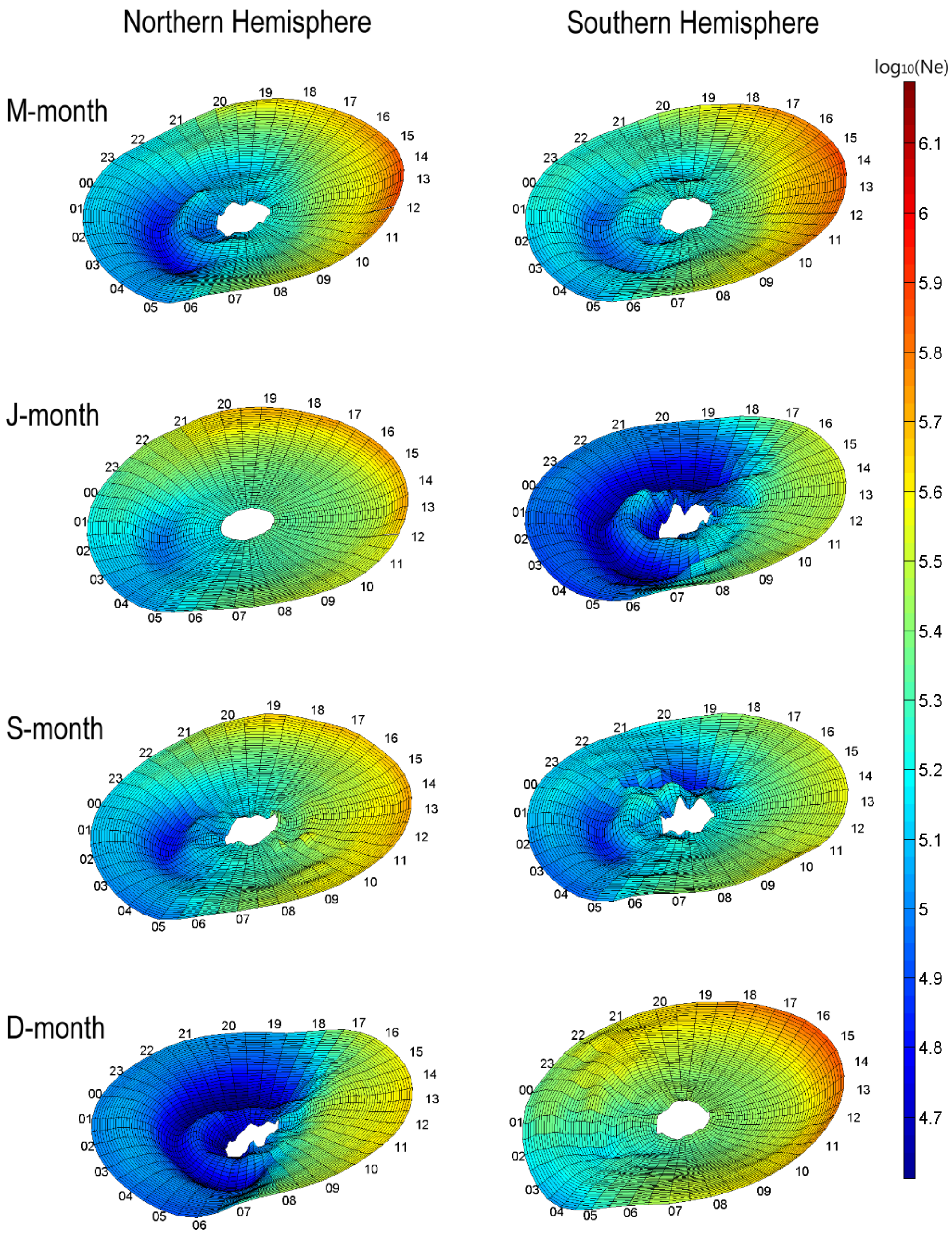
FORMOSAT-3/COSMIC NmF2 Persudo-3D structure
Northern Hemisphere, M-month

Terminator waves?




lat ×alt ×time: 2°×2km ×0.5hr

# Seasonal Variation




Lee et al. (JGR, 2011)

The seasonal averaged pseudo 3-D images of the F2 peak density map (log10 (Ne), $cm^{-3}$) from February 2008 to January 2009 in magnetic polar coordinates for the March equinox, June solstice, September equinox, and December solstice. The inner and outer perimeters are 80° and 30° in magnetic latitude. The left and right columns are results in the Northern and Southern hemispheres, respectively. The color and vertical change refer to the electron density, and the numbers around each plot give the geomagnetic local time.

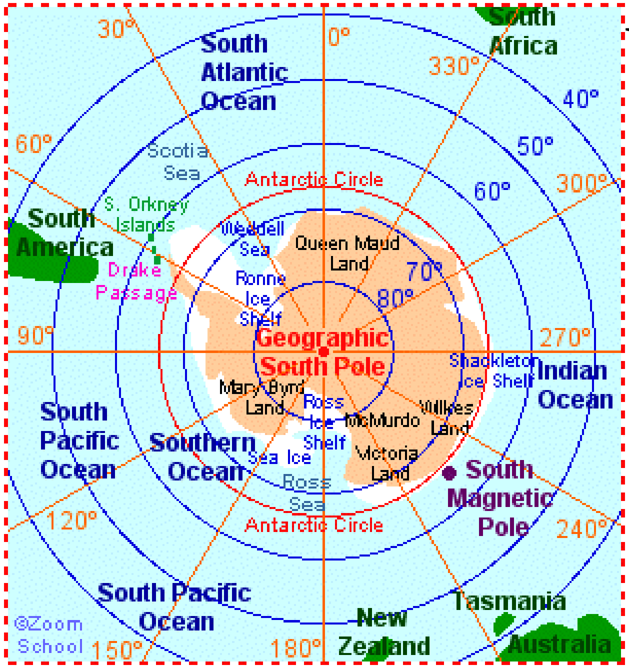
# Remark

- Results show that the mid-latitude trough extends from dusk to dawn in all four seasons and is most pronounced in the winter hemisphere.
- The troughs in the two hemispheres are asymmetric, where the trough in the Northern Hemisphere is more evident and stronger than that in the Southern Hemisphere during the equinoctial seasons.

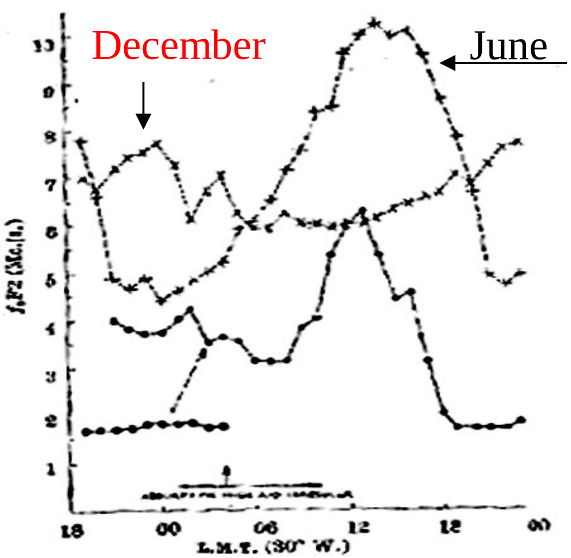
# Ionospheric Weddell Sea Anomaly

Stronger electron density Ne in nighttime than that in daytime over the Weddell Sea area during the Summer

# Weddell Sea Anomaly

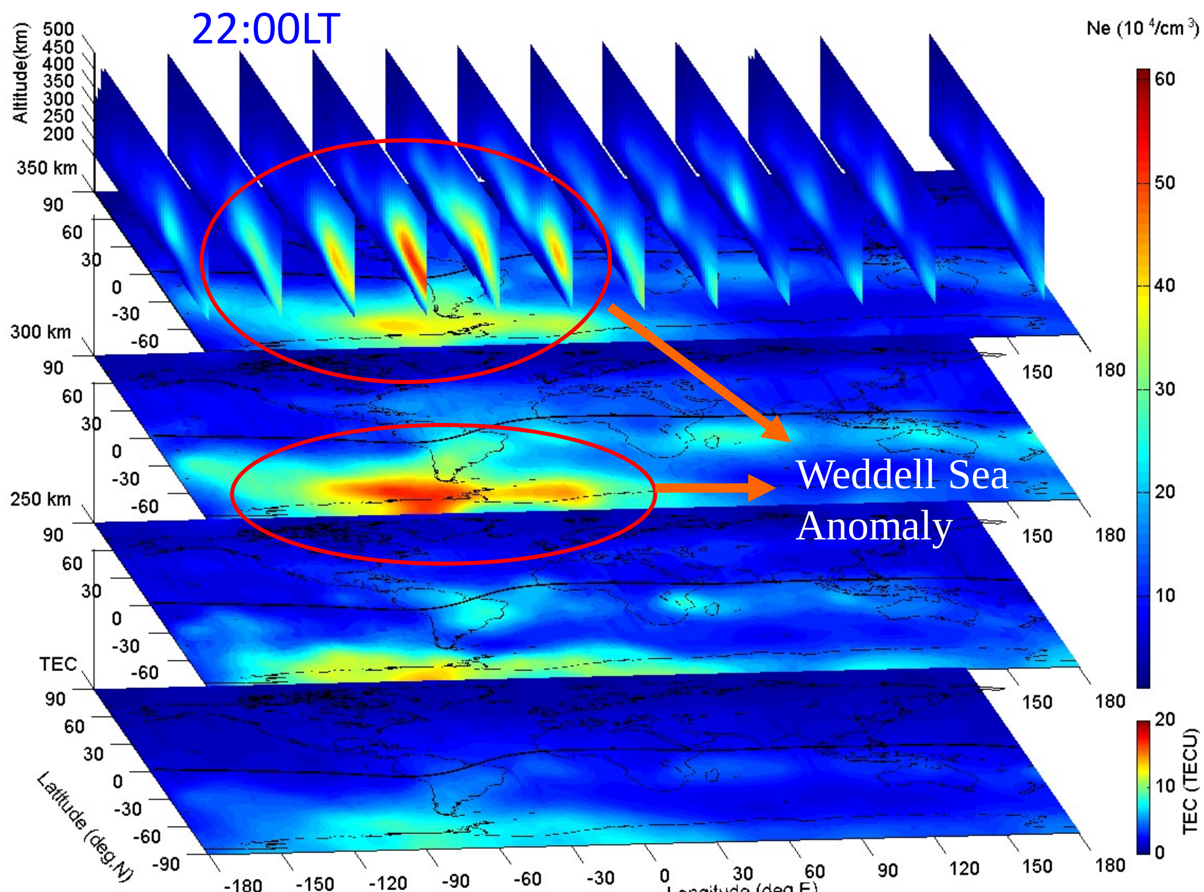



1. Stronger nighttime Ne than that during daytime
2. Discovered 50 years ahead of renewed observation by FORMOSAT-3/COSMIC
3. First glance of its vertical structure by F3/C!




Ionosonde Observation

(Bellchambers and Piggott, 1958)




Lin et al. [2009]

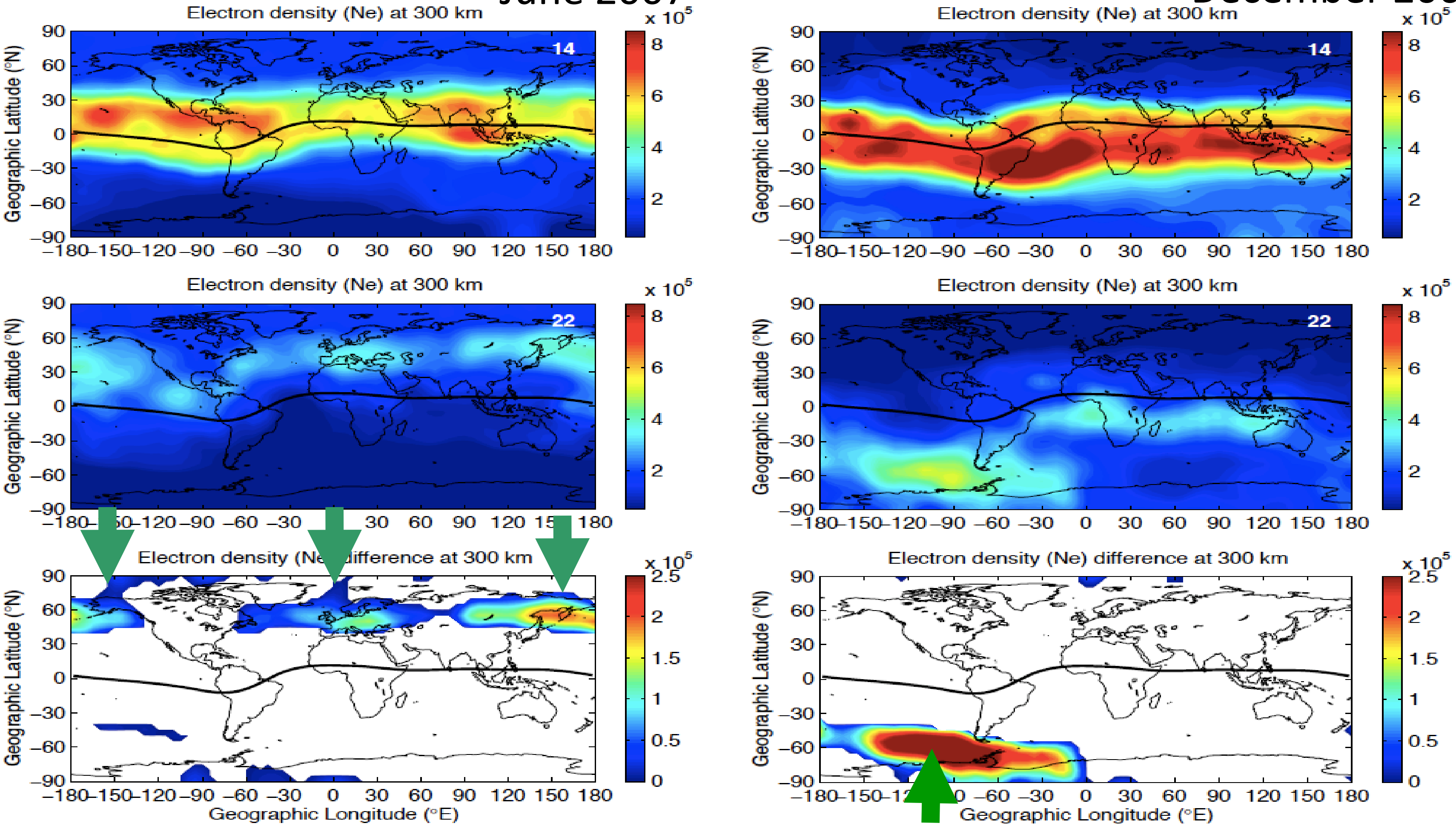
Not only occurred in the Southern hemisphere but also in the North

- Categorized as the Mid-latitude Summer Nighttime Anomaly (MSNA)

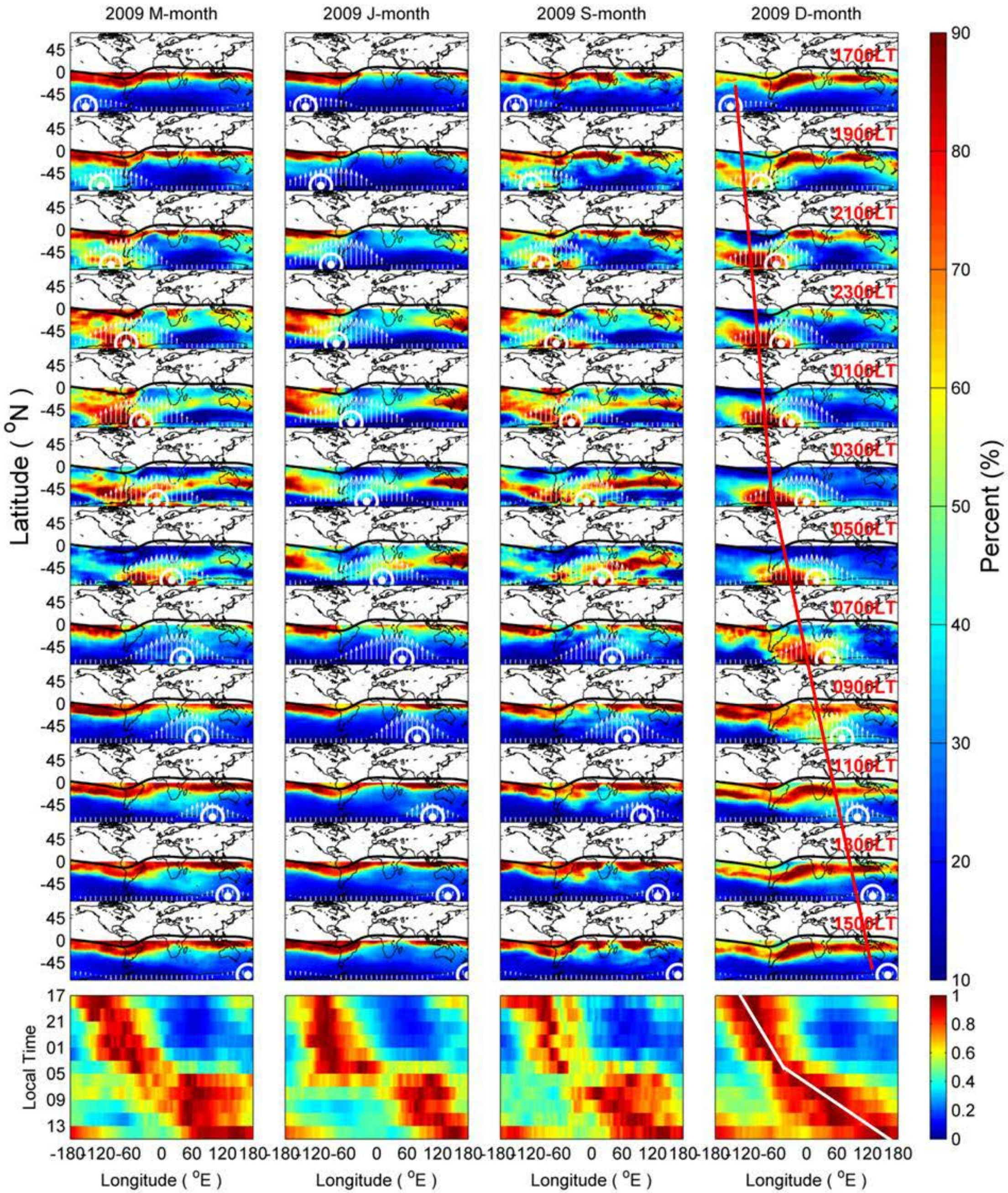
Ne(2200LT) > Ne(1400LT)

- driven by equatorward meridional neutral wind

June 2007 December 2007

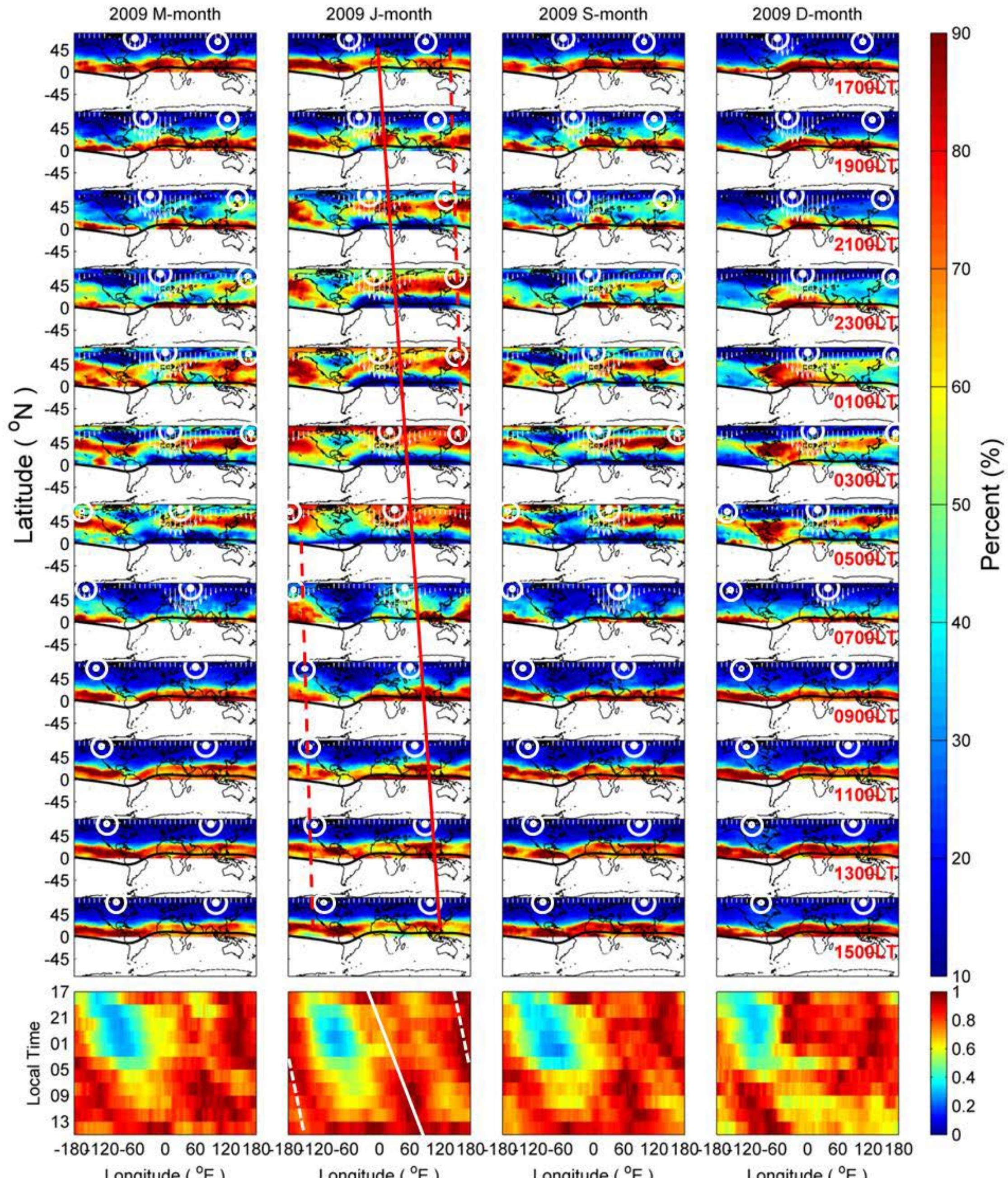



Lin et al. [2010]




Diurnal variations of F3/C electron density maps at 300km altitude at various global fixed local times in the four months in the southern hemisphere

Chang et al. [2014]




Diurnal variations of F3/C electron density maps at 300km altitude at various global fixed local times of the four months in the northern hemisphere.

Chang et al. [2014]

# Remark

- It is found that the multiple-speeds in the eastward phase shift are about of 167 and 296m/s for WSA feature in the southern hemisphere, while the peaked double MSNA s with speeds yield 91 and 121m/s in the northern hemisphere.
- The WSA/MSNA features in fact yield eastward phase shift and appear all year round.

# Ionospheric Scintillation

S. Basu et al. / Journal of Atmospheric and Solar-Terrestrial Physics 64 (2002) 1745–1754 

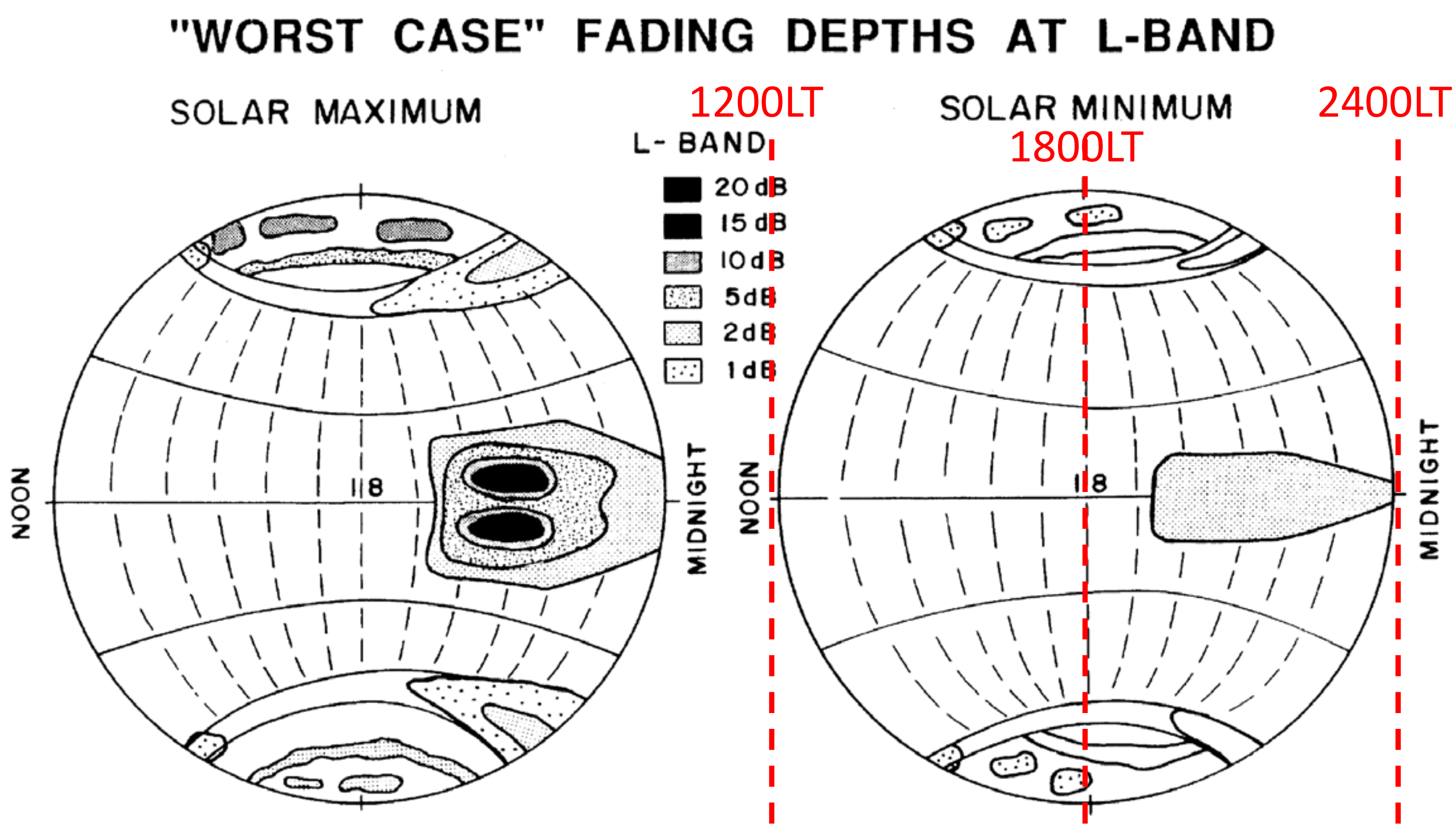
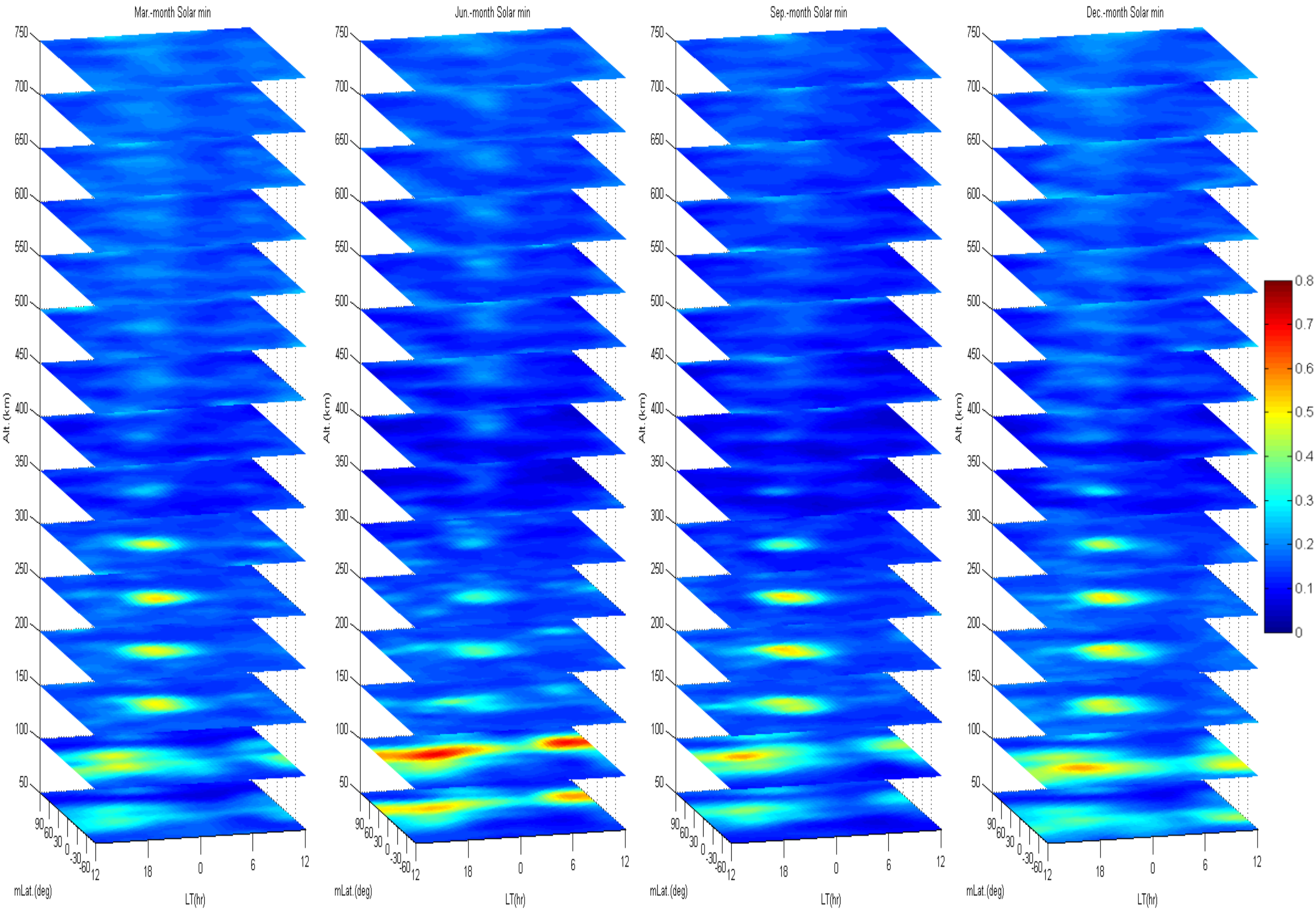


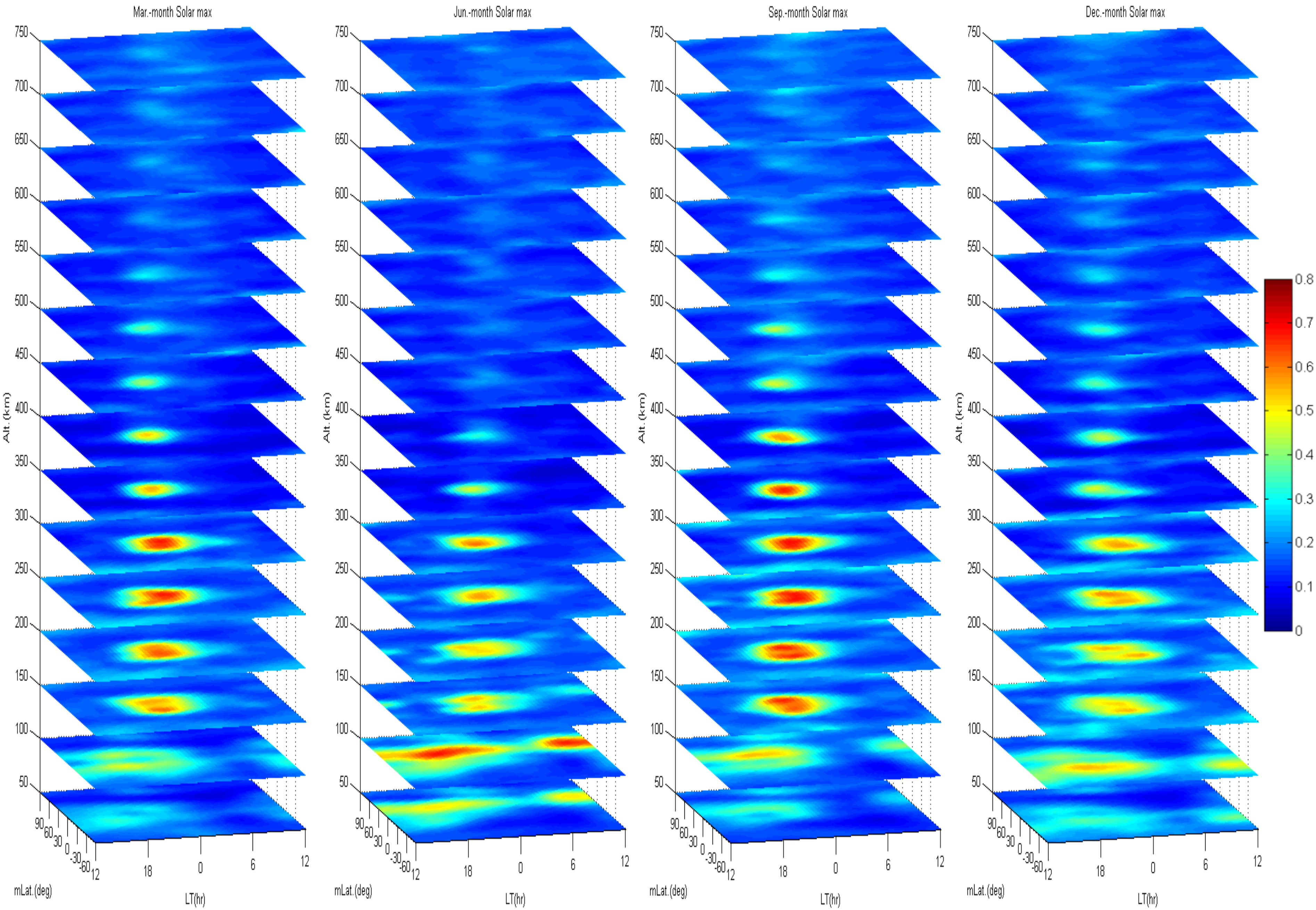

Fig. 1. Schematic of the global morphology of scintillations at L-band frequencies during the solar maximum (left panel) and solar minimum (right panel) conditions. Reproduced from S. Basu and K.M. Groves, Specification and forecasting of outages on satellite communication and navigation systems, Space Weather, Geophysical Monograph 125, 424–430, 2001. Published 2001 by the American Geophysical Union. Reproduced/modified by permission of American Geophysical Union.

Basu et al. [JASTP 2002]

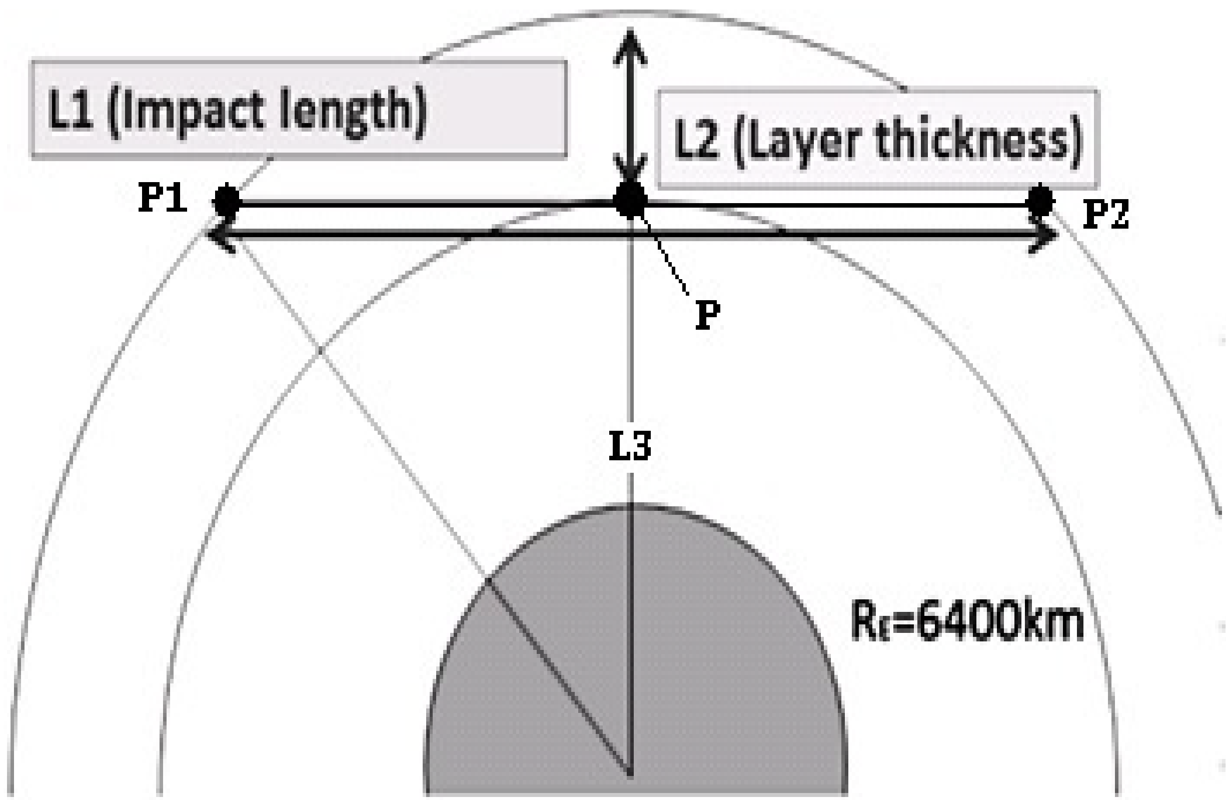
# S4 Max altitude slice at various MLT in Solar min 2008-2009



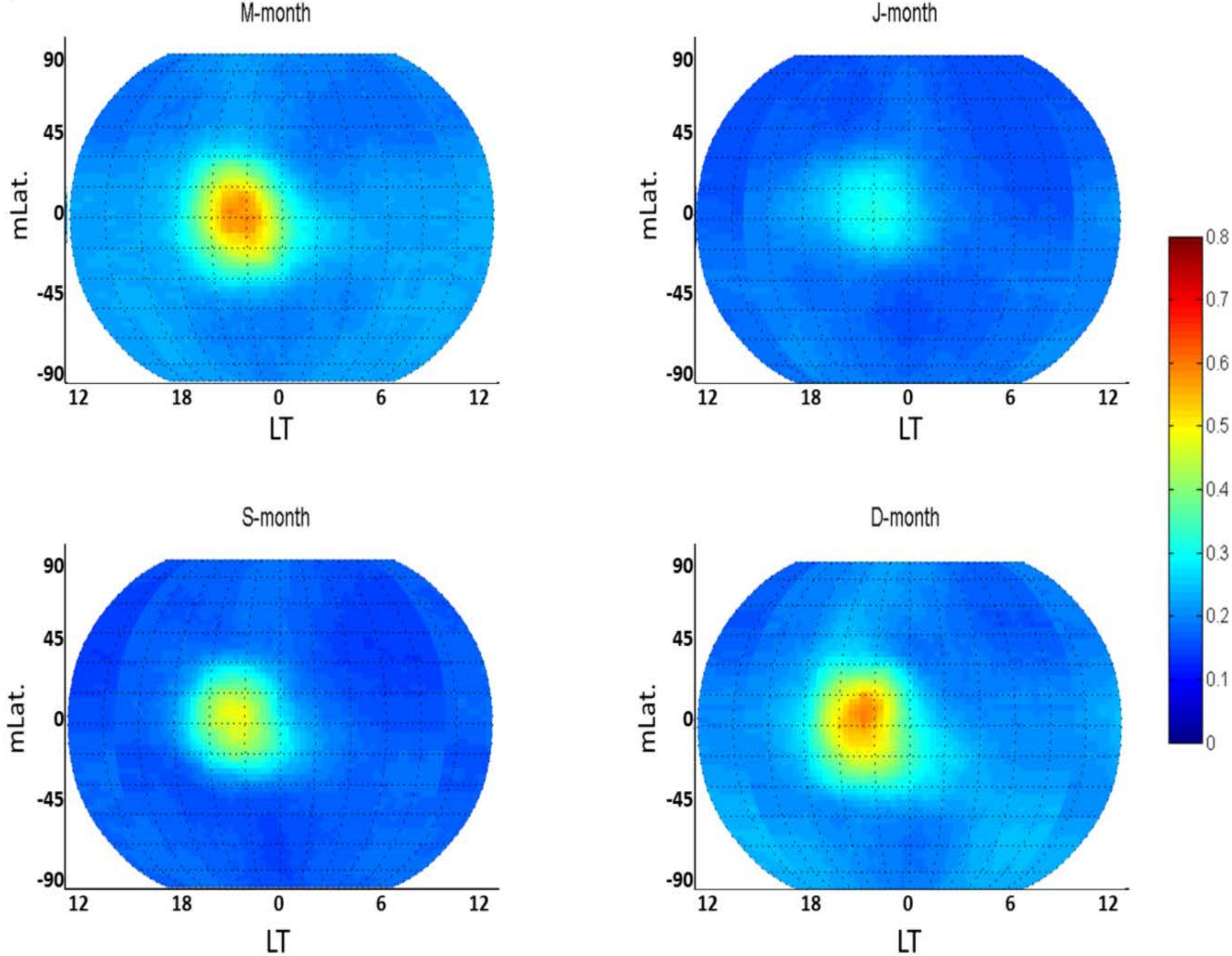
# S4 Max altitude slice at various MLT in Solar Max 2012-2013



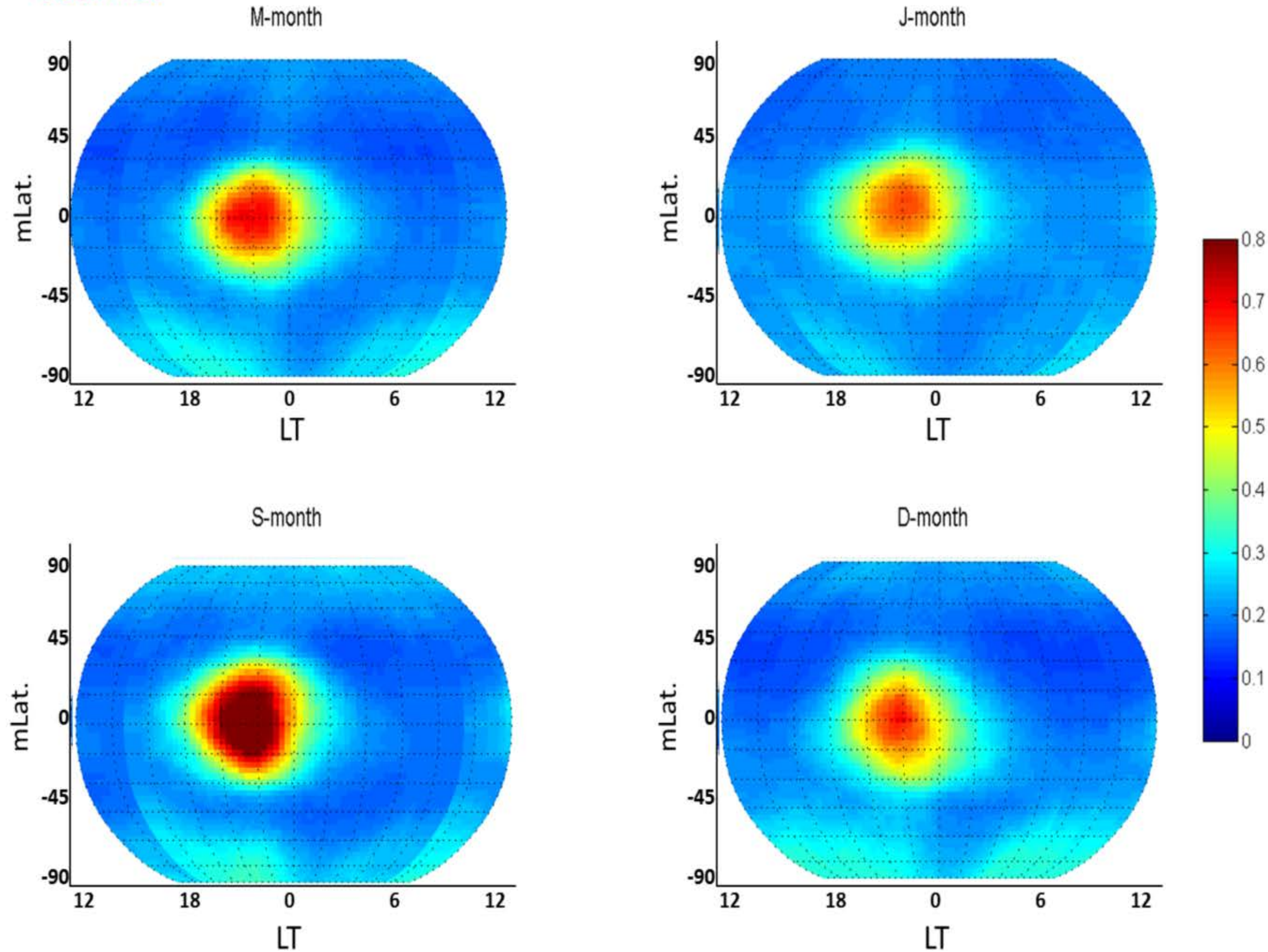
# Conversion of Scintillation S4 Experienced on the Ground



(a) SolarMin

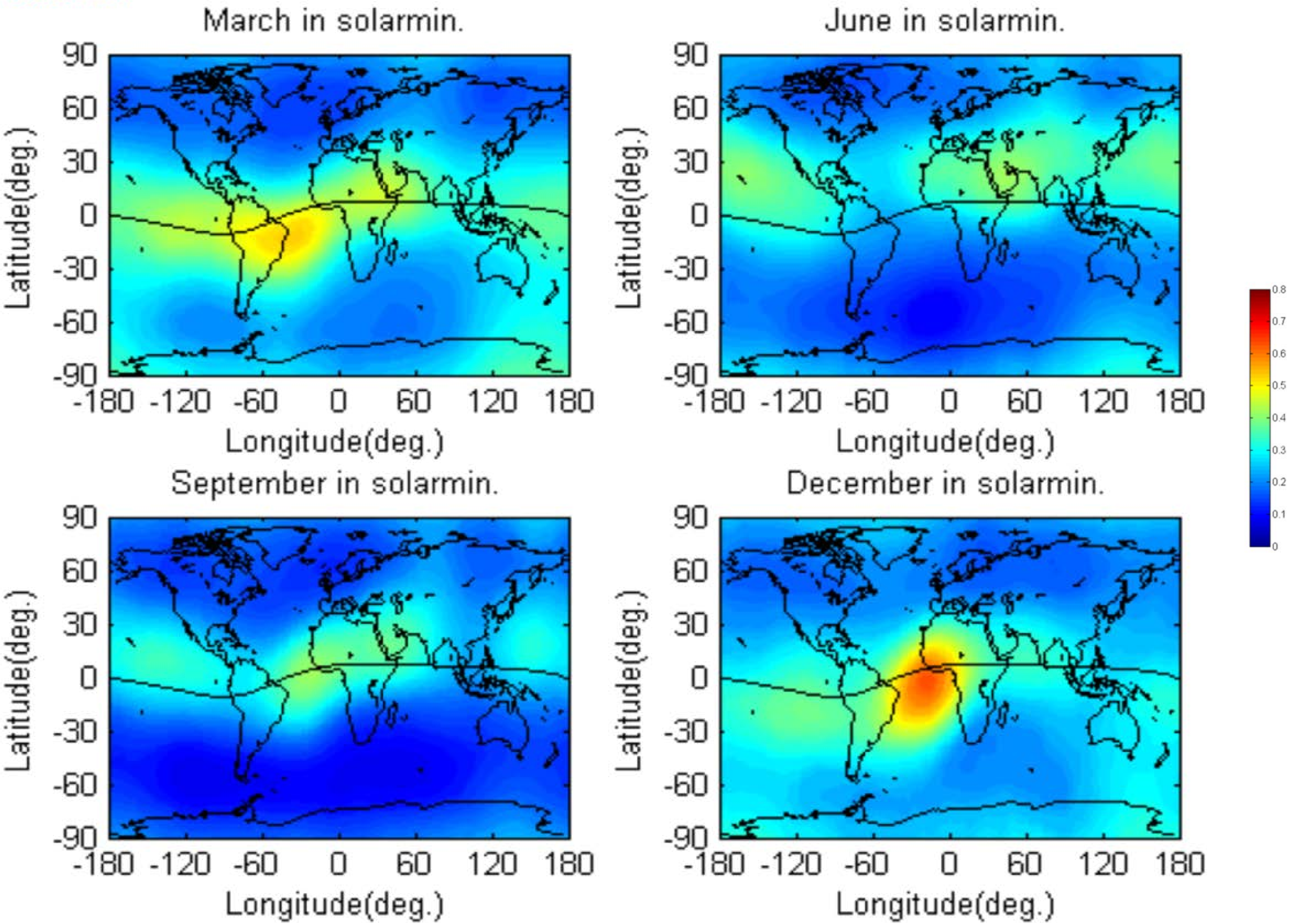

M-month
J-month
S-month
D-month
mLat.
90
45
0
-45
-90
12
18
0
6
12
LT
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

(b) SolarMax


M-month
J-month
S-month
D-month
90
45
0
-45
-90
mLat.
12
18
0
6
12
LT
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

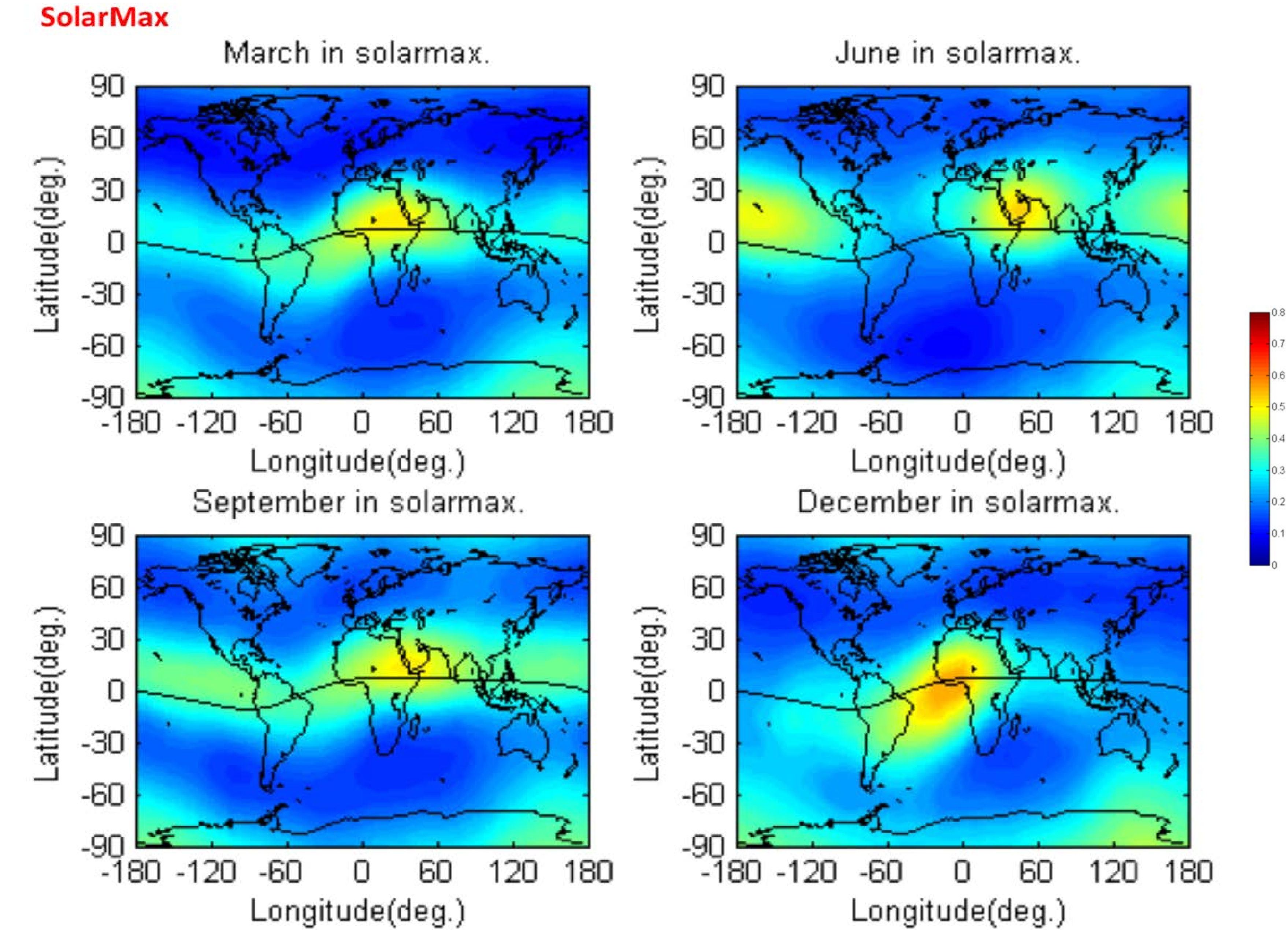
(a)

**SolarMin**



March in solarmin.
June in solarmin.
September in solarmin.
December in solarmin.
Latitude(deg.)
Longitude(deg.)
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

(b)

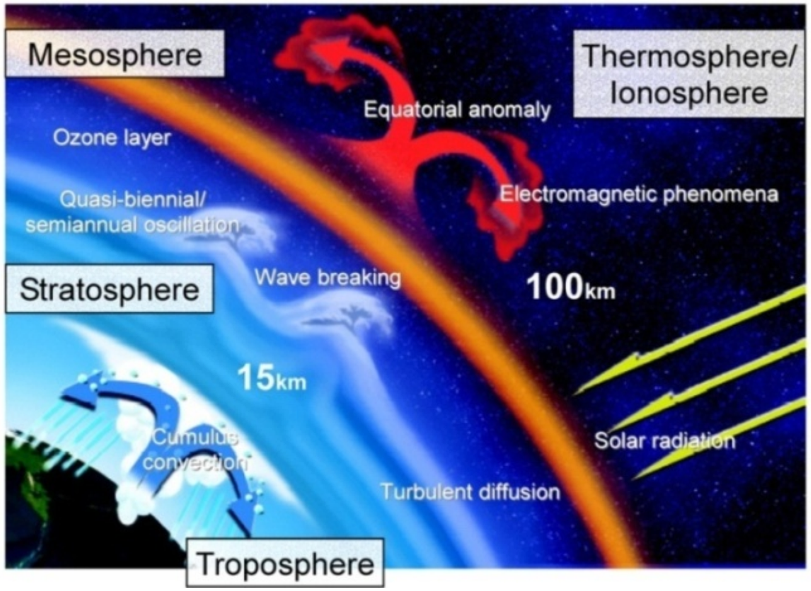

SolarMax
March in solarmax.
June in solarmax.
September in solarmax.
December in solarmax.
Latitude(deg.)
Longitude(deg.)
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

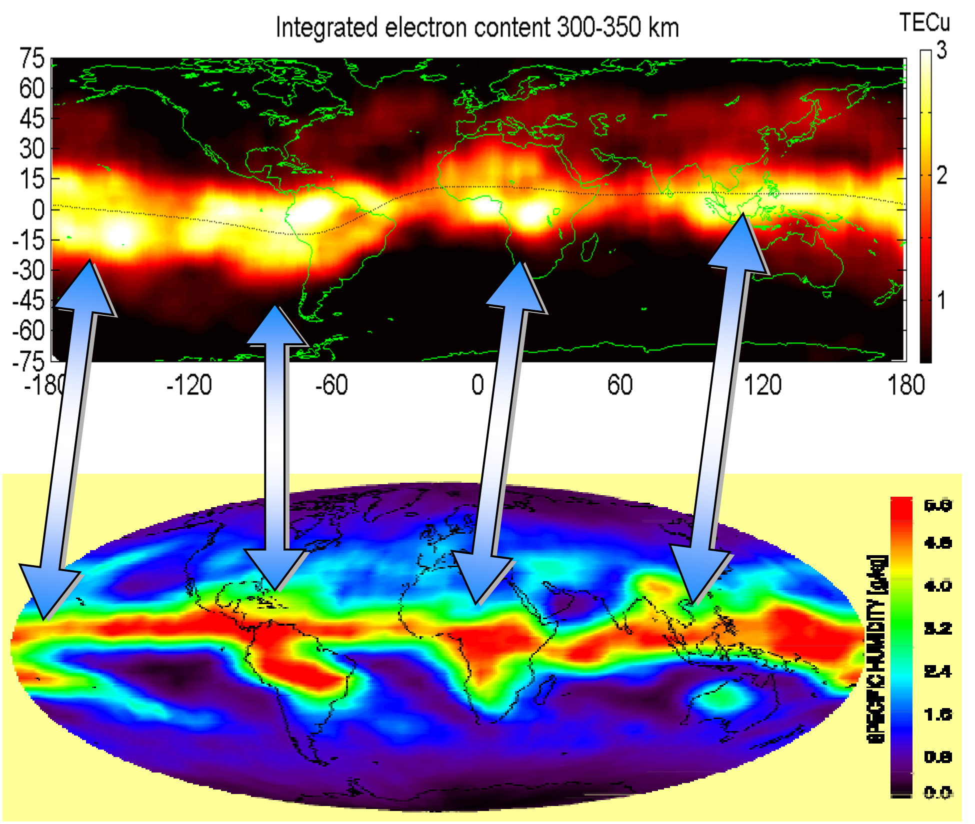
# Remark

- F3/C provides 3D structure and dynamics of the ionospheric scintillation of GPS (GNSS) signals for the positioning, navigation, and communication applications.

# Simultaneous Observations

F3/C RO simultaneously profiling the atmosphere and ionosphere can be used to have a better understanding on the AI coupling (energy and wave ).

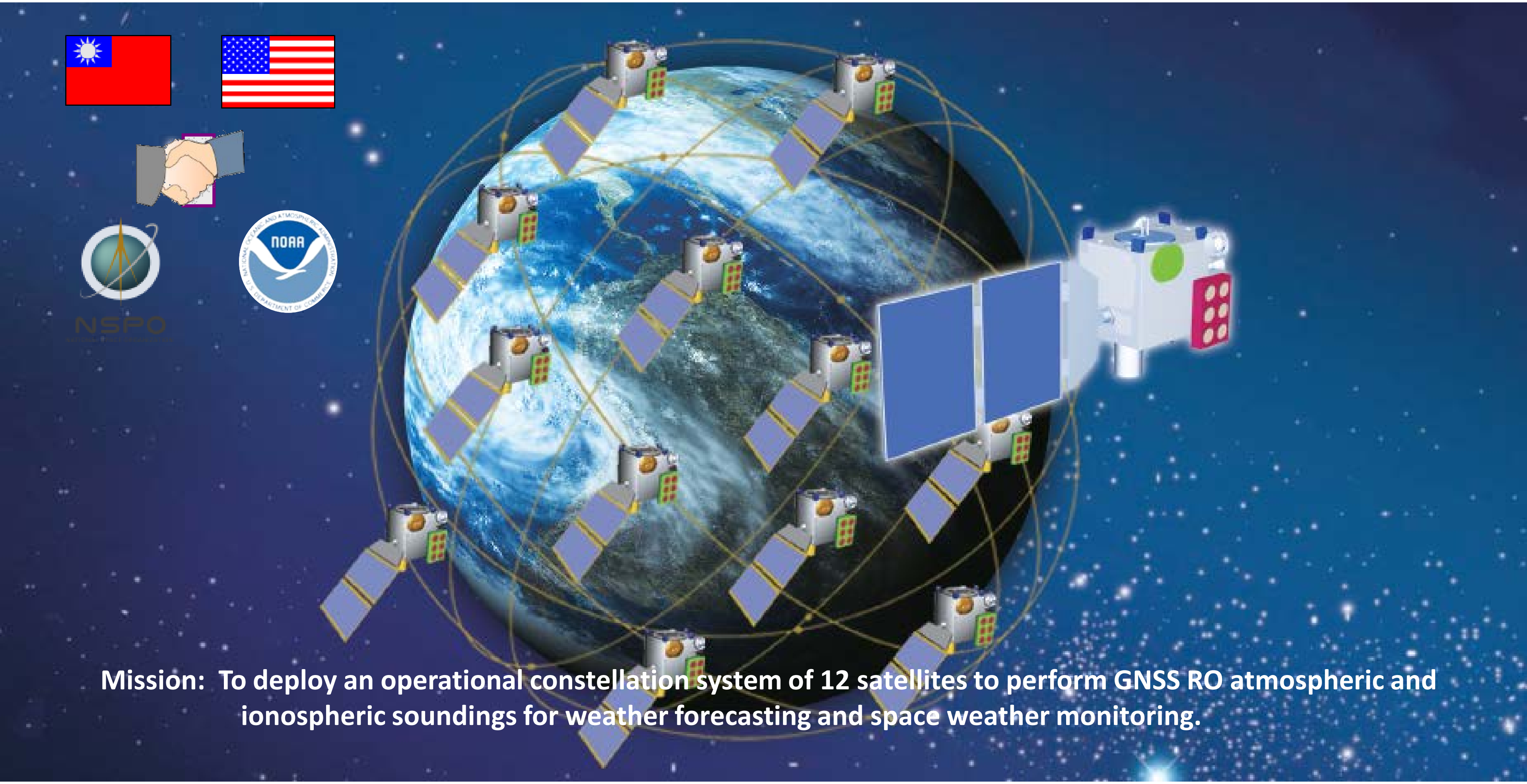


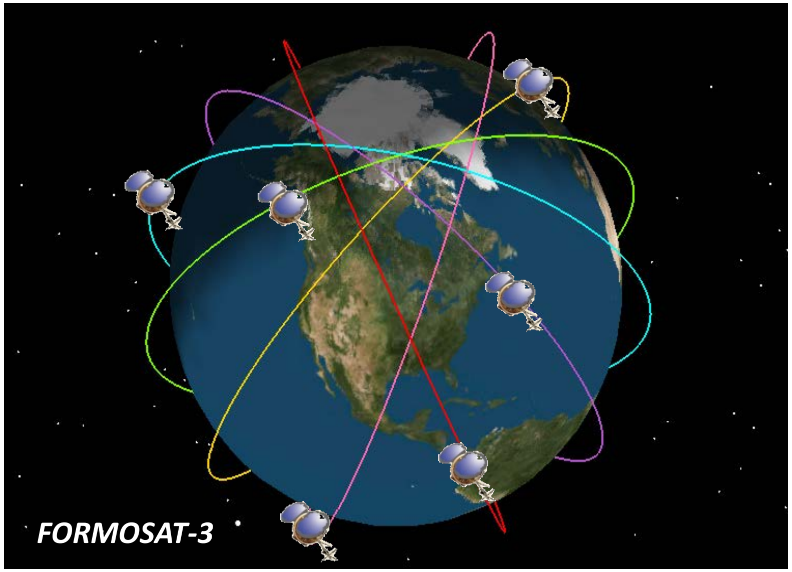

Atmospheric humidity at 5 km altitude

[Courtesy of Dr. Jens. Wickert of the GFZ]

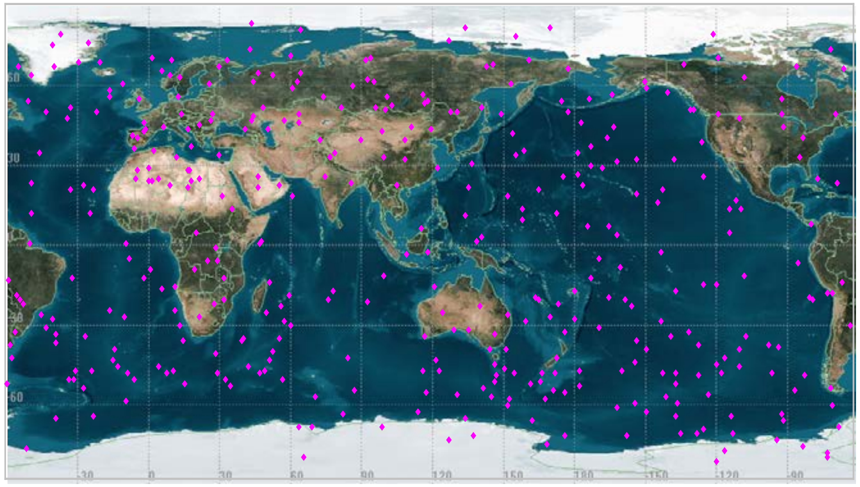
# FORMOSAT-7/COSMIC-2

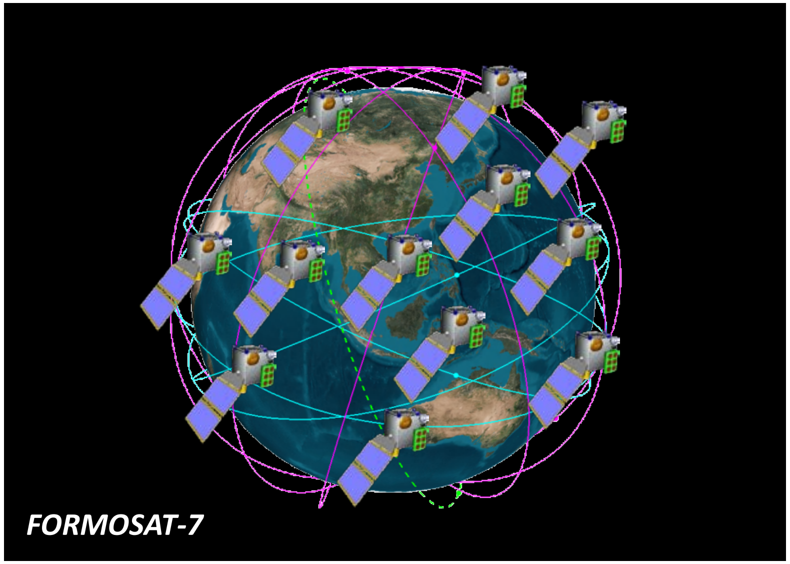


# Comparison of Data Coverage

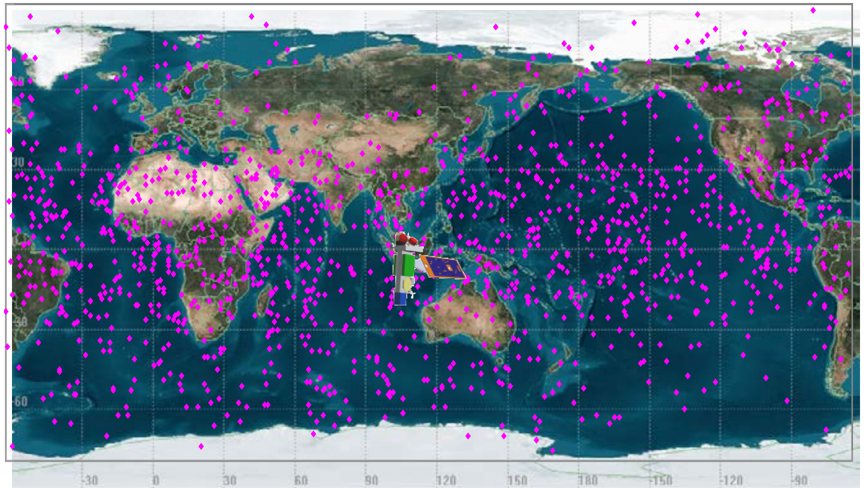


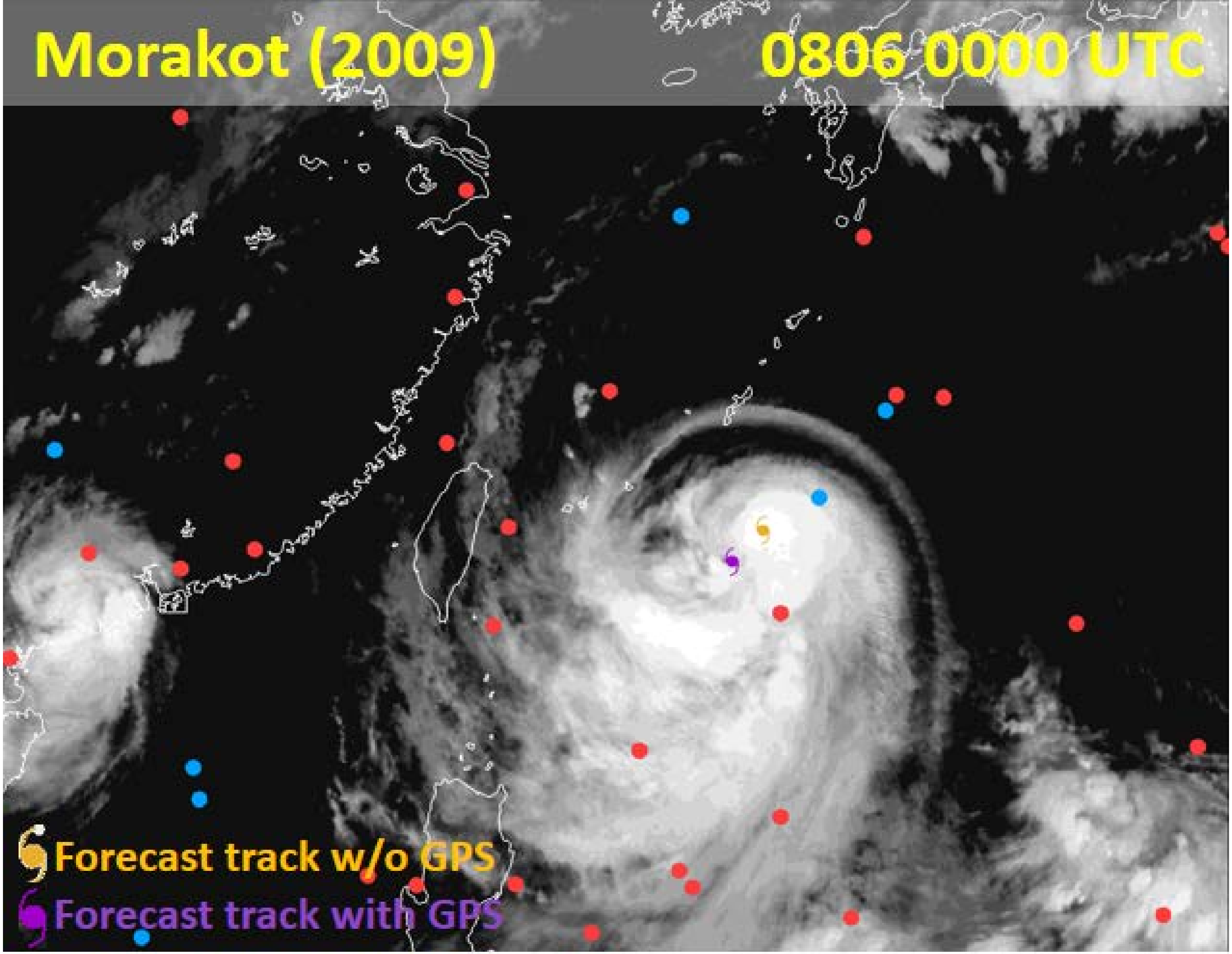

**FORMOSAT-3 Occultations – 3 Hrs Coverage**






**FORMOSAT-7 Occultations – 3 Hrs Coverage**

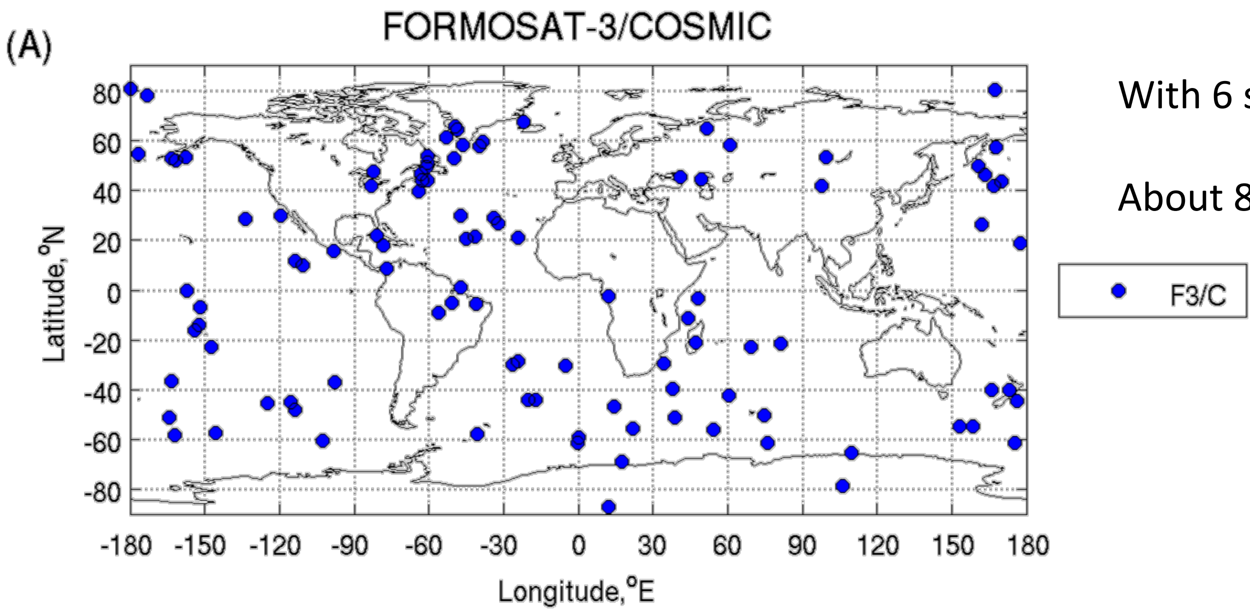





●FORMOSAT-3
●FORMOSAT-7-1
●FORMOSAT-7-2

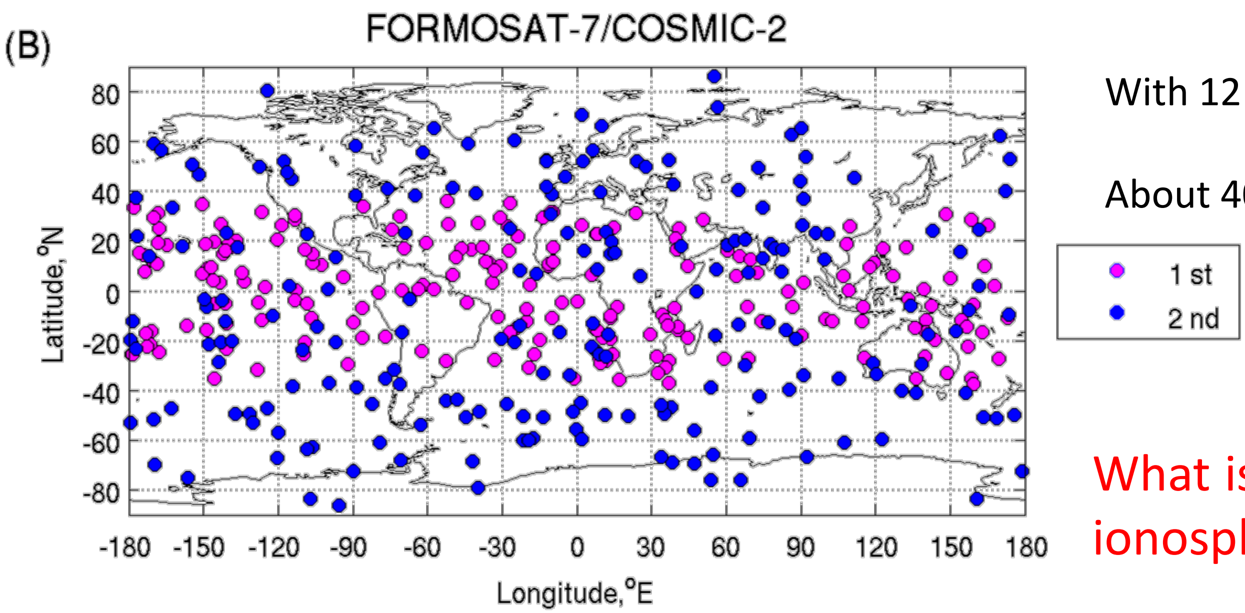
NARLabs NSPO TTFRI

# F7/C2 vs F3/C




With 6 satellites + GPS, 60 minutes

About 80-100 profiles per hour

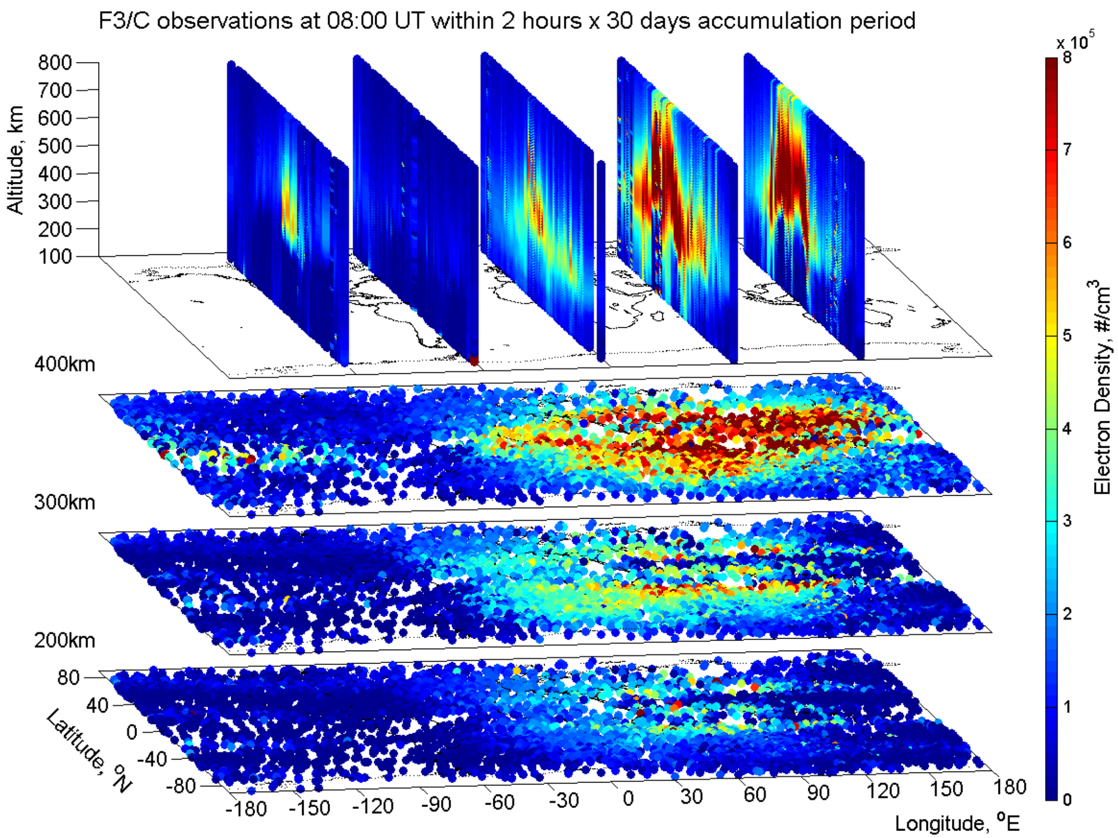



With 12 satellites + GPS, 60 minutes

About 400 profiles per hour

What is future impact of F7/C2 on ionospheric research?

# Ionospheric Weather Monitoring



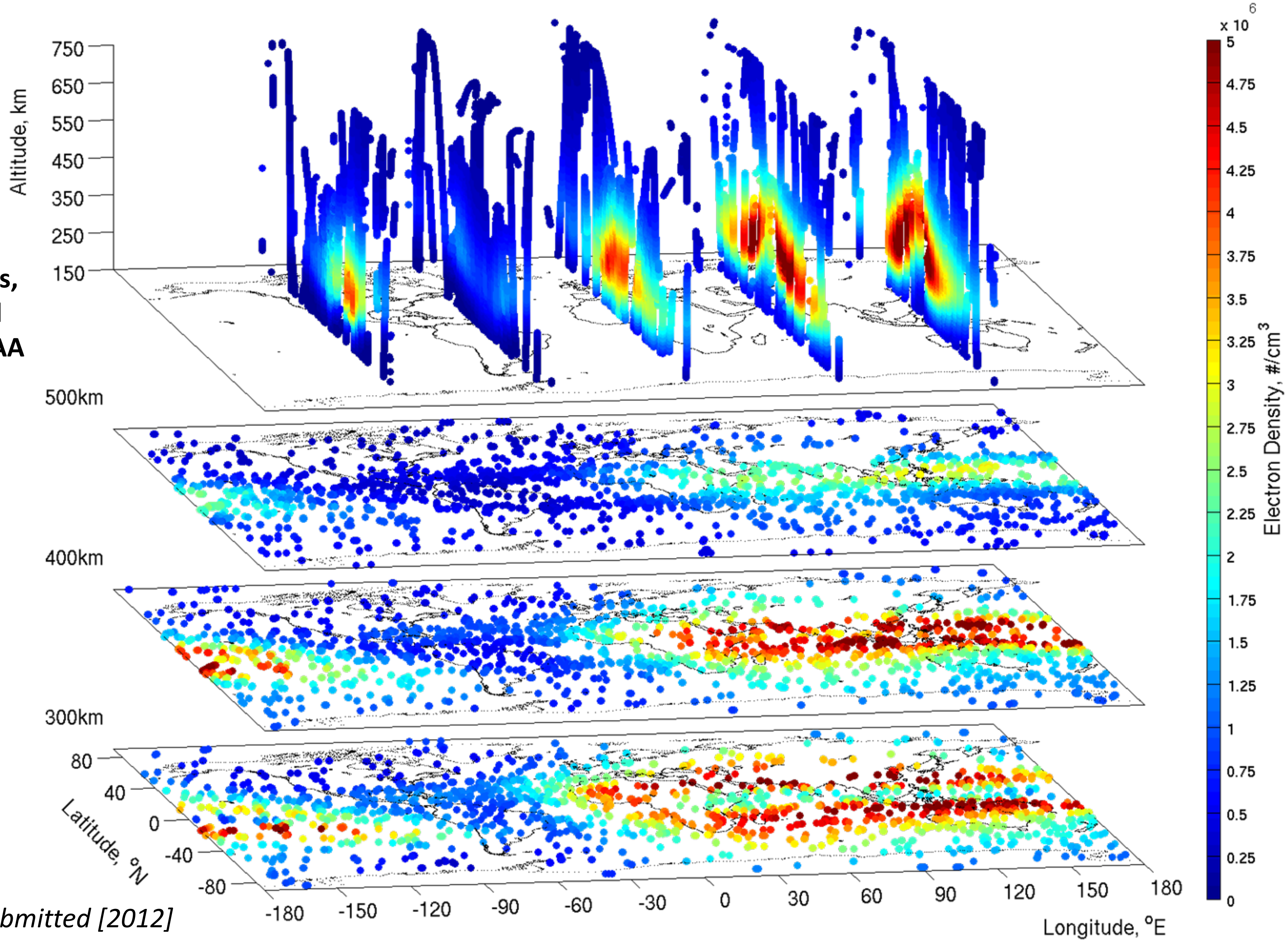

Latitudinal slices are at -120°, -60°, 0° 60° and 120° longitude with a interval of ±2.5°.

- Solar activity variations
- Seasonal variations
- Monthly variations
- Tidal effects
- Diurnal variations
- Semi-diurnal variations
- Disturbed period effects
- Other temporal variations
- Irregularities

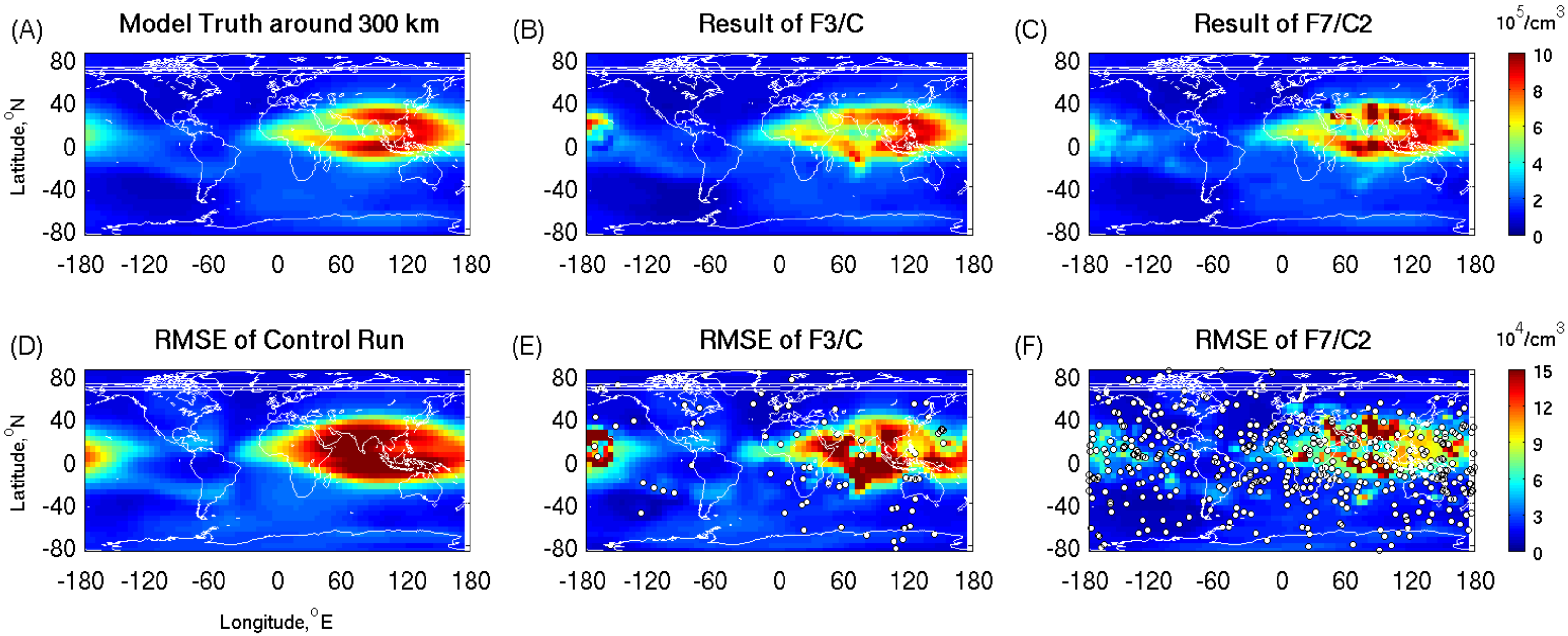
Could it be advanced by F7/C2 ?

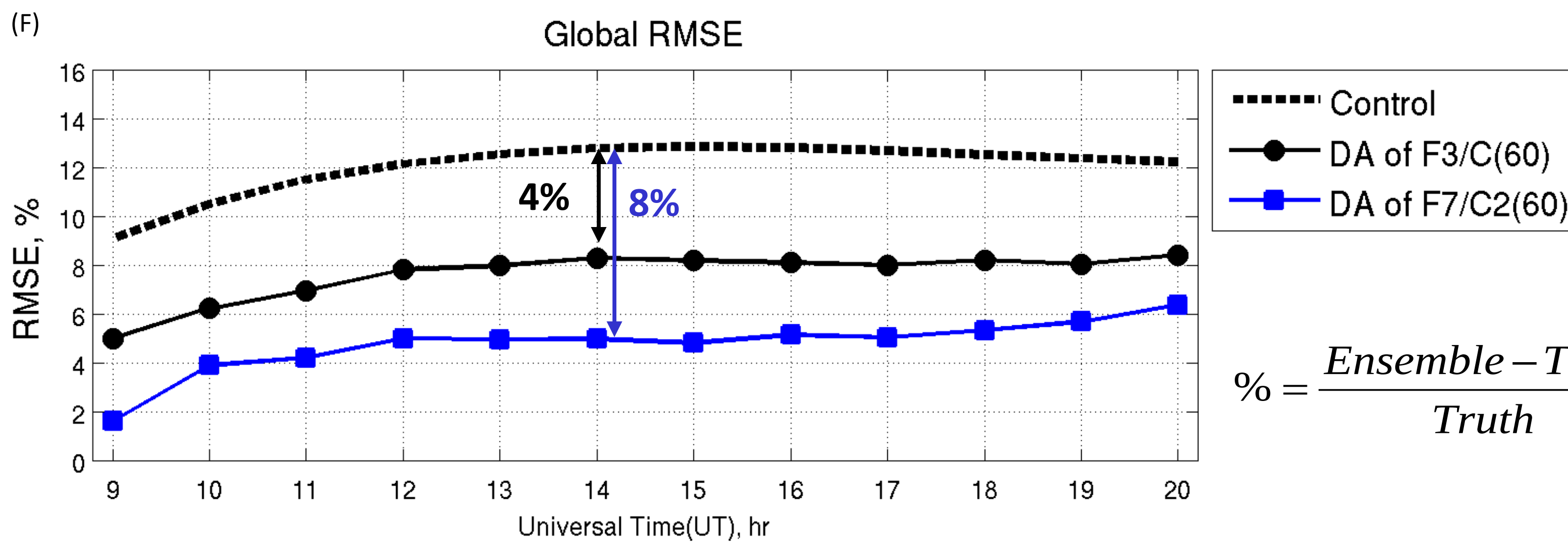
Simulated F7/C2 observations at 08:00 UT within 1 hour x 1 day accumulation period

**12 satellites, 28 GPS and 24 GLONAAA**



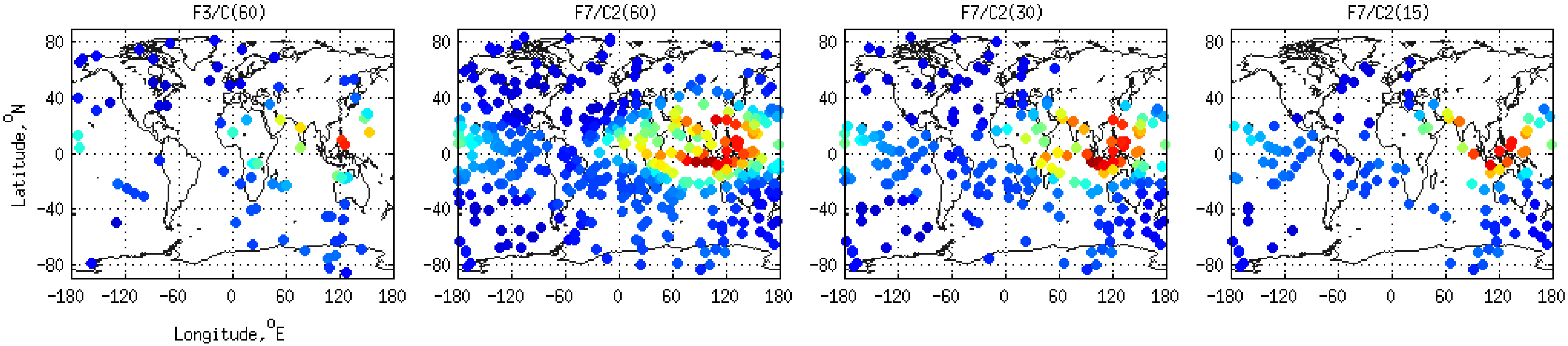

*Lee et al. submitted [2012]*

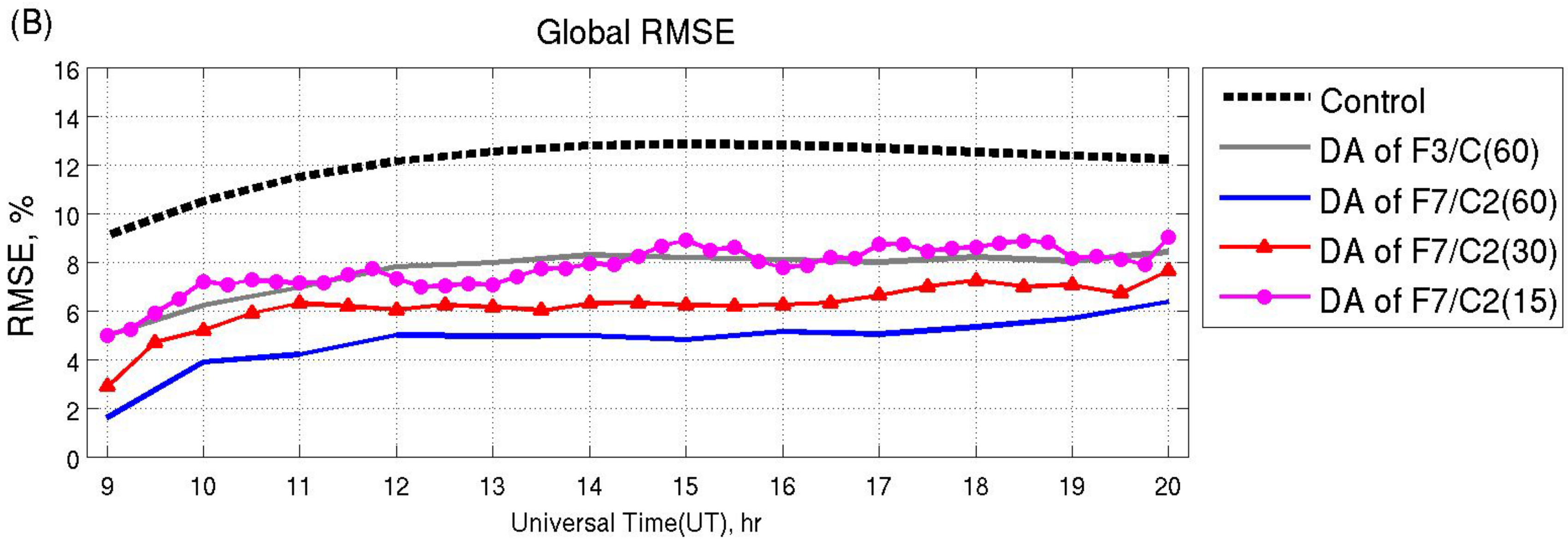



$$\% = \frac{Ensemble - Truth}{Truth} \times 100$$

# Shorten assimilation window




*Lee et al.* [JGR 2013]

The F7/C2 data latency might not be less than 15 minutes for operational assimilation.

# Conclusion

- F7/C2 shall play an extremely essential role for the weather forecast.
- F7/C2 will make that ionospheric monitoring and space weather forecast become reality, especially positioning, navigation, and communication applications.