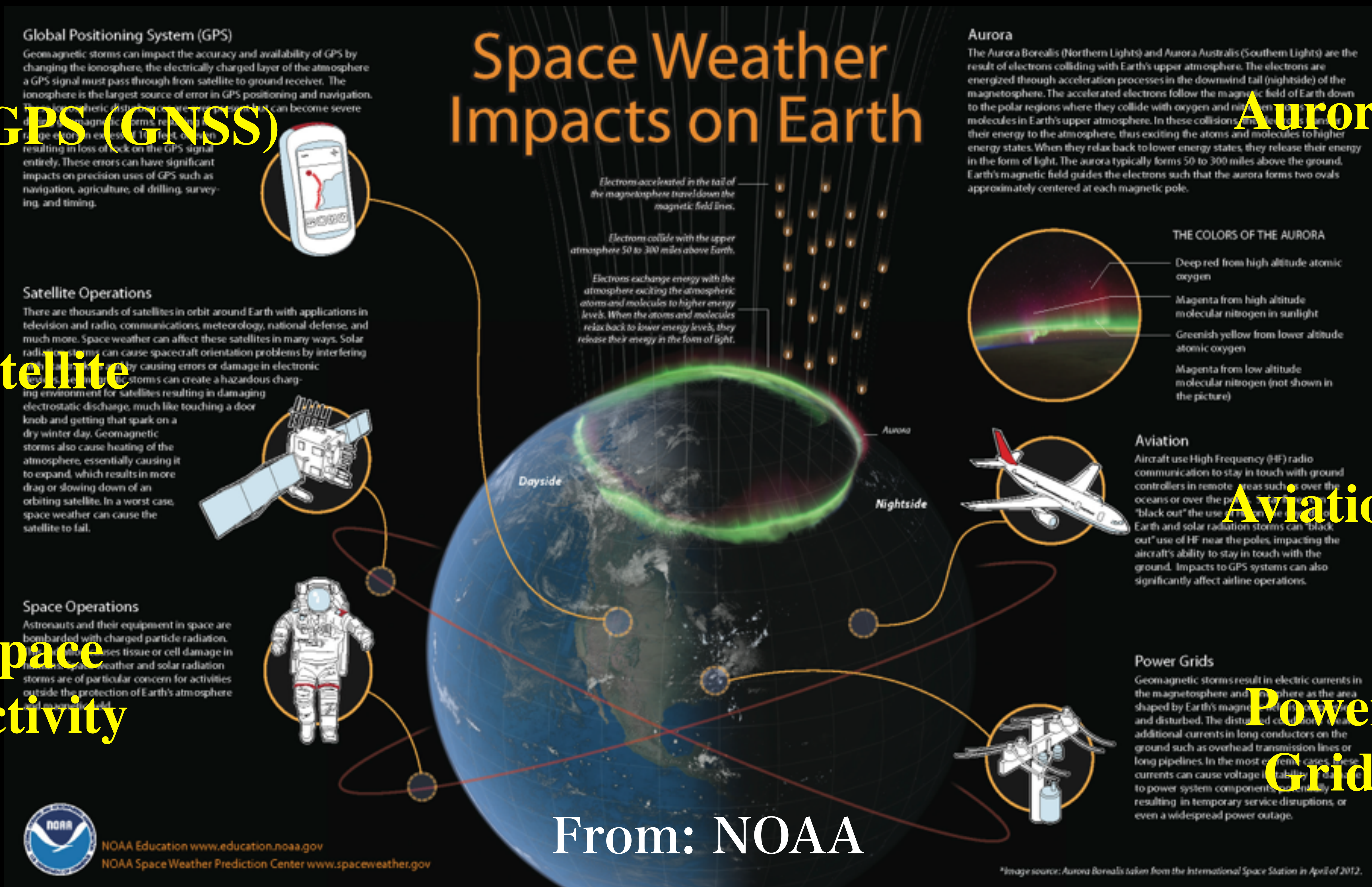
Global Navigation Satellite Systems
and
Space Weather in the Ionosphere

Keisuke Hosokawa

keisuke.hosokawa@uec.ac.jp

Space Weather

Overview - Summary by NOAA

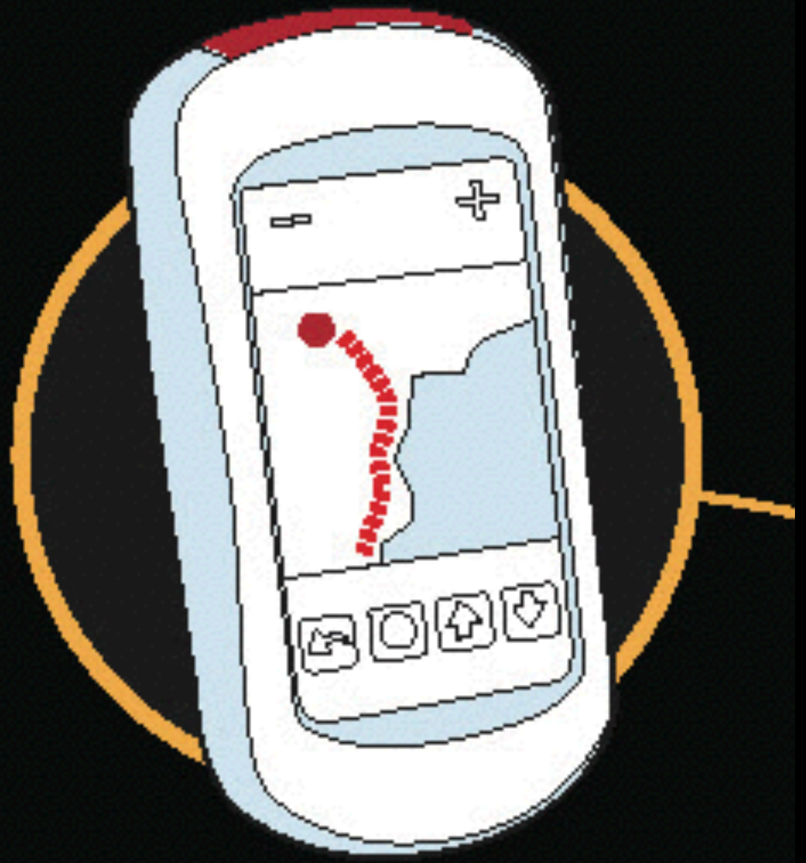


Space Weather

Space Weather Effects on the Global Positioning System

Global Positioning System (GPS)

Geomagnetic storms can impact the accuracy and availability of GPS by changing the ionosphere, the electrically charged layer of the atmosphere a GPS signal must pass through from satellite to ground receiver. The ionosphere is the largest source of error in GPS positioning and navigation. These ionospheric disturbances are ever-present but can become severe during geomagnetic storms, resulting in range errors in excess of 100 feet, or even resulting in loss of lock on the GPS signal entirely. These errors can have significant impacts on precision uses of GPS such as navigation, agriculture, oil drilling, surveying, and timing.



1 feet ~ 30 cm

Outline

- Ionosphere

  Quick exercise: Browsing radar data from Norway

- Key ideas of GNSS

- Mechanism of ionospheric effects on GNSS

- Two major ionospheric impacts on GNSS

  1. Positioning error

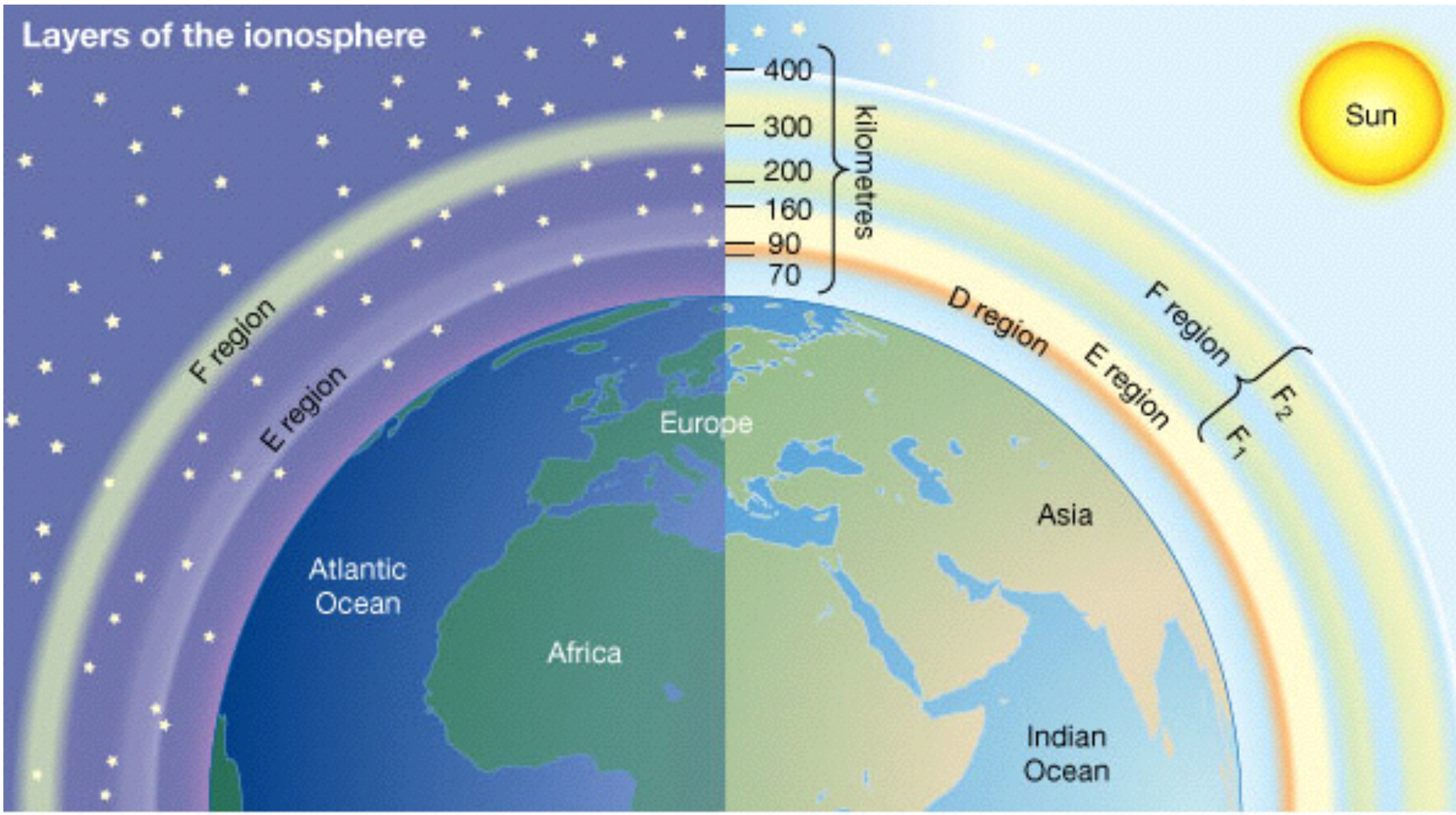
     Quick exercise: Browsing GPS TEC data in US

  2. Scintillation effect

     Quick exercise: Browsing GPS scintillation data

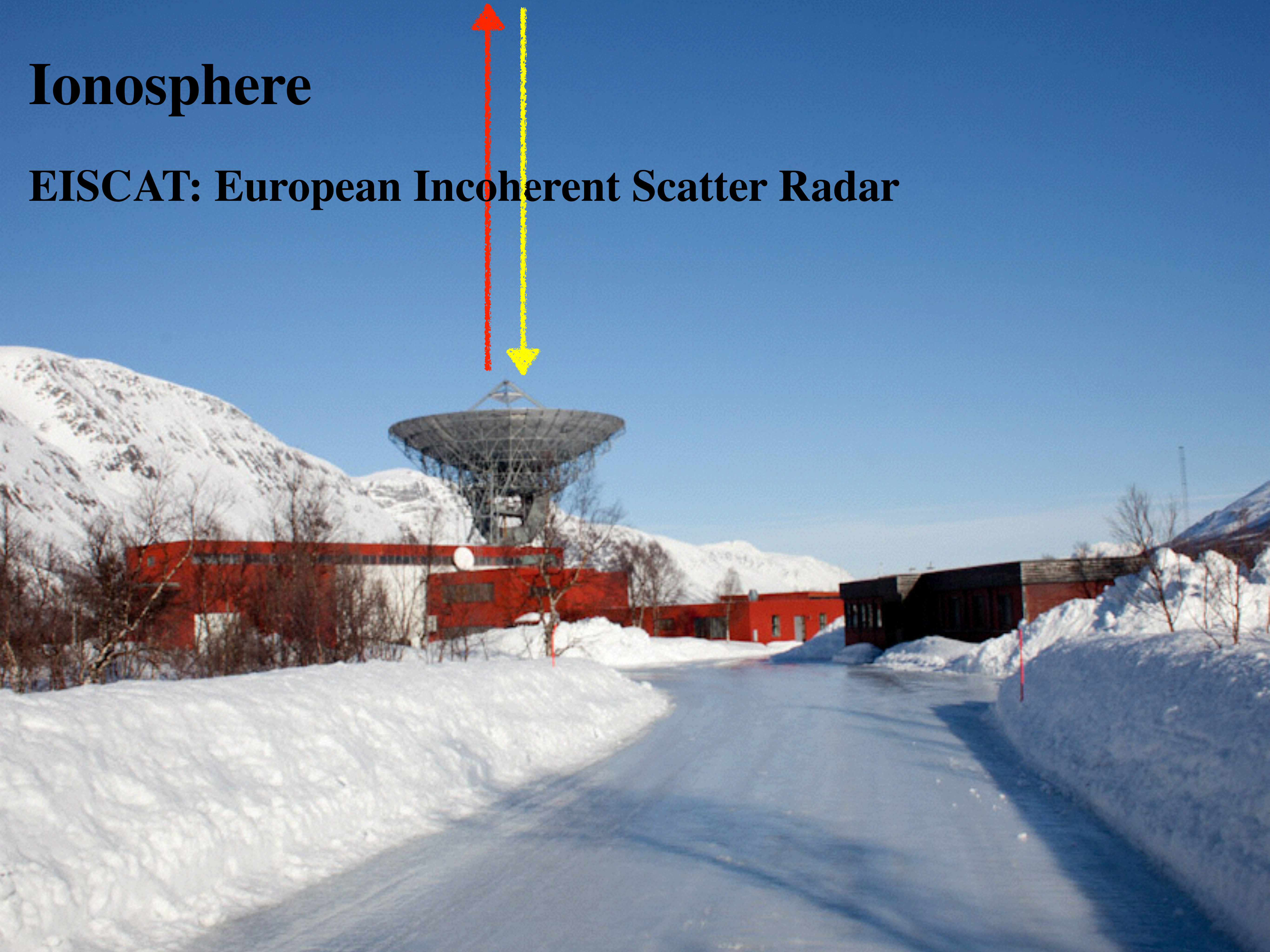
Ionosphere

Region of Ionized Particles in the Earth’s Upper Atmosphere



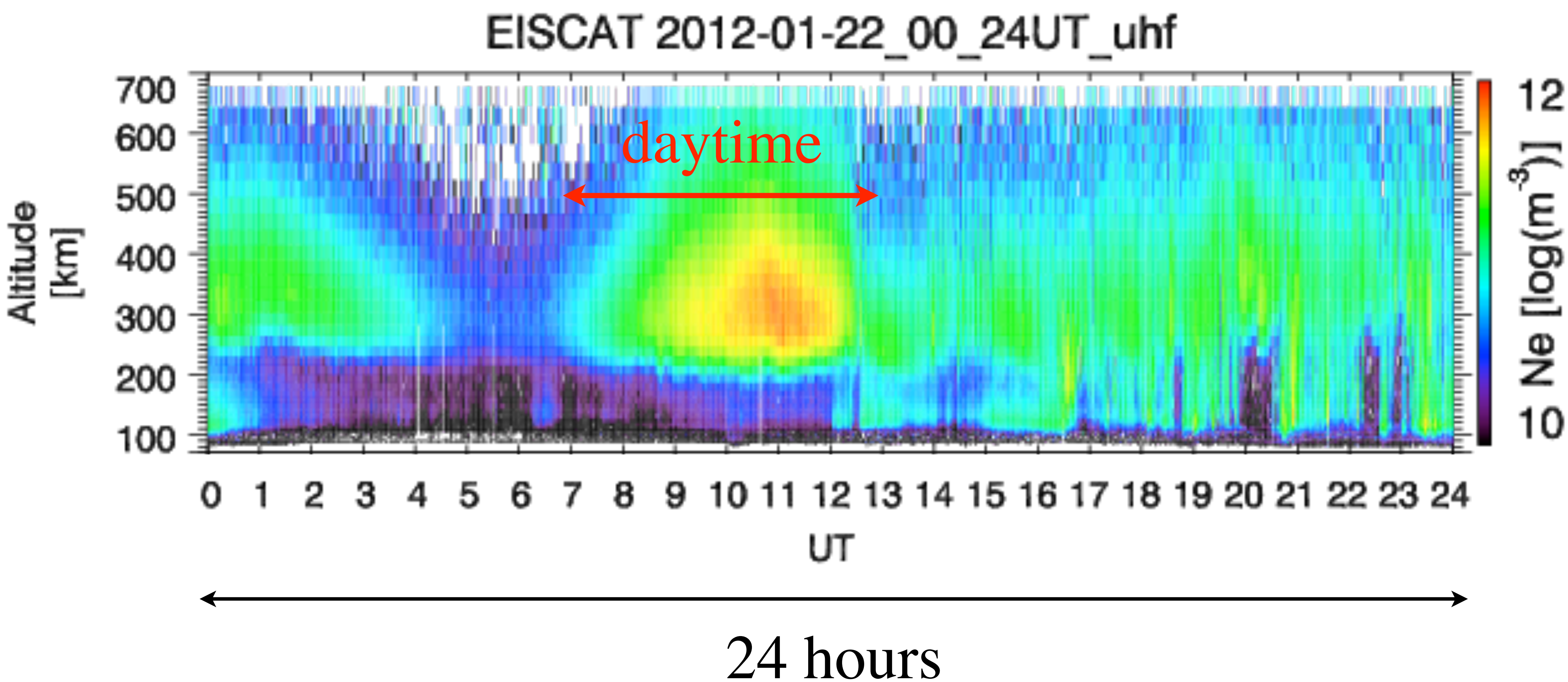
Ionosphere

EISCAT: European Incoherent Scatter Radar



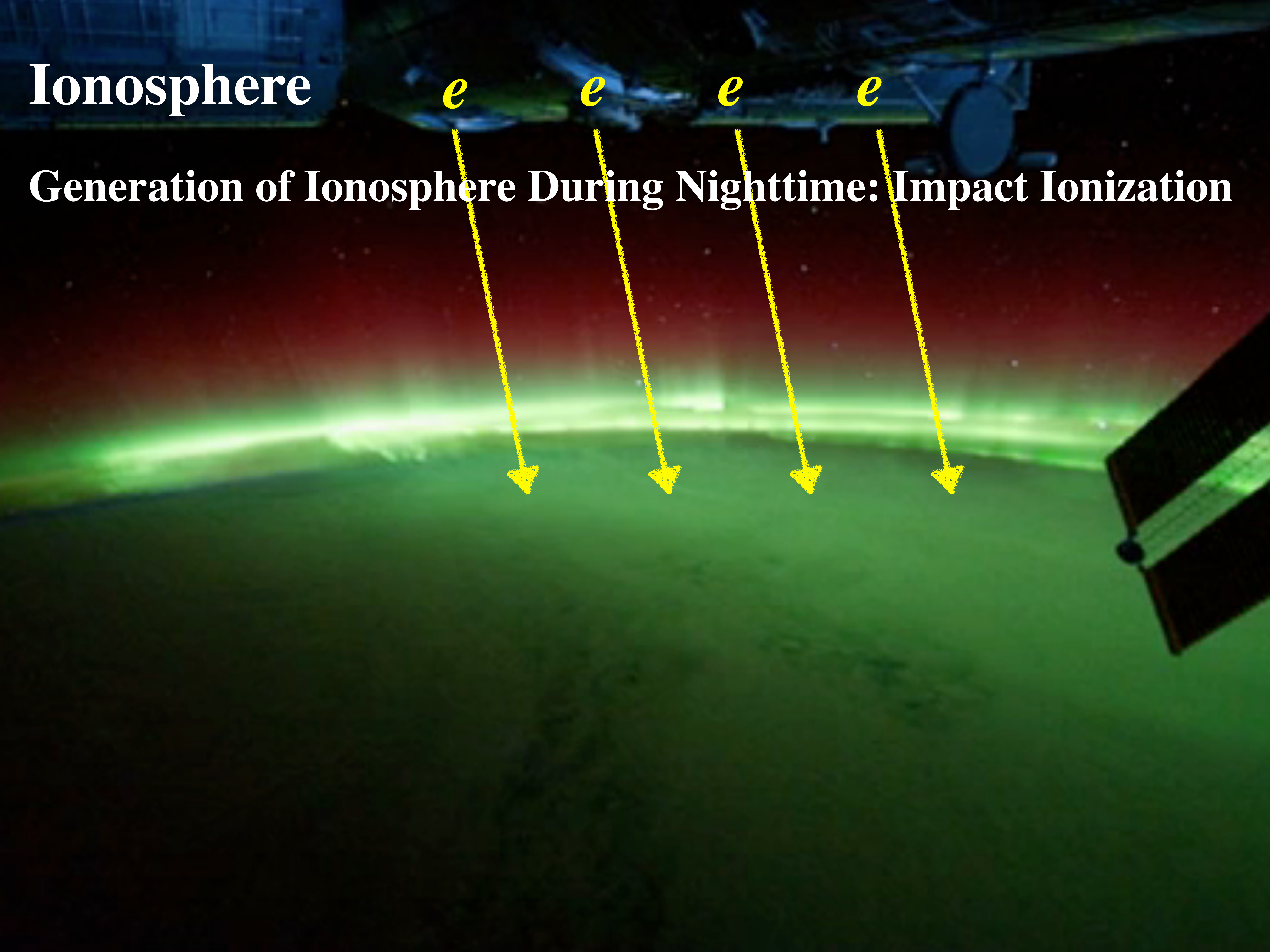
Ionosphere

Generation of Ionosphere During Daytime: Photo Ionization



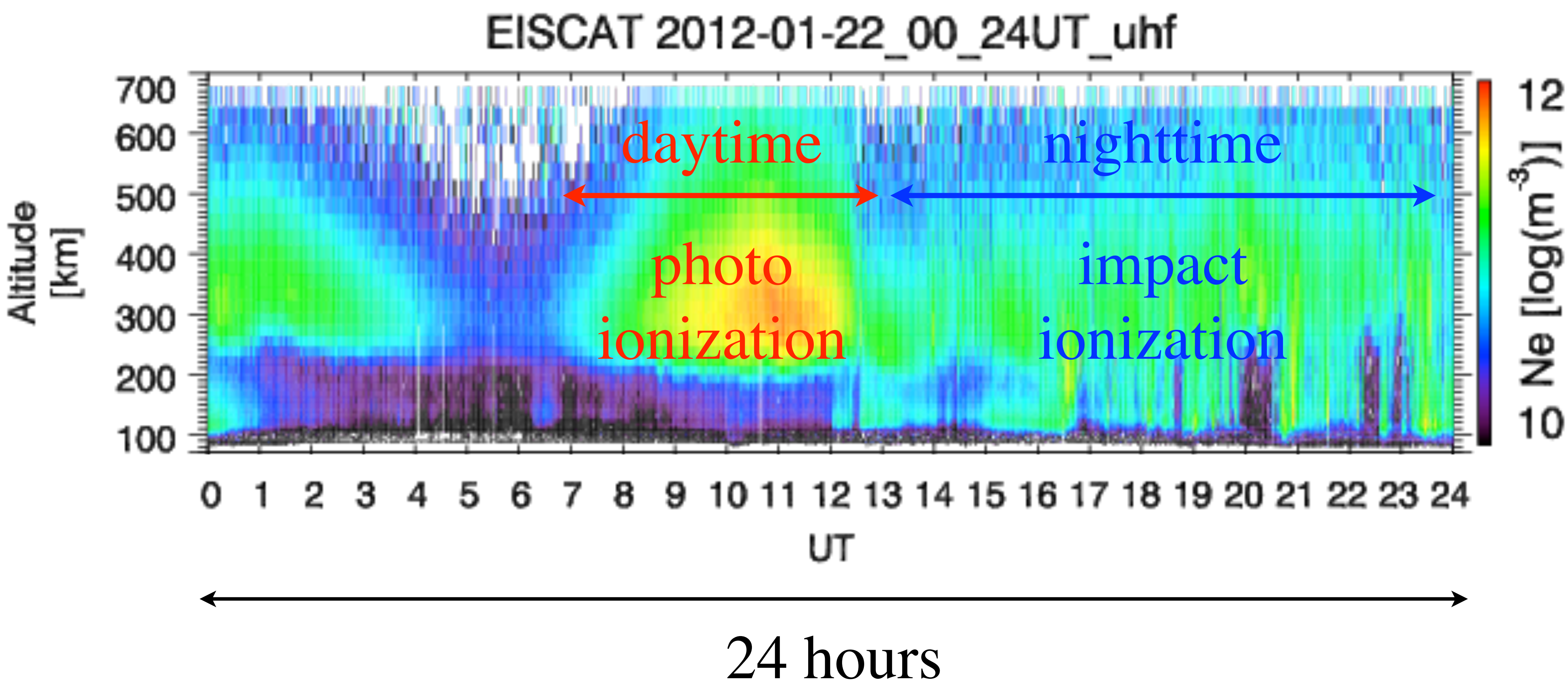
Ionosphere

Generation of Ionosphere During Nighttime: Impact Ionization



Ionosphere

Generation of Ionosphere During Nighttime: Impact Ionization



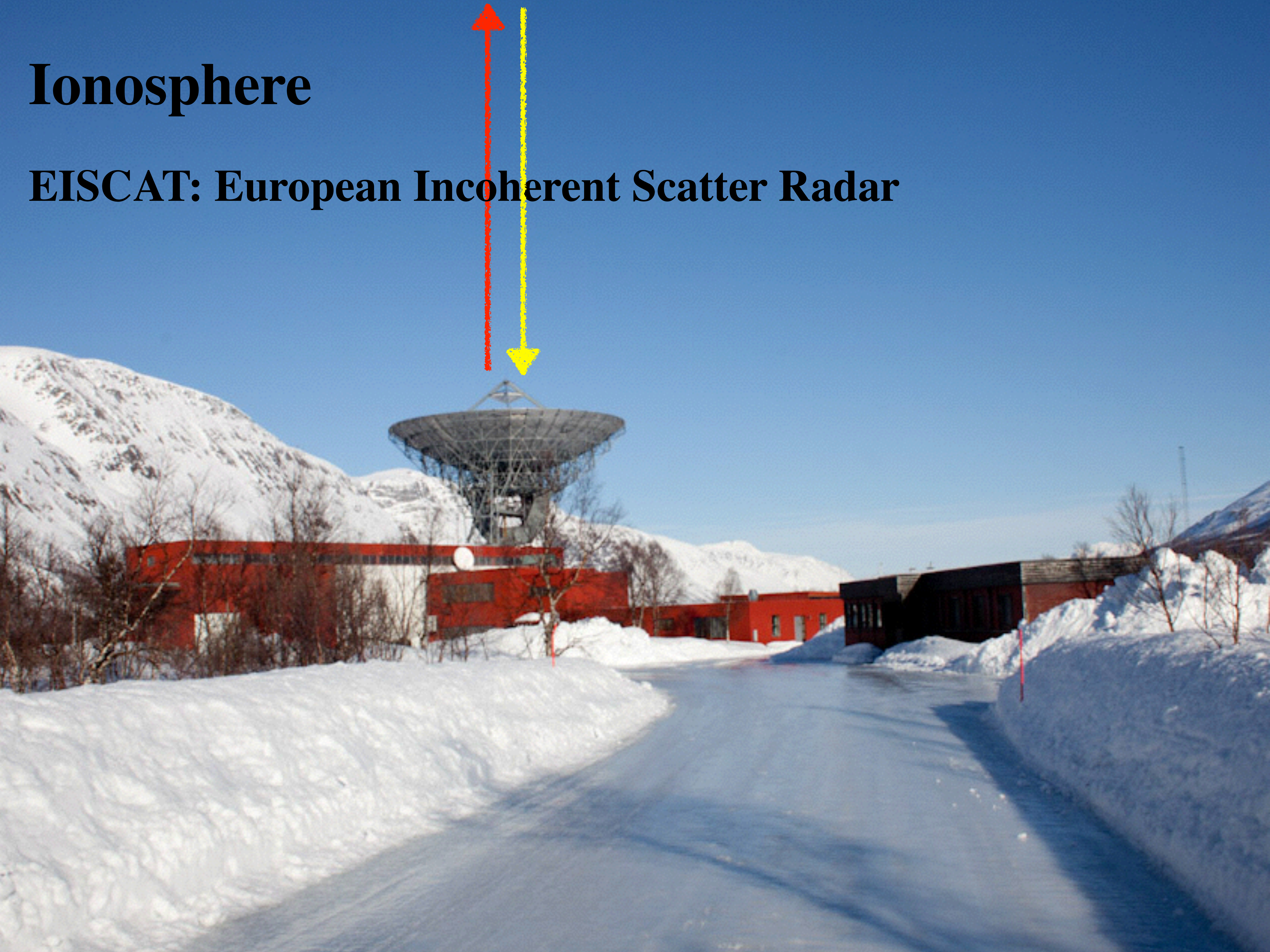
Outline

- Ionosphere
  Quick exercise: Browsing radar data from Norway

- Key ideas of GNSS

- Mechanism of ionospheric effects on GNSS

- Two major ionospheric impacts on GNSS
  1. Positioning error
     Quick exercise: Browsing GPS TEC data in US
  2. Scintillation effect
     Quick exercise: Browsing GPS scintillation data


Ionosphere
EISCAT: European Incoherent Scatter Radar

Quick exercise: browsing radar data from Norway

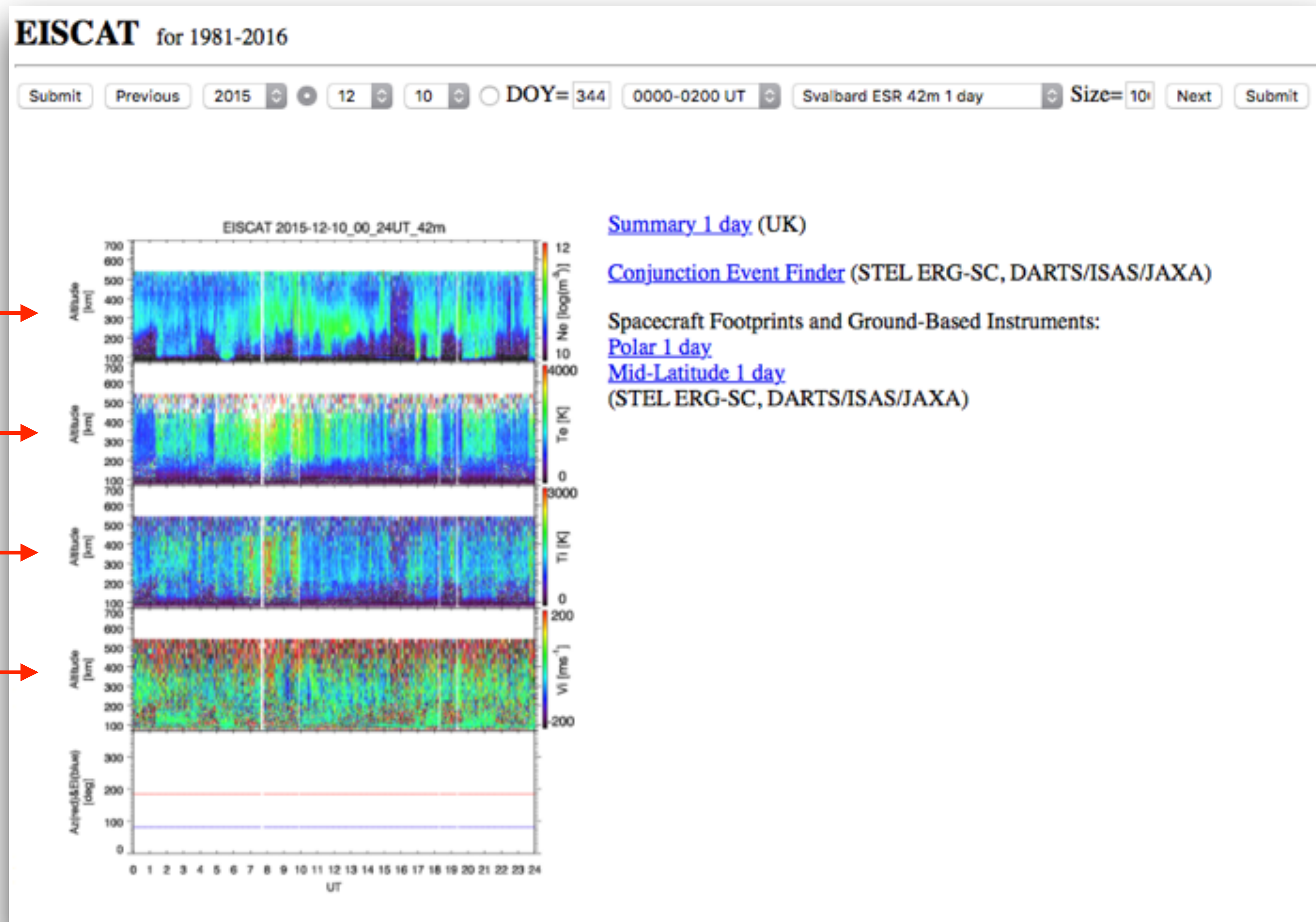
- Visit http://133.57.20.115/www/cgi-bin/eiscat.cgi

Electron Density

Electron Temperature

Ion Temperature

Ion Velocity



Change radar to "Tromso UHF radar"

2. Press Submit

EISCAT for 1981-2016

Submit | Previous | 2015 | 12 | 10 | DOY= 344 | 0000-0200 UT | Svalbard ESR 42m 1 day | Size= 10 | Next | Submit

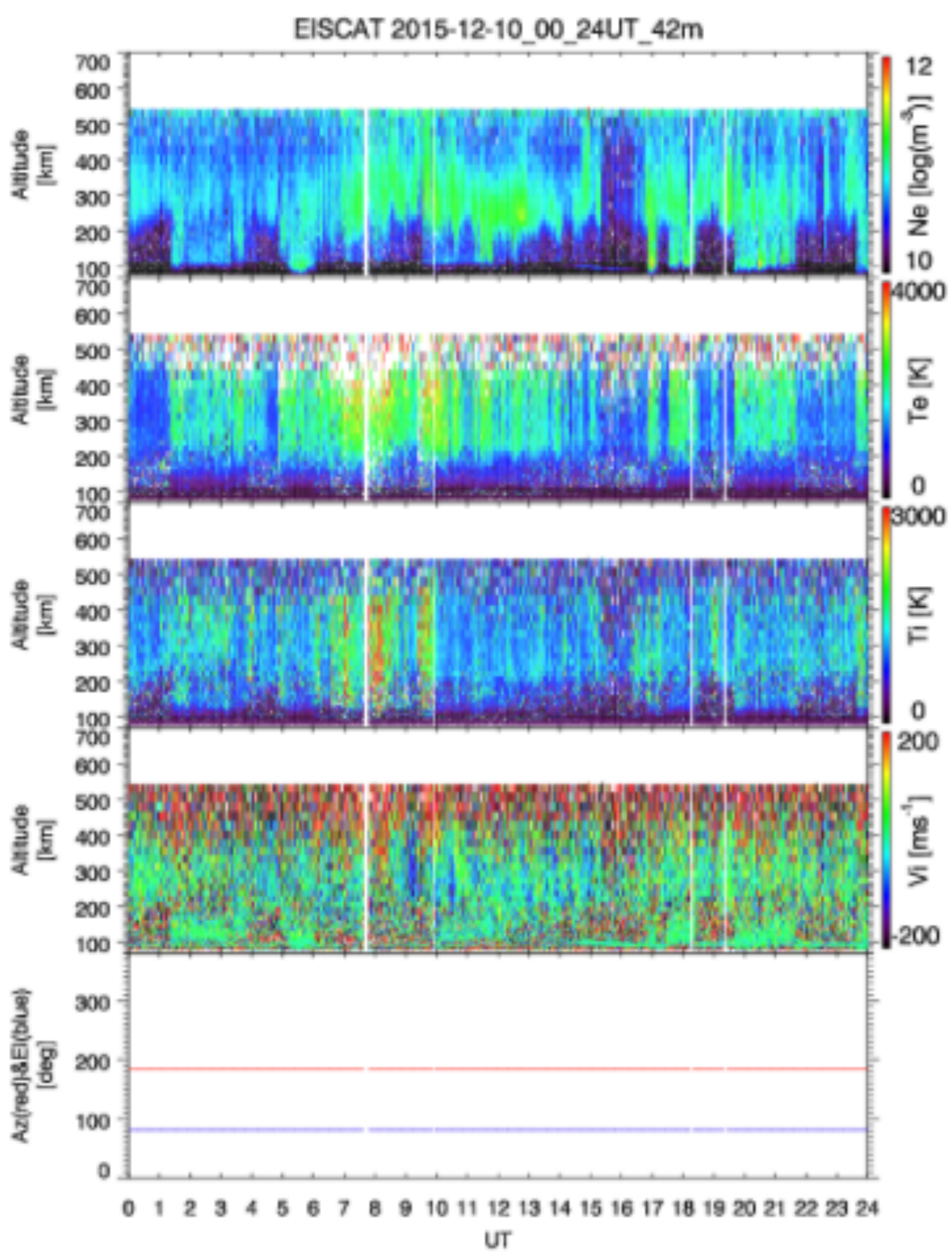
1. Select Tromso UHF radar 1 day

Ne

Te

Ti

Vi



Summary 1 day (UK)

Conjunction Event Finder (STEL ERG-SC, DARTS/ISAS/JAXA)

Spacecraft Footprints and Ground-Based Instruments:
Polar 1 day
Mid-Latitude 1 day
(STEL ERG-SC, DARTS/ISAS/JAXA)

Change date of plot - previous day and next day

EISCAT for 1981-2016

Submit | Previous | 2015 | 12 | 10 | DOY= 344 | 0000-0200 UT | Tromso UHF Radar 1 day | Size= 10(| Next | Submit

-1 day

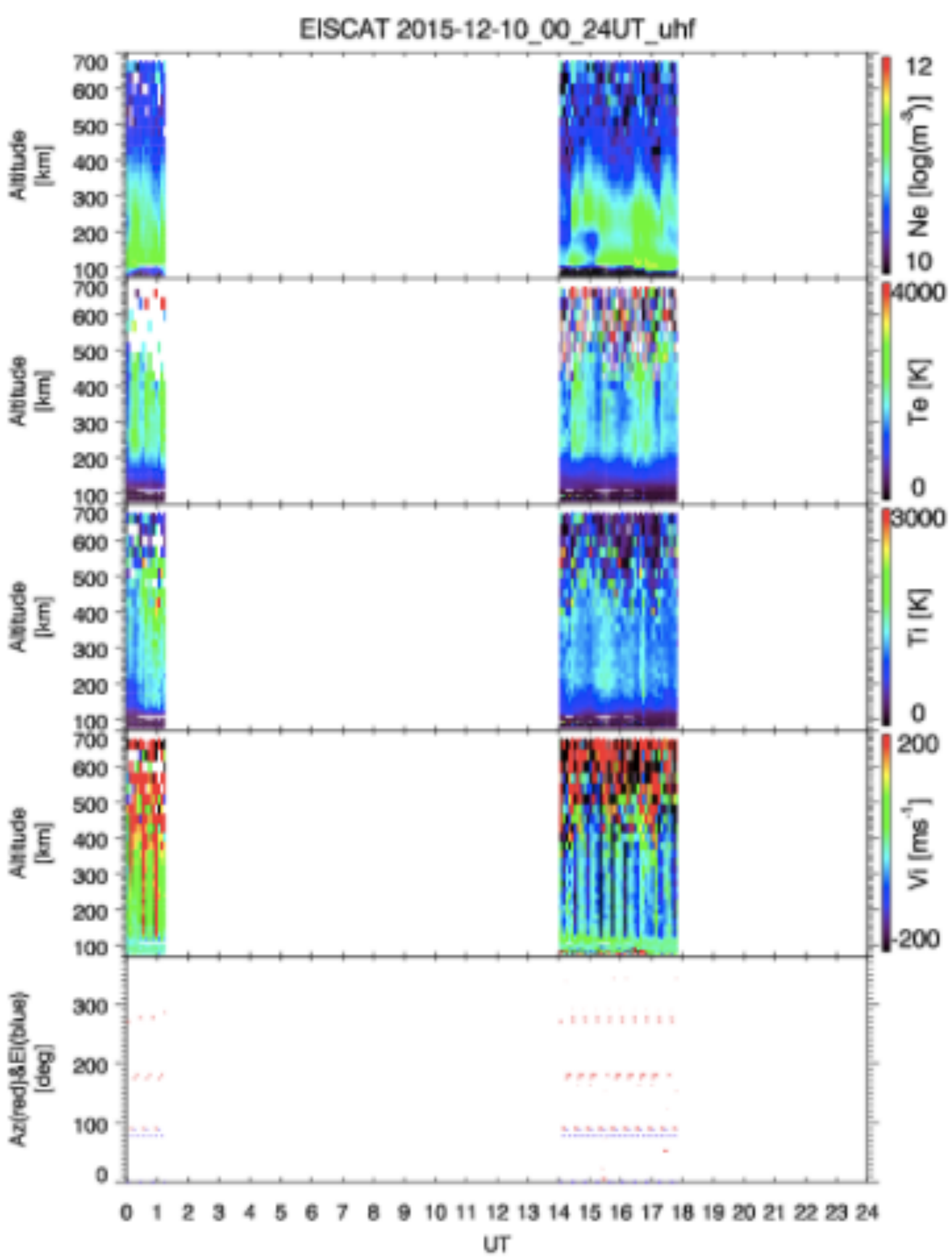
+1 day

Ne

Te

Ti

Vi



Summary 1 day (UK)

Conjunction Event Finder (STEL ERG-SC, DARTS/ISAS/JAXA)

Spacecraft Footprints and Ground-Based Instruments:
Polar 1 day
Mid-Latitude 1 day
(STEL ERG-SC, DARTS/ISAS/JAXA)

Change date of plot - jump to different day

2. Press Submit

EISCAT for 1981-2016

Submit | Previous | 2015 | 12 | 10 | DOY= 344 | 0000-0200 UT | Tromso UHF Radar 1 day | Size= 10(| Next | Submit

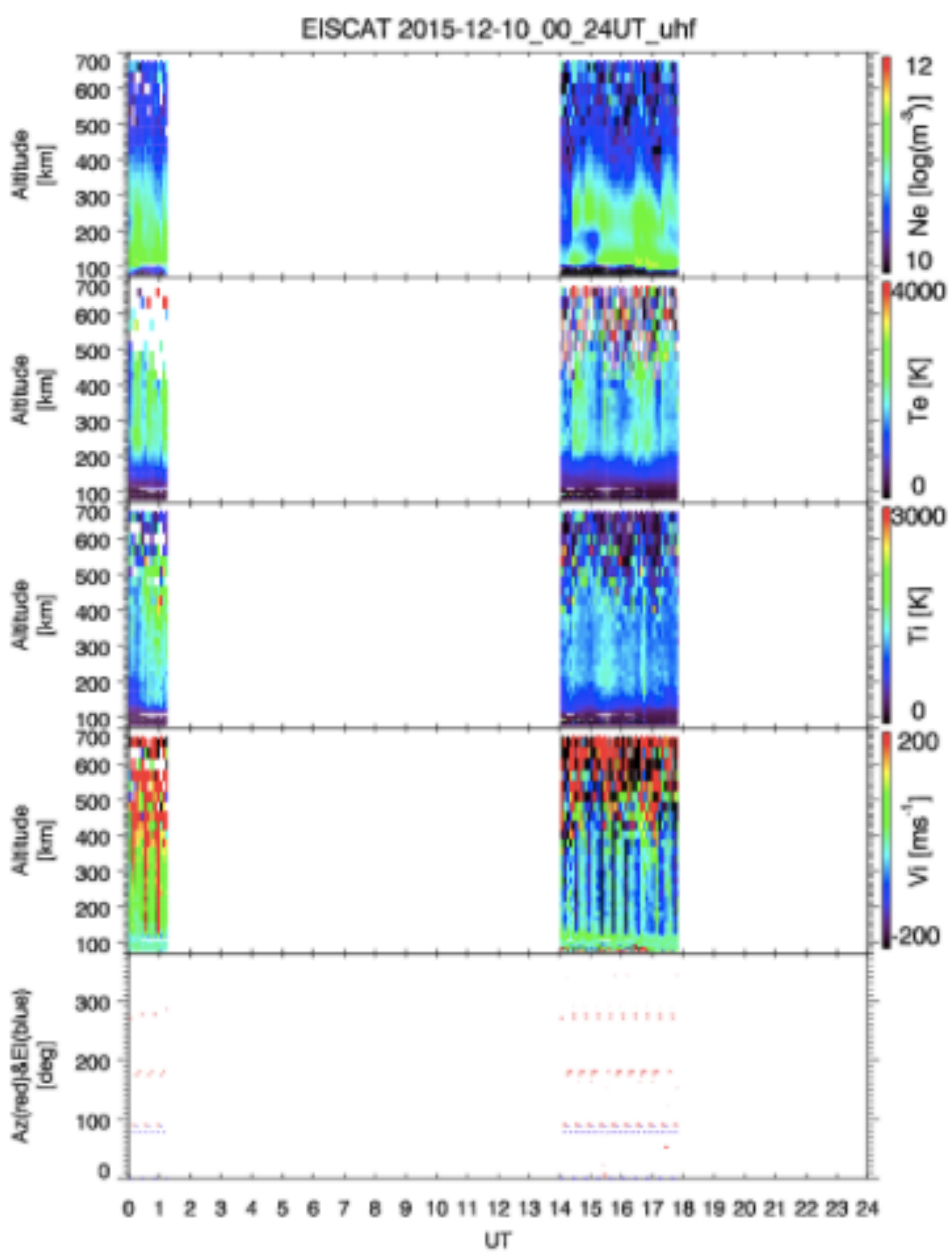
1. Change date (Year, Month, Day)

Ne

Te

Ti

Vi



[Summary 1 day](#) (UK)

[Conjunction Event Finder](#) (STEL ERG-SC, DARTS/ISAS/JAXA)

Spacecraft Footprints and Ground-Based Instruments:
[Polar 1 day](#)
[Mid-Latitude 1 day](#)
(STEL ERG-SC, DARTS/ISAS/JAXA)

Try the following date:

Jan 13, 2012

10 days continuous measurements in Tromso

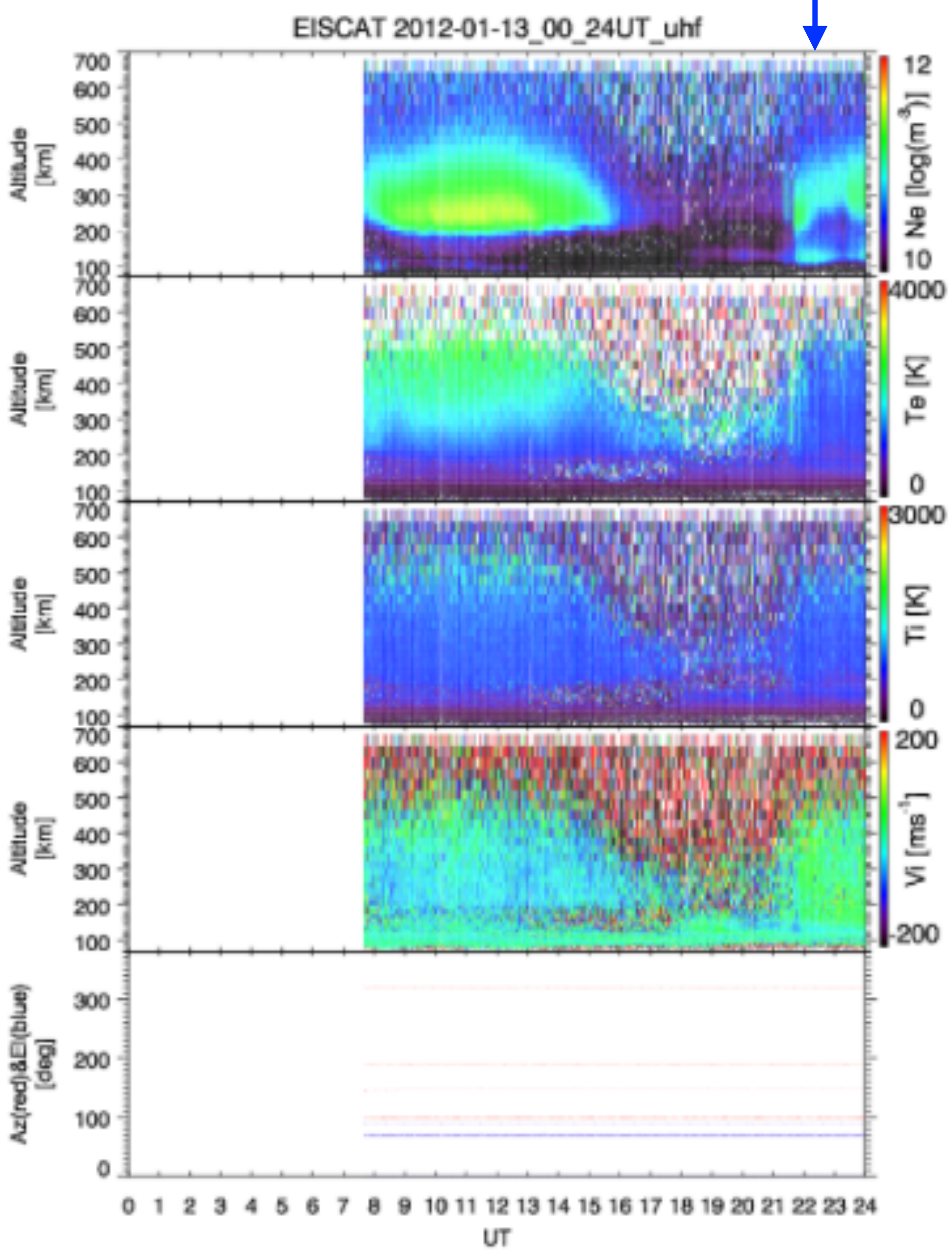
EISCAT for 1981-2016

Submit | Previous | 2012 | 01 | 13 | DOY= 013 | 0000-0200 UT | Tromso UHF Radar 1 day | Size= 10 | Next | Submit

Check next day

Weak impact ionization

Photo ionization



Ne

Te

Ti

Vi

[Summary 1 day] (UK)

[Conjunction Event Finder] (STEL ERG-SC, DARTS/ISAS/JAXA)

Spacecraft Footprints and Ground-Based Instruments:
[Polar 1 day]
[Mid-Latitude 1 day]
(STEL ERG-SC, DARTS/ISAS/JAXA)

10 days continuous measurements in Tromso

EISCAT for 1981-2016

Submit | Previous | 2012 | 01 | 13 | DOY= 013 | 0000-0200 UT | Tromso UHF Radar 1 day | Size= 10 | Next | Submit

Check next day

Weak impact ionization

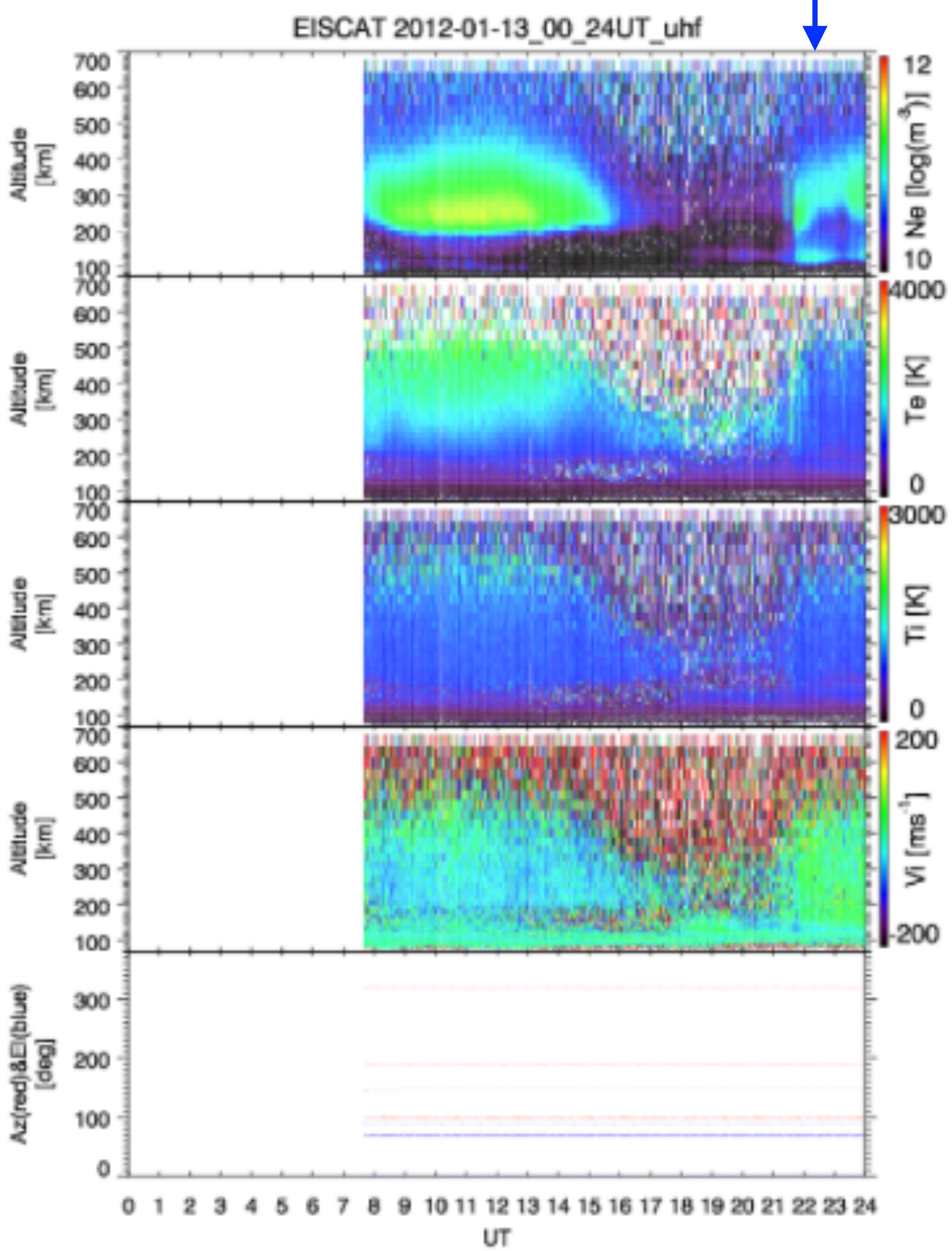
Photo ionization

Ne

Te

Ti

Vi



[Summary 1 day](#) (UK)

[Conjunction Event Finder](#) (STEL ERG-SC, DARTS/ISAS/JAXA)

Spacecraft Footprints and Ground-Based Instruments:
[Polar 1 day](#)
[Mid-Latitude 1 day](#)
(STEL ERG-SC, DARTS/ISAS/JAXA)

The ionosphere never be the same

- Photo ionization: almost similar

- Impact ionization:
large day-to-day variability

10 days later, on Jan 22, 2012

EISCAT for 1981-2016

Submit | Previous | 2012 | 01 | 22 | DOY= 022 | 0000-0200 UT | Tromso UHF Radar 1 day | Size= 10 | Next | Submit

Photo ionization

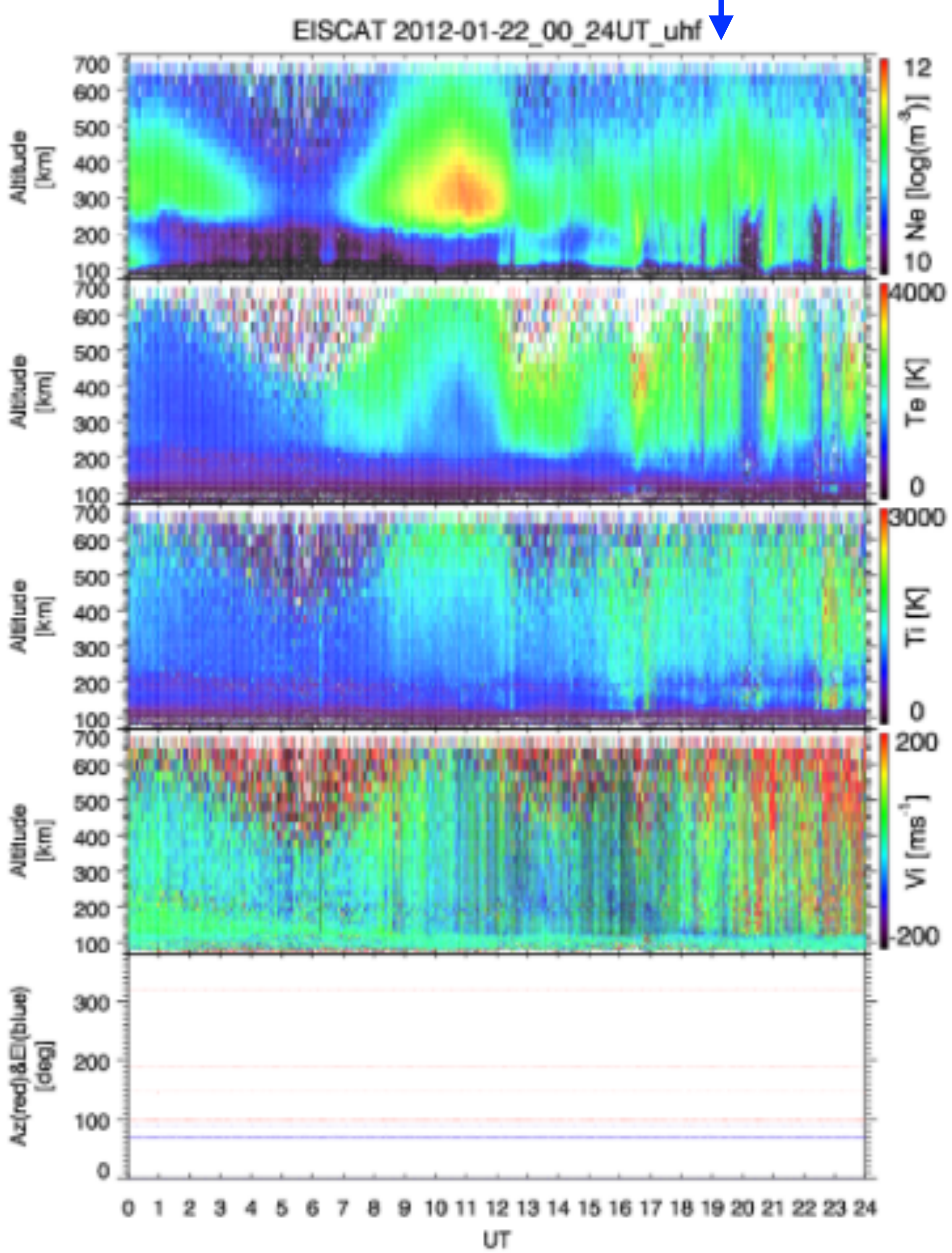
Strong impact ionization

Ne

Te

Ti

Vi

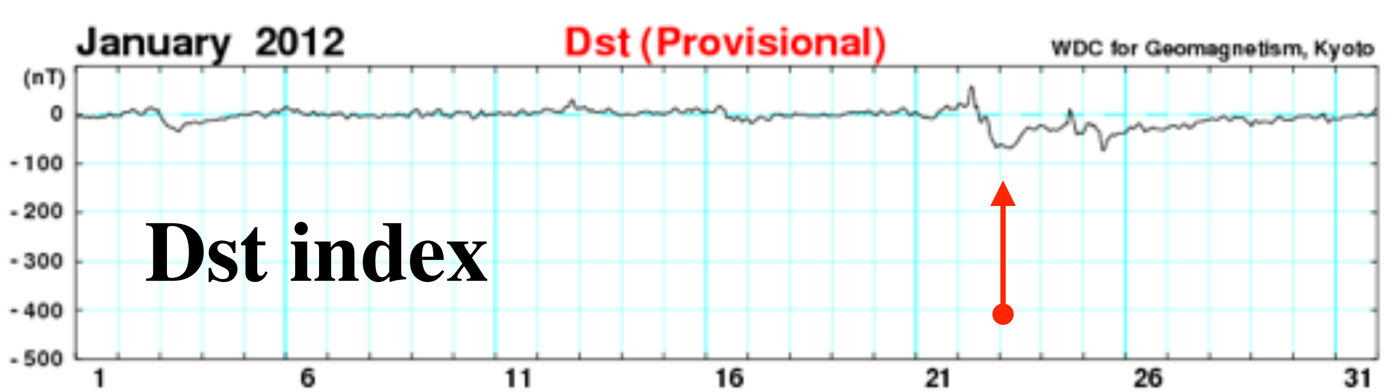


[Summary 1 day](#) (UK)

[Conjunction Event Finder](#) (STEL ERG-SC, DARTS/ISAS/JAXA)

Spacecraft Footprints and Ground-Based Instruments:
[Polar 1 day](#)
[Mid-Latitude 1 day](#)
(STEL ERG-SC, DARTS/ISAS/JAXA)

Jan 22 is a stormy day:



The ionosphere is disturbed during magnetic storms

Check aurora data in Tromso on Jan 22, 2012

- http://nordlys.nipr.ac.jp/acaurora/Tromso/html/backnumber.html

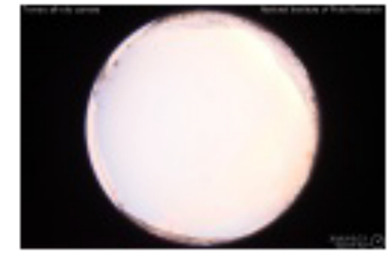
Check aurora data in Tromso on Jan 22, 2012

Tromso all-sky camera

National Institute of Polar Research

Contact on this page: miyaoka@nipr.ac.jp

Back Number

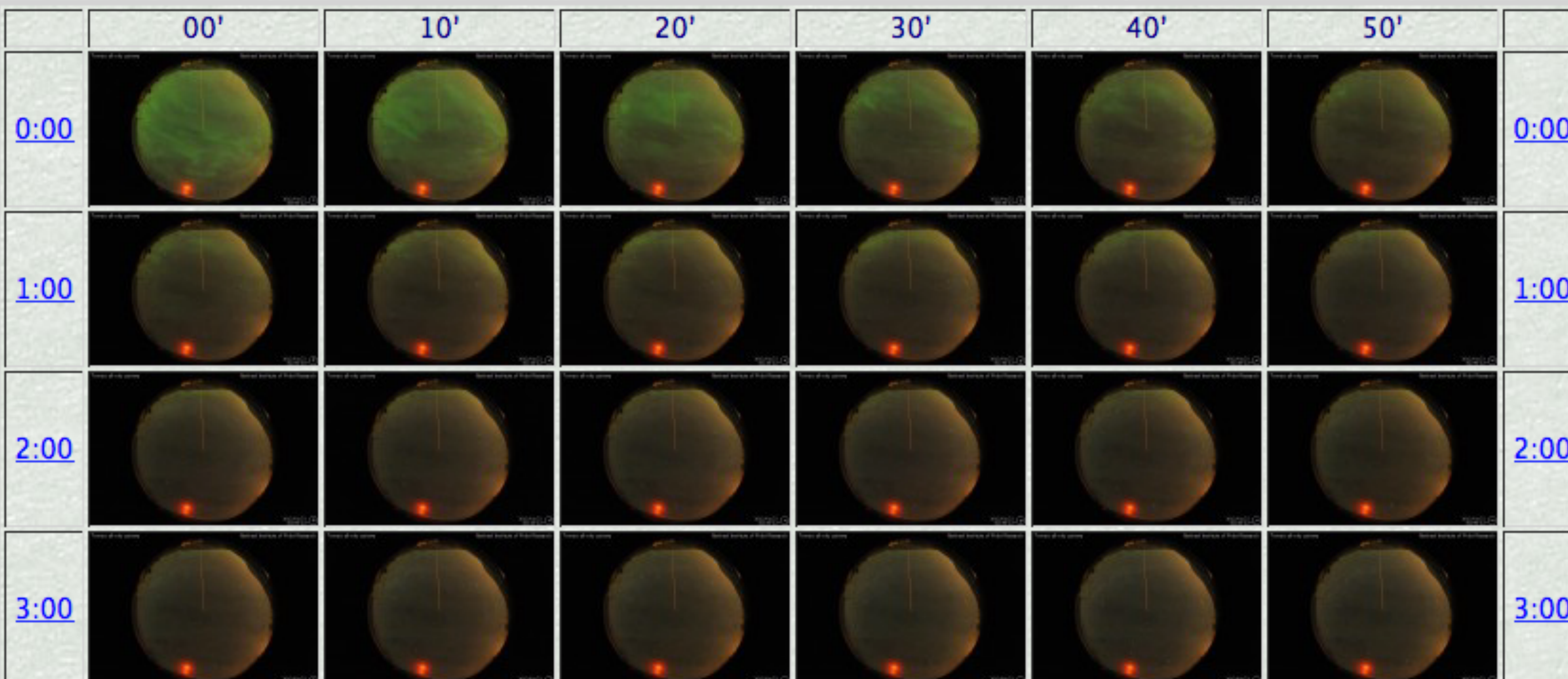


latest image

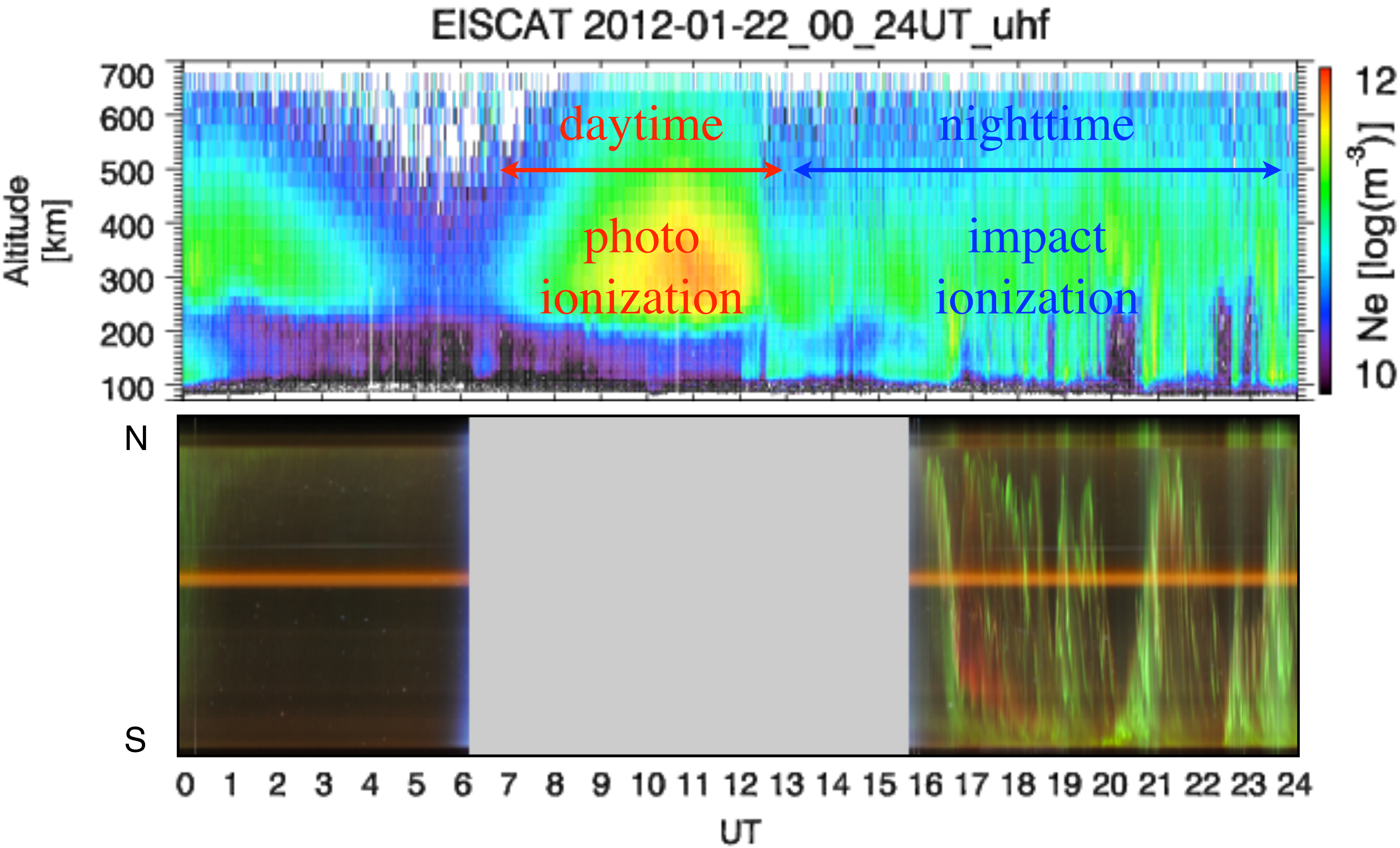
Date: Jan. 22, 2012

Check movie?

Hourly animation by clicking the time Daily animation (720*480pixel)



Check aurora data in Tromso on Jan 22, 2012



Let’s play with the EISCAT and Aurora data

- EISCAT:
  http://133.57.20.115/www/cgi-bin/eiscat.cgi

  EISCAT data are available from 1981 to 2015
  But, the operation of the radar is not continuous

- All-sky camera in Tromso:
  http://nordlys.nipr.ac.jp/acaurora/Tromso/html/backnumber.html

  Aurora data in Tromso are available only during winter
  Continuous operation of the camera has started in 2009

Outline

- Ionosphere

  Quick exercise: Browsing radar data from Norway

- Key ideas of GNSS

- Mechanism of ionospheric effects on GNSS

- Two major ionospheric impacts on GNSS

  1. Positioning error

     Quick exercise: Browsing GPS TEC data in US

  2. Scintillation effect

     Quick exercise: Browsing GPS scintillation data

Global Navigation Satellite Systems

GNSS: Global Navigation Satellite System

↳ GPS (USA), GLONASS (Russia) in full operation

↳ Galileo (EU), BeiDou II (China) will be fully operative

Regional Navigation Satellite System

↳ QZSS (Japan), BeiDou I (China), IRNSS (India)

Mission

Provide "precise" position and time not only for navigation of cars, airplanes and ships but also various social activities.

Key idea → Trilateration

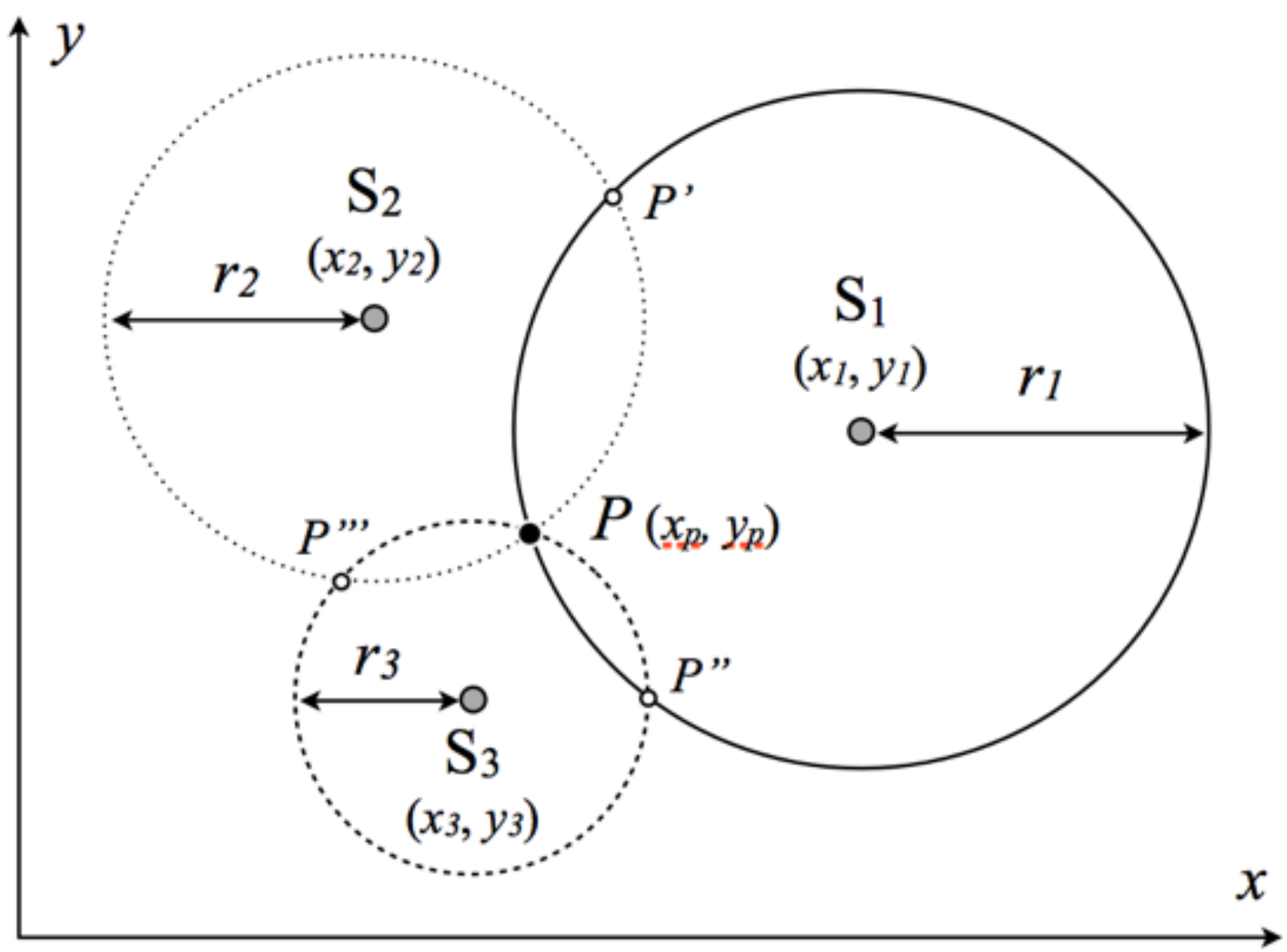
Concept of Satellite Navigation

Trilateration:
2D case

$$r_1^2 = (x_p - x_1)^2 + (y_p - y_1)^2$$

$$r_2^2 = (x_p - x_2)^2 + (y_p - y_2)^2$$

$$r_3^2 = (x_p - x_3)^2 + (y_p - y_3)^2$$



Unknown: x_p, and y_p
↳ equations are solvable.

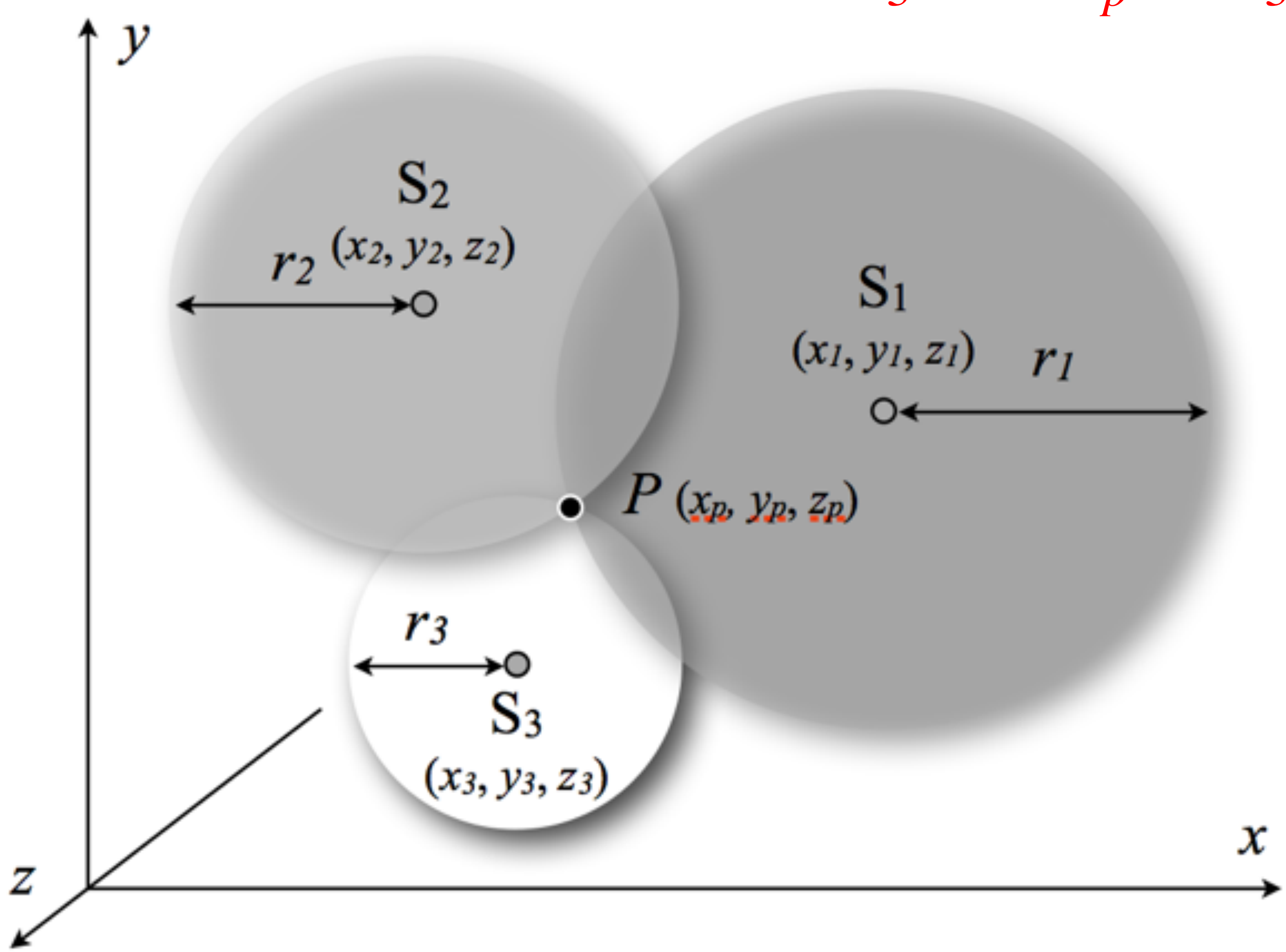
Concept of Satellite Navigation

Trilateration:
3D case
circles → spheres

$$r_1^2 = (x_p - x_1)^2 + (y_p - y_1)^2 + (z_p - z_1)^2$$

$$r_2^2 = (x_p - x_2)^2 + (y_p - y_2)^2 + (z_p - z_2)^2$$

$$r_3^2 = (x_p - x_3)^2 + (y_p - y_3)^2 + (z_p - z_3)^2$$

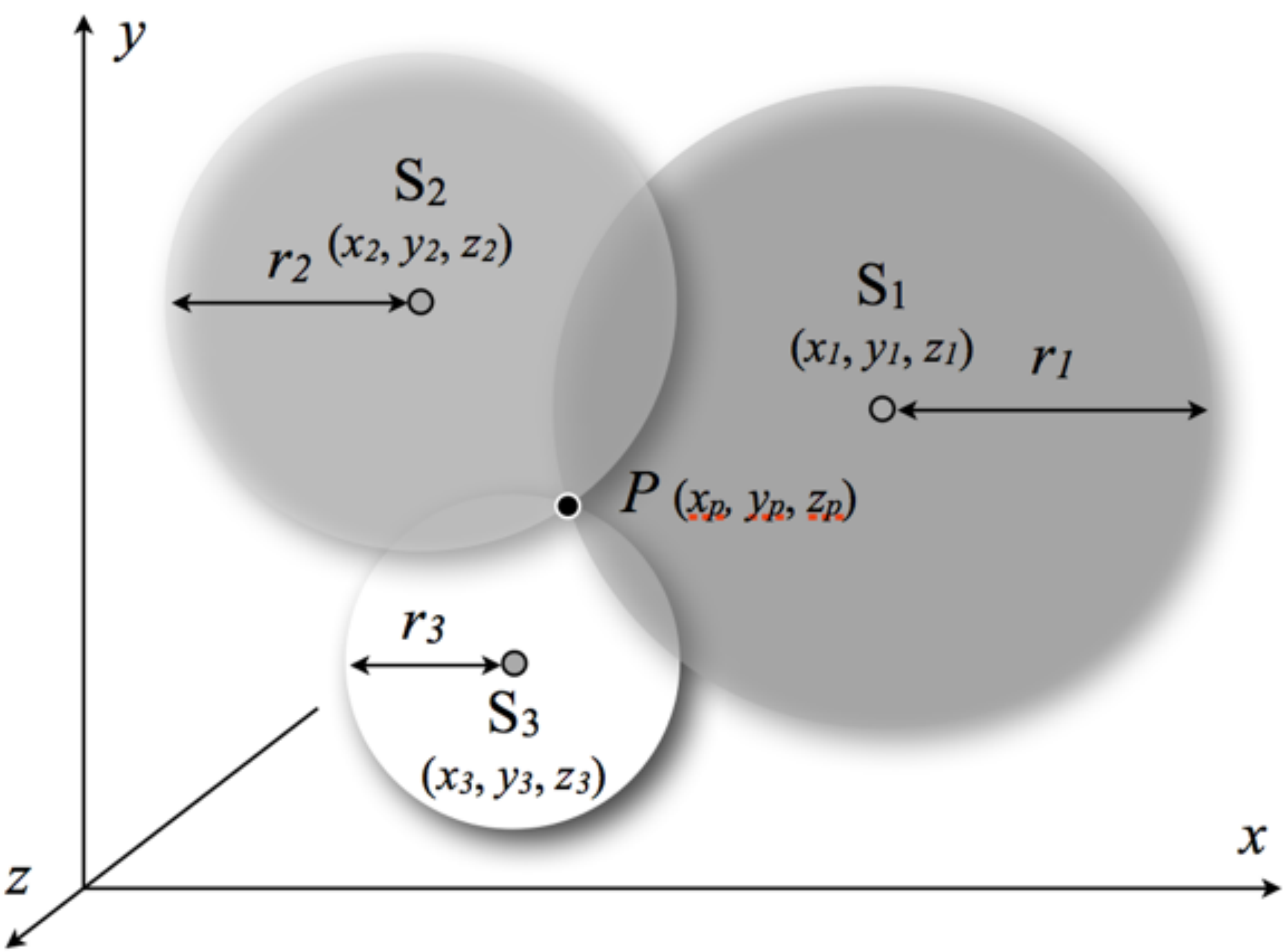


Unknown: x_p, y_p and z_p
↳ equations are solvable.

Concept of Satellite Navigation

Trilateration requires

1. To know the precise positions of base stations
2. To observe the distances from at least 3 base stations



Basic Parameters of GNSS Satellite

Space System

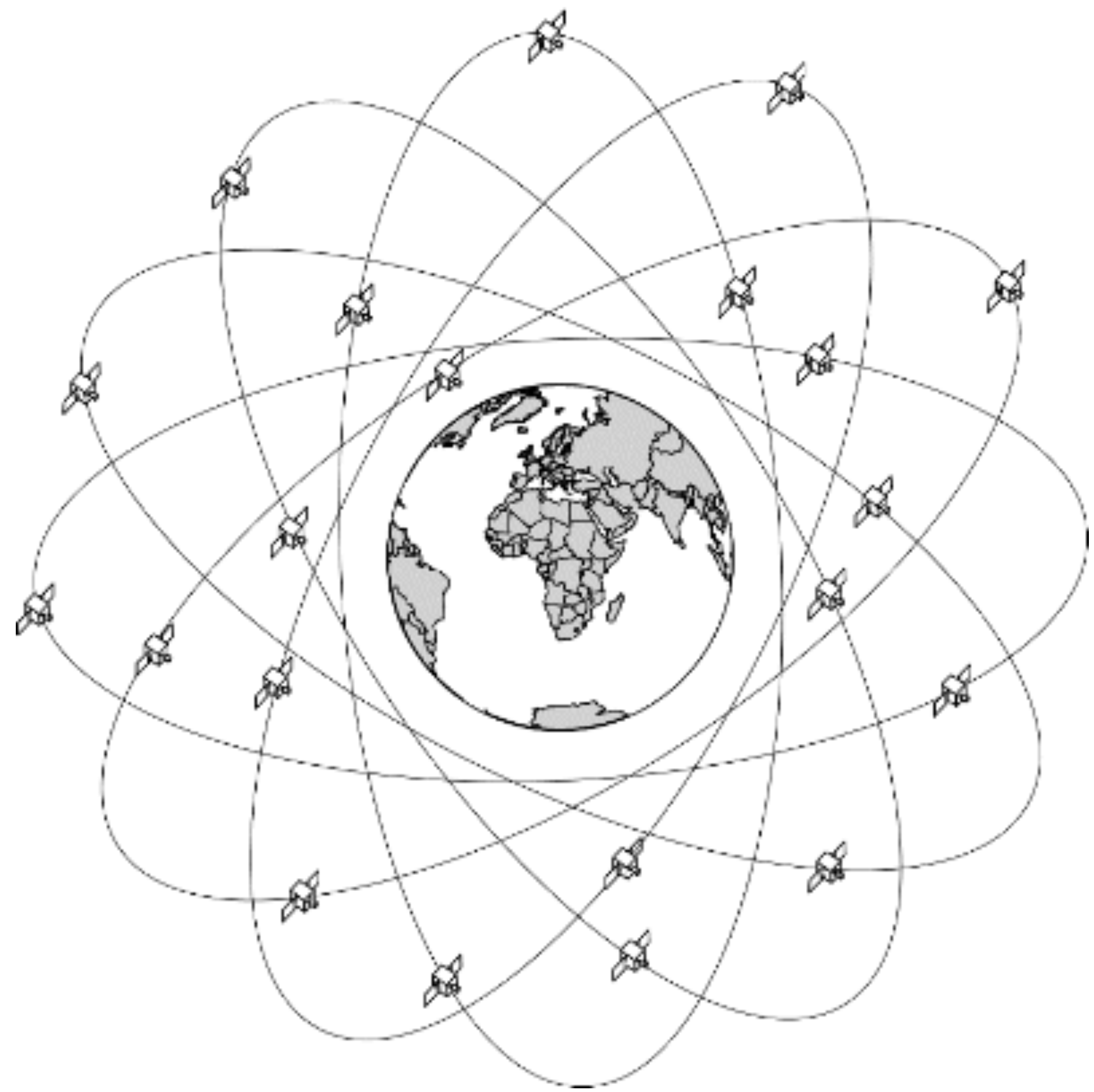
Summary of the GPS system in space

- Altitude:20,200 km
- Orbital period: 11 h 58 m

- 6 orbital planes: inclination = 55°
- 4 satellites on each orbital plane

→ the total number of satellites

$$= 4 \times 6 + 8 \text{ (spare)} = 32$$

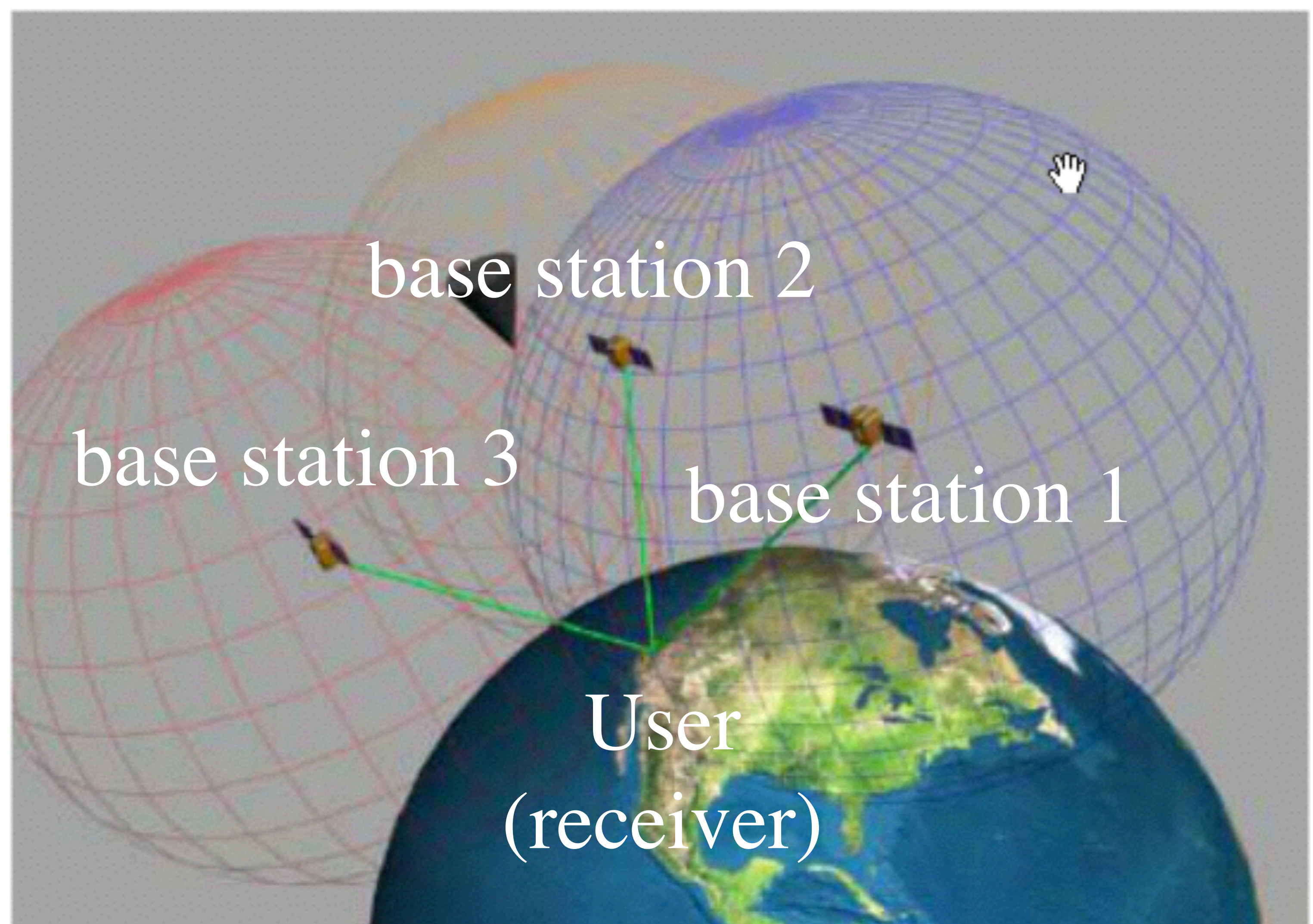


Concept of Satellite Navigation

Satellite-based 3D Trilateration → Base stations: up in the space
(exact position is known)

Q: How do we measure the distances to the satellites (base stations)?

A: Use radio waves always transmitted from the satellite, and estimate the travel time of the radio waves from the satellite to the ground.

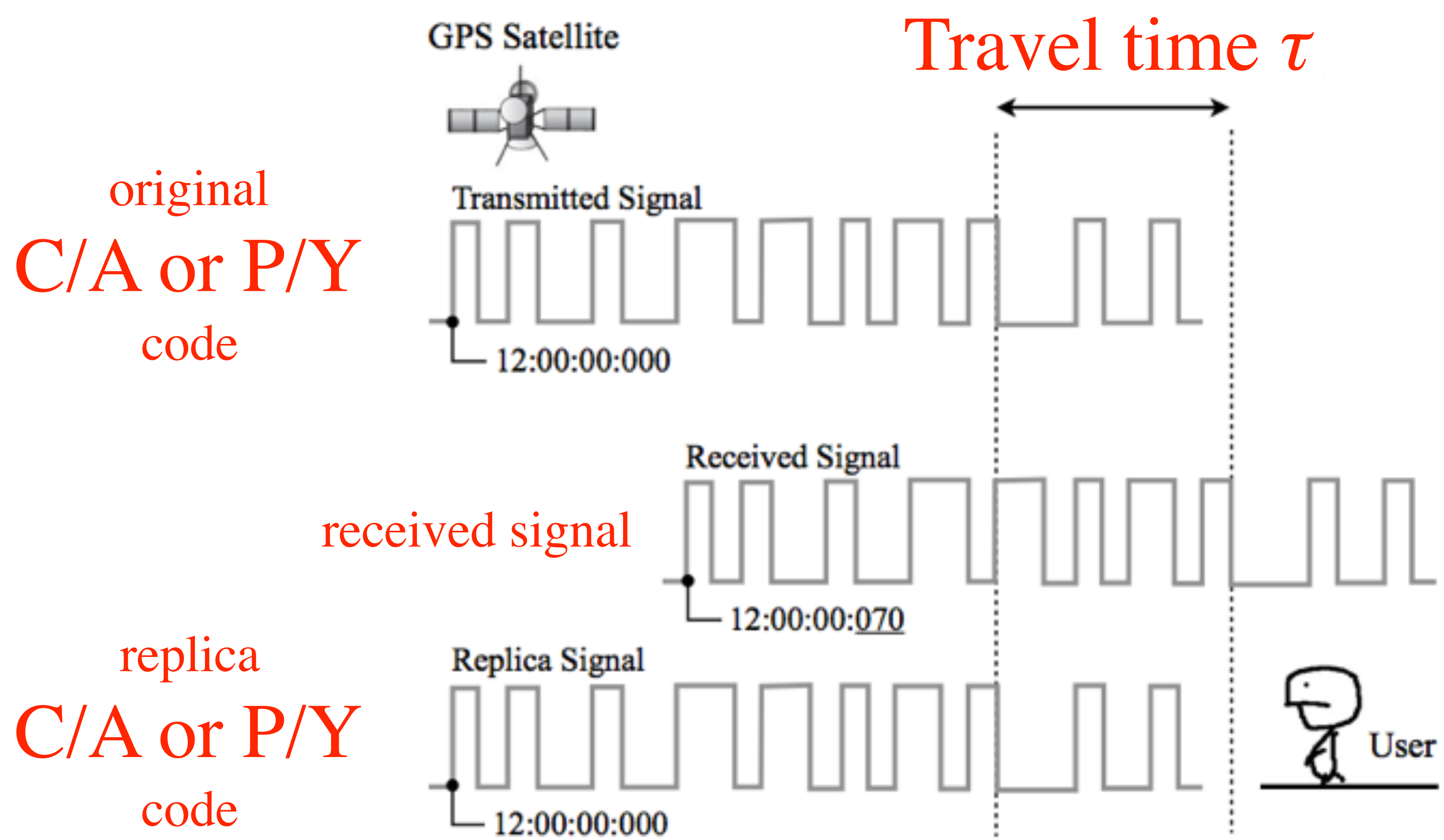


Basic Parameters of GNSS Satellite

Derivation of Transit Time τ

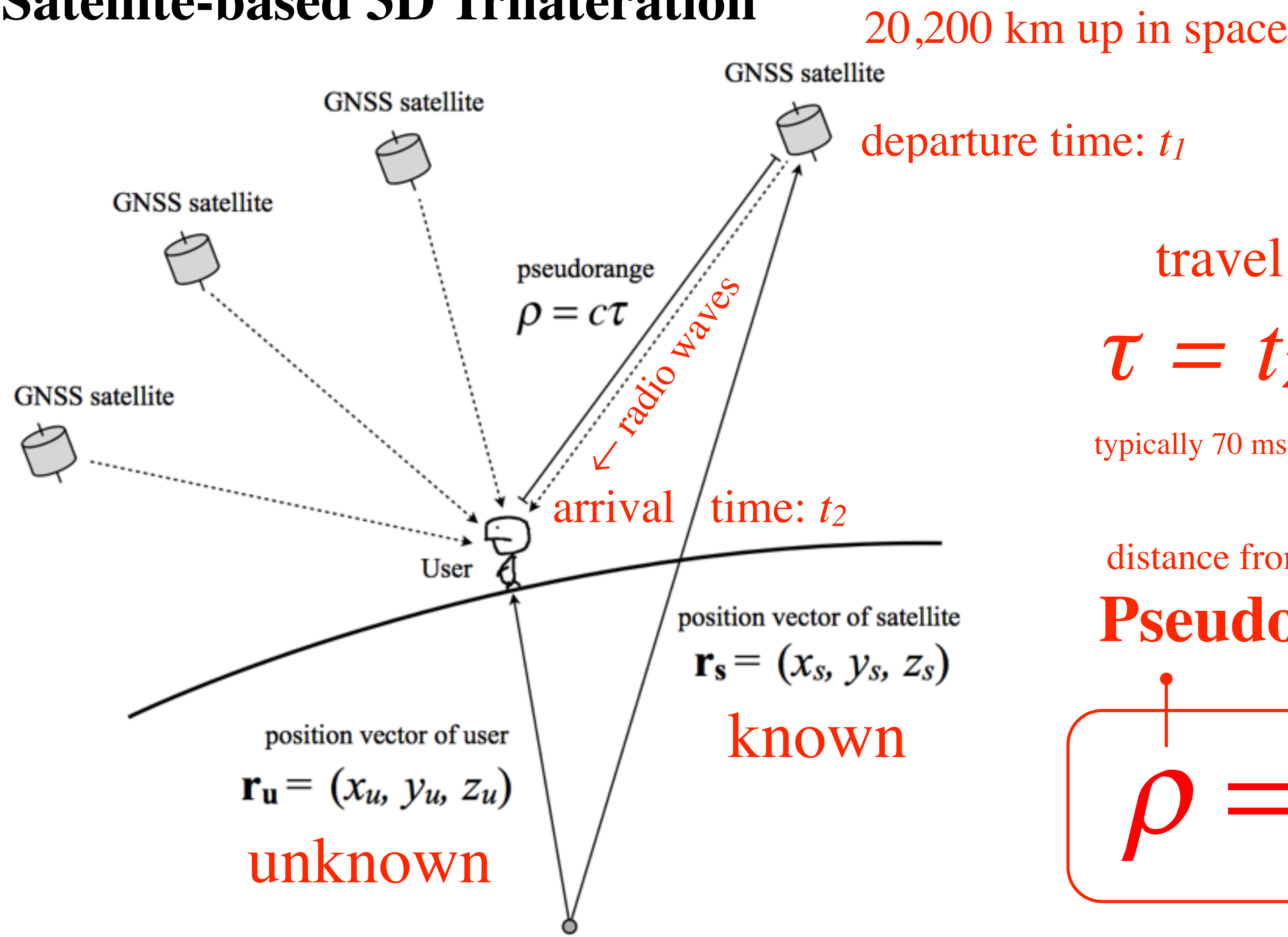
Q. How do we measure the travel time τ ?

A. The travel time τ is derived by calculating a correlation between received coded signal and its replica at the receiver.



Concept of Satellite Navigation

Satellite-based 3D Trilateration



travel time

$$\tau = t_2 - t_1$$

typically 70 ms for GPS case

distance from satellites

Pseudorange

$$\boxed{\rho = c\tau}$$

Outline

- Ionosphere

  Quick exercise: Browsing radar data from Norway

- Key ideas of GNSS

- Mechanism of ionospheric effects on GNSS

- Two major ionospheric impacts on GNSS

  1. Positioning error

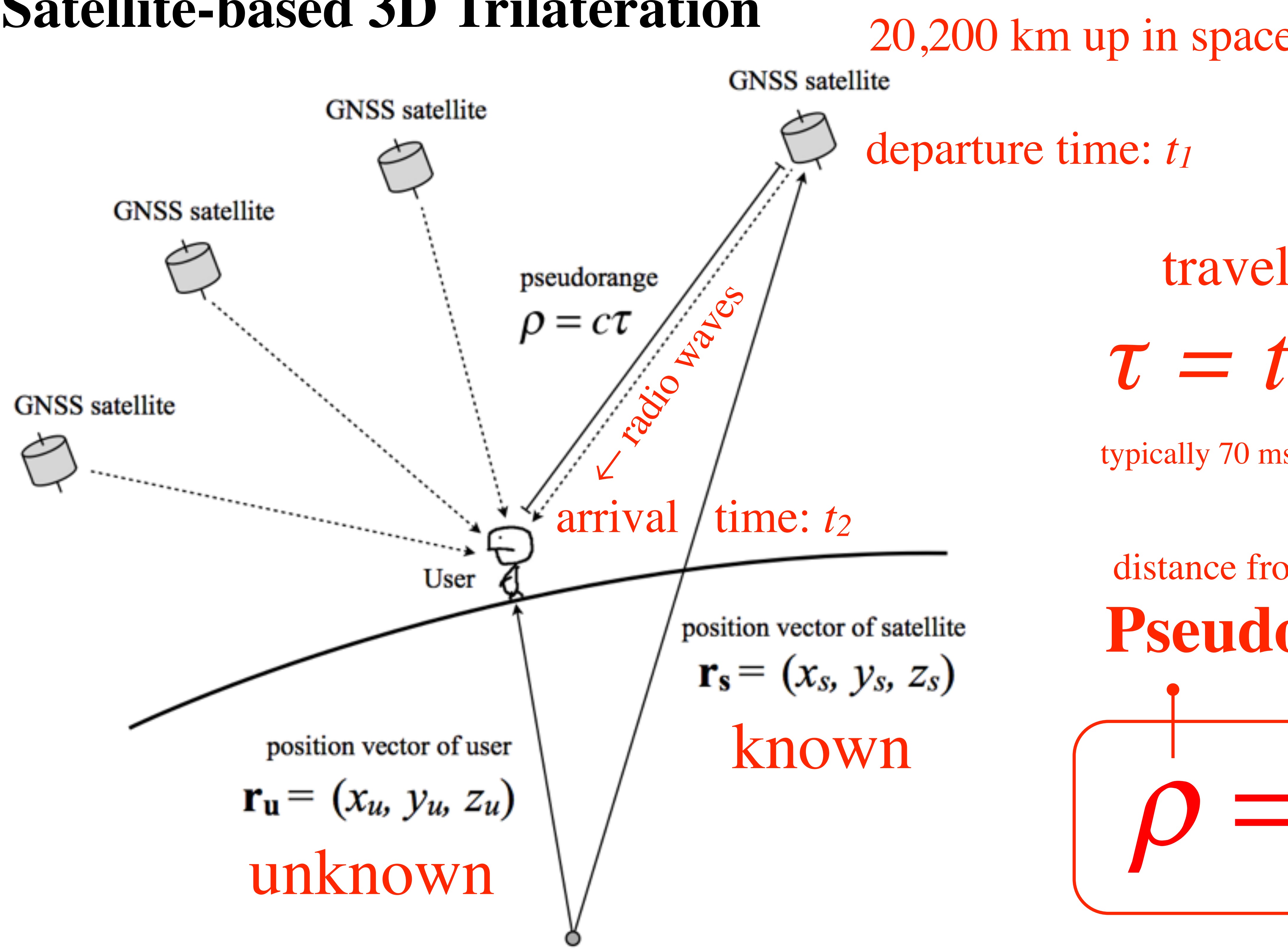
     Quick exercise: Browsing GPS TEC data in US

  2. Scintillation effect

     Quick exercise: Browsing GPS scintillation data

Concept of Satellite Navigation

Satellite-based 3D Trilateration



travel time

$$\tau = t_2 - t_1$$

typically 70 ms for GPS case

distance from satellites

Pseudorange

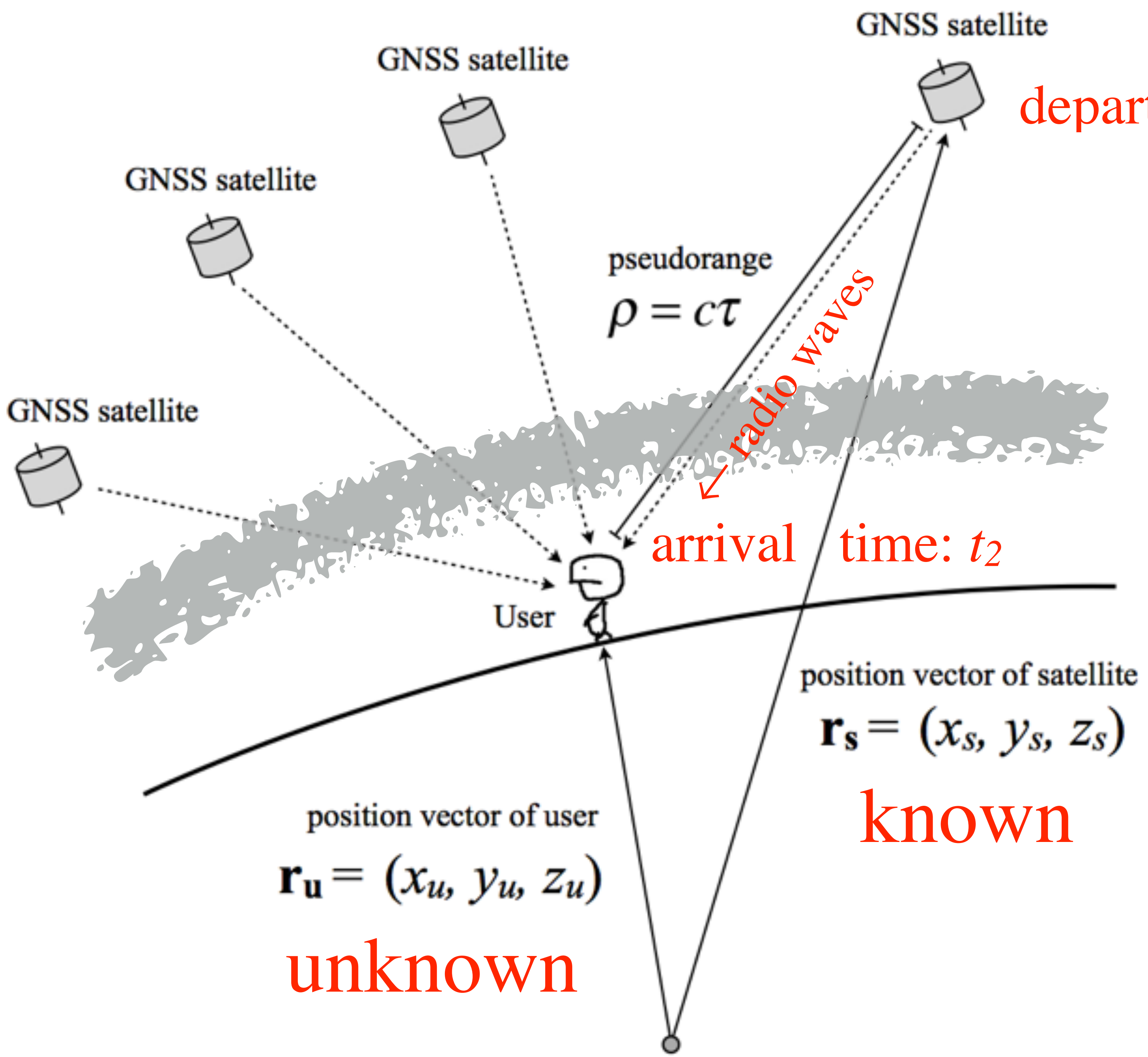
$$\boxed{\rho = c\tau}$$

Concept of Satellite Navigation

Satellite-based 3D Trilateration

20,200 km up in space

departure time: t_1



travel time

$$\tau = t_2 - t_1$$

typically 70 ms for GPS case

distance from satellites

Pseudorange

$$\boxed{\rho = c\tau}$$

Phase Velocity and Group Velocity

Refractive Index:

Propagation of light (i.e., radio waves) in a medium depends on the refractive index n, which is defined as

$$n = \frac{c}{v}$$

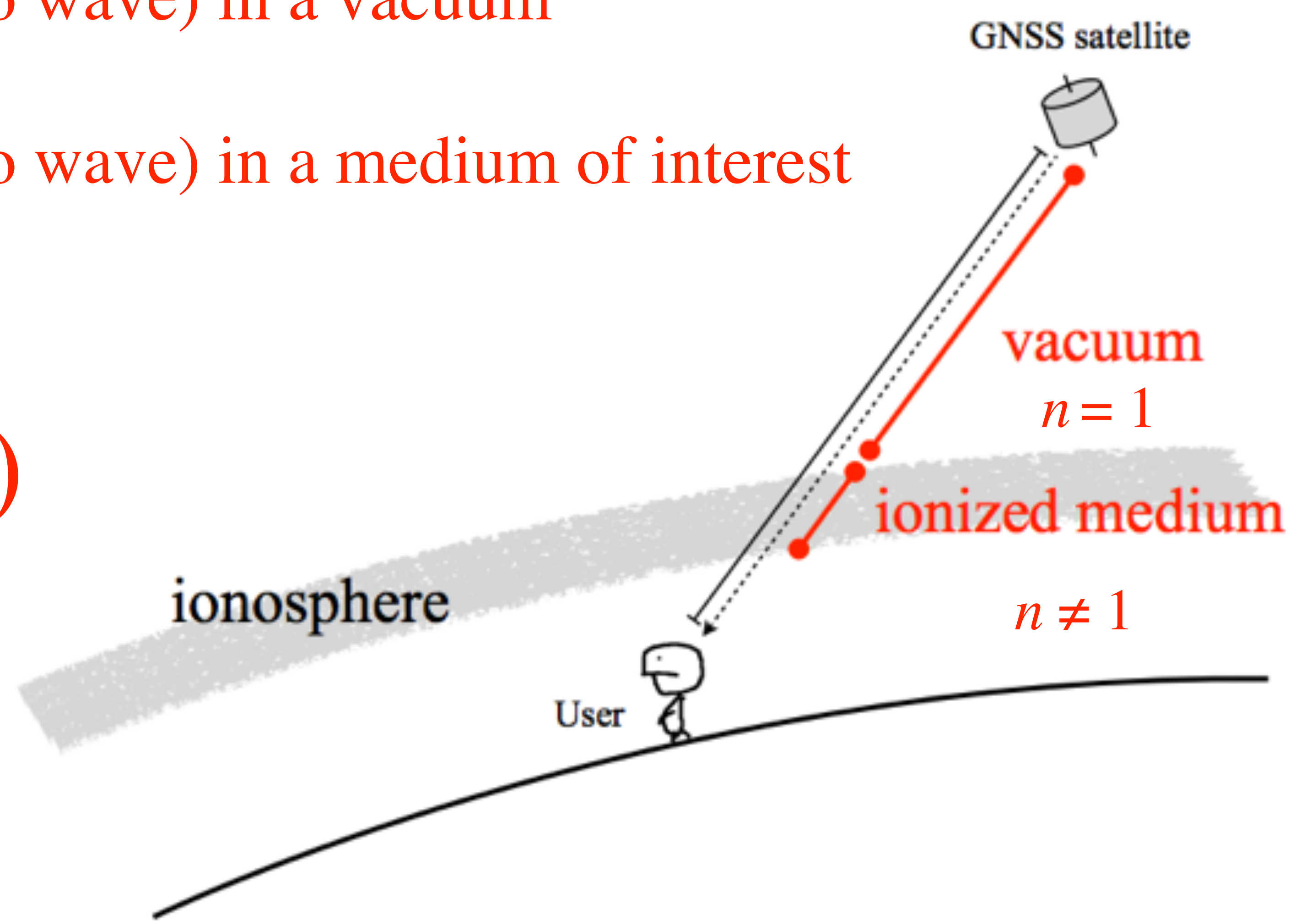
c → speed of light (radio wave) in a vacuum

v → speed of light (radio wave) in a medium of interest

$n = 1: v = c$ (vacuum)

$n < 1: v > c$ (faster)

$n > 1: v < c$ (slower)



Impact of Ionosphere on GNSS

$$n = \frac{c}{v}$$

Refractive Index in Ionized Medium

Refractive index for coded GNSS signal in the ionosphere:

10^{12} m^{-3} in the ionosphere

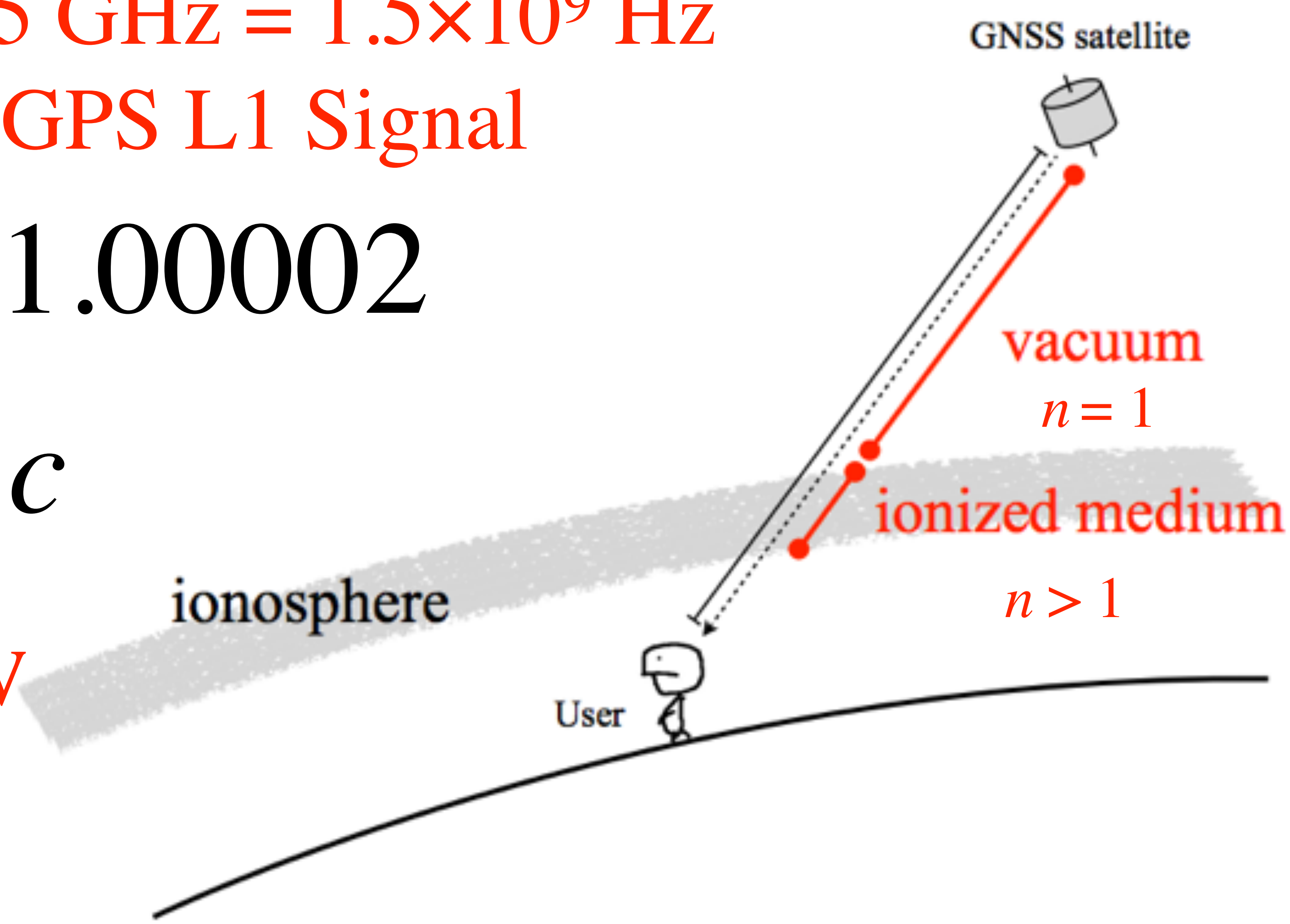
$$n = 1 + \frac{40.3 n_e}{f^2}$$

~1.5 GHz = 1.5×10^{9} Hz
for GPS L1 Signal

$$\approx 1 + 2.0 \times 10^{-5} = 1.00002$$

$$\rightarrow \; v \approx 0.99998 \times c$$

Coded GPS signals slow
down in the ionosphere



Impact of Ionosphere on GNSS

Possible Impact on GNSS

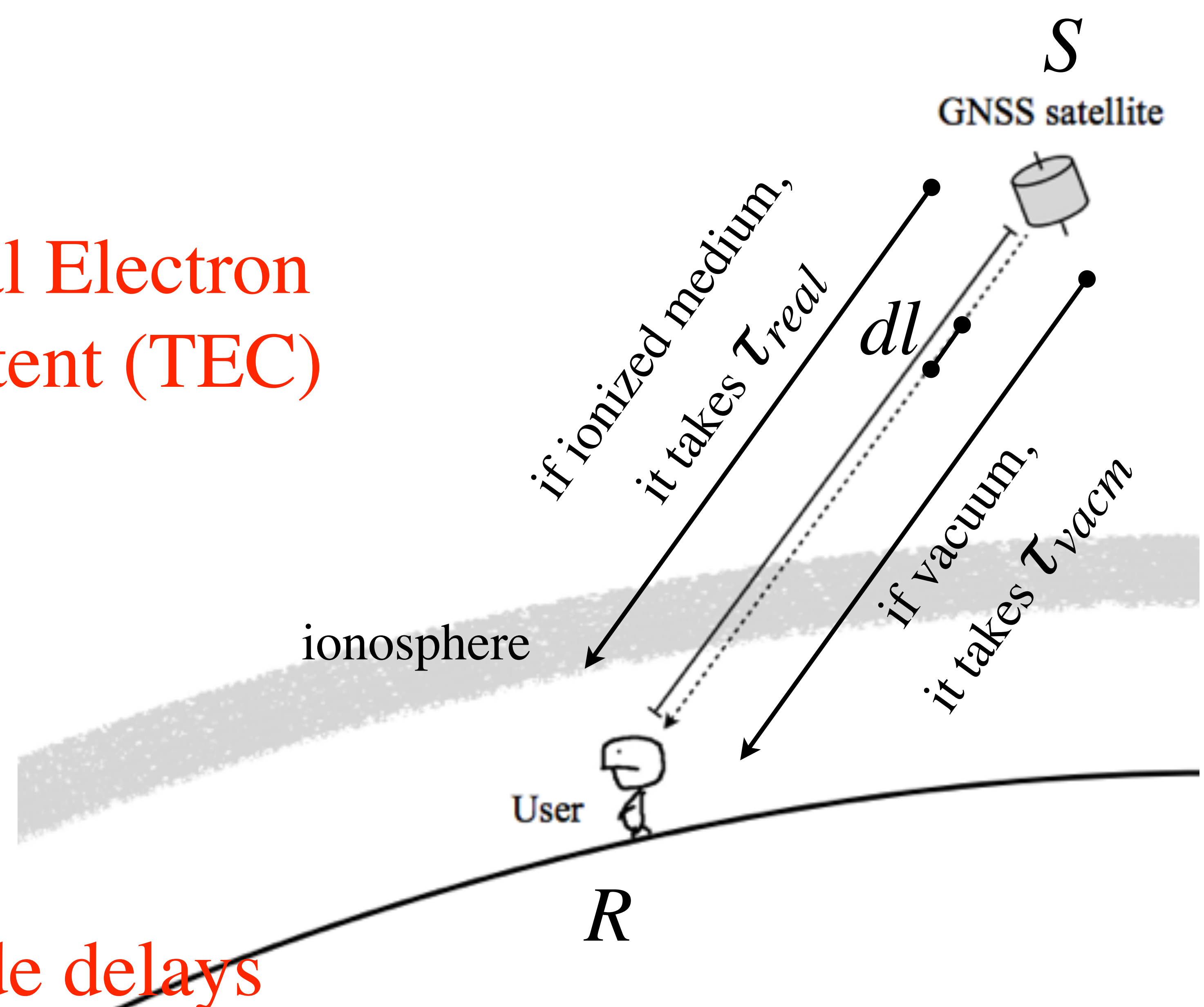
The delay of the coded GNSS signal is ...

$$
\begin{aligned}
\Delta\tau &= \frac{1}{c}\int_S^R \frac{40.3 n_e(l)}{f^2} dl \\
&= \frac{40.3}{cf^2}\boxed{\int_S^R n_e(l) dl} \\
&= +\frac{40.3\text{TEC}}{cf^2} \qquad (16)
\end{aligned}
$$

Total Electron Content (TEC)

Coded signals always delay

→ More electrons, larger code delays



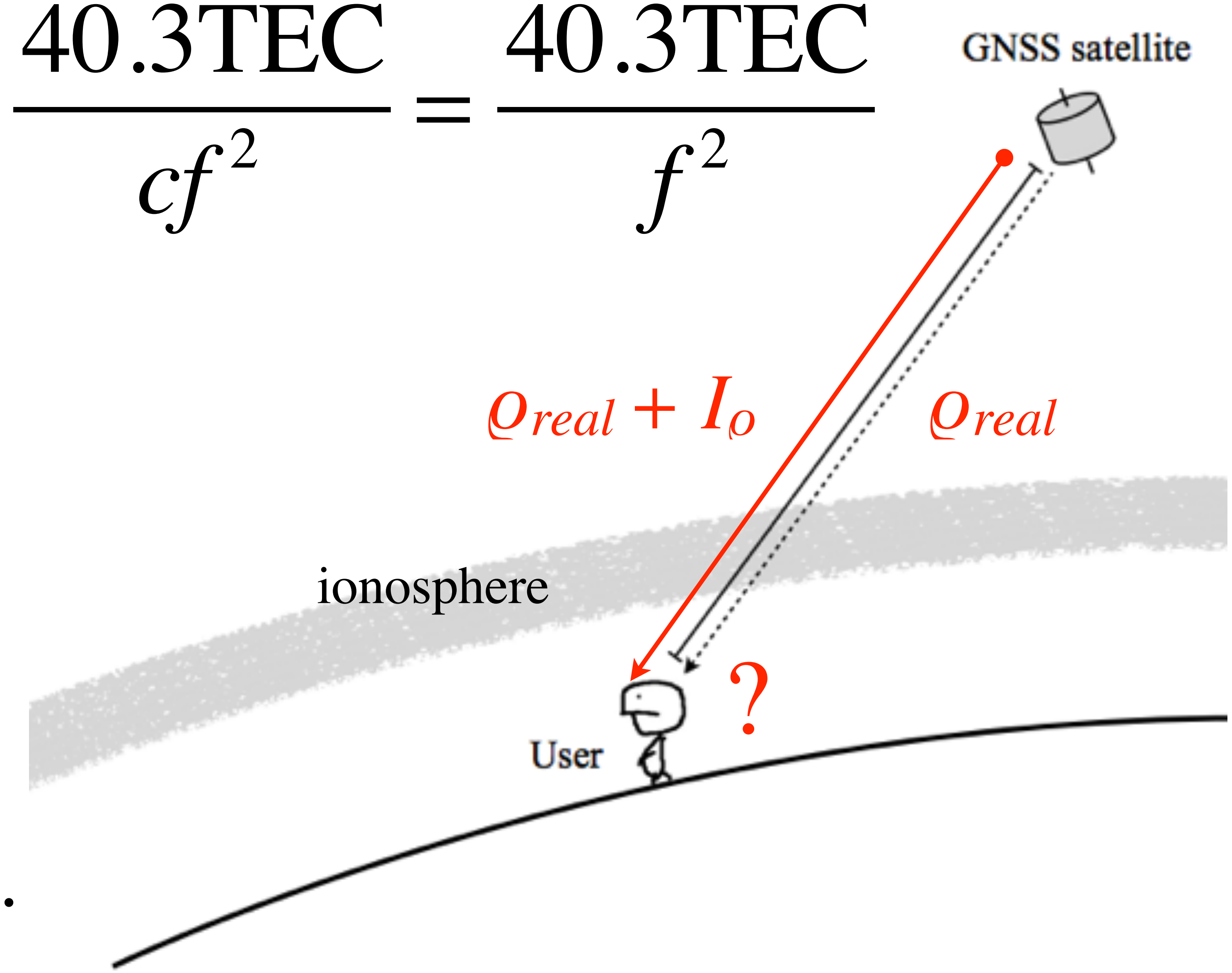
Impact of Ionosphere on GNSS

Possible Impact on GNSS

The delay in travel time corresponds to an error in pseudorange:

$$I_\rho = c \times \Delta\tau = c \times \frac{40.3\mathrm{TEC}}{cf^2} = \frac{40.3\mathrm{TEC}}{f^2}$$

Error in pseudorange ϱ



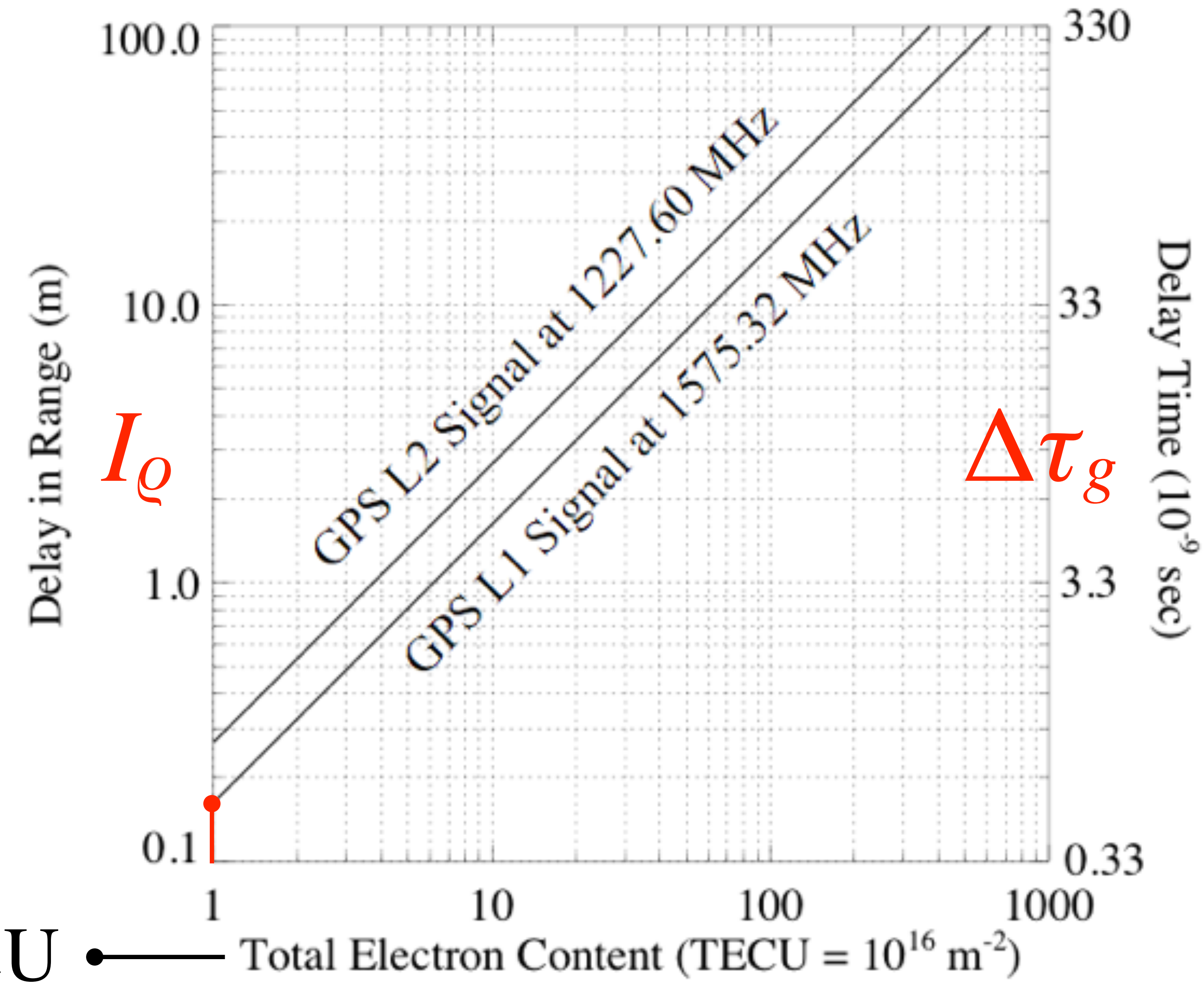
When the electron density in the ionosphere increases, that is TEC increases, pseudorange is overestimated.

Impact of Ionosphere on GNSS

Possible Impact on GNSS

1 TECU → 16 cm error in pseudorange

$$I_\rho = \frac{40.3TEC}{f^2}$$



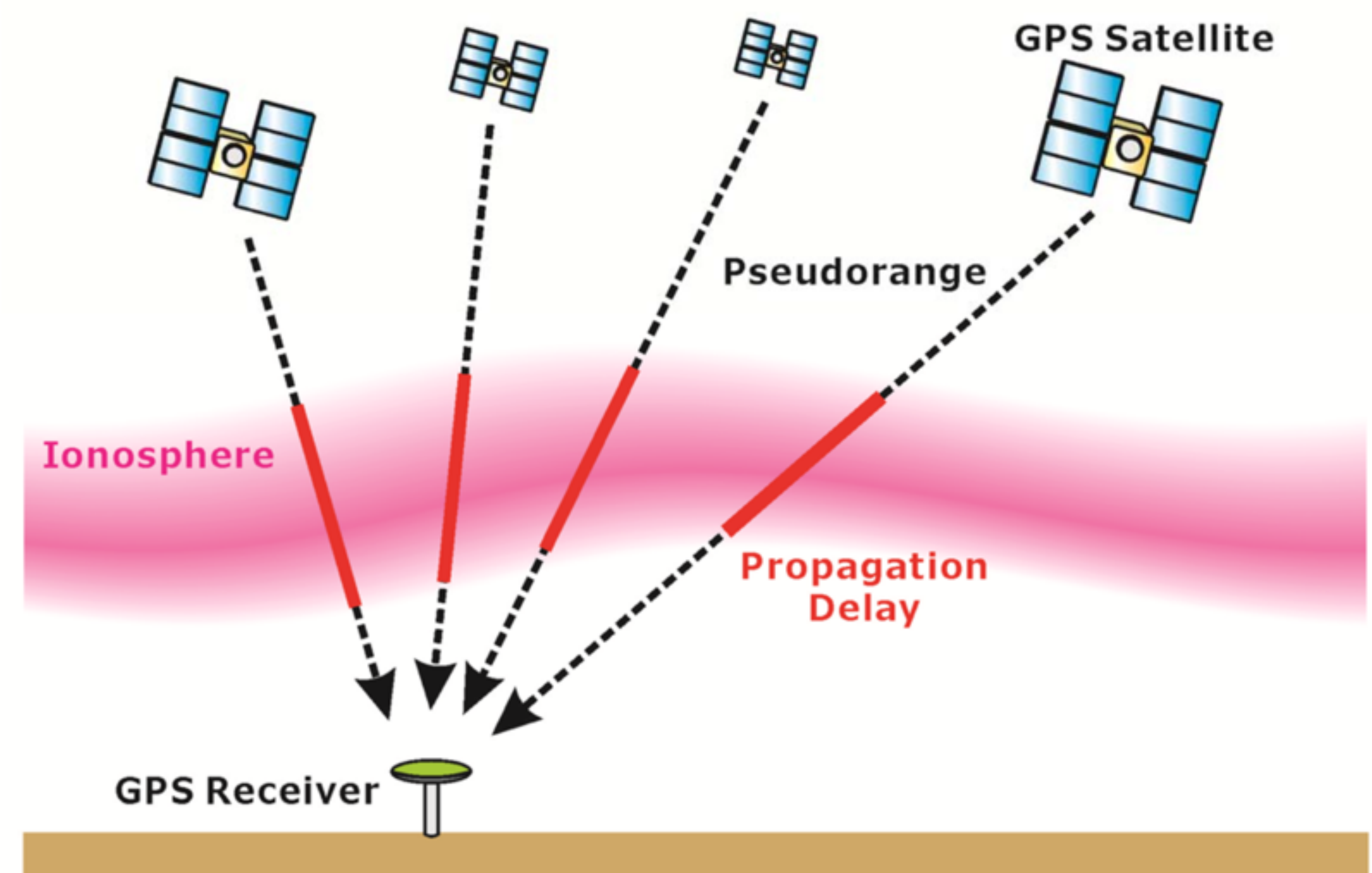
TEC in unit of TECU

GPS Positioning Error due to Ionosphere

Ionospheric effect on GNSS

$$I_\rho = \frac{40.3\,TEC}{f^2}$$

1 TECU = 16 cm



Outline

- Ionosphere

  Quick exercise: Browsing radar data from Norway

- Key ideas of GNSS

- Mechanism of ionospheric effects on GNSS

- Two major ionospheric impacts on GNSS

  1. Positioning error

     Quick exercise: Browsing GPS TEC data in US

  2. Scintillation effect

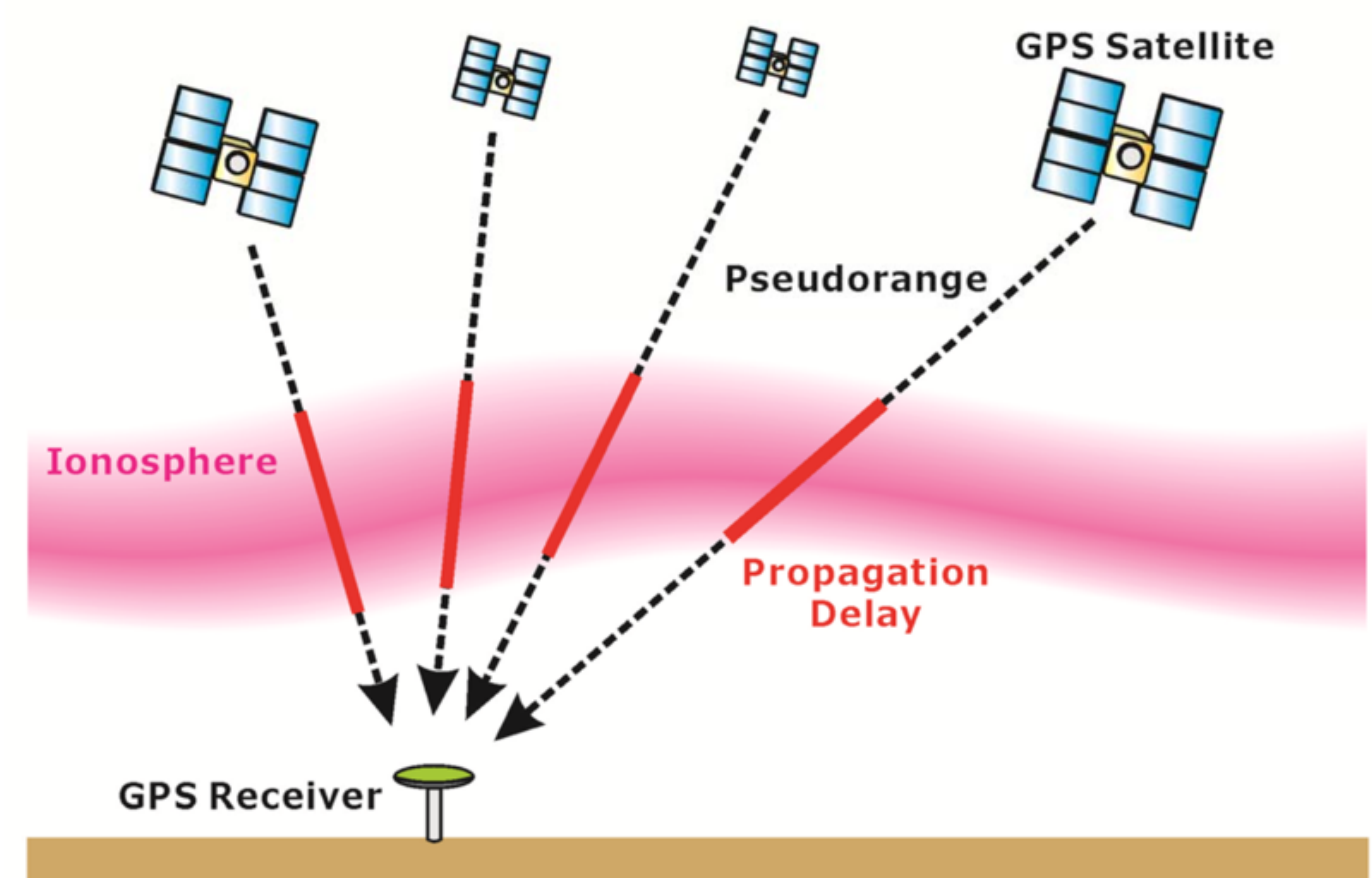
     Quick exercise: Browsing GPS scintillation data

GPS Positioning Error due to Ionosphere

Ionospheric effect on GNSS – 1

$$I_\rho = \frac{40.3\text{TEC}}{f^2}$$

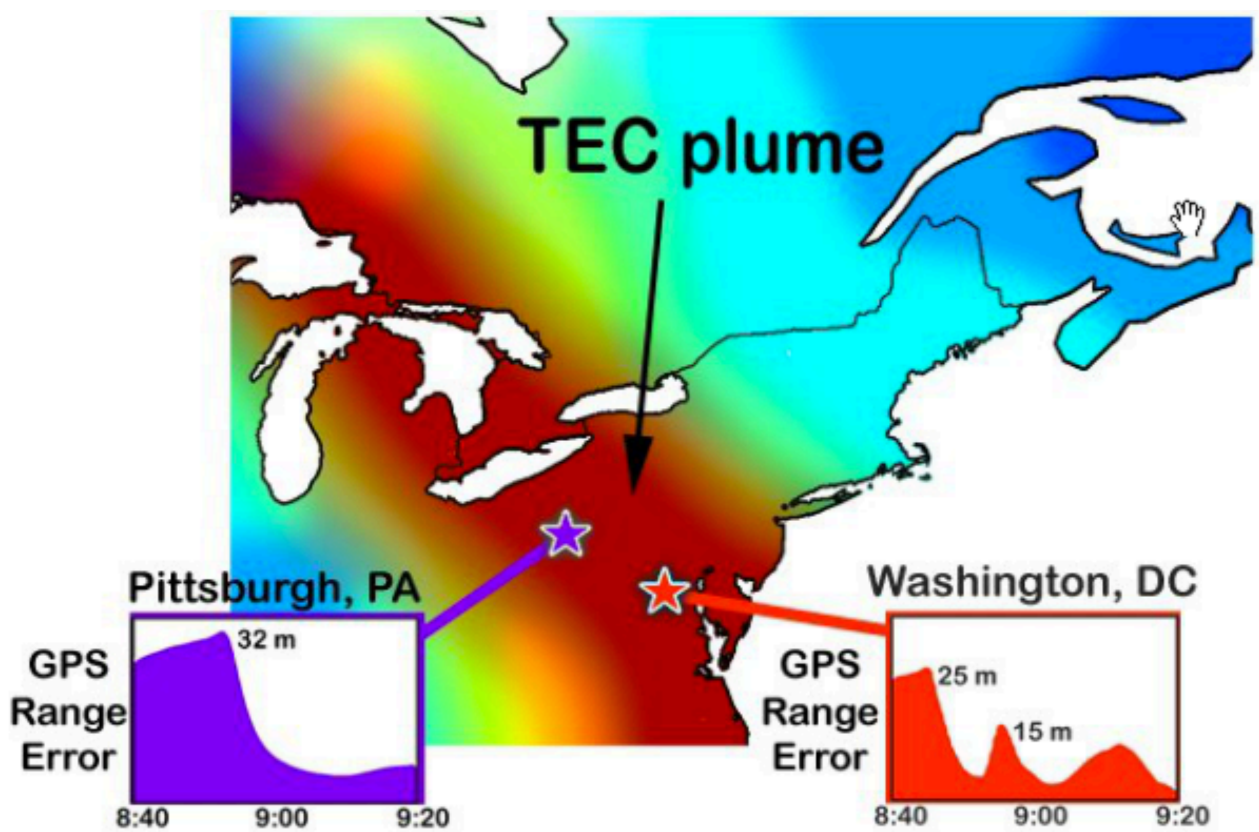
1 TECU = 16 cm



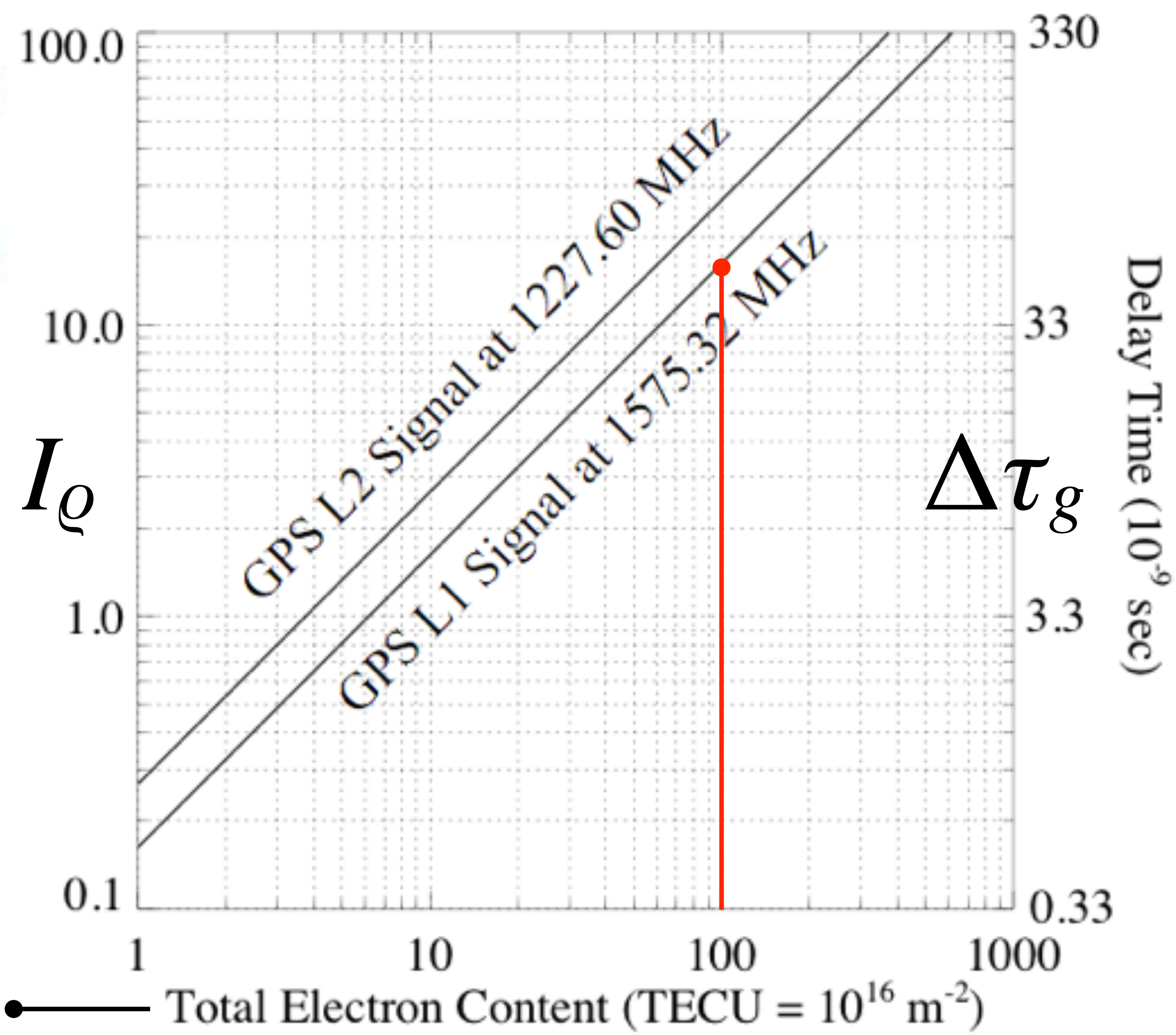
Impact of Ionosphere on GNSS

Possible Impact on GNSS

100 TECU → over 10 m error in pseudorange!



Coster et al., 2010

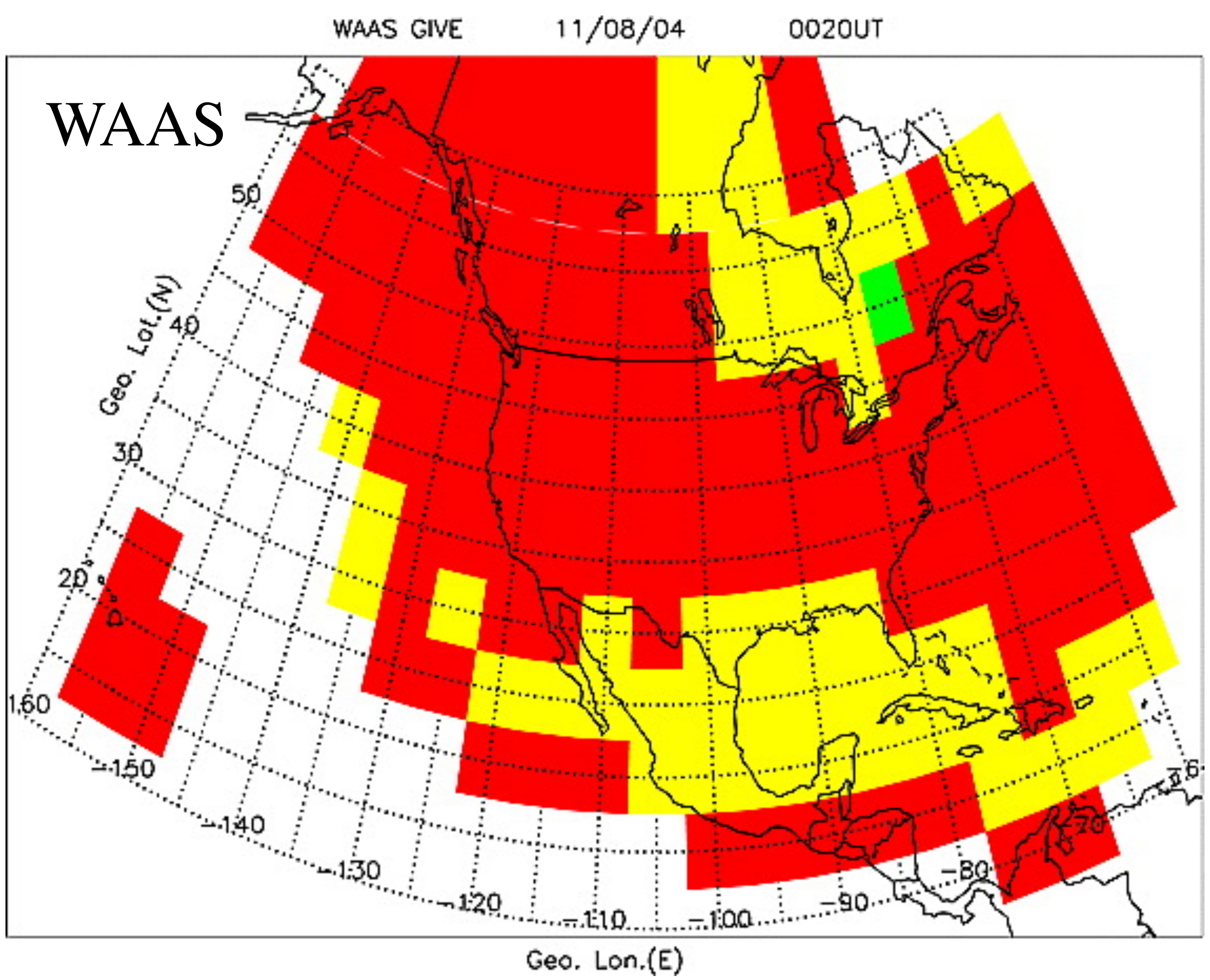


TEC in unit of TECU

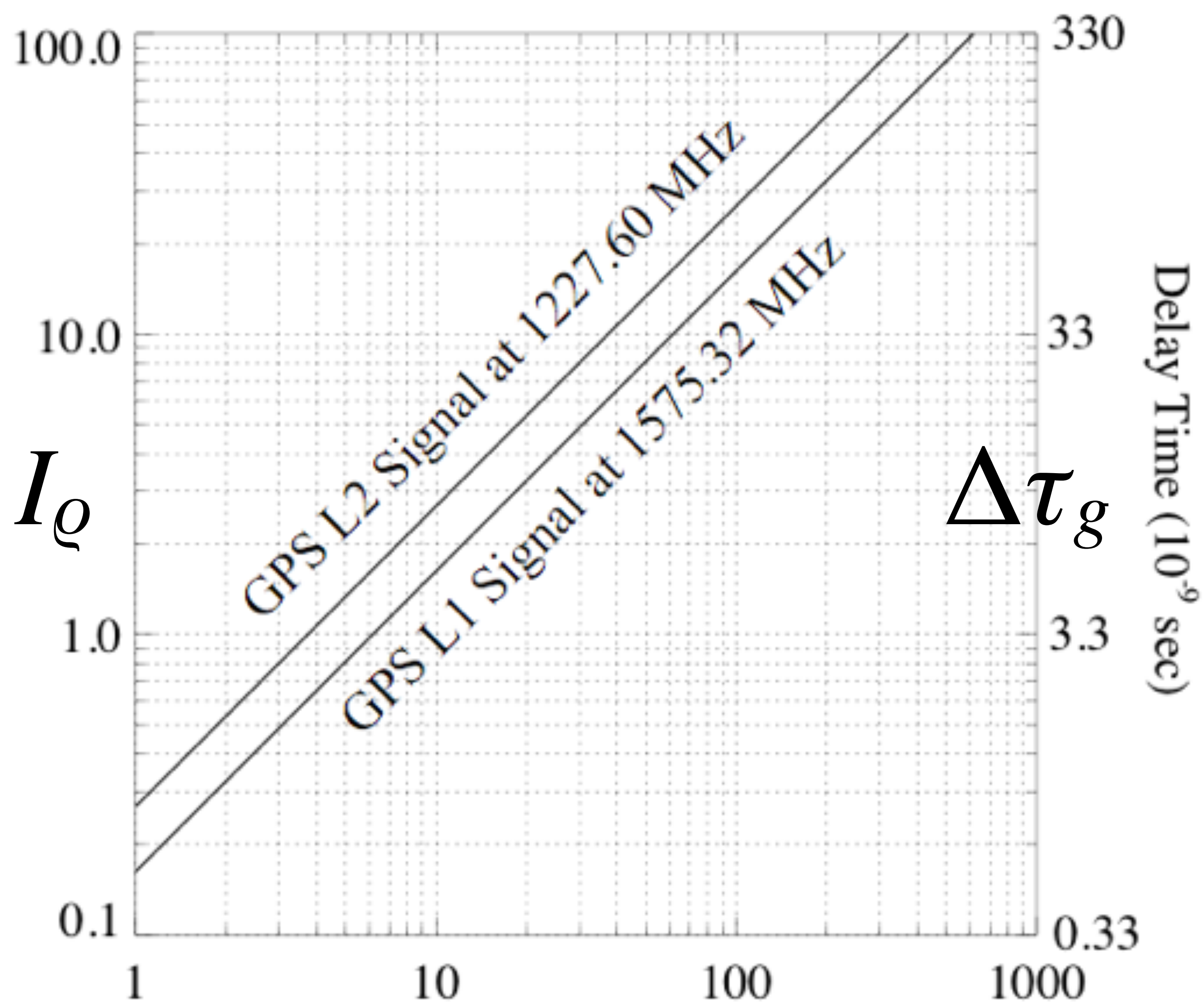
Impact of Ionosphere on GNSS

Possible Impact on GNSS

100 TECU → over 10 m error in pseudorange!



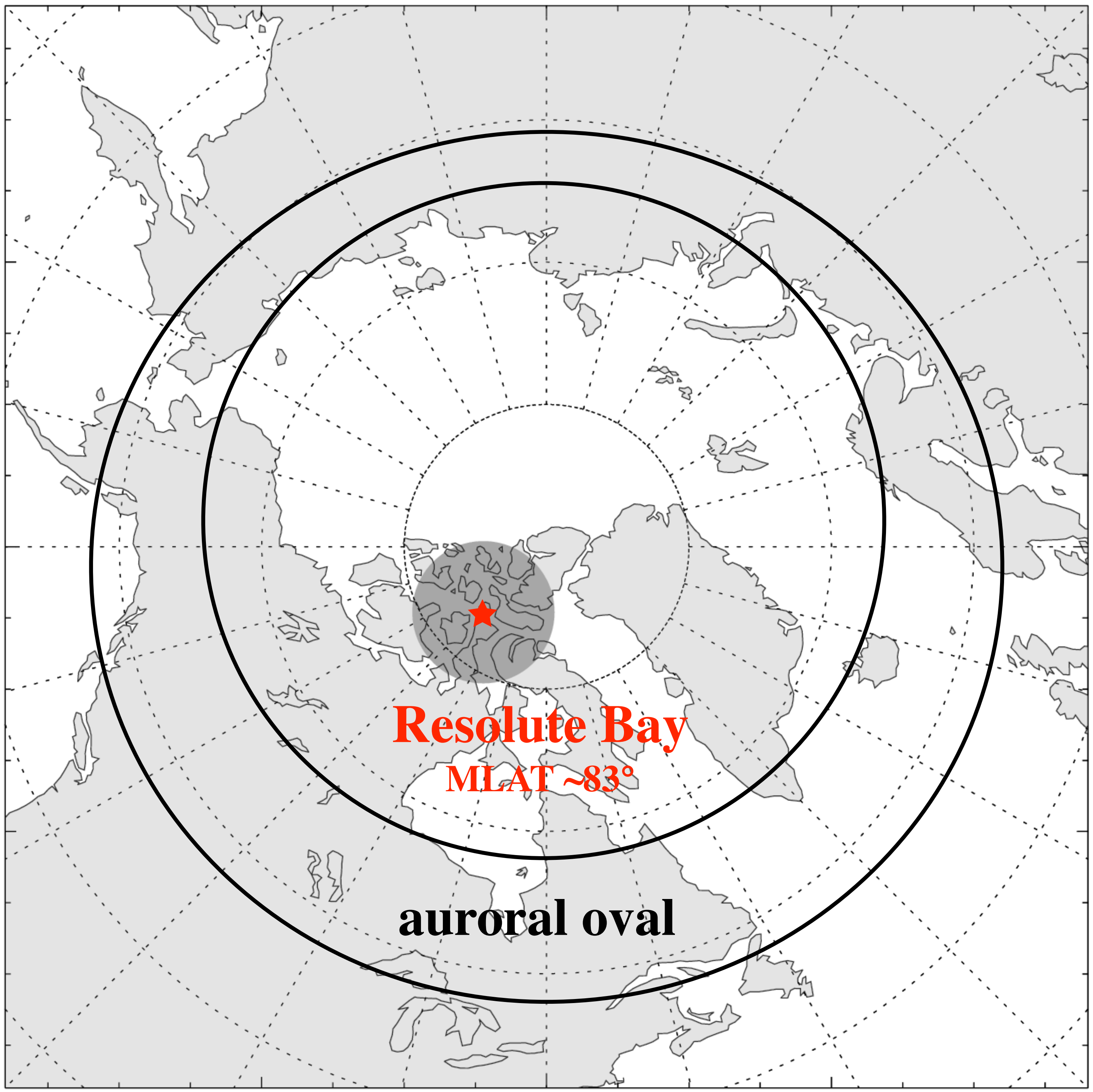
Basu et al., 2008



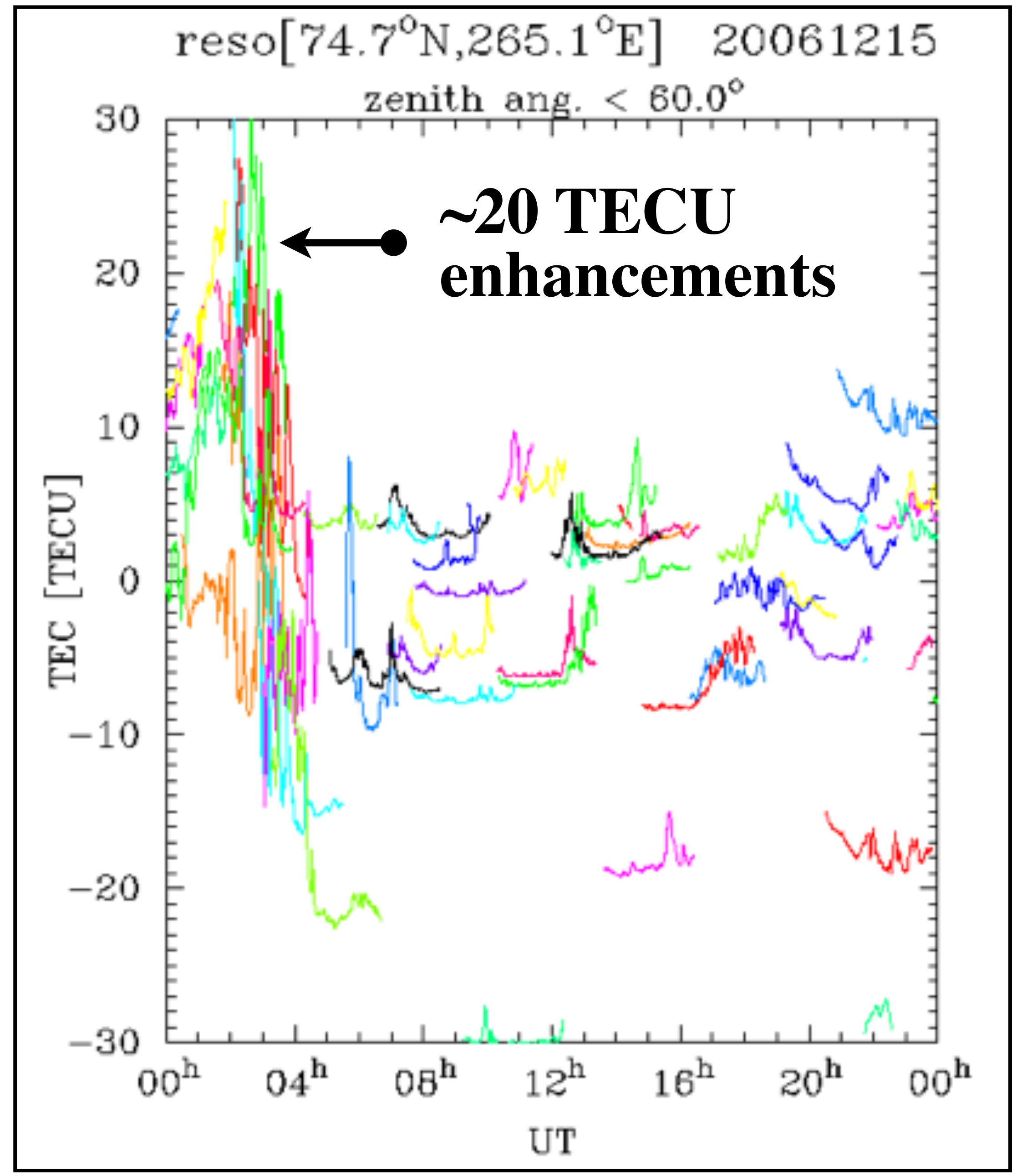
TEC in unit of TECU

TEC Enhancement in the Polar Region

A magnetic storm in 2006



TEC data from Resolute Bay



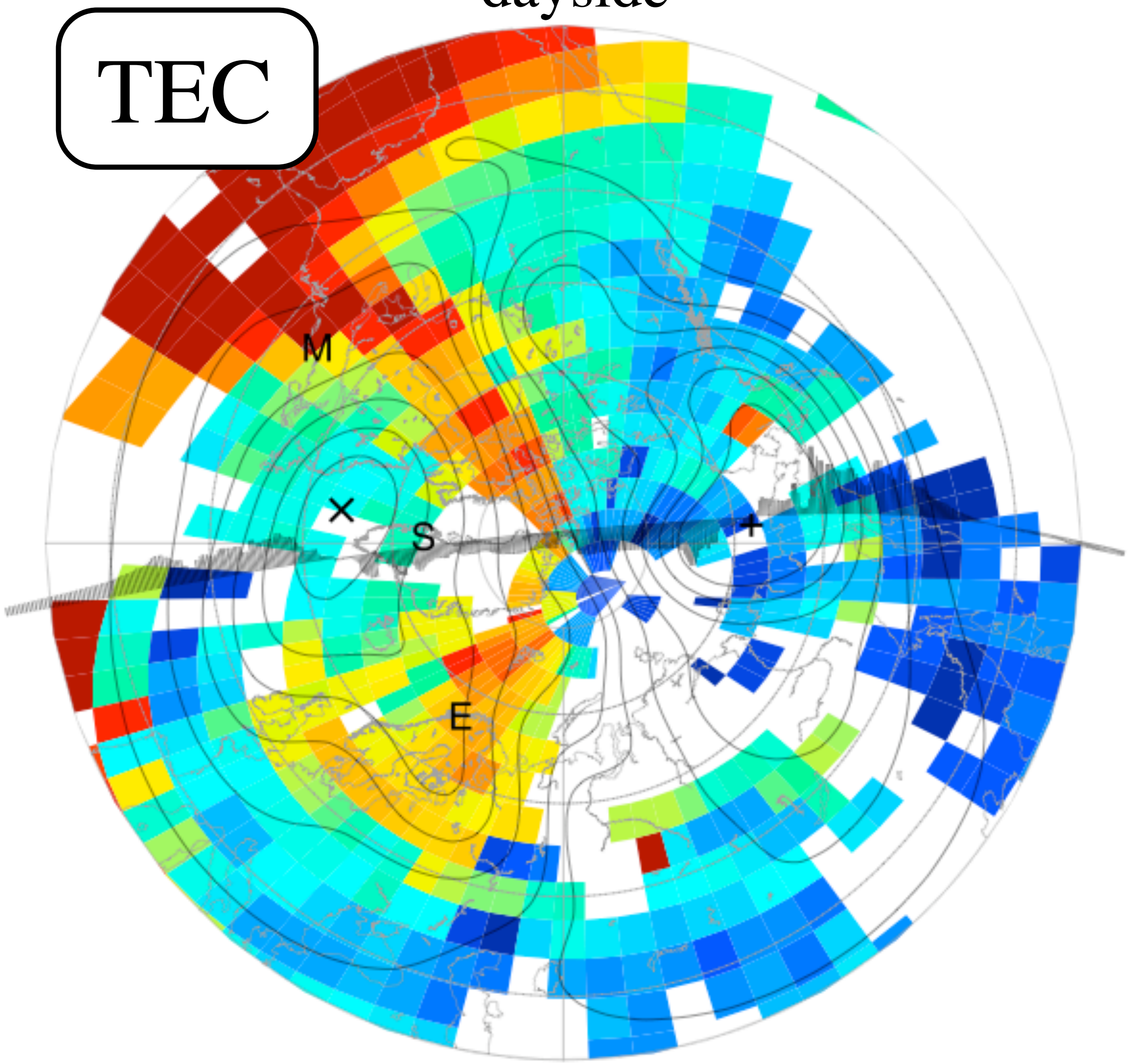
December 15, 2006

TEC Enhancement in the Polar Region

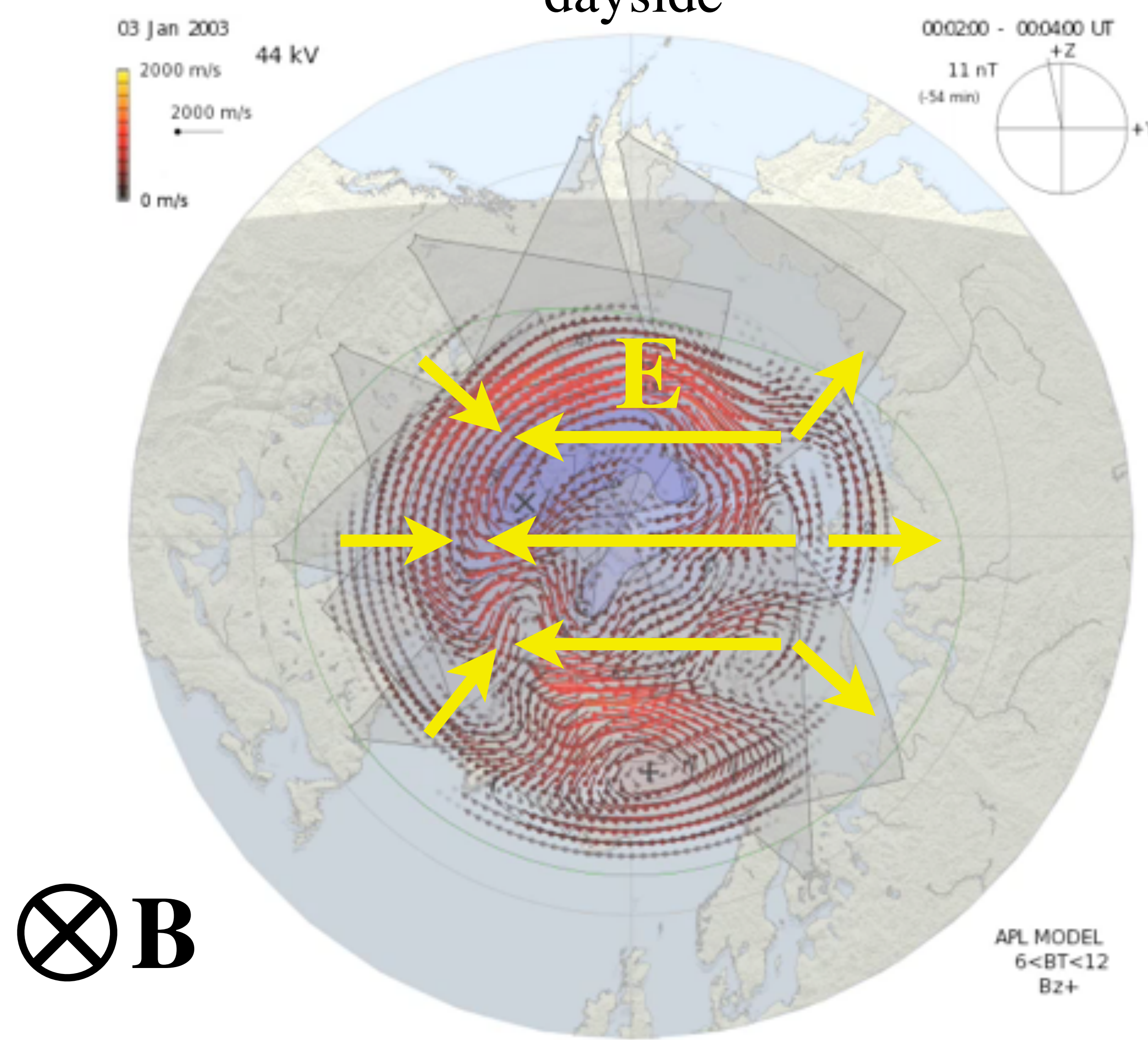
Plasma motion in the high-latitude ionosphere - F region:

E×B drift: $\mathbf{v} = \dfrac{\mathbf{E} \times \mathbf{B}}{B^2}$

dayside



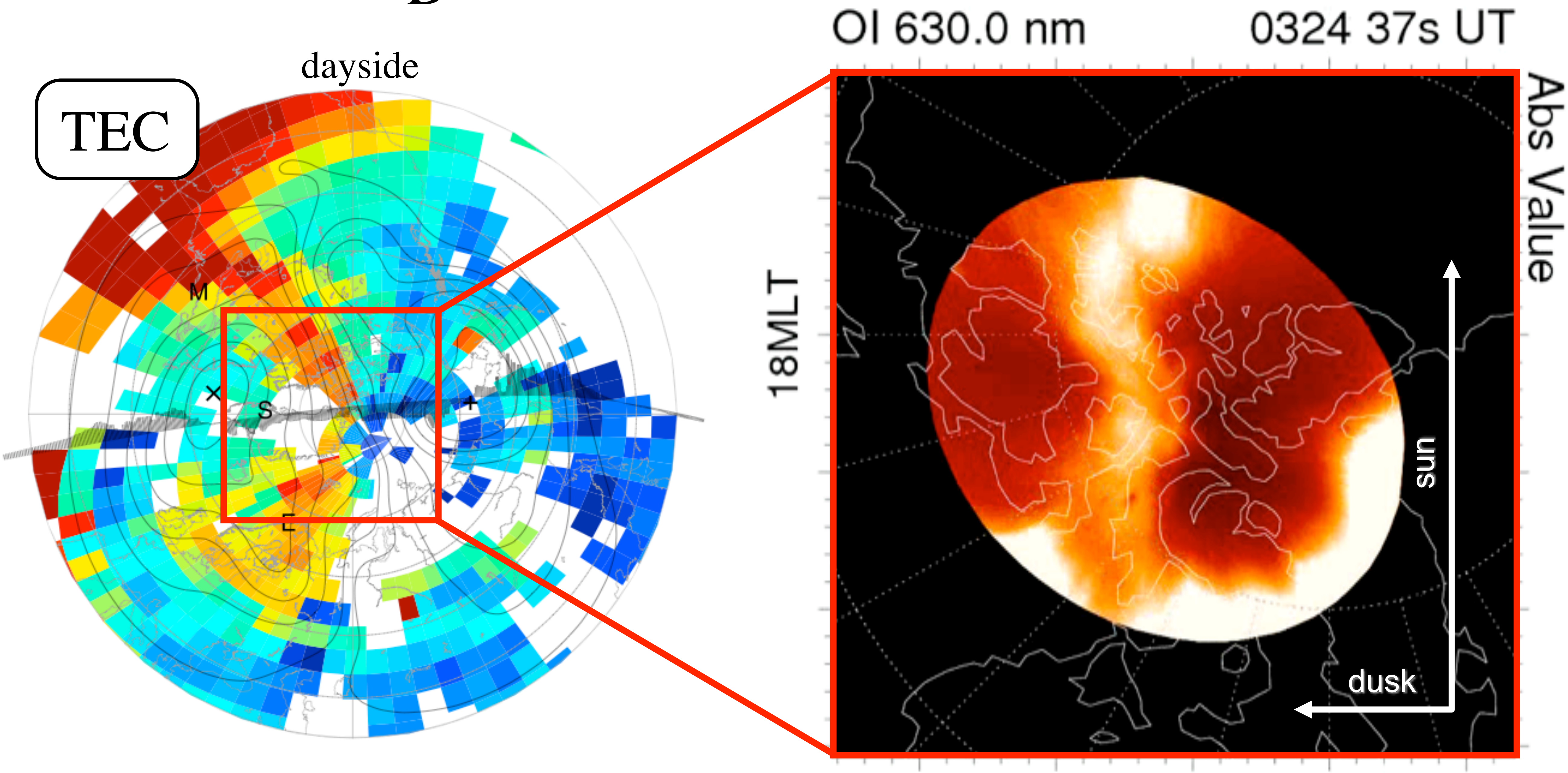
dayside



TEC Enhancement in the Polar Region

Plasma motion in the high-latitude ionosphere - F region:

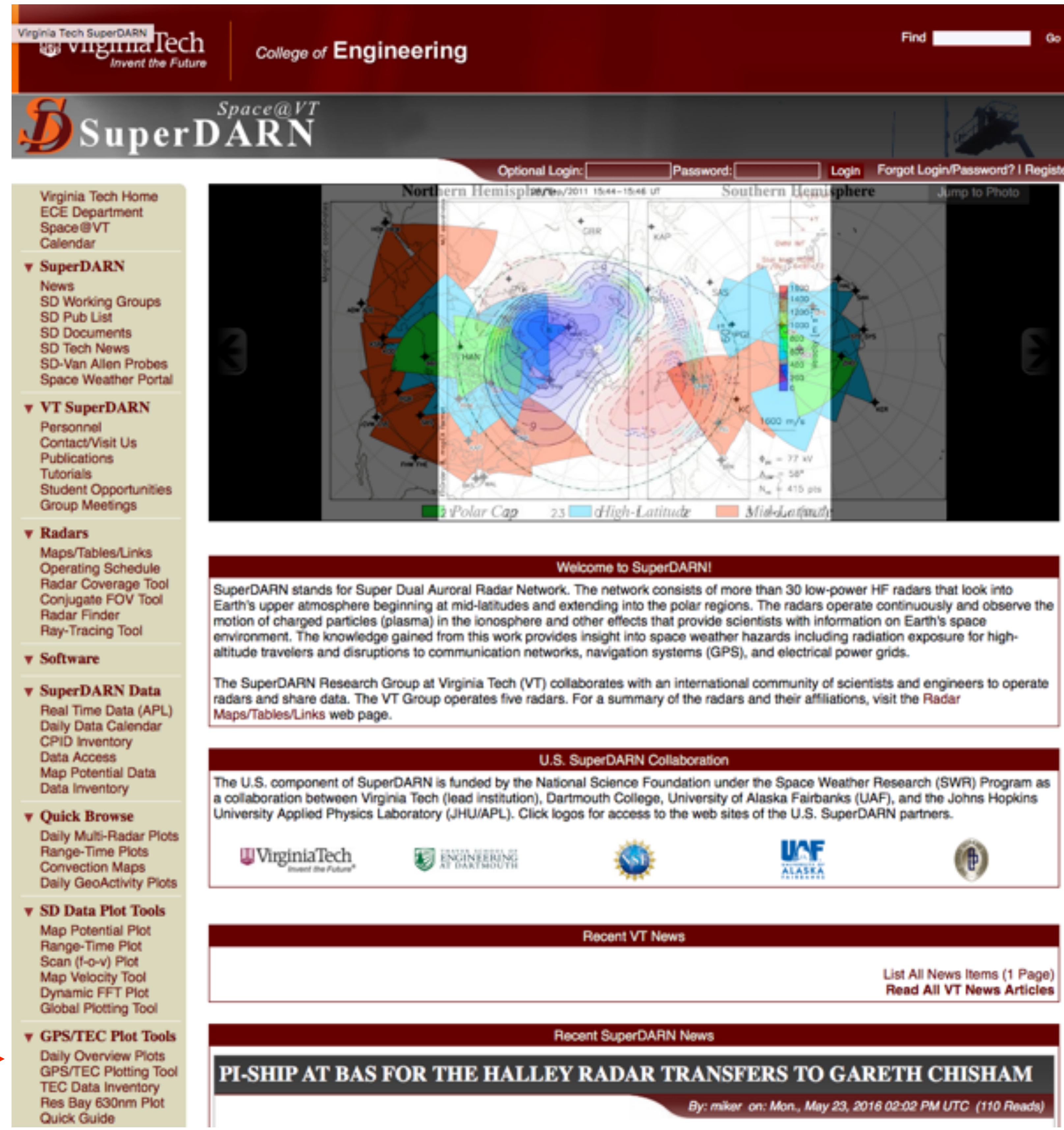
E×B drift: $$\mathbf{v} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$



Quick exercise: Browsing GPS-TEC data in US

Visit VT website:

http://vt.superdarn.org



Click

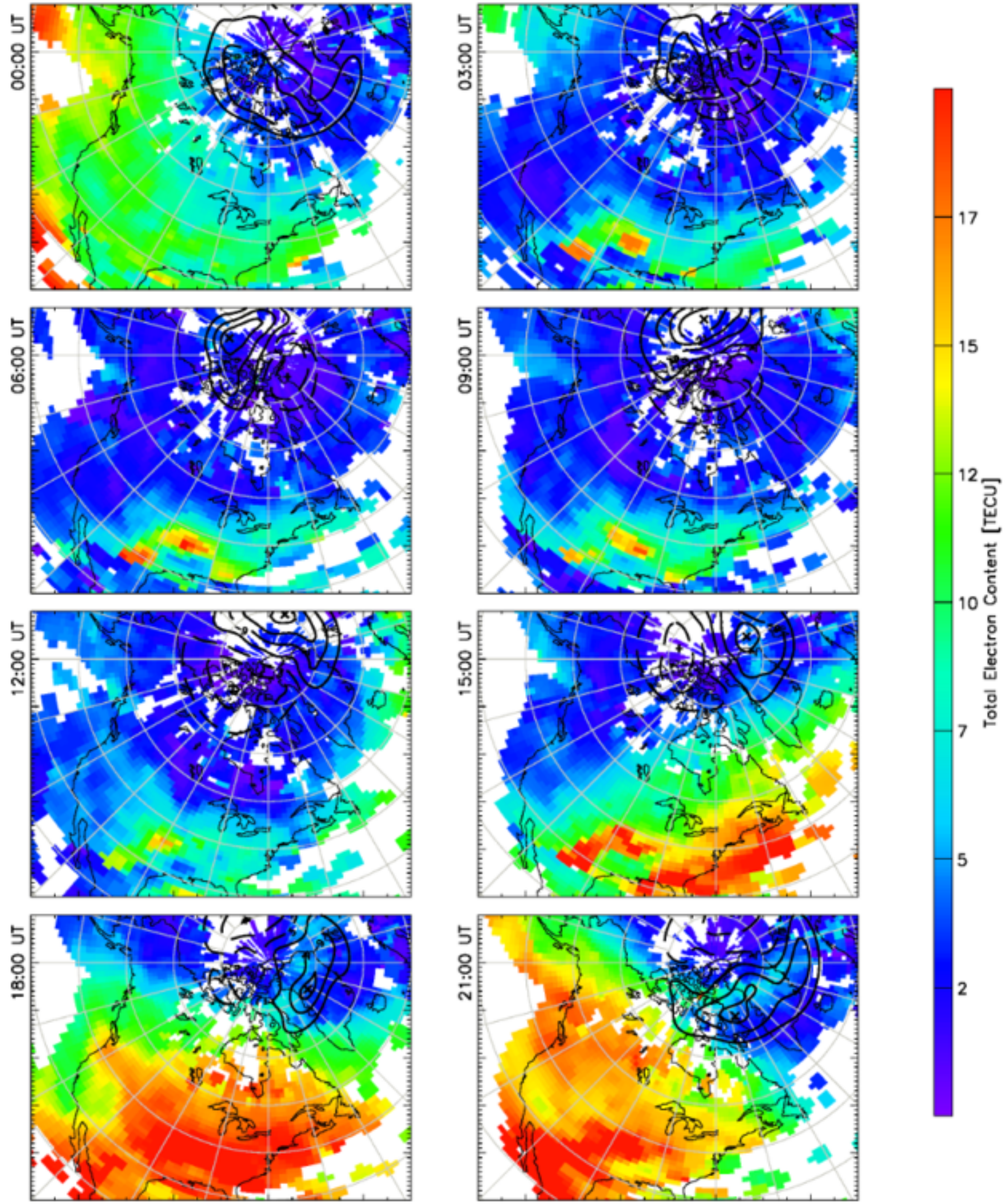
Daily Overview Plots

in the GPS/TEC Plot Tools section

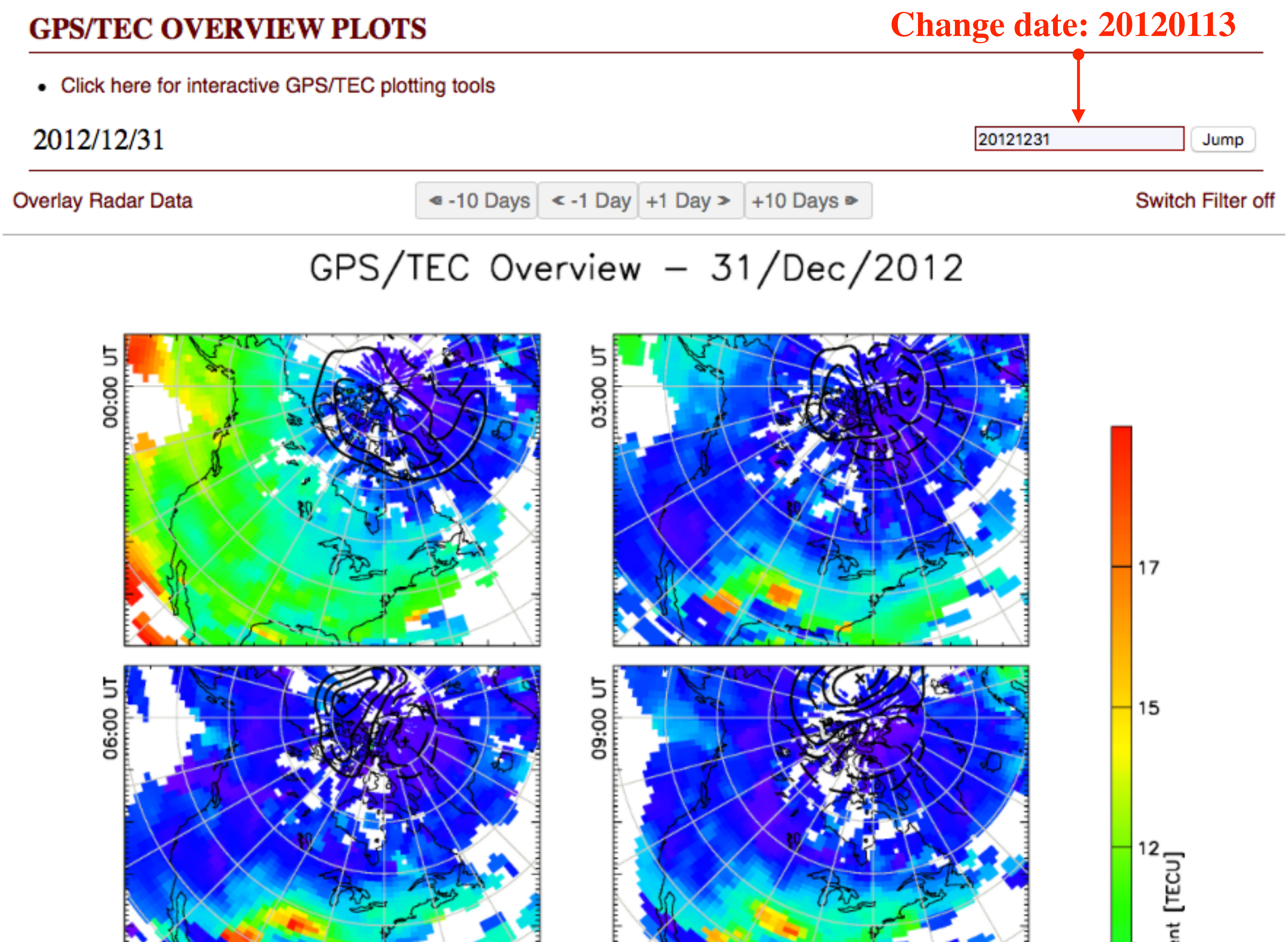
Dec 31, 2012

00 UT ~ 15 LT in US
03 UT ~ 18 LT in US
06 UT ~ 21 LT in US
09 UT ~ 00 LT in US
12 UT ~ 03 LT in US
15 UT ~ 06 LT in US
18 UT ~ 09 LT in US
21 UT ~ 12 LT in US

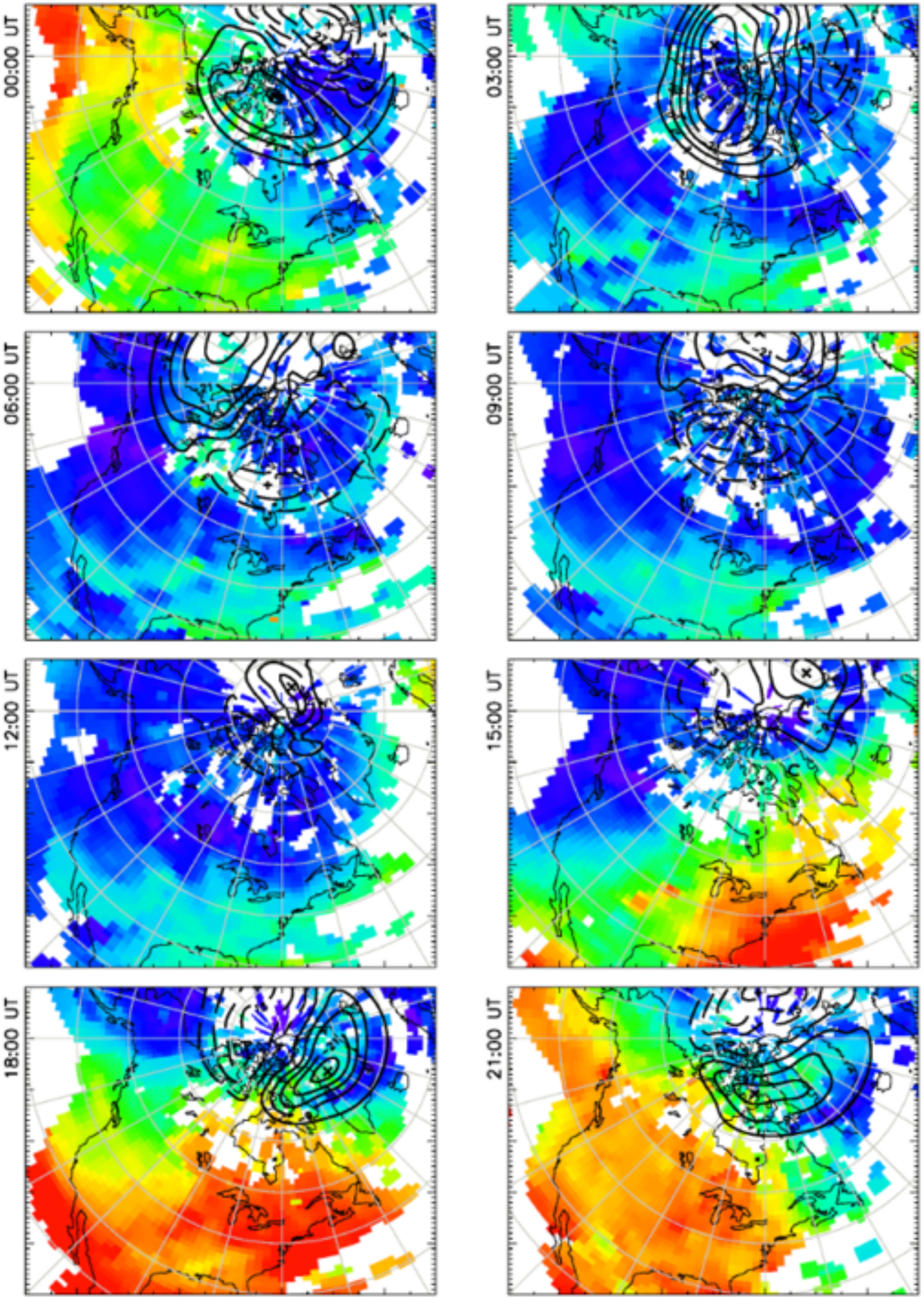
Photo ionization



Jump to Jan 13, 2012, and check the following 10 days

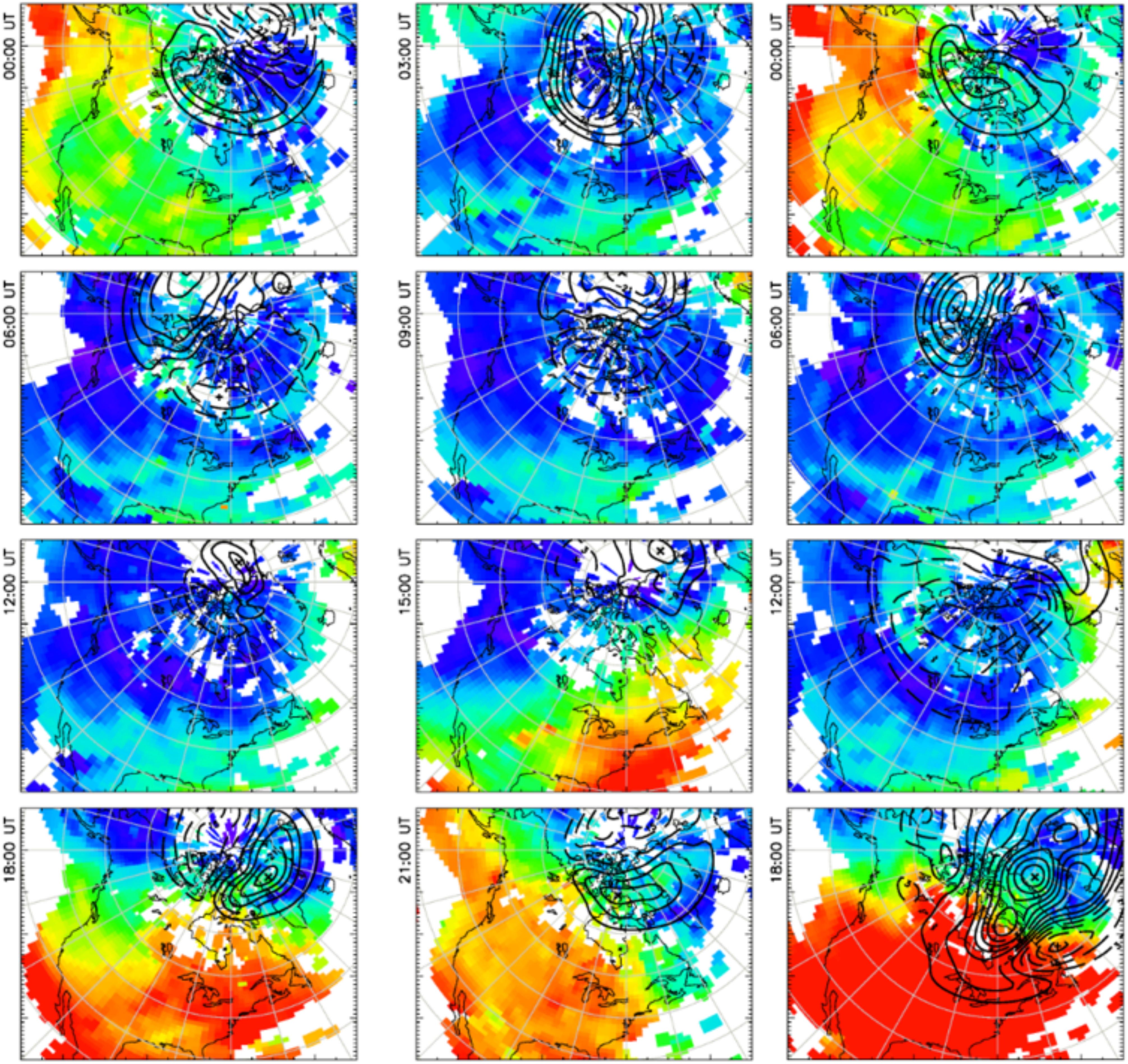


Jan 13, 2012



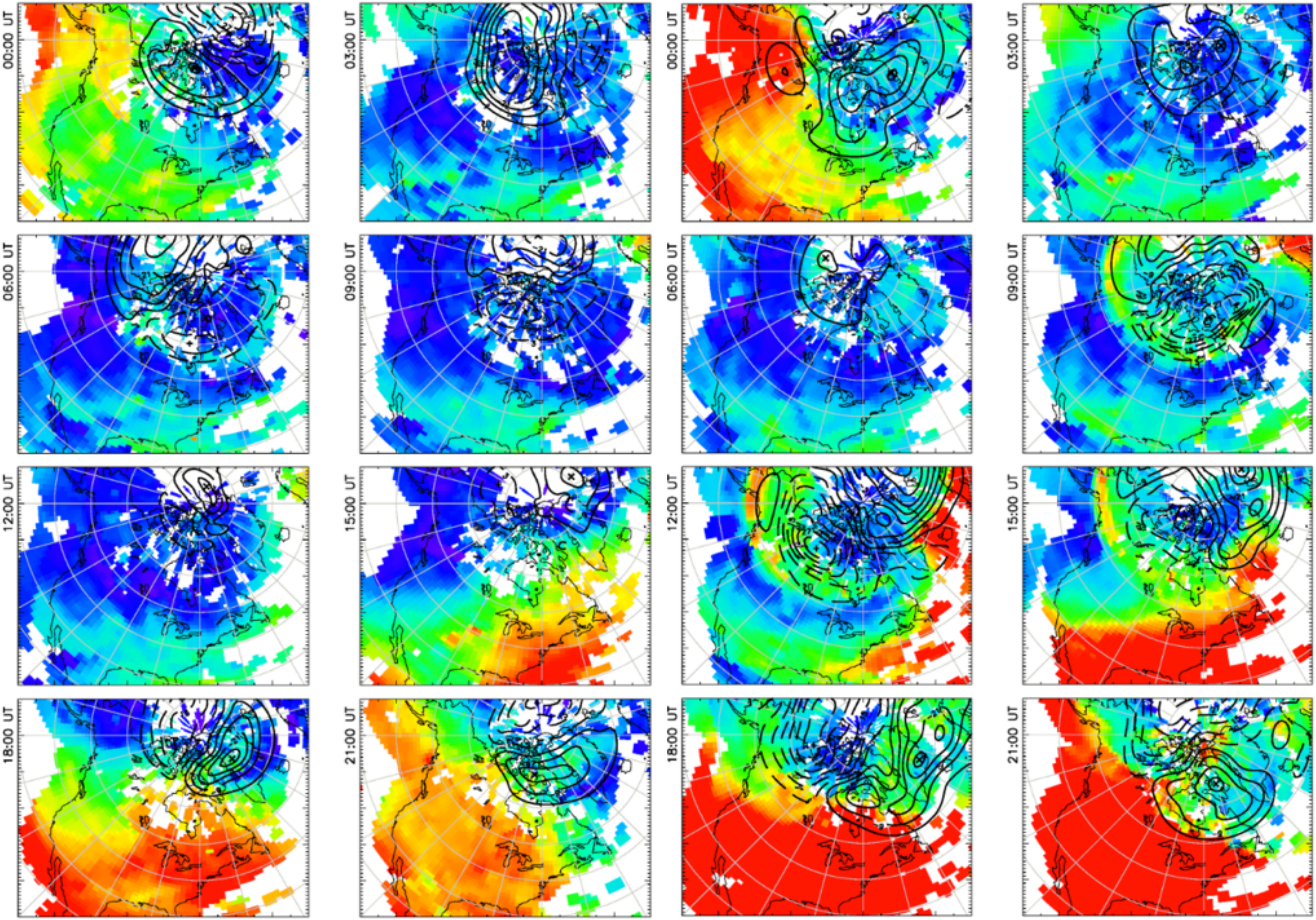
Jan 13, 2012

Jan 16, 2012

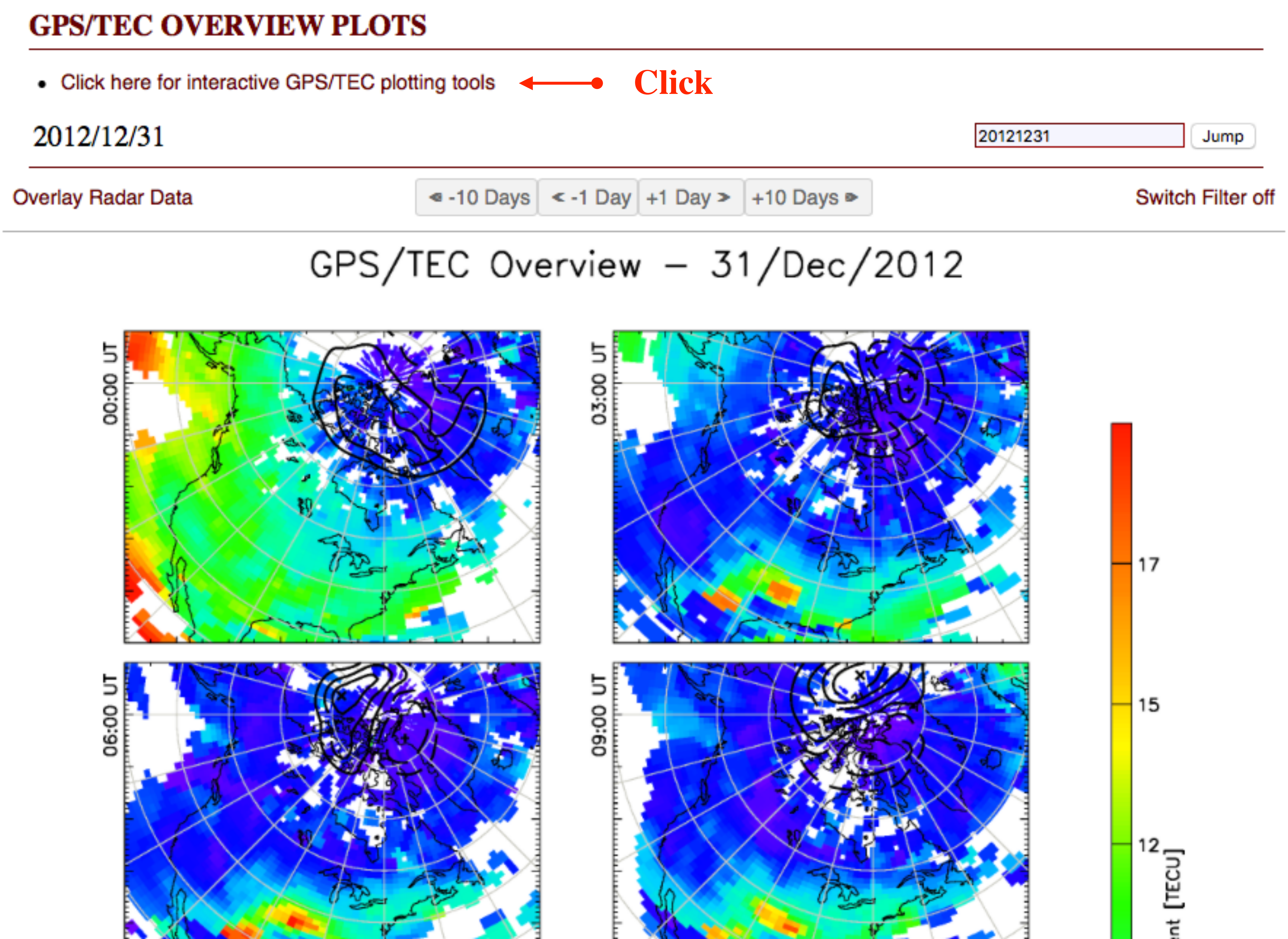


Jan 13, 2012

Jan 22, 2012



Plot the data on Jan 22 in a different format



Plot the data on Jan 22 in a different format

INTERACTIVE GPS/TEC PLOTTING - FOUR PLOT

- Click here to create single plots ← Click
- Click here to create animated movies

Plot

Hemisphere	Year	Month	Day	Hour	Minute
North	2016	Jun	10	0	01

TEC Parameter	Scale (TECU)			
Total Electron Content	Min Value:	0	Max Value:	20

Median Filtering						
Lat/Lon Bin:	1	2	Start Lat:	20	Threshold:	0.20

Coordinates						
Magnetic	XRange:	-50	30	YRange:	-50	10

Convection Map	
☐ Plot Convection Map	☐ Plot Heppner-Maynard Boundary

North Radars		
☐ Inuvik (inv 64)	☐ Rankin (rkn 65)	☐ Clyde River (cly 66)
☐ King Salmon (ksr 16)	☐ Kodiak (kod 7)	☐ Saskatoon (sas 5)
☐ Goose Bay (gbr 1)	☐ Pykkvibaer (pyk 9)	☐ Prince George (pgr 6)
☐ Kapuskasing (kap 3)	☐ Stokkseyri (sto 8)	☐ Hankasalmi (han 10)
☑ Hokkaido (hok 40)	☑ Hokkaido West (hkw 41)	☑ Blackstone (bks 33)
☑ Wallops Island (wal 32)	☑ Fort Hays West (fhw 204)	☑ Fort Hays East (fhe 205)
☑ Christmas Valley West (fhw 206)	☑ Christmas Valley East (fhe 207)	☑ Adak West (adw 208)
☑ Adak East (ade 209)		

Plot the data on Jan 22 in a different format

INTERACTIVE GPS/TEC PLOTTING - SINGLE PLOT

- Click here to create animated movies
- Click here to create a four plot overview

Change data to Jan 22, 2012 20:00

Plot

Hemisphere	Year	Month	Day	Hour	Minute
North	2016	Jun	10	0	01

TEC Parameter	Scale			
Total Electron Content	Min Value:	0	Max Value:	20
TEC Error	Min Value:	0	Max Value:	10
None (map only)				

Median Filtering

Apply Median Filtering — Lat/Lon Bin: 1 2 — Start Lat: 20 — Threshold: 0.10

Plot Latitudinal TEC Gradient

Coordinates

Magnetic — XRange: -50 30 — YRange: -50 10

Select MLT

Rotate map by: 0 deg. (clockwise)

Convection Map

Plot Convection Map — Plot Heppner-Maynard Boundary — Plot Day/Night Terminator

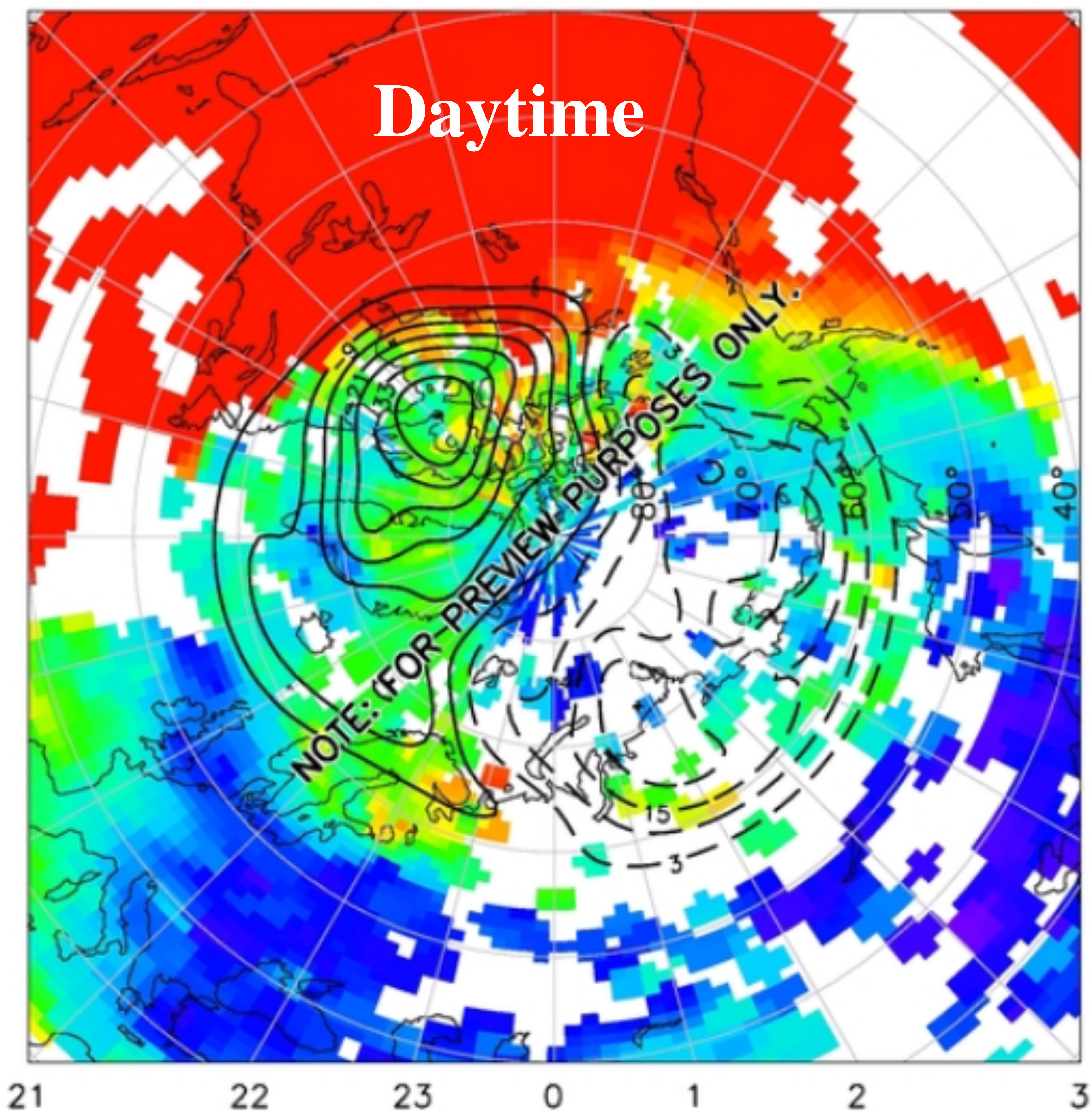
Radar Measurements

Plot Radar Measurements — Select All

Plot — Debug:

Press Plot

TEC Data Inventory



Daytime
NOTE: (FOR PREVIEW PURPOSES ONLY.
80°
70°
60°
50°
40°
15
3
21
22
23
0
1
2
3

Outline

- Ionosphere

    Quick exercise: Browsing radar data from Norway

- Key ideas of GNSS

- Mechanism of ionospheric effects on GNSS

- Two major ionospheric impacts on GNSS

    1. Positioning error

        Quick exercise: Browsing GPS TEC data in US

    2. Scintillation effect

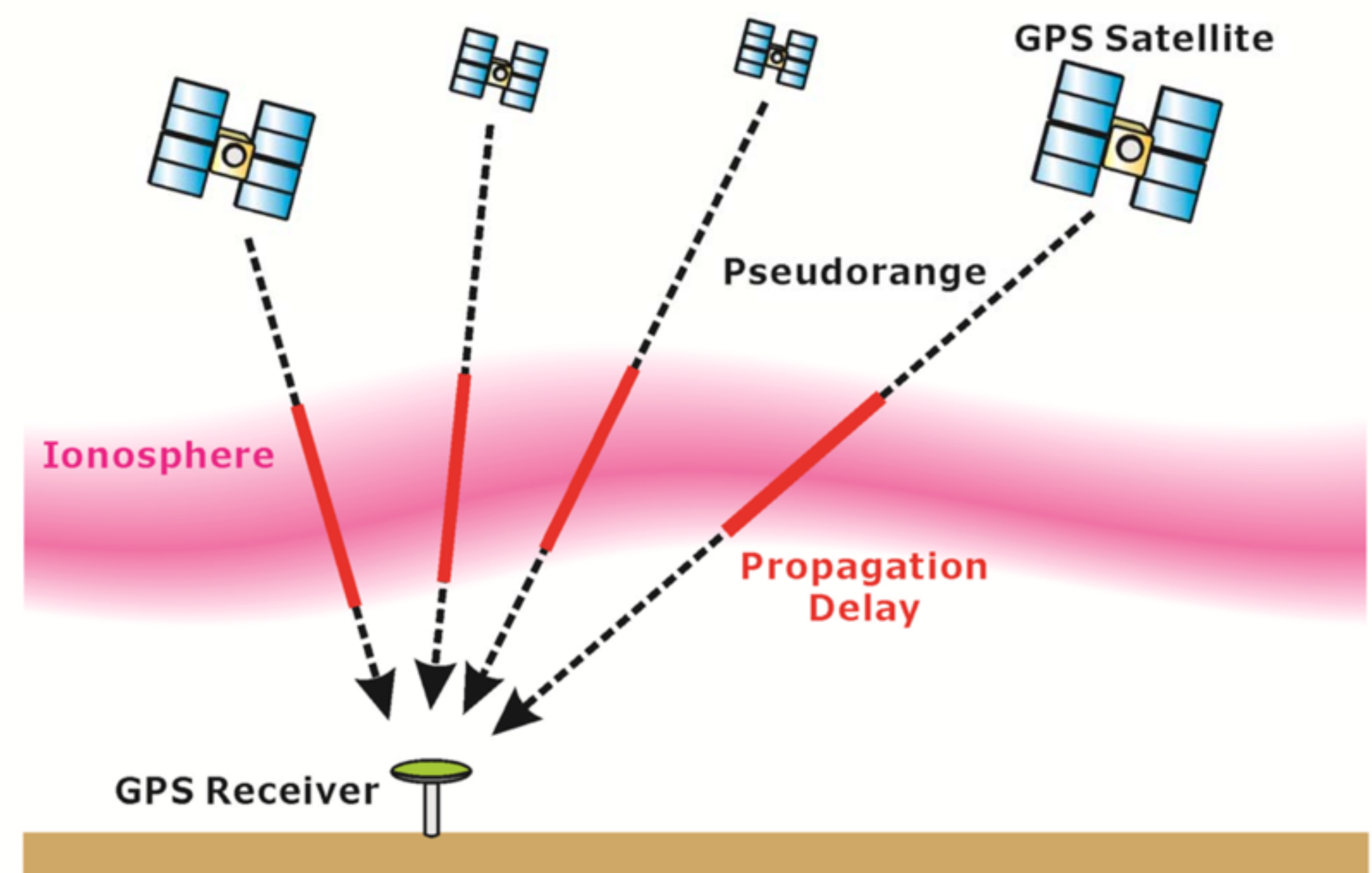
        Quick exercise: Browsing GPS scintillation data

GPS Positioning Error due to Ionosphere

Ionospheric effect on GNSS – 1

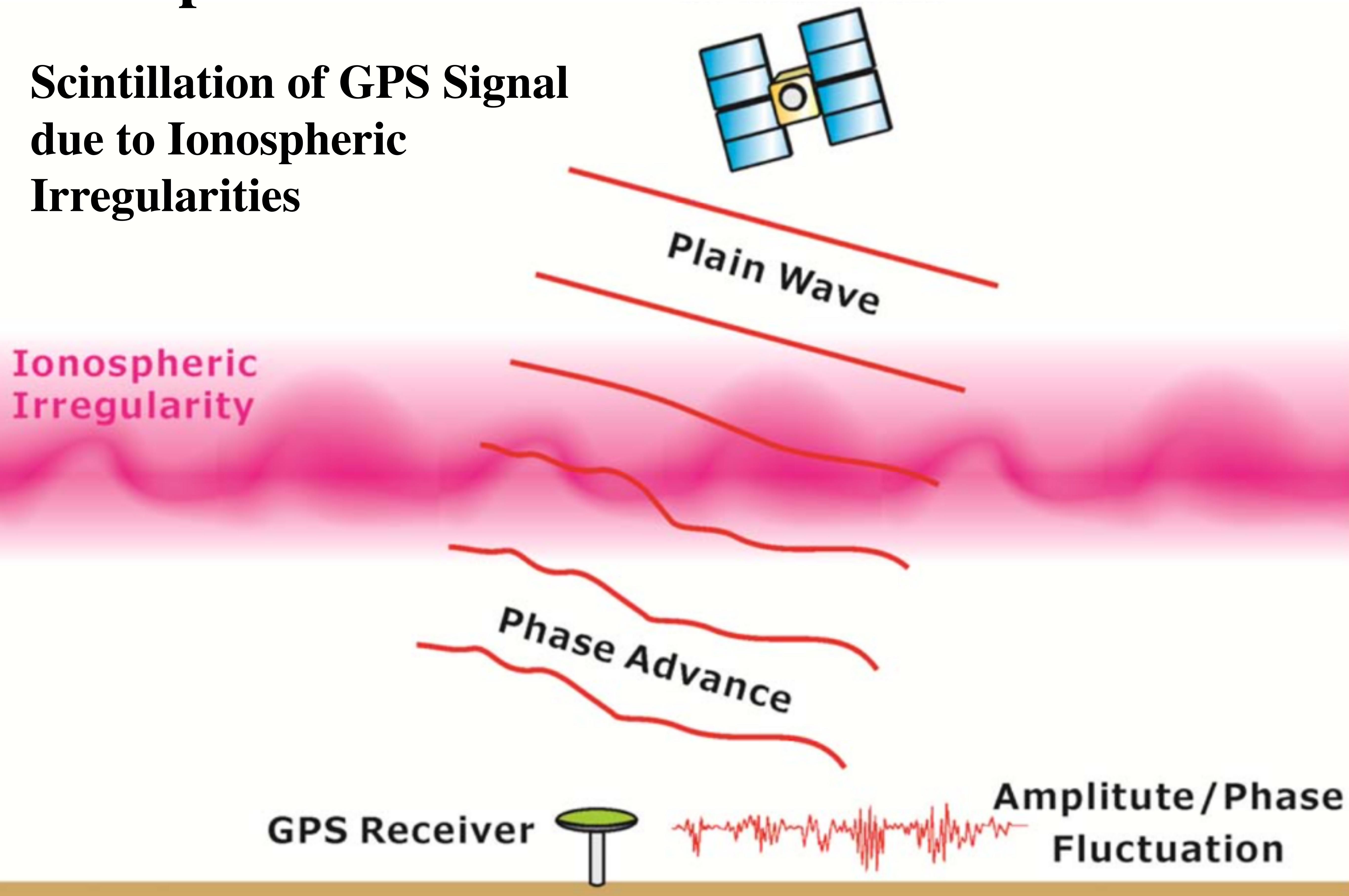
$$I_\rho = \frac{40.3\,\mathrm{TEC}}{f^2}$$

1 TECU = 16 cm



Ionospheric Effect on GNSS - 2

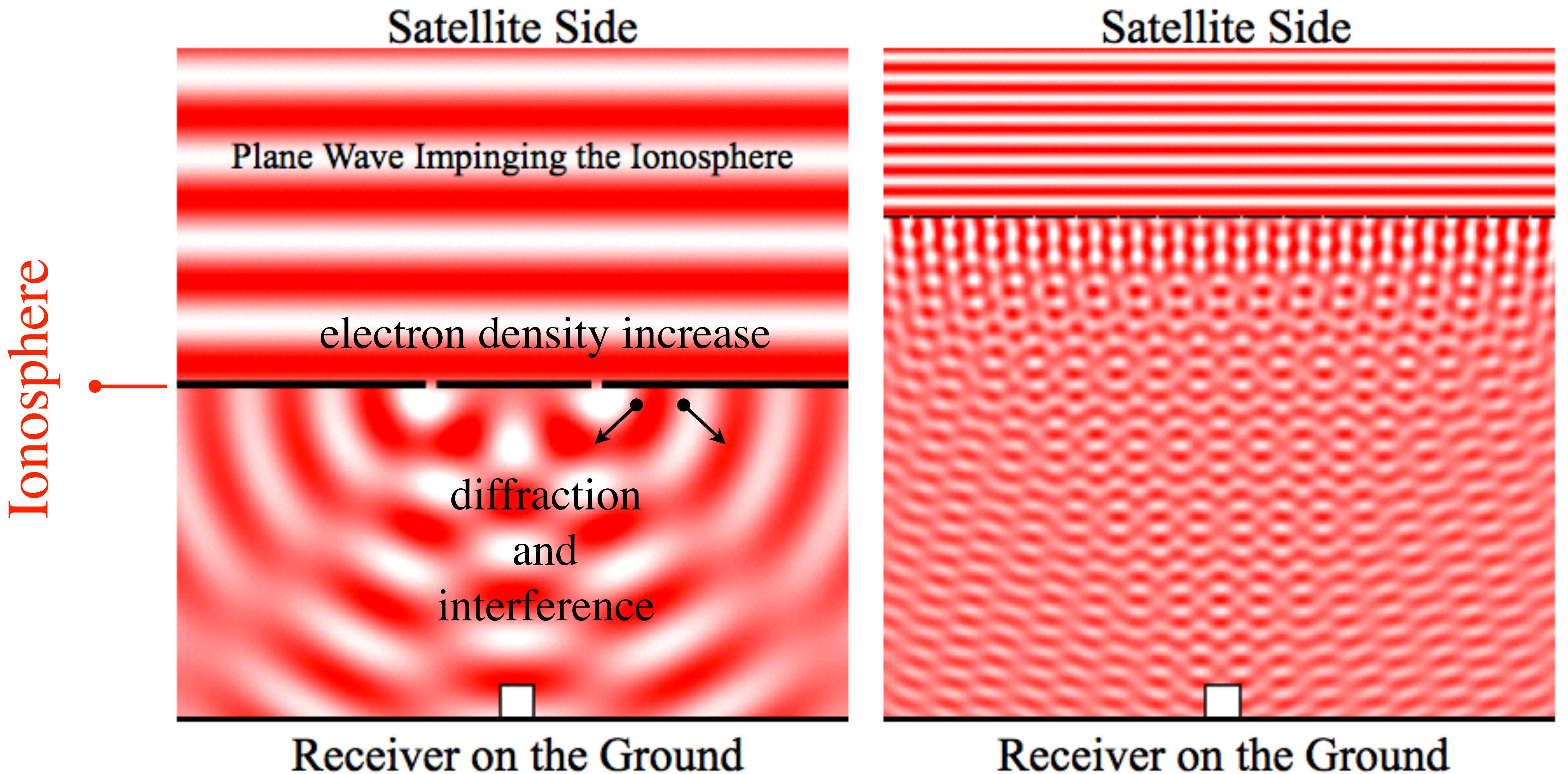
Scintillation of GPS Signal due to Ionospheric Irregularities



Ionospheric Scintillations

Scintillations: Fluctuations in the received signal on the ground

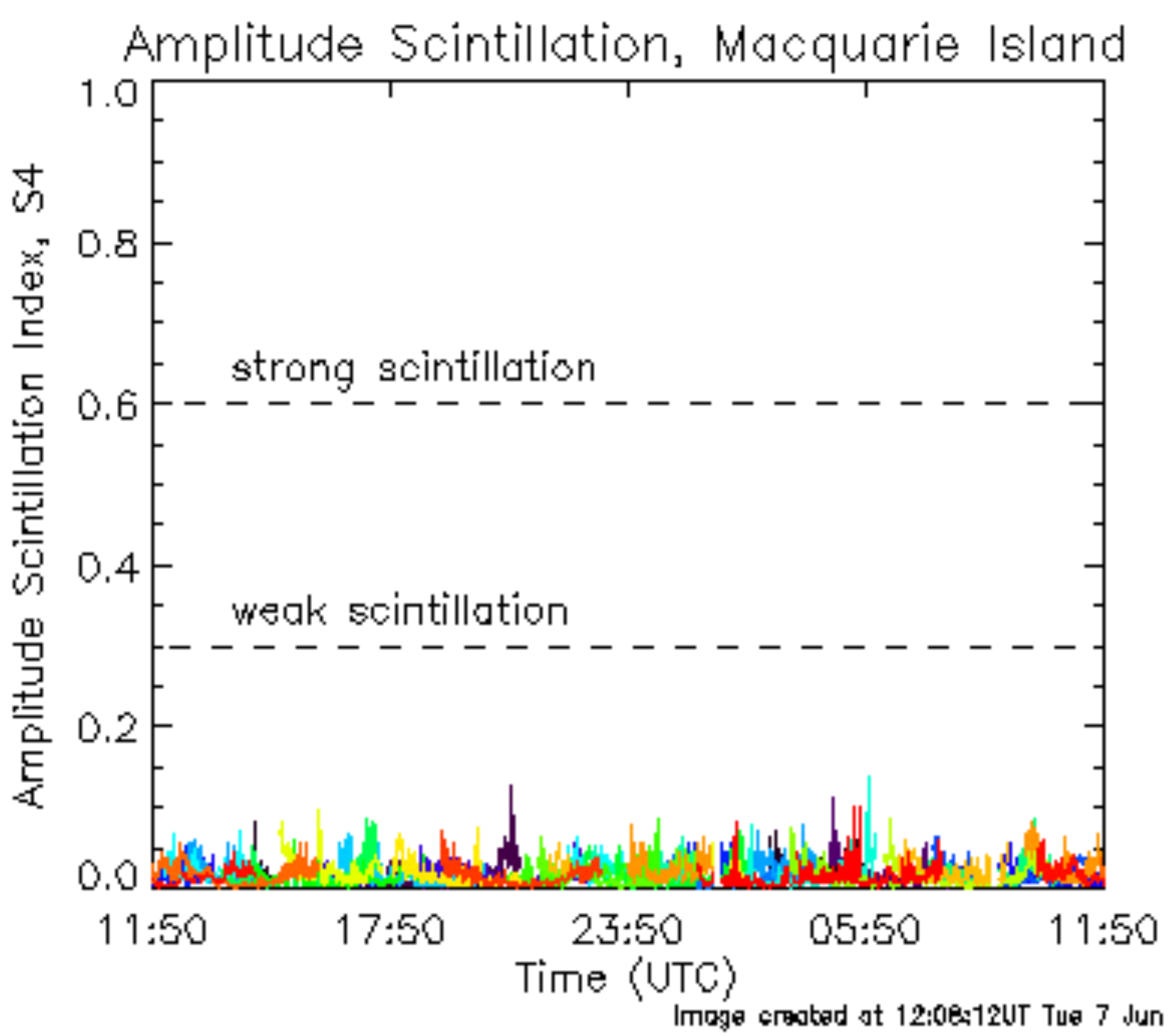
Cause: interference of diffracted signals by the irregular ionosphere



Two Types of Scintillation

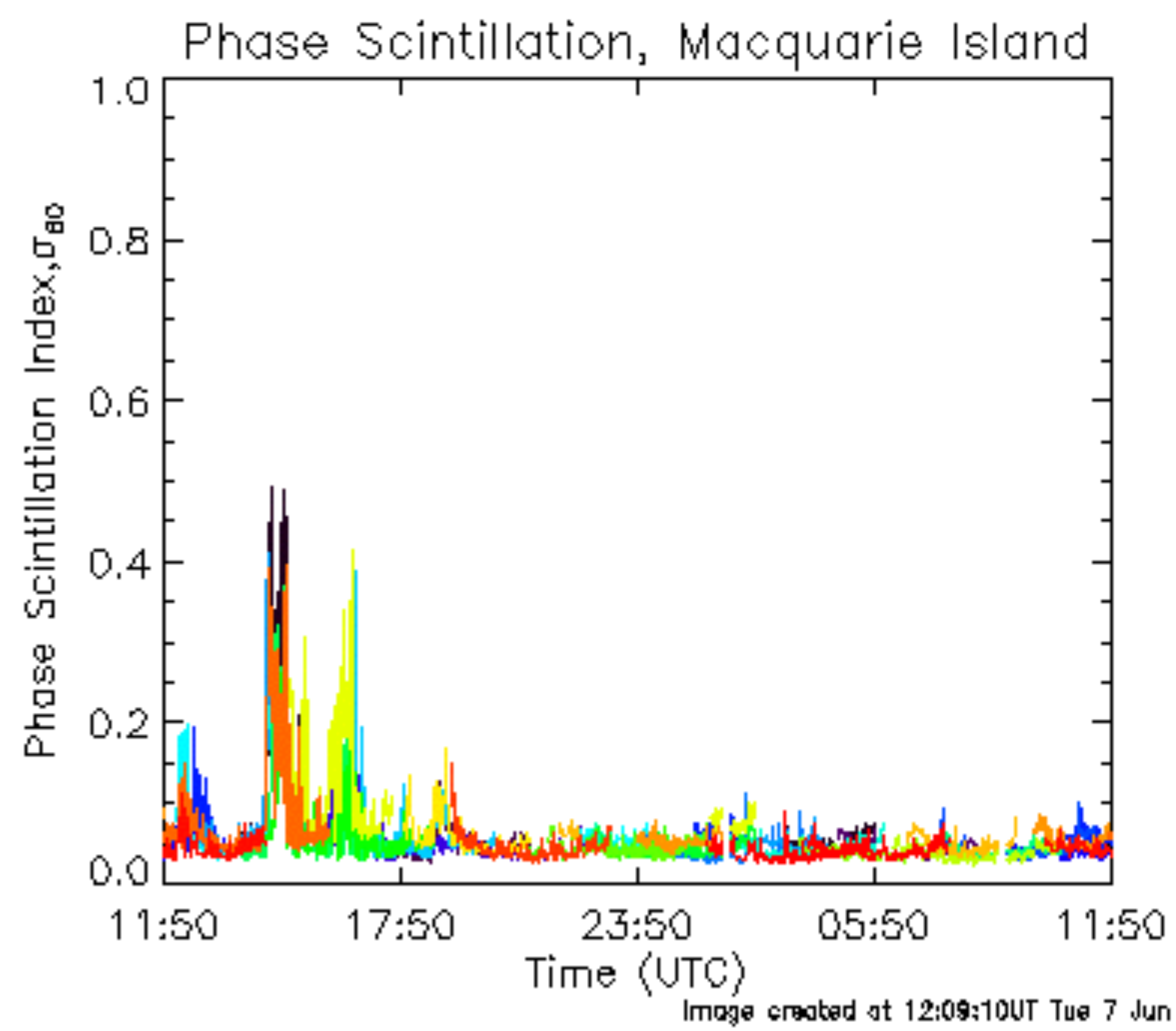
Amplitude scintillation:

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$$



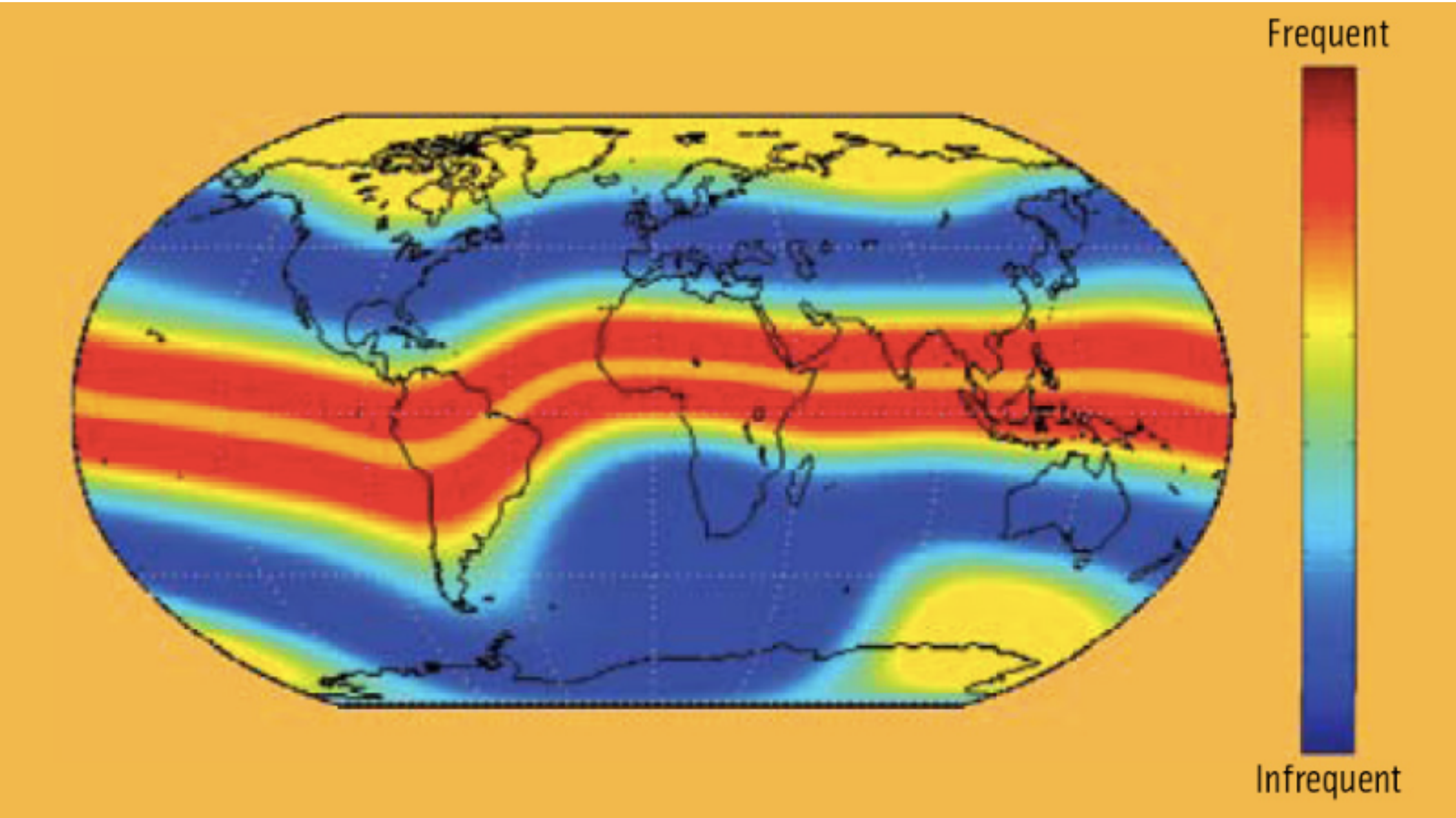
Phase Scintillation:

$$\sigma_\varphi = \mathrm{STDB}(\varphi)$$



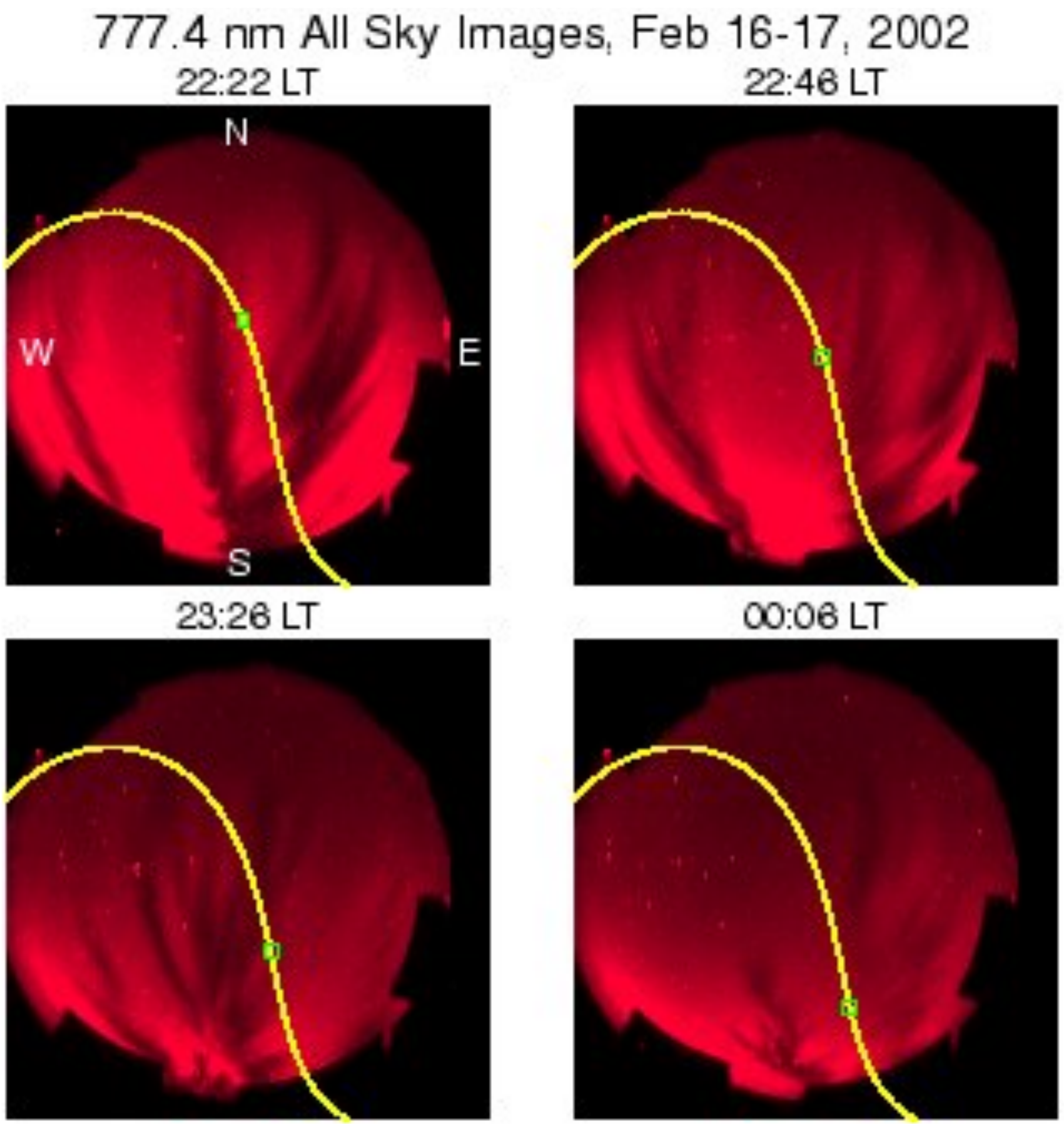
Global Distribution of GPS Scintillations

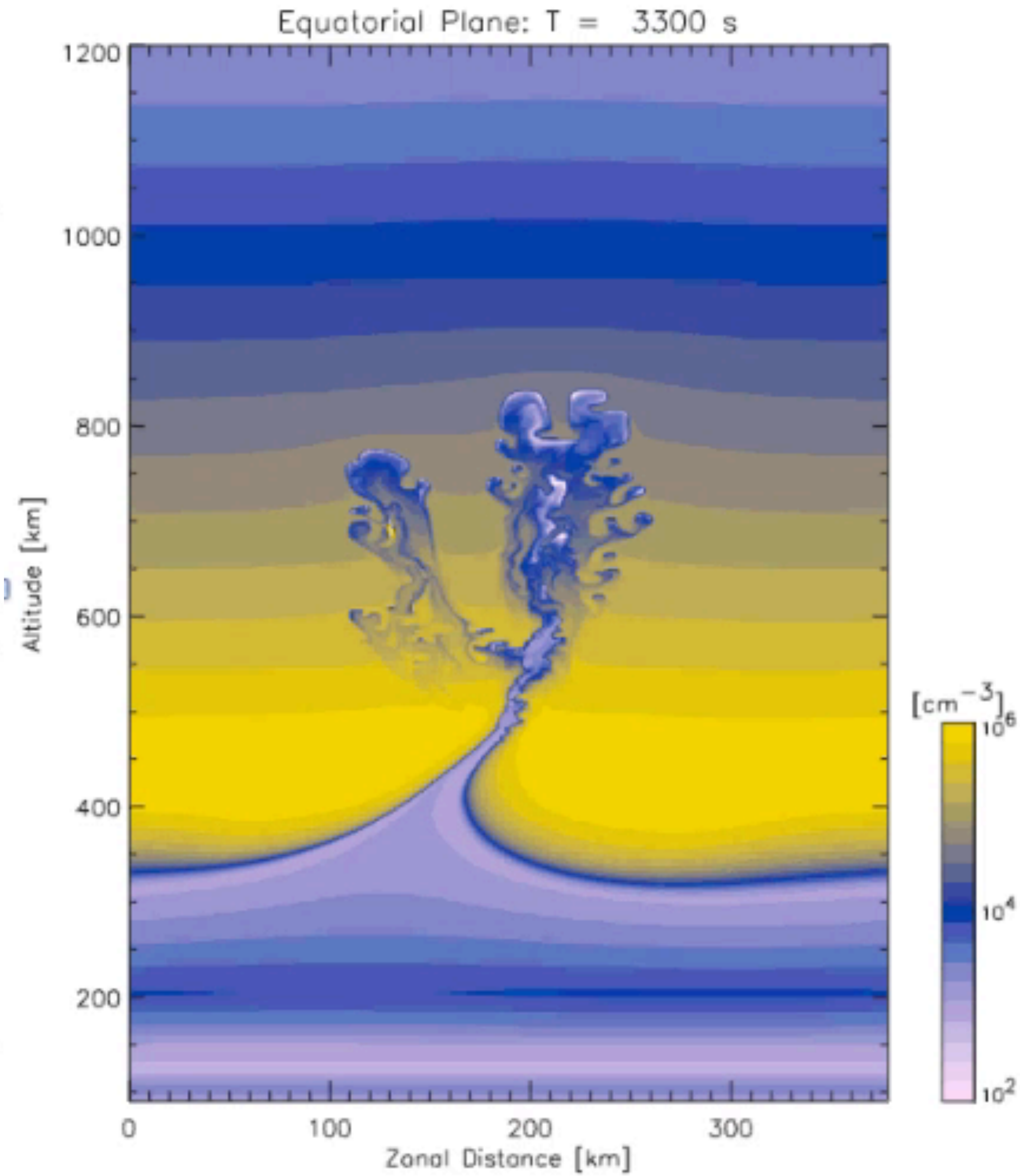
Two Hotspots of Scintillation: Equatorial and Polar Regions



Source of Equatorial Scintillations

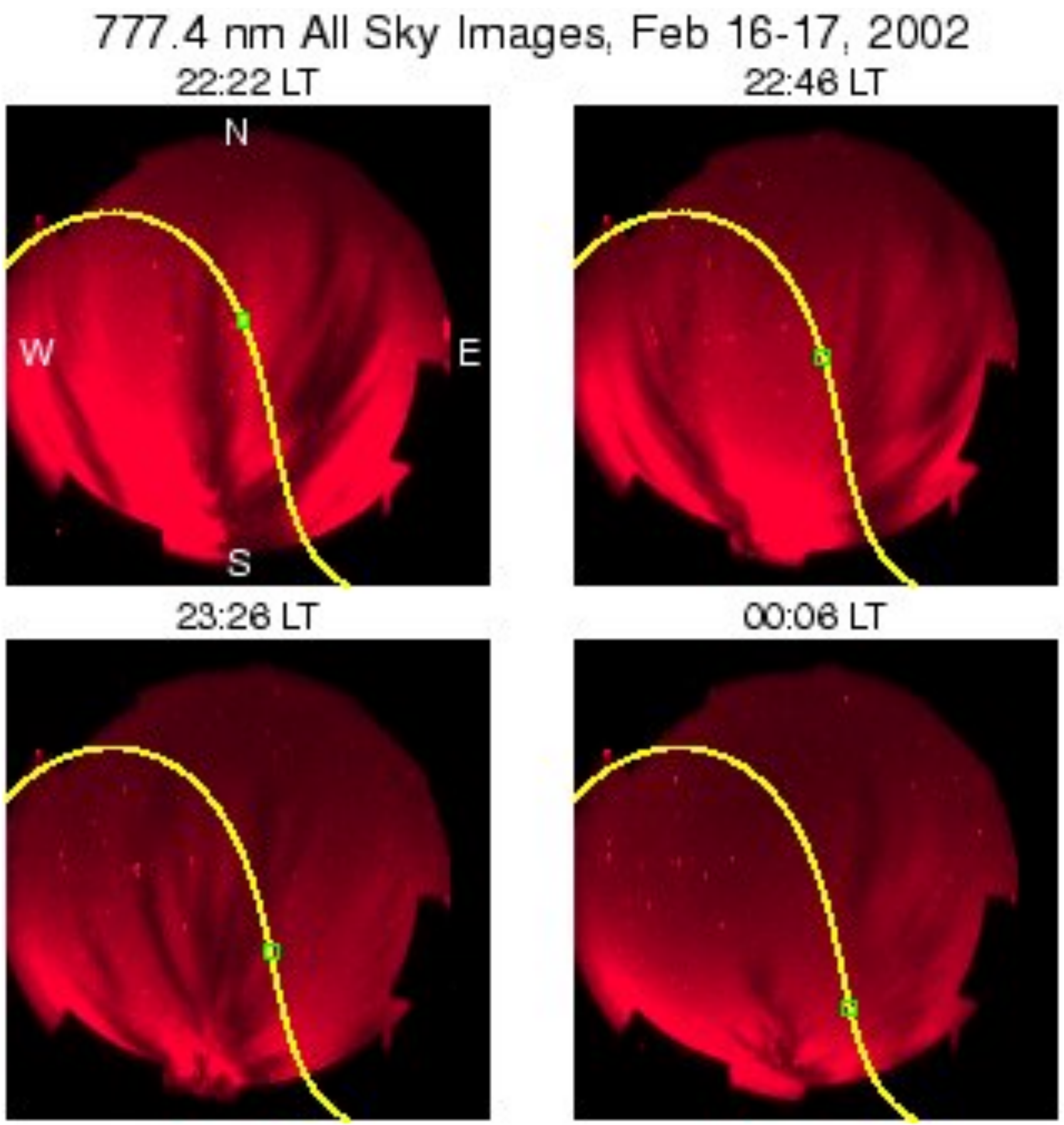
Plasma Bubble

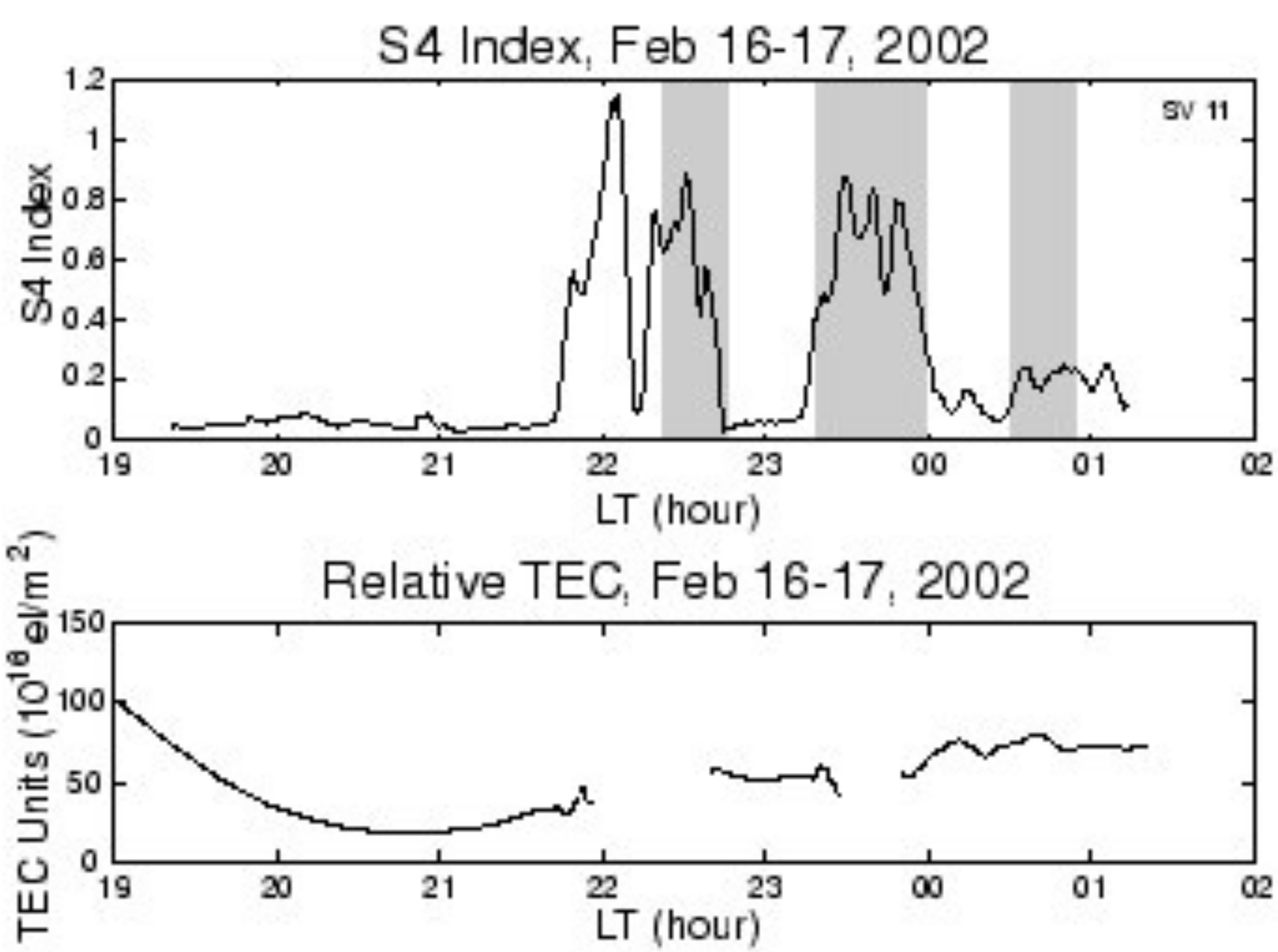




Source of Equatorial Scintillations

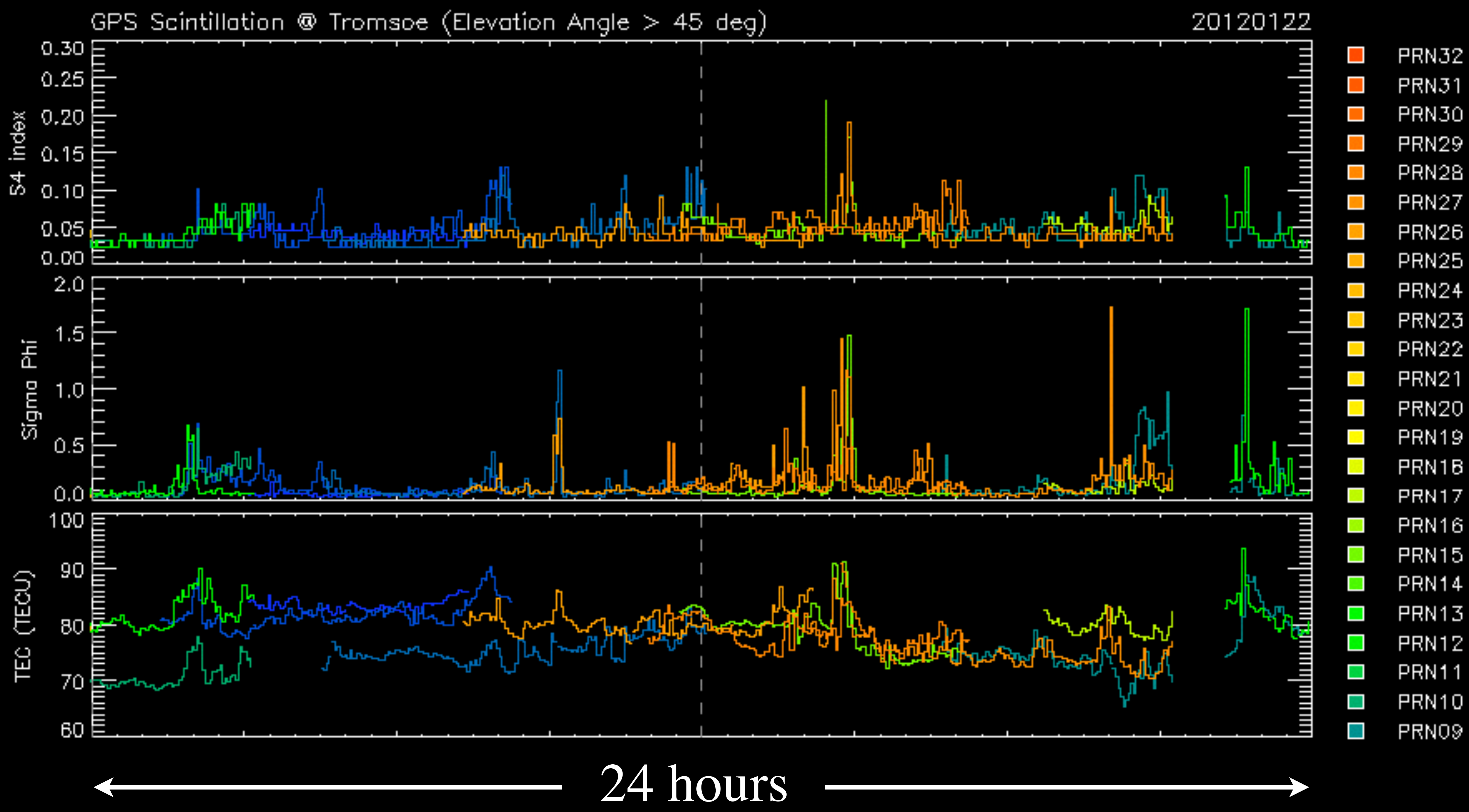
Plasma Bubble: Effect on GPS Scintillations





Source of High-Latitude Scintillations

GPS Scintillation Measurement in Tromso, Norway



Quick exercise: Browsing GPS Scintillation Data

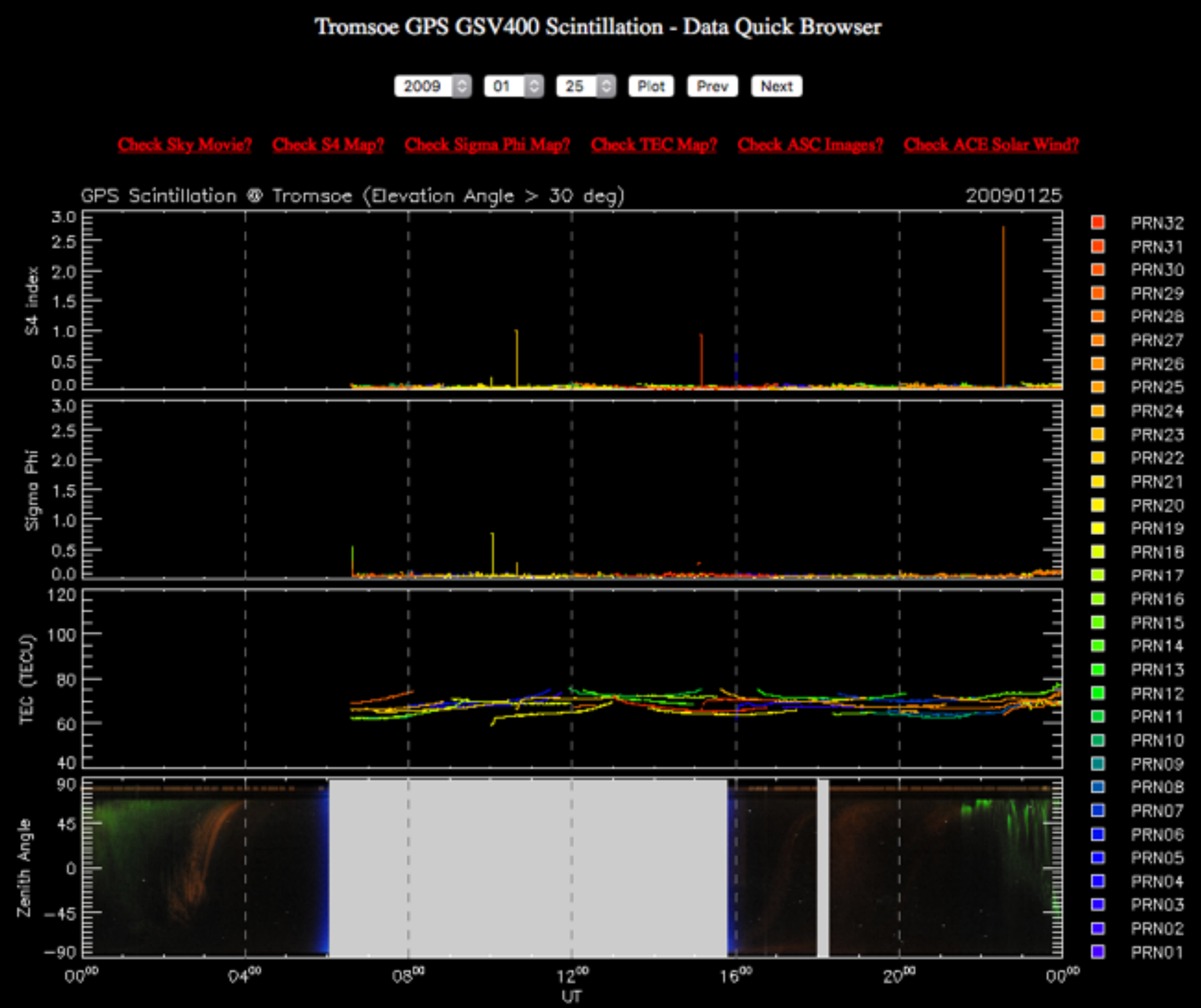
http://gwave.cei.uec.ac.jp/cgi-bin/hosokawa/tromsoe/tromsoe.cgi

S4 index
amplitude scintillation

Sigma phi
phase scintillation

TEC

Aurora Data

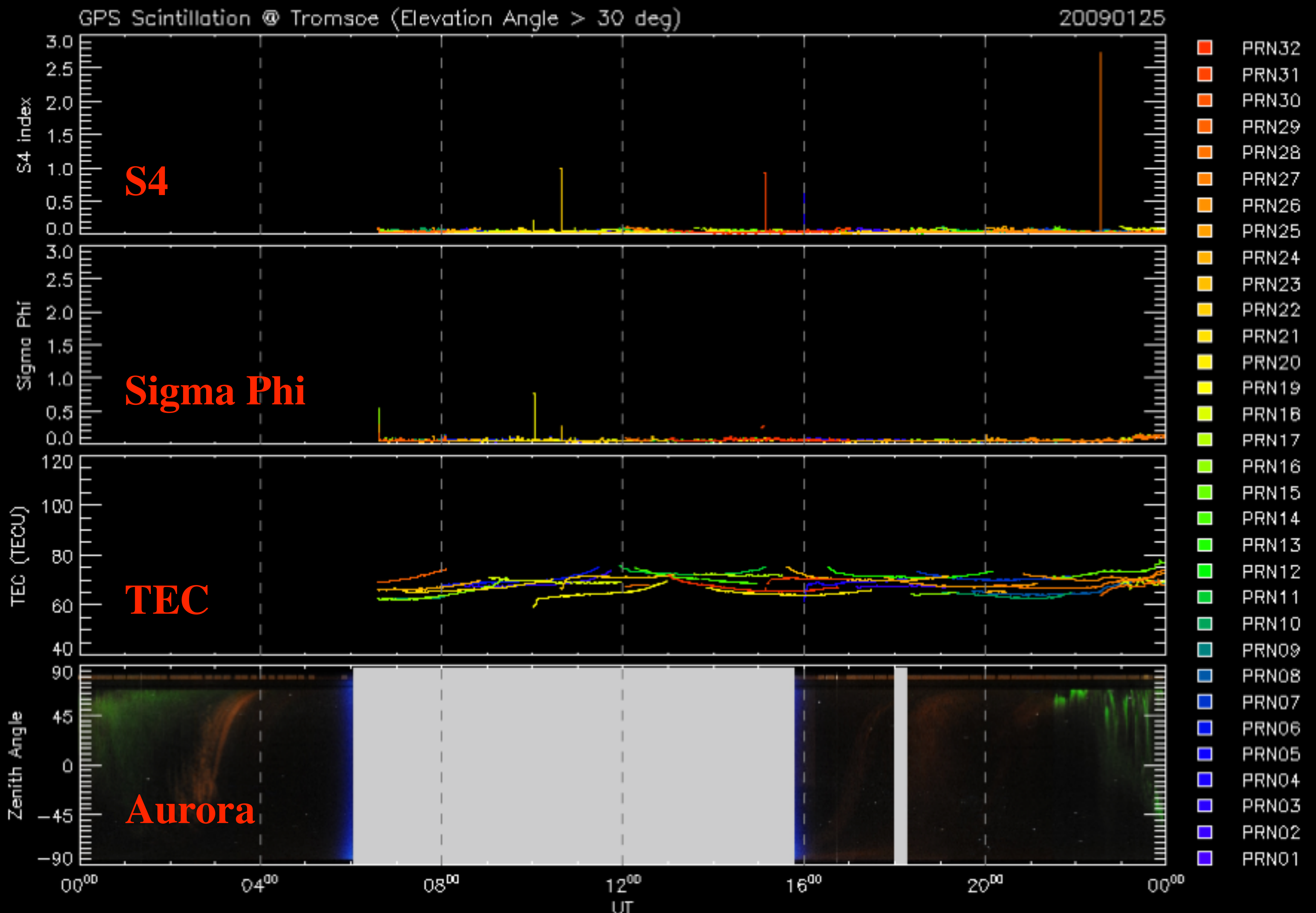


Tromsoe GPS GSV400 Scintillation - Data Quick Browser

Change date

2009 | 01 | 25 | Plot | Prev | Next

Check Sky Movie? Check S4 Map? Check Sigma Phi Map? Check TEC Map? Check ASC Images? Check ACE Solar Wind?



Jump to Jan 20, 2012, and check the following 10 days

Check various movies (heavy)

Aurora data in 2D

SW data

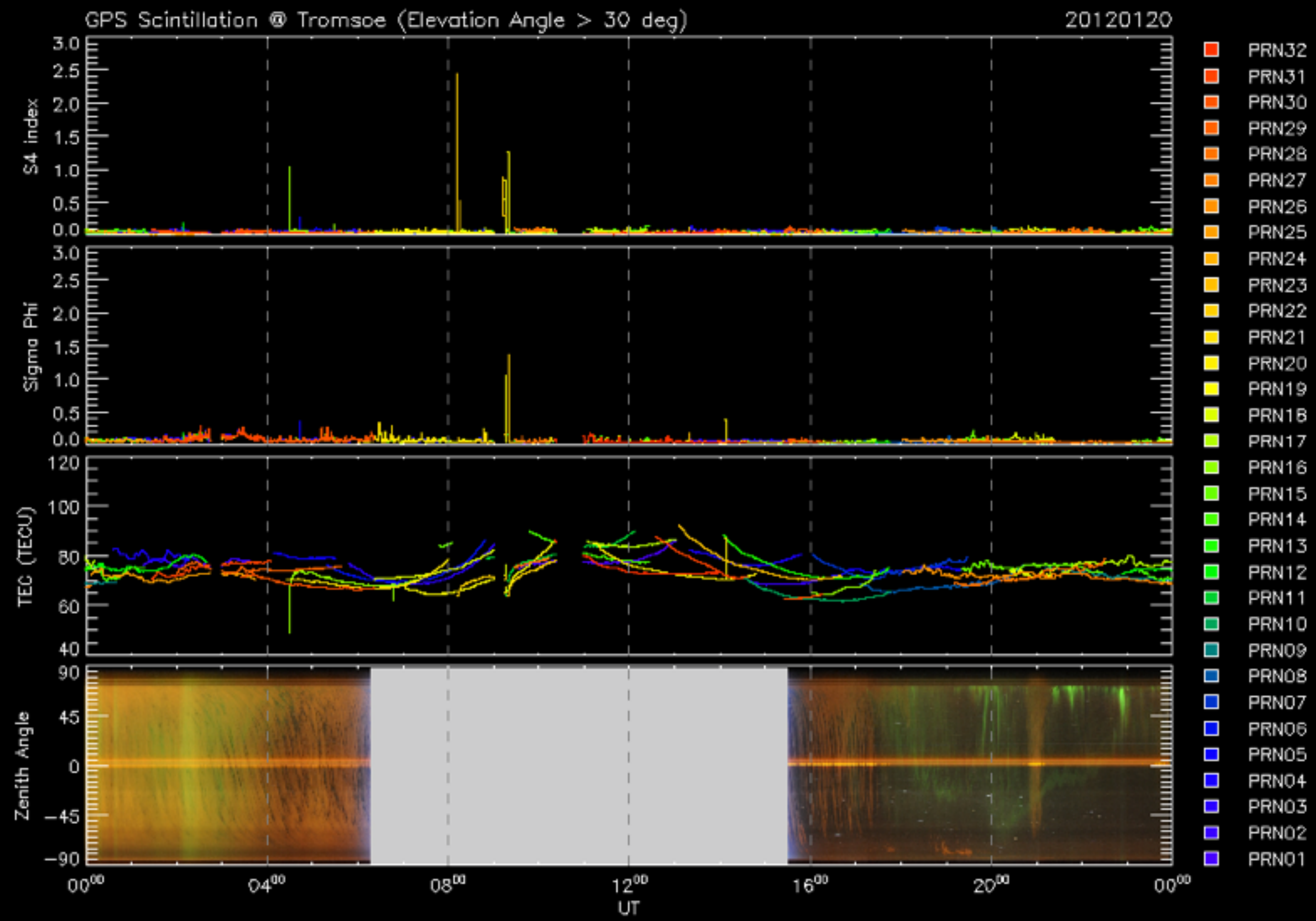
Check Sky Movie? Check S4 Map? Check Sigma Phi Map? Check TEC Map? Check ASC Images? Check ACE Solar Wind?

S4

Sigma Phi

TEC

Aurora



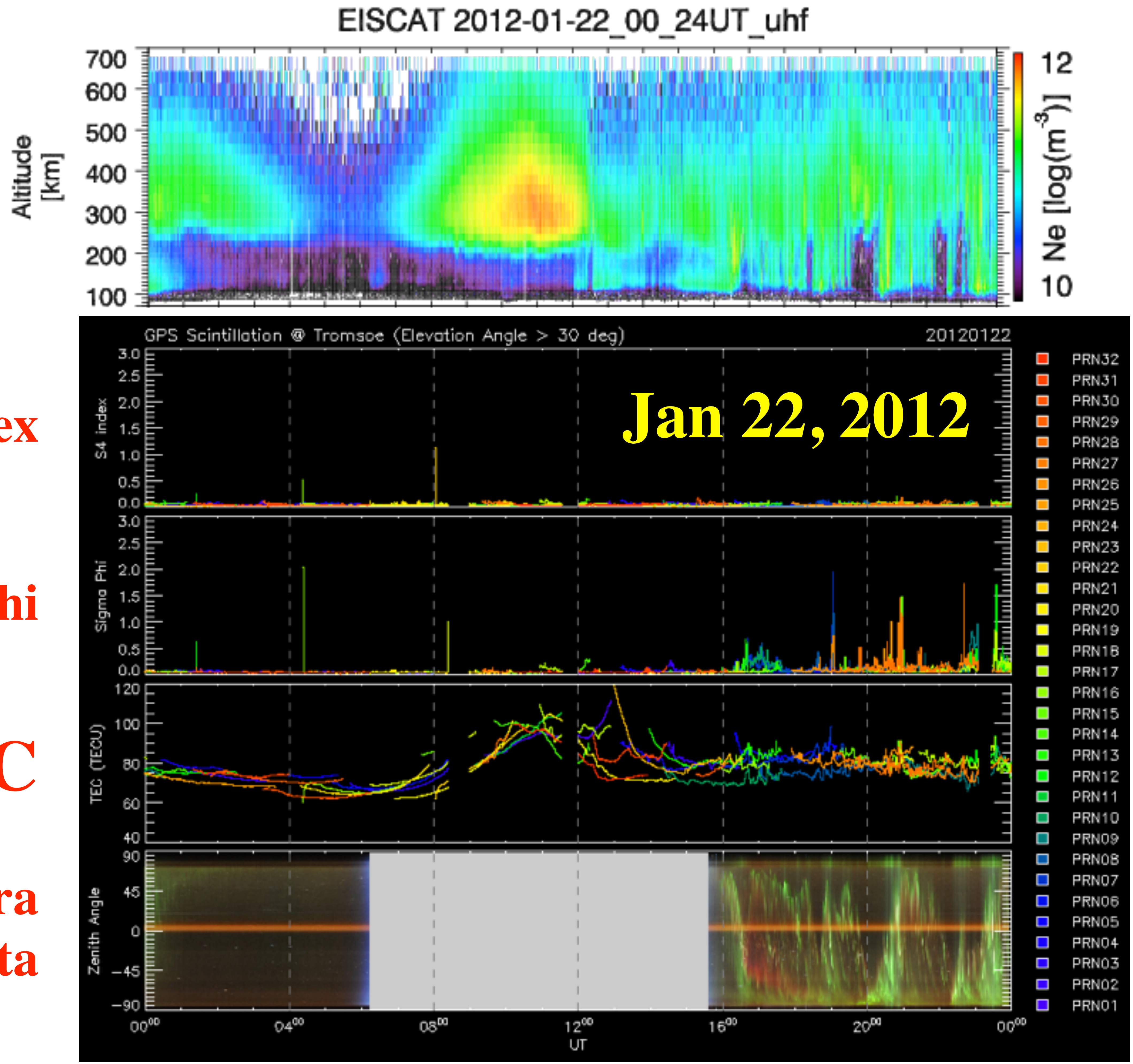
Ne

S4 index

Sigma phi

TEC

Aurora
Data



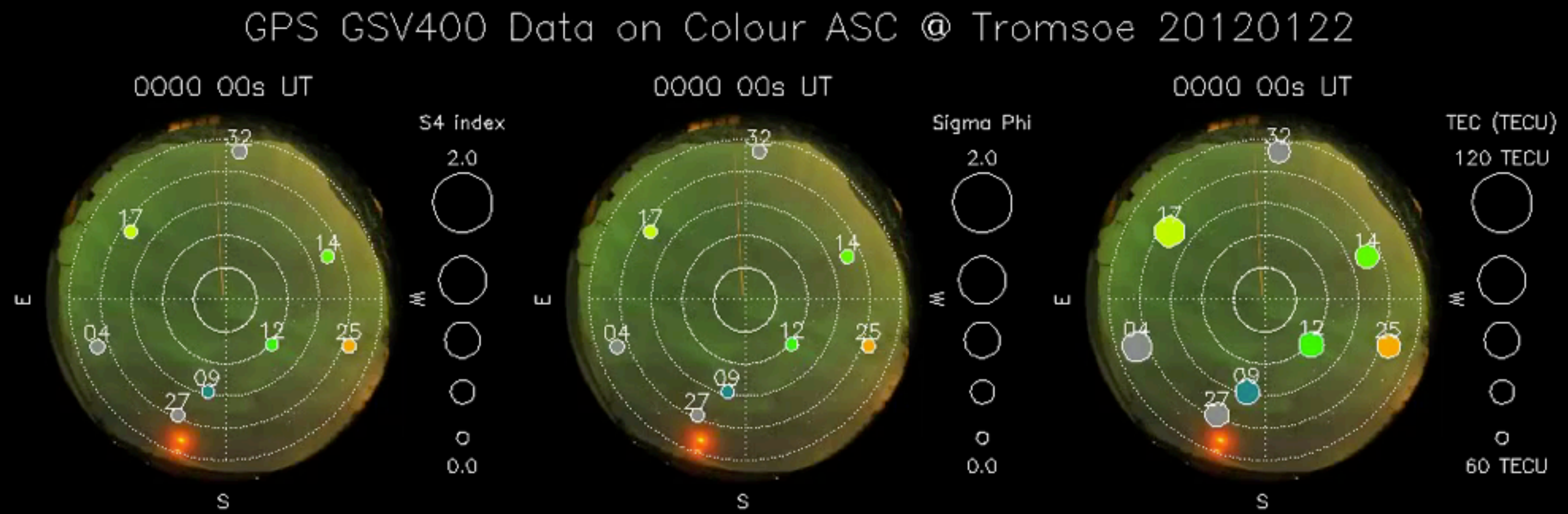
Data on Jan 22, 2012

The size of the circles indicates the intensity of the parameters

S4 index
amplitude scintillation

Sigma phi
phase scintillation

TEC



Summary: GNSS + Space Weather

Two major ionospheric space weather impacts on GNSS

Positioning Error due to enhancement of TEC

$$I_\rho = \frac{40.3\mathrm{TEC}}{f^2}$$

Scintillation effect

1. Phase scintillation
2. Amplitude scintillation