System Science from Above and Below: Past, Present, Future

Anthea J. Coster,

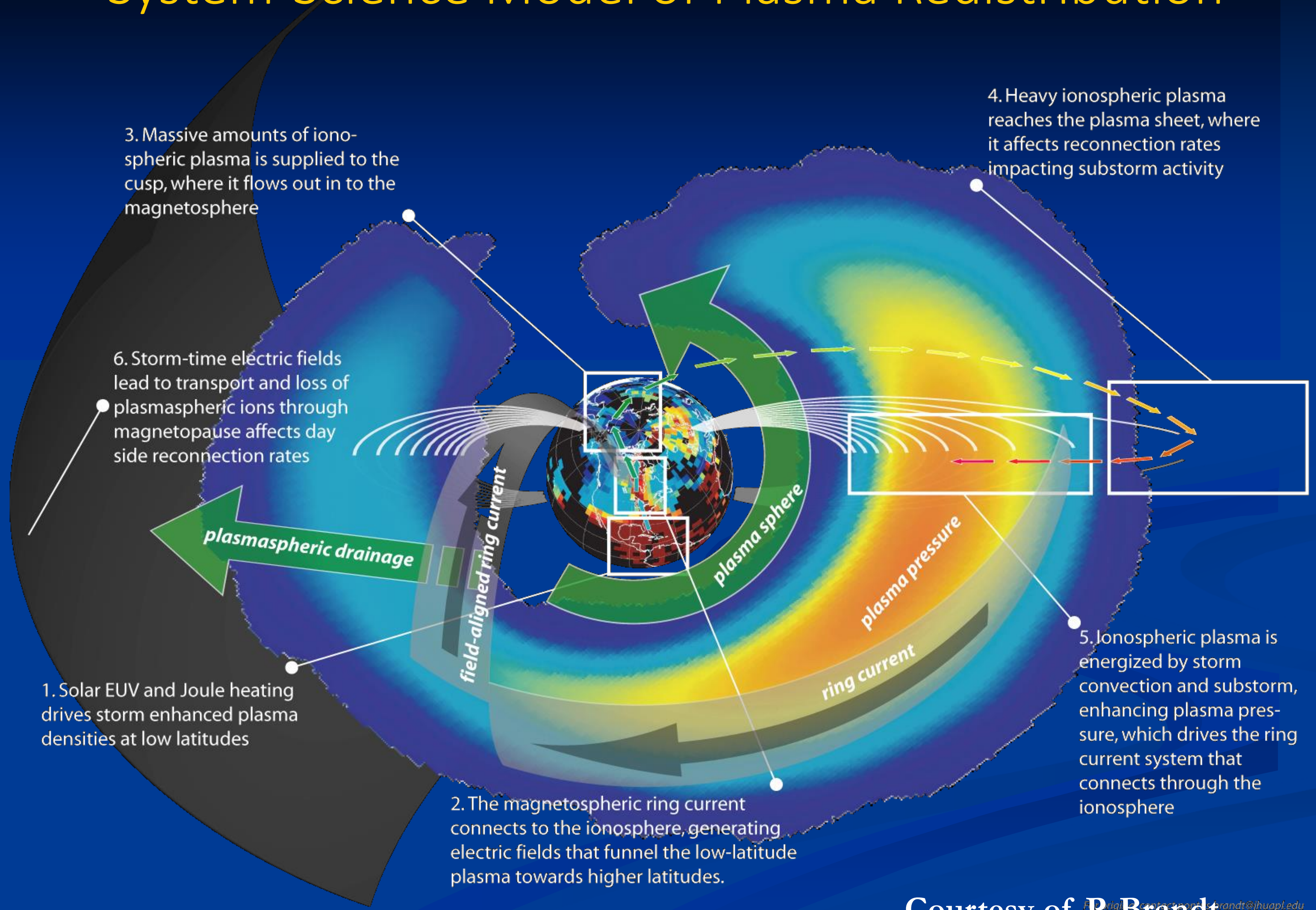
the entire Haystack staff past and present,

the many, many people

I have collaborated with,

and all the GNSS signals

System-Science Model of Plasma Redistribution



Courtesy of P. Brandt

Outline

History – mine

System Science

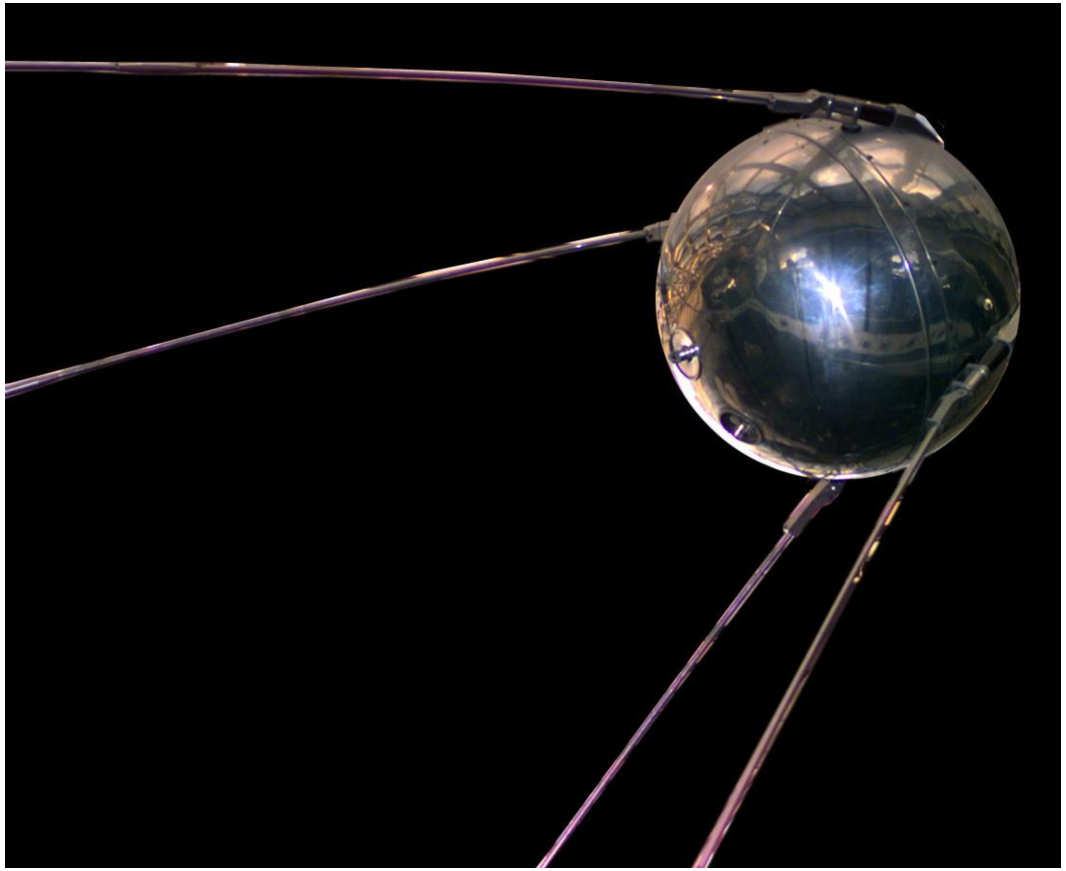
Past (pre and post-GPS)

Current

Future

Space Age – First satellite launched 1957

4,550 satellites in orbit, as of Sept. 1, 2021



SPUTNIK

President Kennedy’s Address at Rice University in 1962 on the Nation's Space Effort

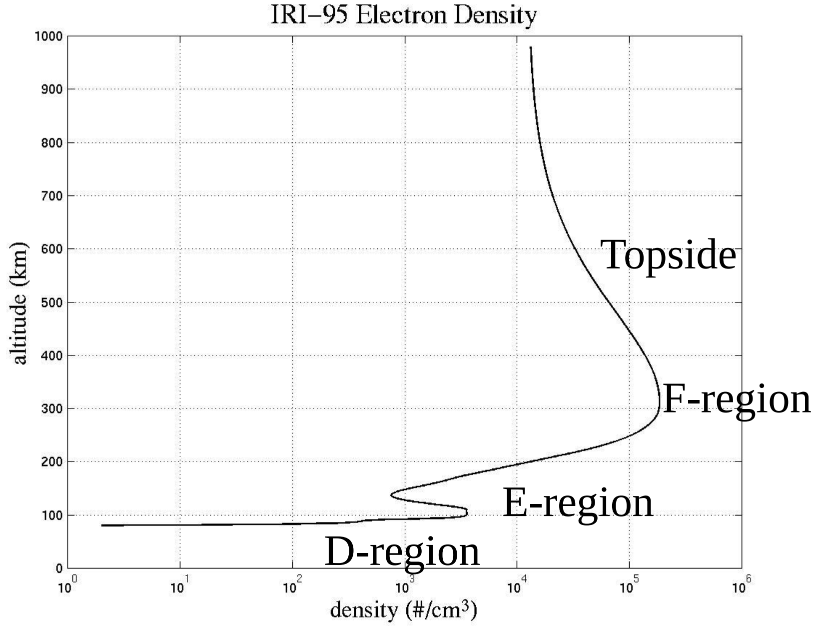
https://www.youtube.com/watch?v=QXqlziZV63k

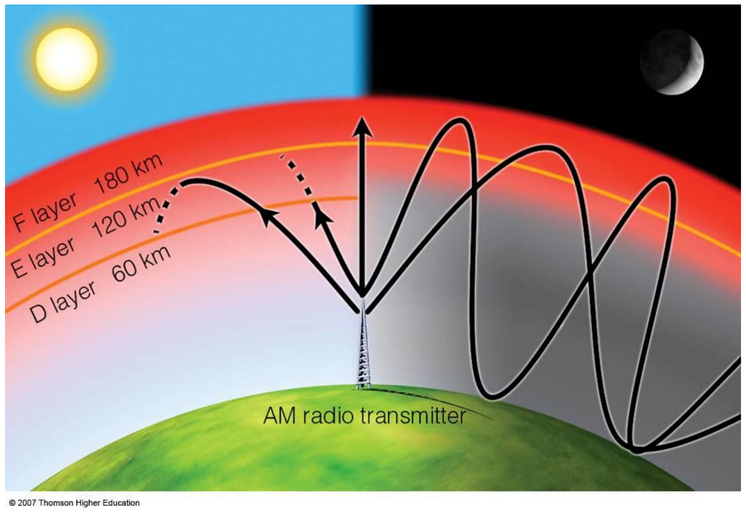
But why, some say, the Moon? Why choose this as our goal? And they may well ask, why climb the highest mountain? Why, 35 years ago, fly the Atlantic? Why does Rice play Texas?

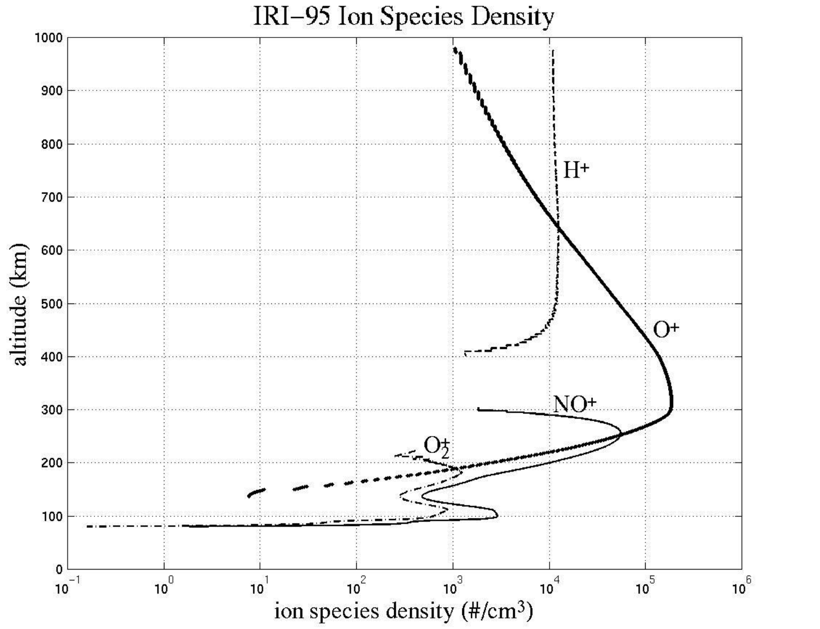
We choose to go to the Moon! ... We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard; because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win ...

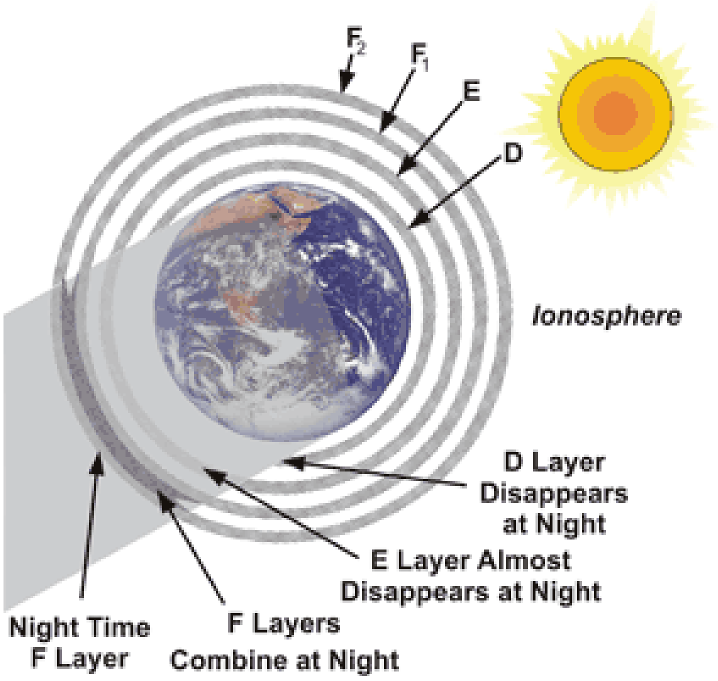
Calculators cost approximately 3 mos. of room and board. Computer programs all done on punch cards.

The Ionosphere









Experience with different radars

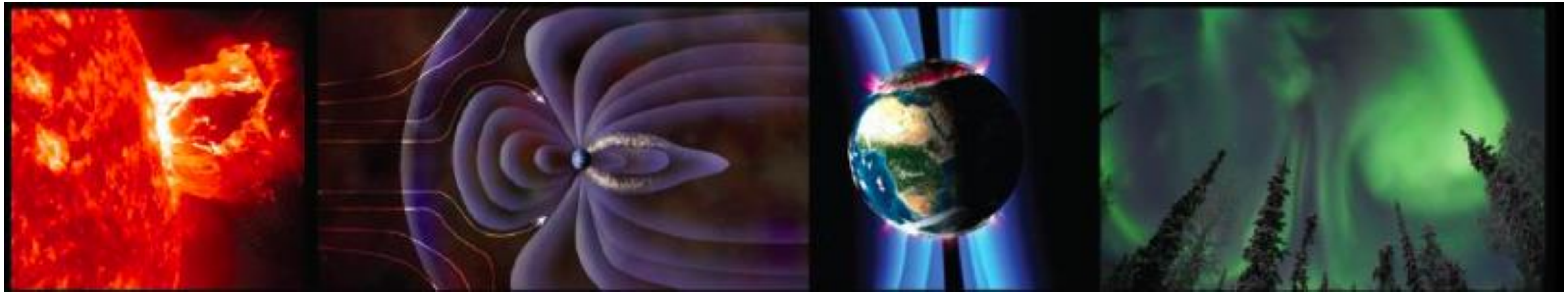
9-track tapes, Calcomp plotters, no personal computers, no word processors

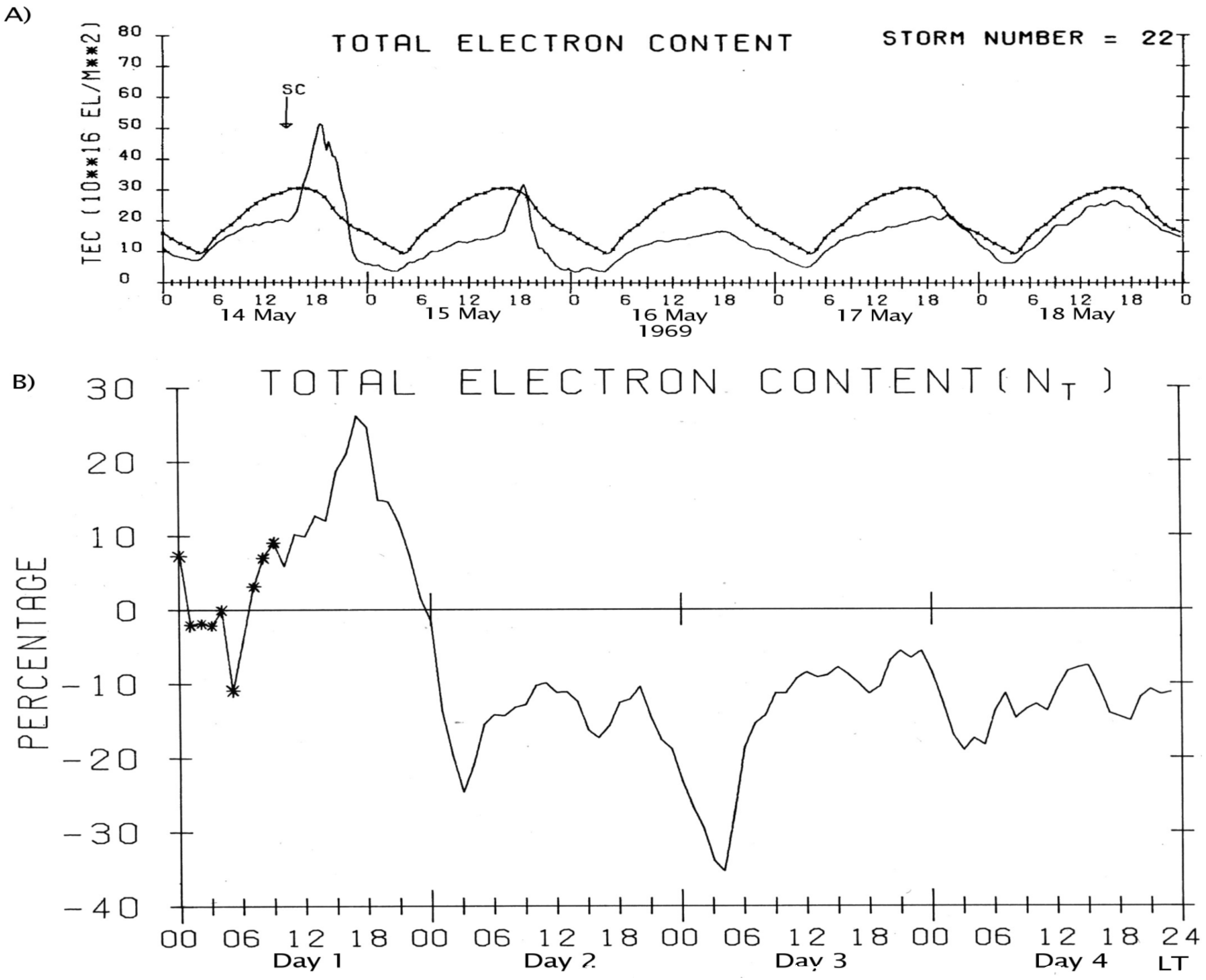
<u>Outline</u>

History – mine

System Science

- **Past (pre [illegible] GPS)**
- **Current**
- **Future**

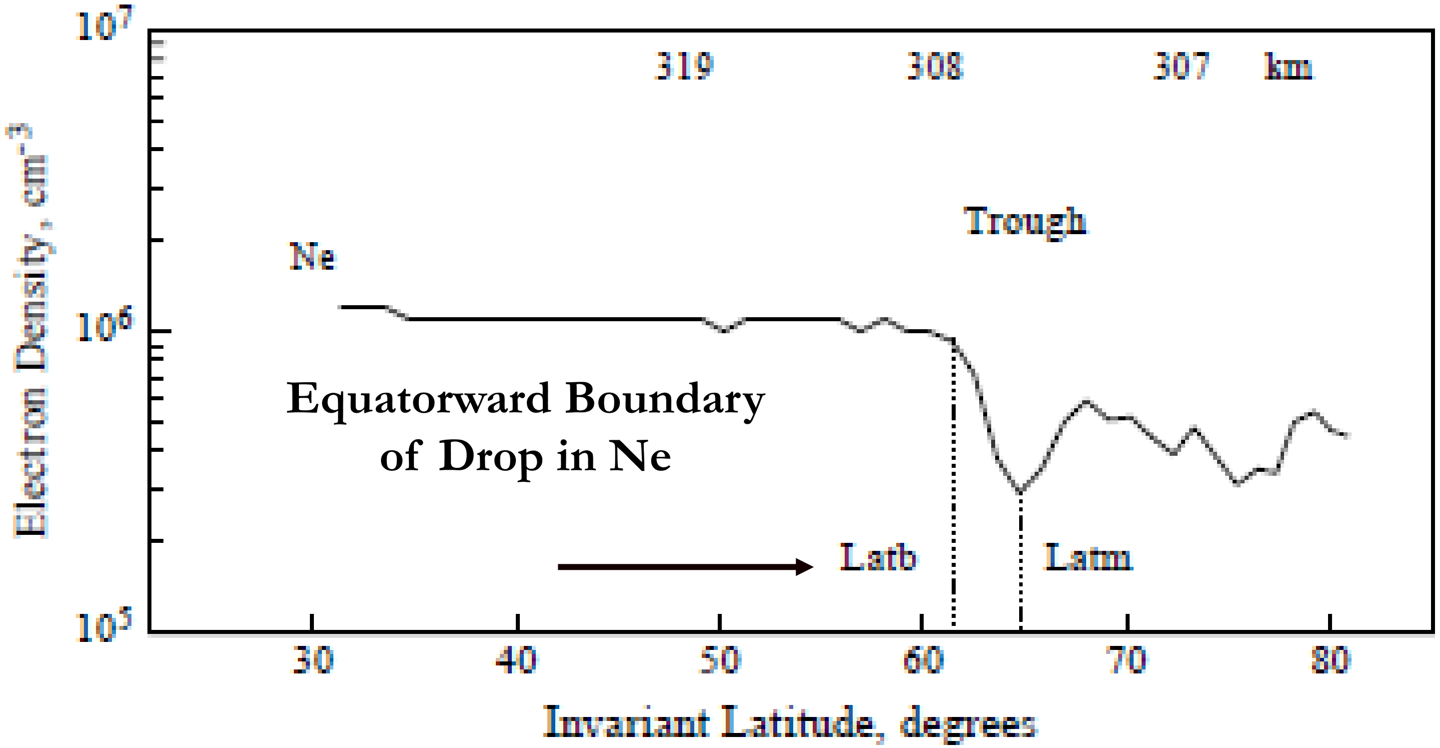




Data Collected at Sagamore Hill, MA using a Faraday Rotation Technique

14 May 1969

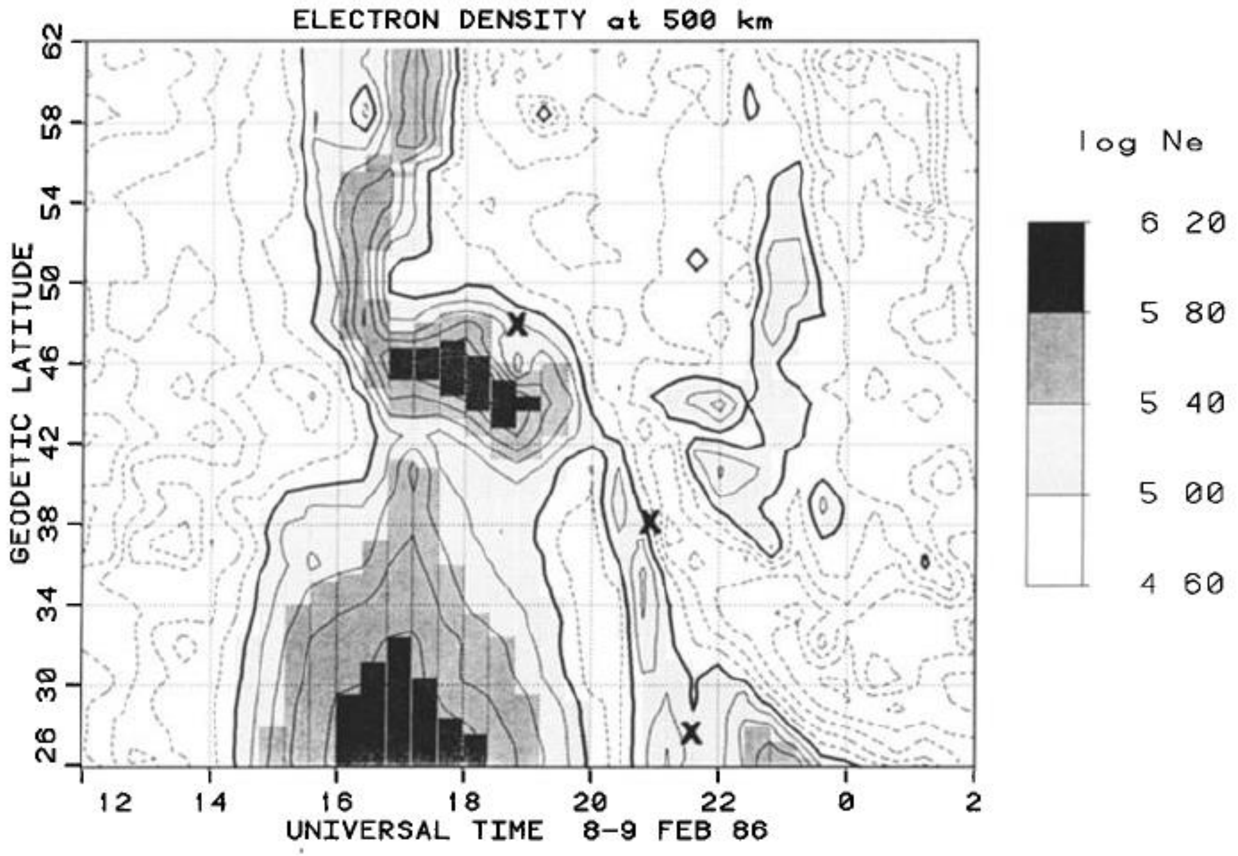
Electron density variation at middle and subauroral latitudes : Trough

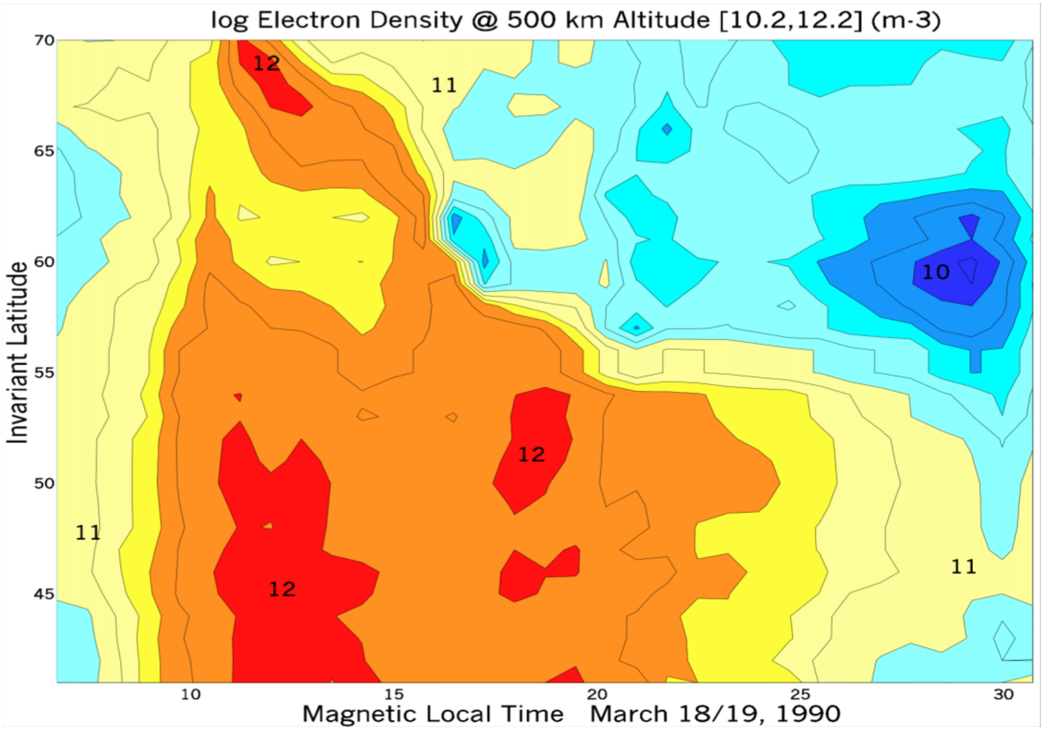


Data from DE 2 satellite in N. hem. 9 Dec 1981 at 7.6 UT (6 pm local).

Prolss, Ionospheric Storms at Mid-Latitudes: A Short Review MIDD

Early Storm Enhanced Density Measurement, 1986 and 1990





Foster, J. C. (1993), Storm time plasma transport at middle and high latitudes, *J. Geophys. Res.*, 98(A2), 1675– 1689, doi:10.1029/92JA02032.

Outline

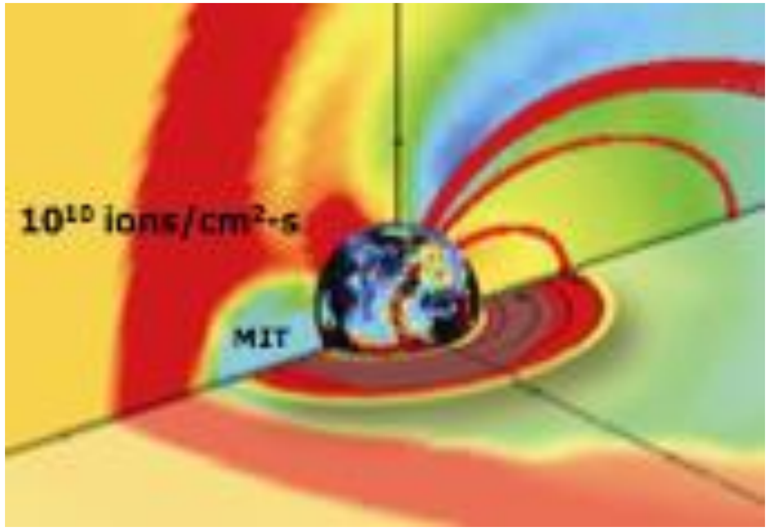
History – mine

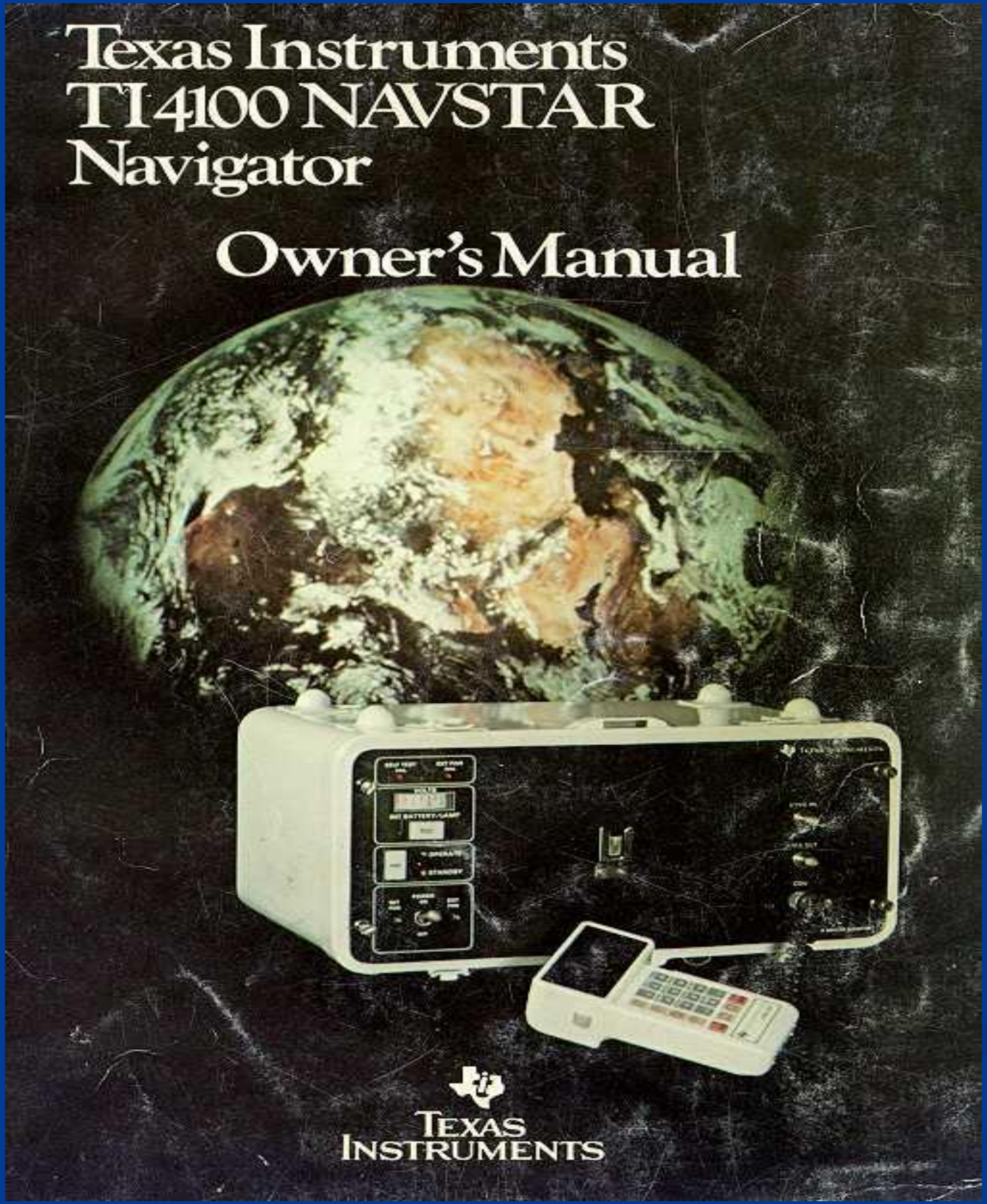
System Science

Past → **GPS era**

Current

Future

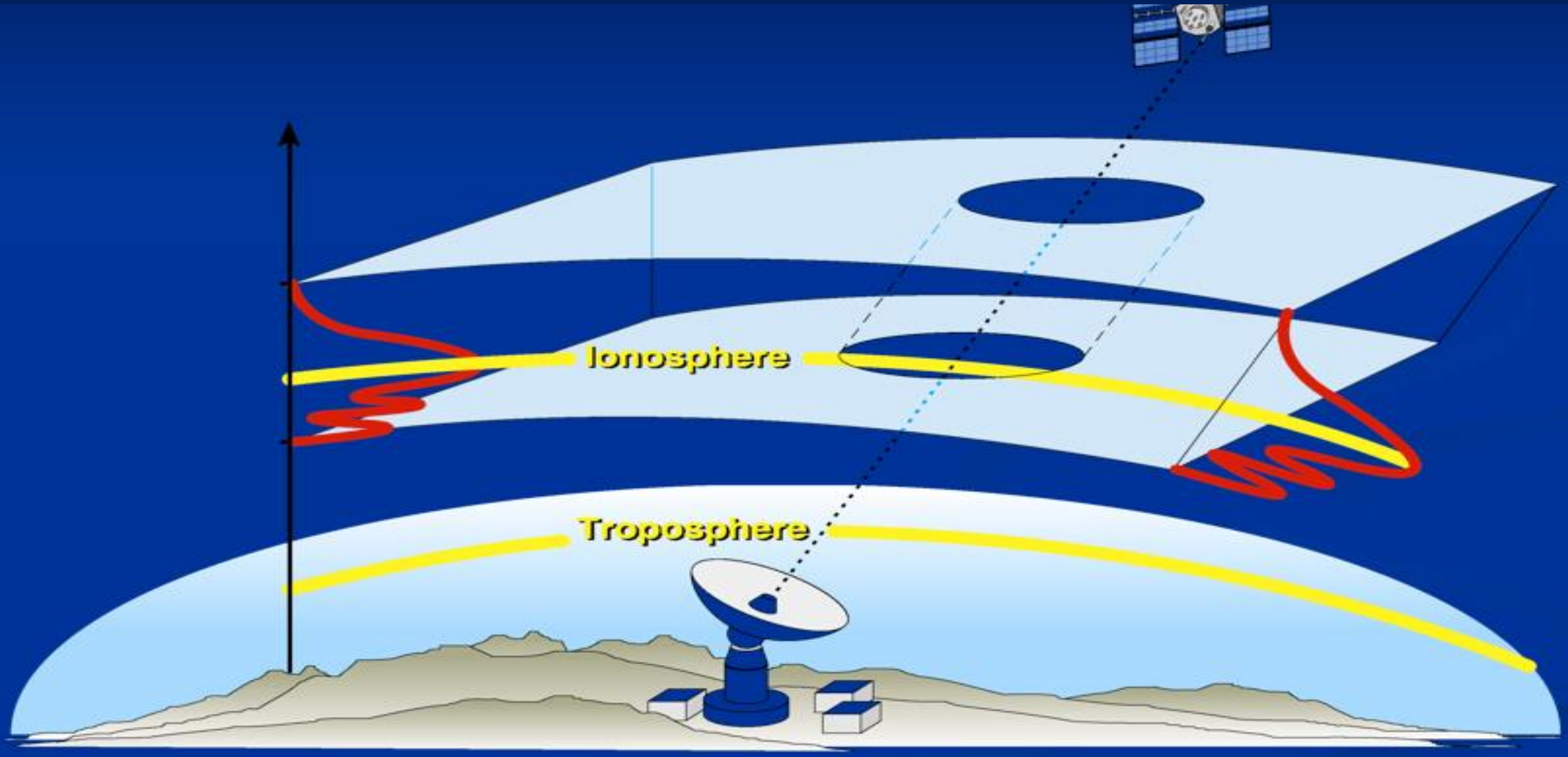




$150,000 with the MIT discount in 1985.

Could only track 4 satellites at a time.

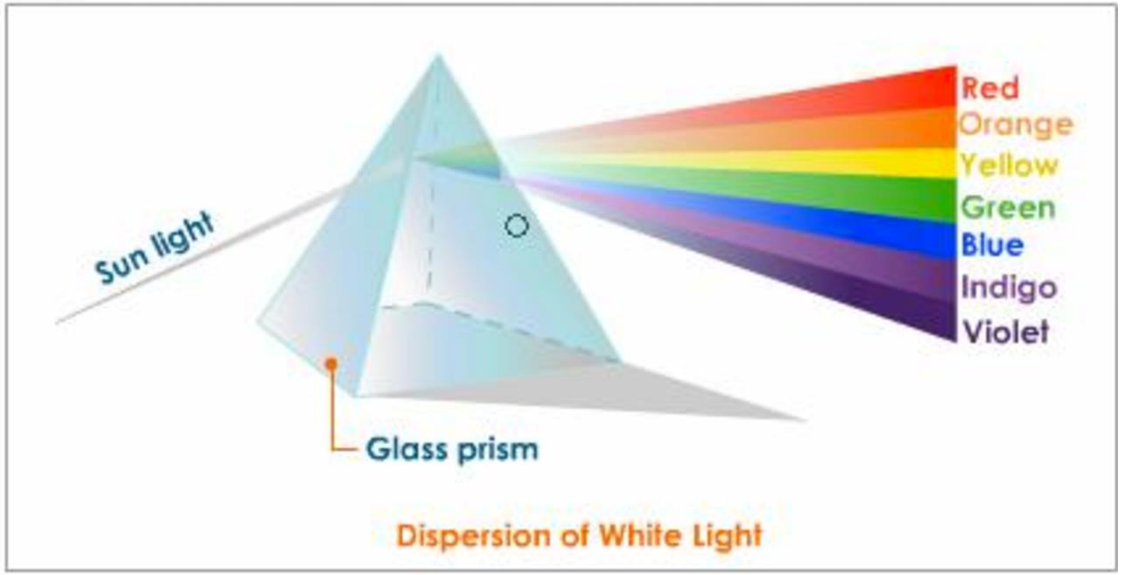
Satellites transmit/receive radio wave signals that propagate through the atmosphere



From Attila Komjathy, JPL

Refraction and Dispersion

$$n = \frac{c}{v_{\mathrm{p}}}.$$



Appleton-Hartree Equation

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{\frac{1}{2}Y^2\sin^2\theta}{1-X-iZ} \pm \frac{1}{1-X-iZ}\left(\frac{1}{4}Y^4\sin^4\theta + Y^2\cos^2\theta\,(1-X-iZ)^2\right)^{1/2}}$$

or, alternatively[4]:

$$n^2 = 1 - \frac{X(1-X)}{1 - X - \frac{1}{2}Y^2\sin^2\theta \pm \left(\left(\frac{1}{2}Y^2\sin^2\theta\right)^2 + (1-X)^2\,Y^2\cos^2\theta\right)^{1/2}}$$

n = complex refractive index

$i = \sqrt{-1}$

$X = \frac{\omega_0^2}{\omega^2}$

$Y = \frac{\omega_H}{\omega}$

$Z = \frac{\nu}{\omega}$

ε_0 = permittivity of free space

μ_0 = permeability of free space

B_0 = ambient magnetic field strength

e = electron charge

m = electron mass

θ = angle between the ambient magnetic field vector and the wave vector

ν = electron collision frequency

$\omega = 2\pi f$ (radial frequency)

f = wave frequency (cycles per second, or Hertz)

$\omega_0 = 2\pi f_0 = \sqrt{\frac{Ne^2}{\epsilon_0 m}}$ = electron plasma frequency

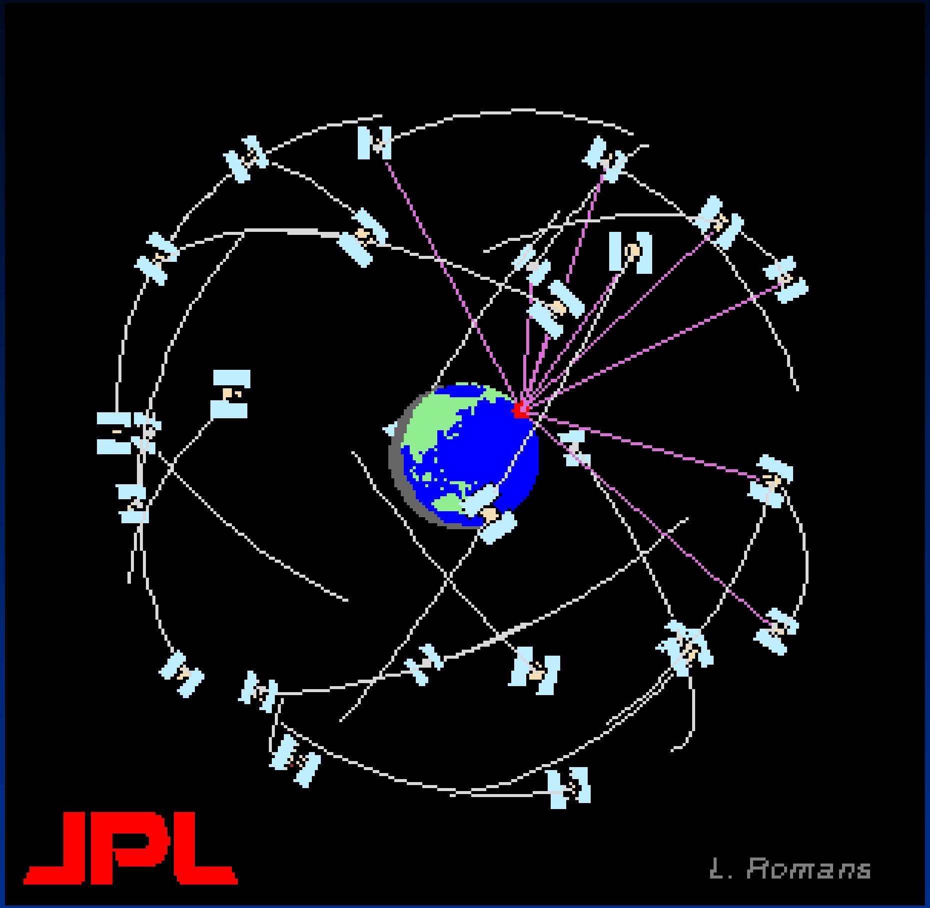
$\omega_H = 2\pi f_H = \frac{B_0|e|}{m}$ = electron gyro frequency

Definition:

TEC = Total Electron Content $(10^{16} \times el/m^{2})$

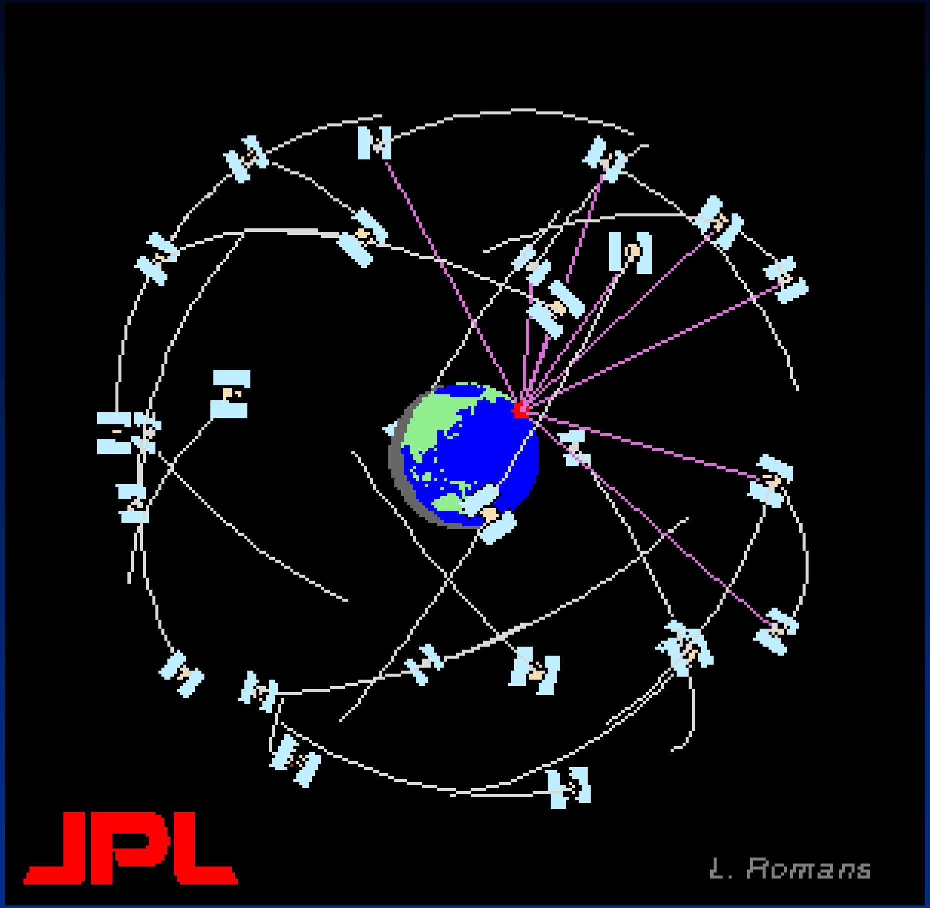
$$\Delta R_{ion}(meters) = \frac{40.3}{f^2}\,TEC$$


Courtesy
Jonathan Makla



GPS Background

- At most 32 satellites
- 6 orbital planes
- 4~6 satellites per plane
- 55º inclination angle
- near circular orbit
- ~ 20000 km altitude
- ~12 hours round trip
  (11 hour 58 min 2.05 sec)

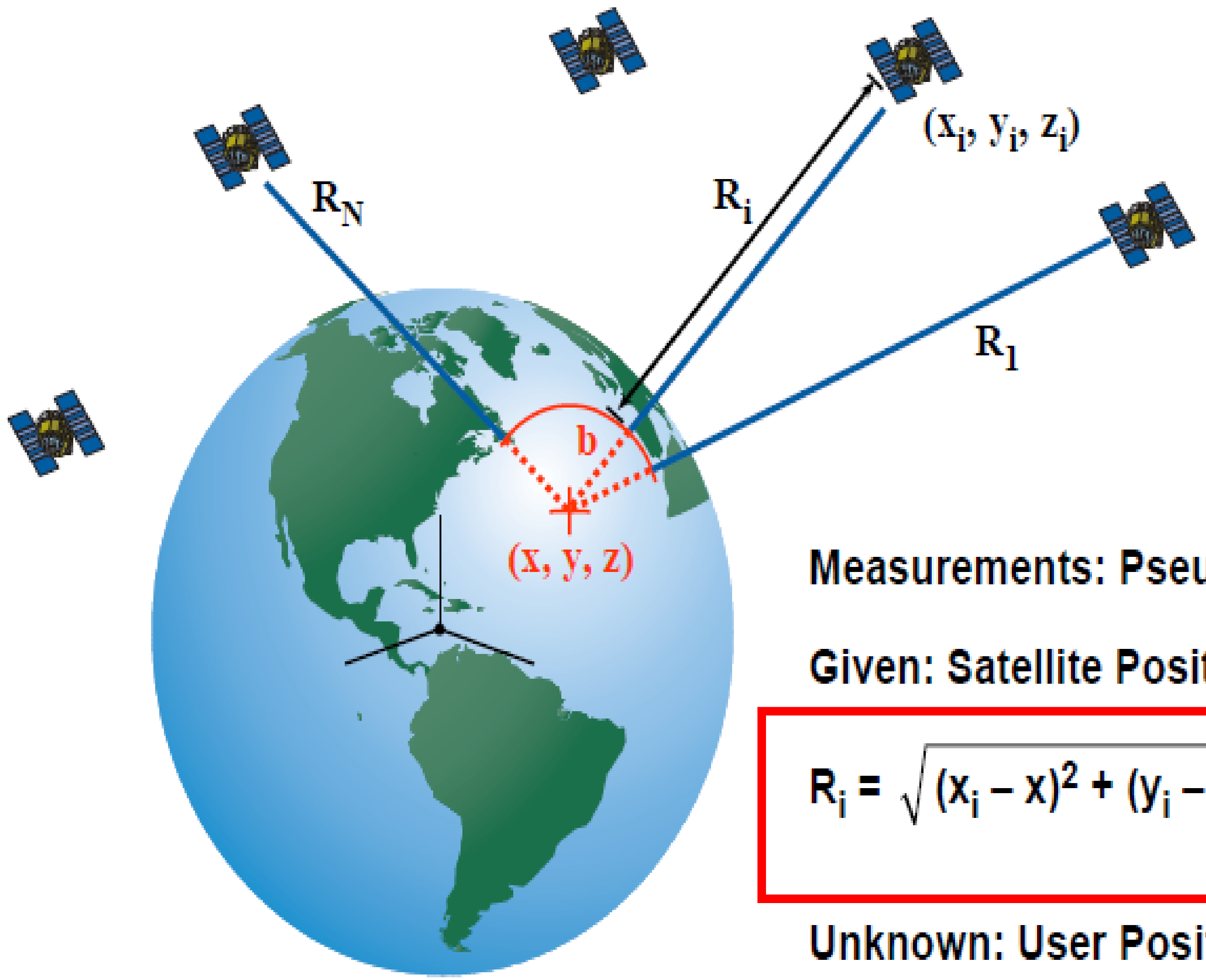


GPS Background

Each GPS spacecraft:

- **Carries highly accurate clock**
- **Transmits its clock and position**
- **Signals are transmitted on 2 (or 3) frequencies**
- **First satellites launched in 1978**
- **Fully operational in 1995 (19 in 1991)**

GPS Positioning



Error Sources:
- Ephemeris Error
- GPS Clock Error
- Receiver Noise
- Multipath
- Atmosphere:
  - Troposphere
  - Ionosphere

Measurements: Pseudoranges $\{R_i\}$

Given: Satellite Positions $\{(x_i, y_i, z_i)\}$

$$\boxed{R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - b, \quad i = 1, 2, \ldots, N}$$

Unknown: User Position (x, y, z)
Receiver Clock Bias b

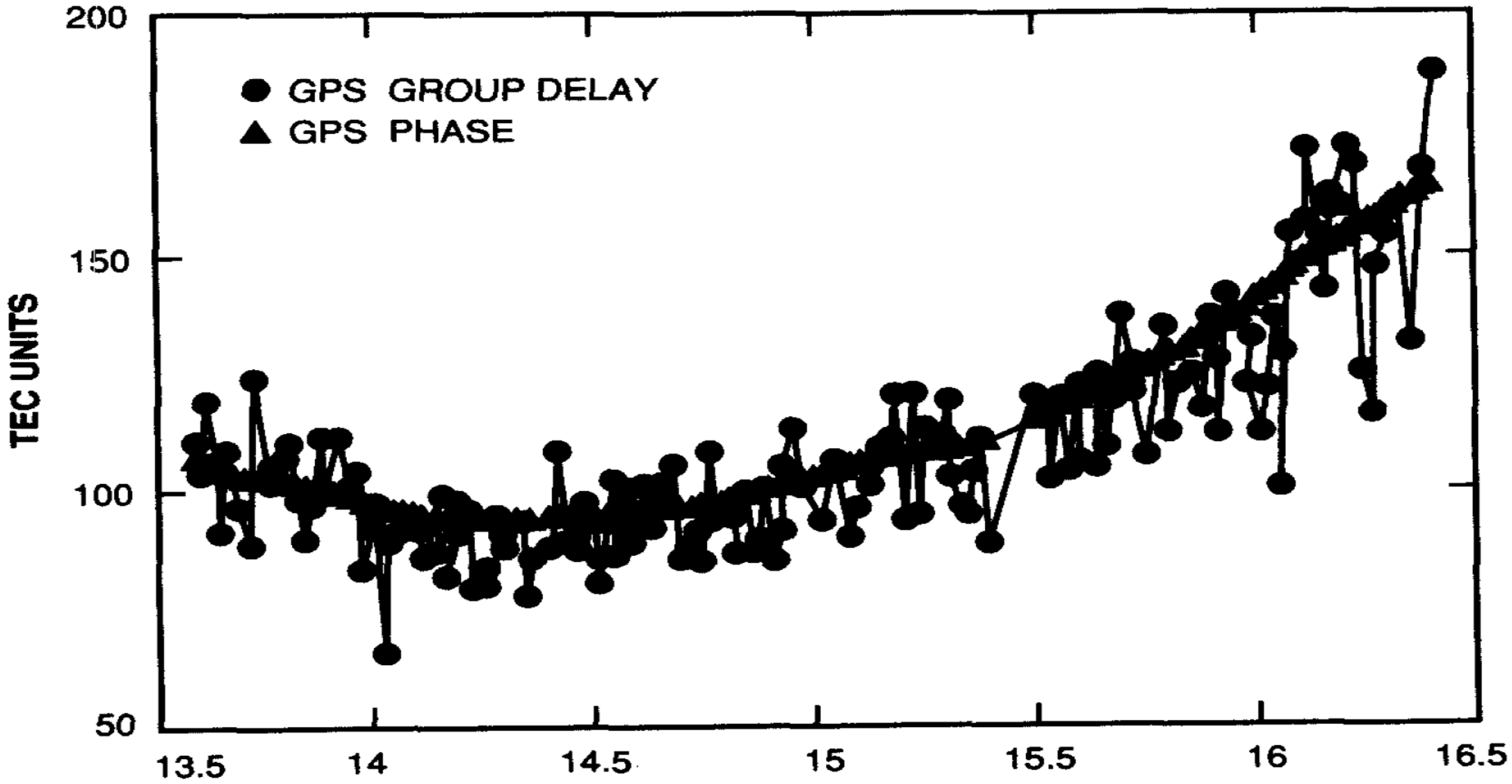
TEC from GPS is measured from the difference of the GPS pseudo-range measurement at two frequencies

$$P_1 - P_2 = 40.3TEC\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right)$$

$$TEC = \frac{1}{40.3}\left(\frac{f_1 f_2}{f_1 - f2}\right)(P_2 - P_1)$$

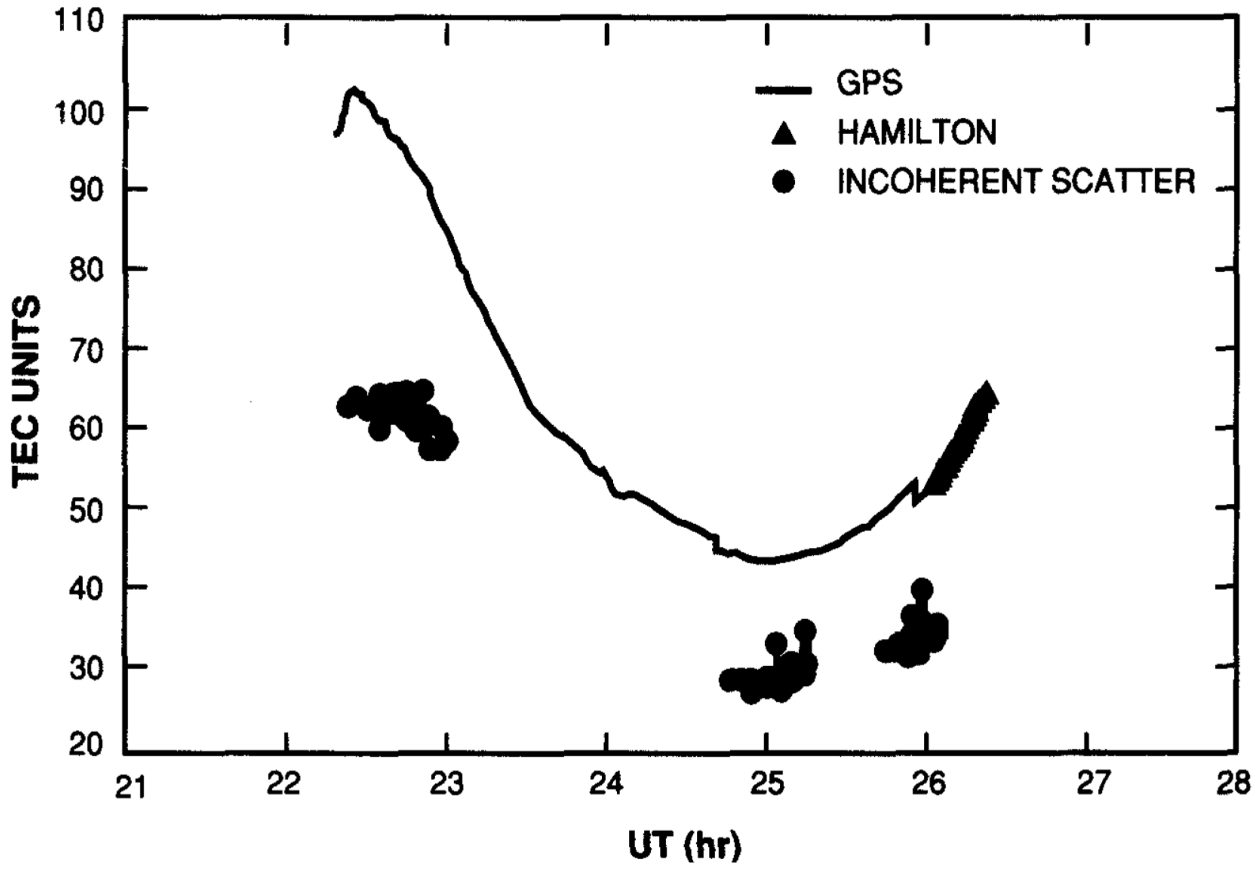
Where P1 and P2 are the pseudo-ranges measured by GPS at the two different frequencies, f1 and f2.

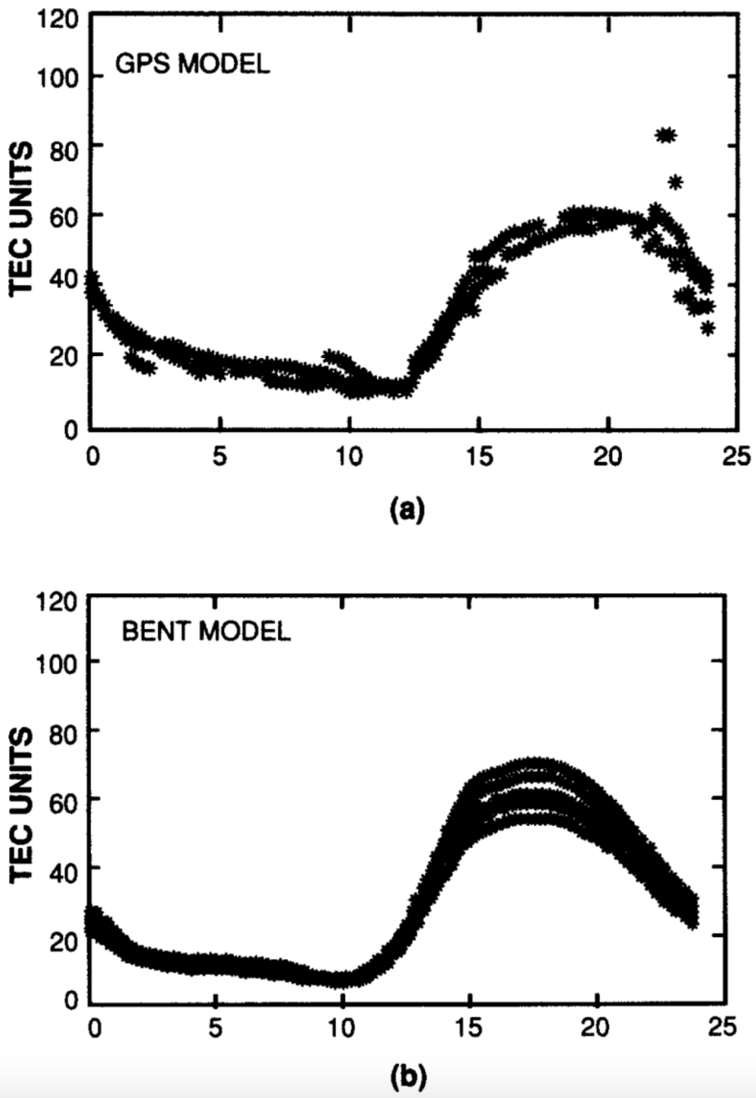
Illustration of GPS Phase and Group Delay TEC data. GPS Sv 6. 1 March 1989



Coster, A. J., E. M. Gaposchkin, and L. E. Thornton, (1992). Real-Time Ionospheric Monitoring System Using GPS, Navigation, Vol. 39, No.2, Summer 1992.

TEC Measurements GPS Sat. 6 27 April 1990





Coster, A. J., E. M. Gaposchkin, and L. E. Thornton, (1992). Real-Time Ionospheric Monitoring System Using GPS, Navigation, Vol. 39, No.2, Summer 1992.

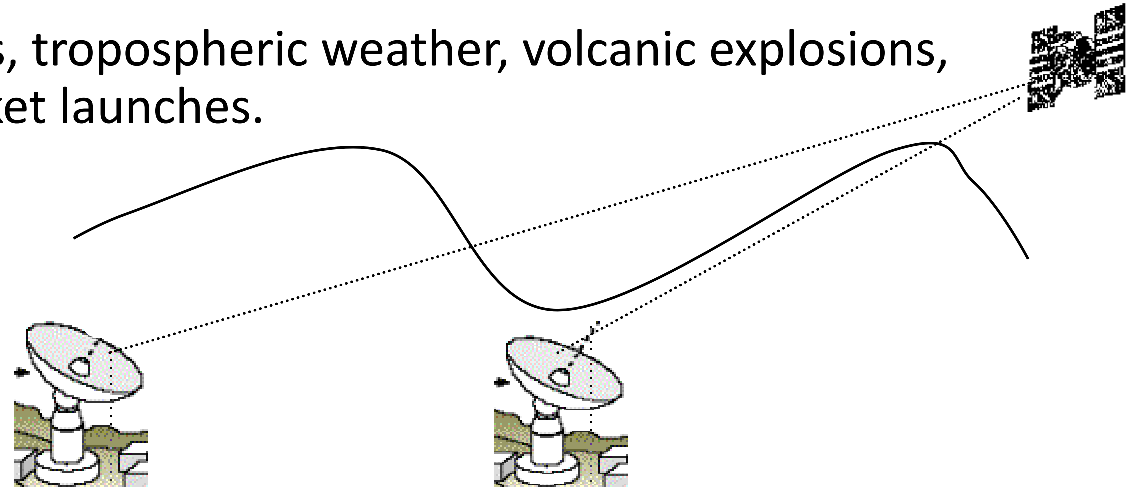
Travelling Ionospheric Disturbances (TIDs)

Differential Ionospheric Errors greater than 34 cm
(2 TEC units) are problematic.

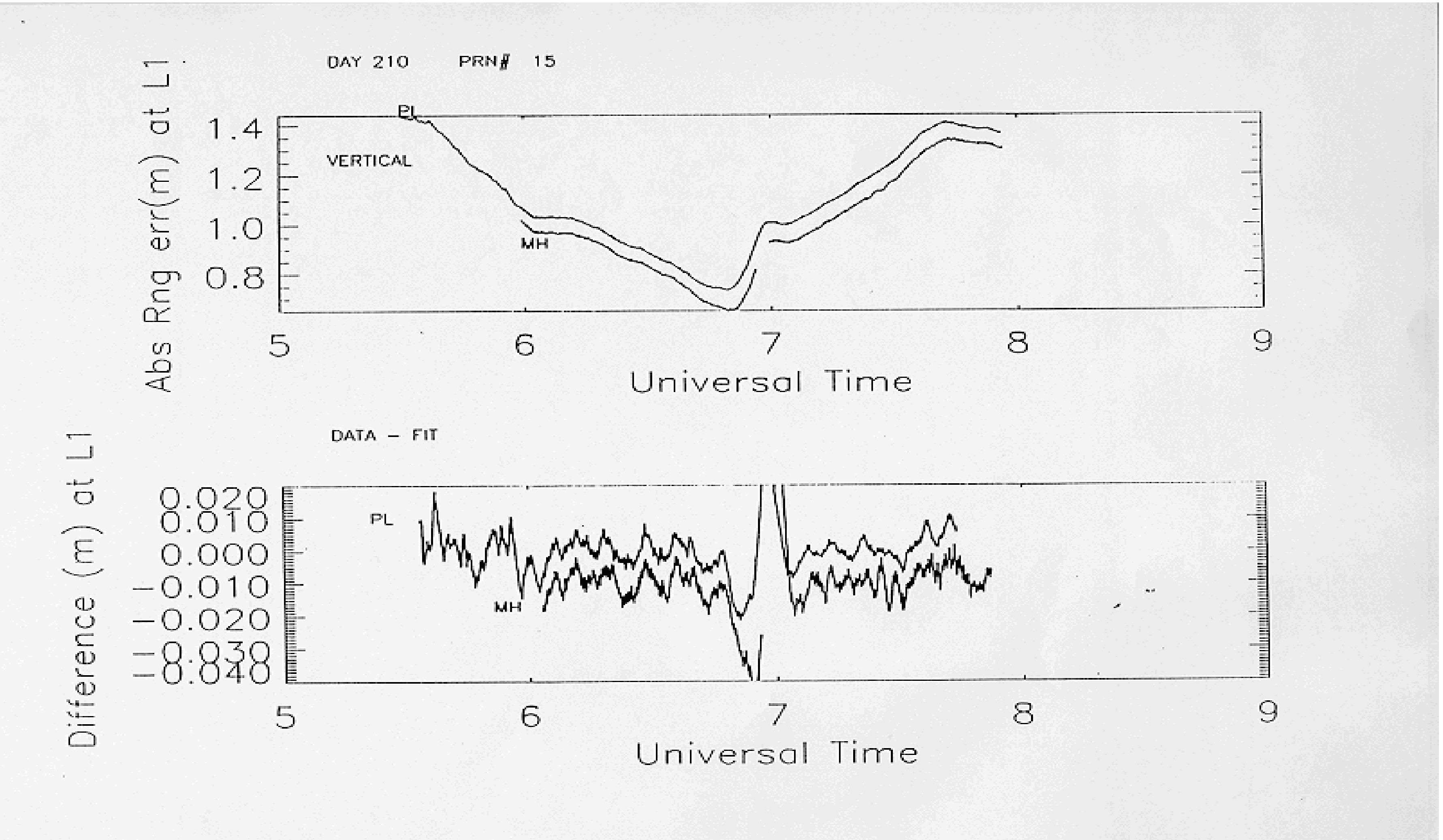
- TIDS are short-term variations in the TEC, covering a large range of periods and amplitudes.

  Originate either:

  - in auroral regions (associated with geomagnetic disturbances (high Kp).
  - Or not. These are generated by unknown sources,possibly:
    - atmospheric tides, tropospheric weather, volcanic explosions, earthquakes, rocket launches.

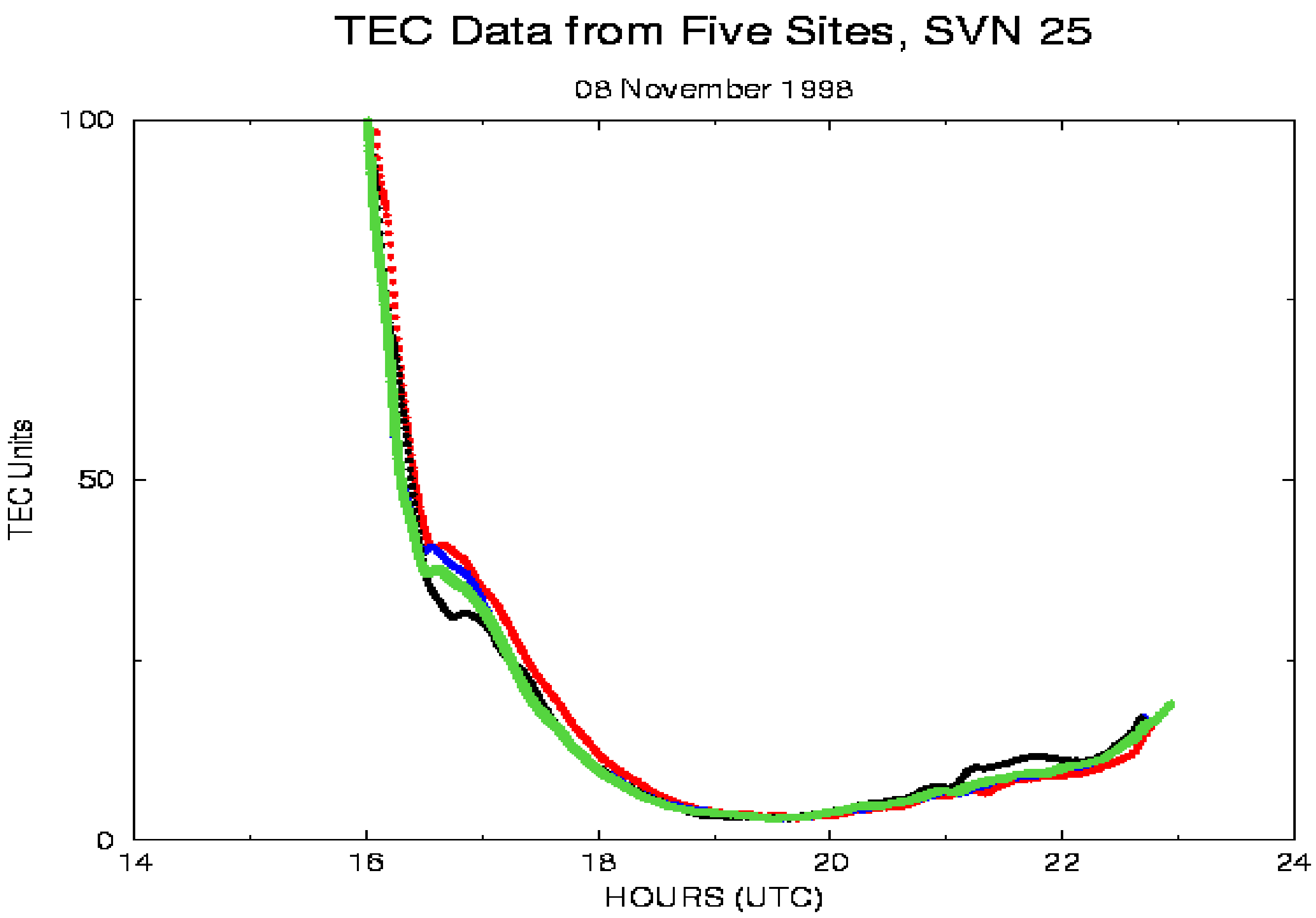


Historical GPS TID Data: 1991
(near solar maximum)

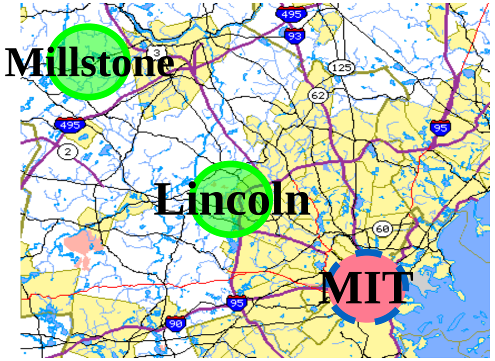


Anthea Coster and Patricia Doherty

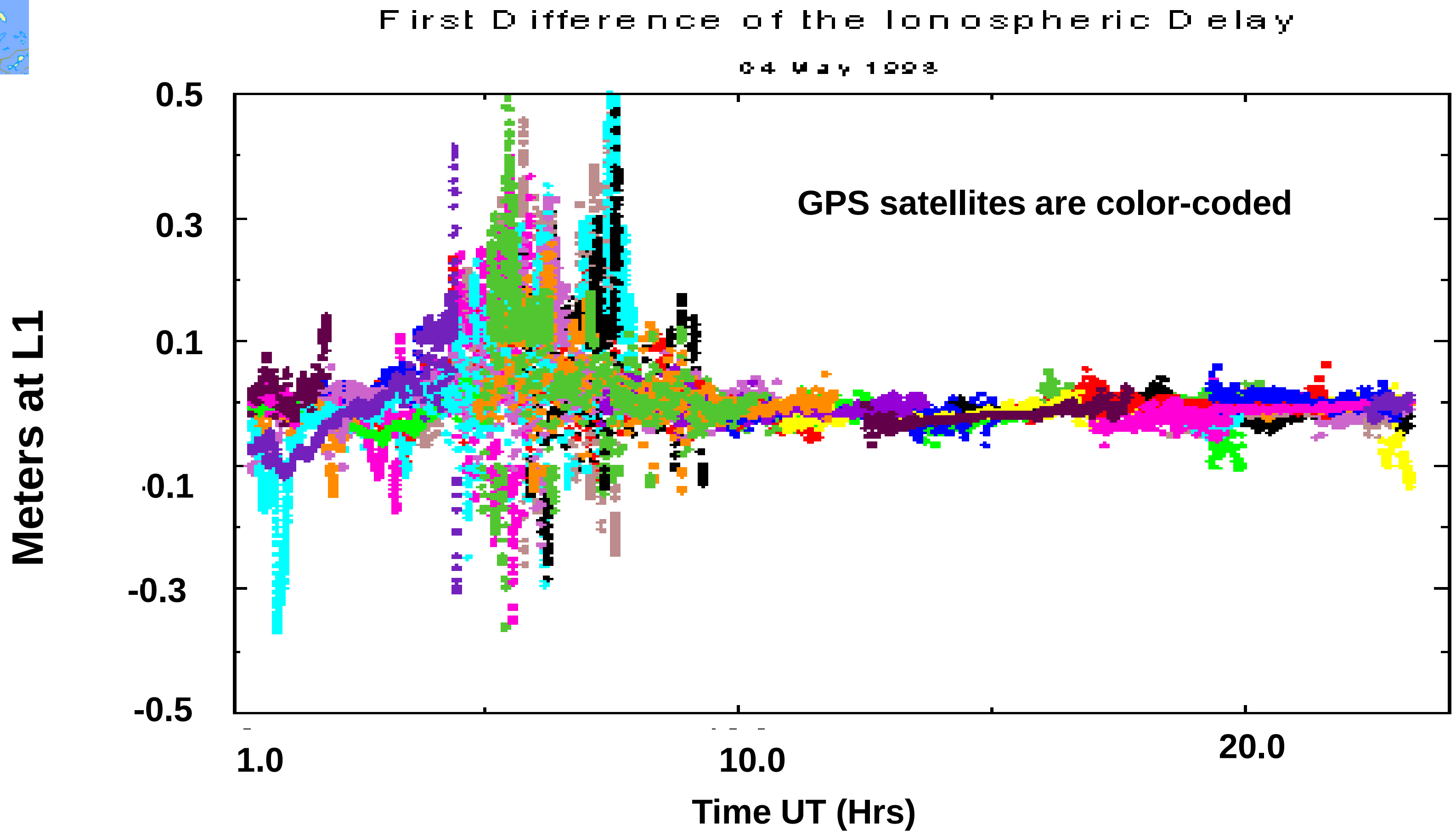
TEC DATA measured from Five Sites



4 May 1997: Kp = 9 (Geomagnetic Storm)



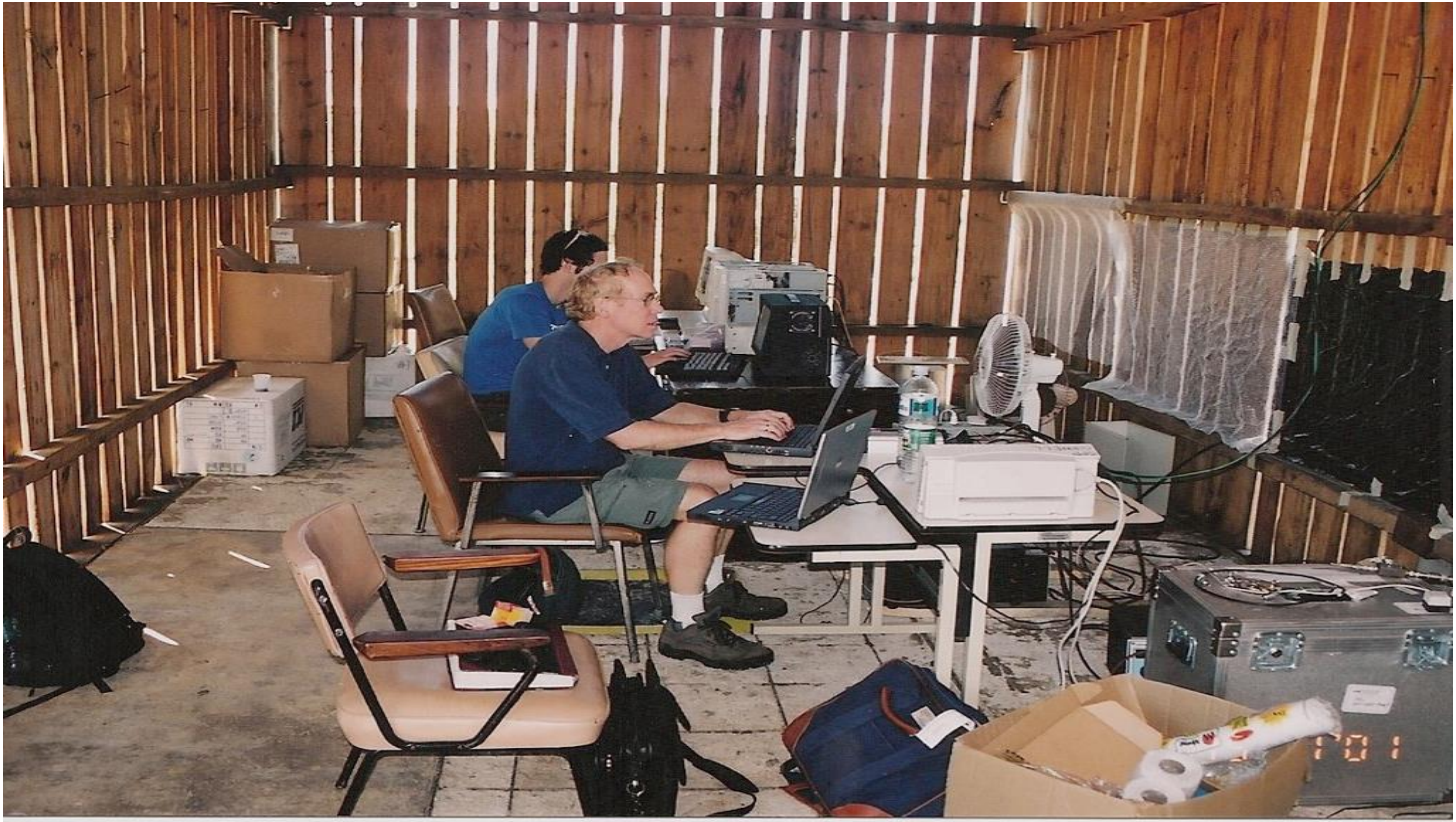
First Difference of Ionospheric Delay



In the 1990’s very few (if any) AGU/CEDAR scientists using GPS TEC data.

Starting in the mid-1990’s, we started organizing yearly sessions at URSI/USNC on “GPS and the ionosphere.”

It became a personal goal of mine to see that GPS data was more utilized by the atmospheric science community.



IGS: International GNSS Service

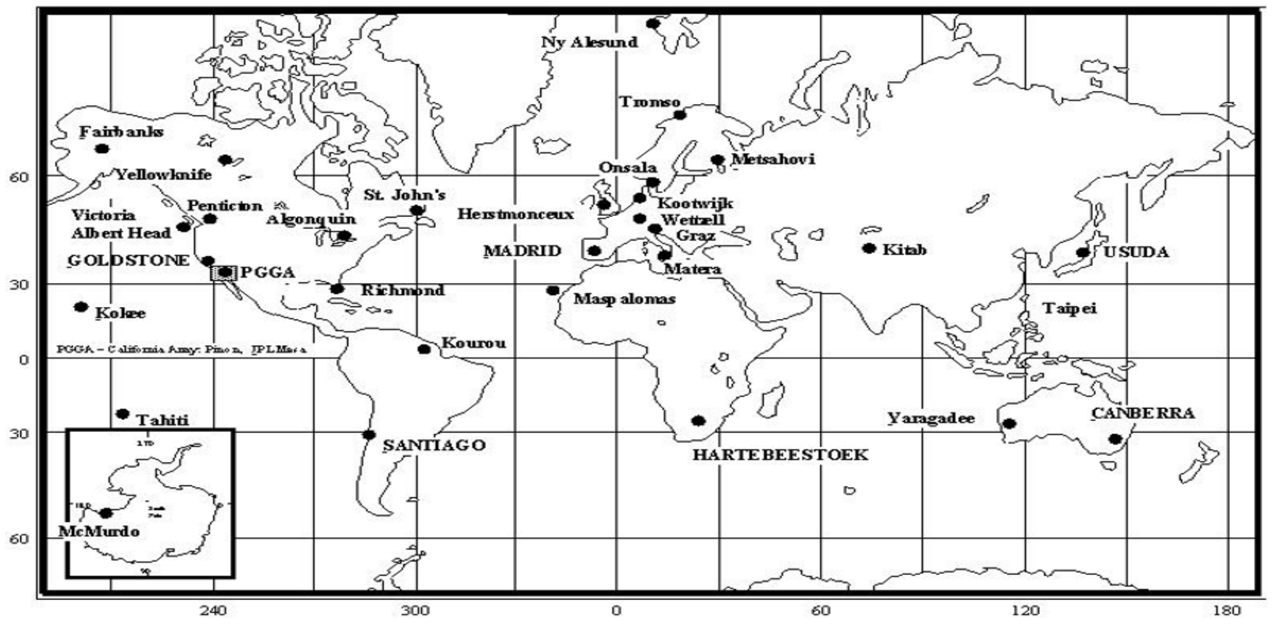
The creation of the IGS was **initiated in 1989** and became an **official International Association of Geodesy service** in 1994.

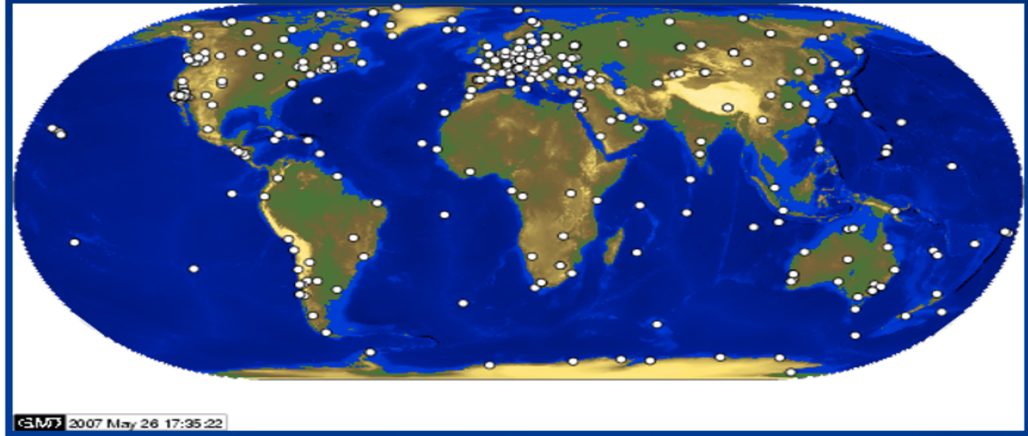
Early user of internet.

Stressed importance of standardized products, freely accessible on the internet.

The **IGS Central Bureau** is located in the USA at JPL. Today the IGS is an **interdisciplinary service in support of Earth Sciences and Society** committed to use of the data from all GNSS.

IGS Development





IGS Network in 2007

In 1992 the IGS was based on about 20 geodetic receivers, 400+ receivers are active and their data retrievable today

Based on this data JPL scientists first developed mapping of TEC across the US

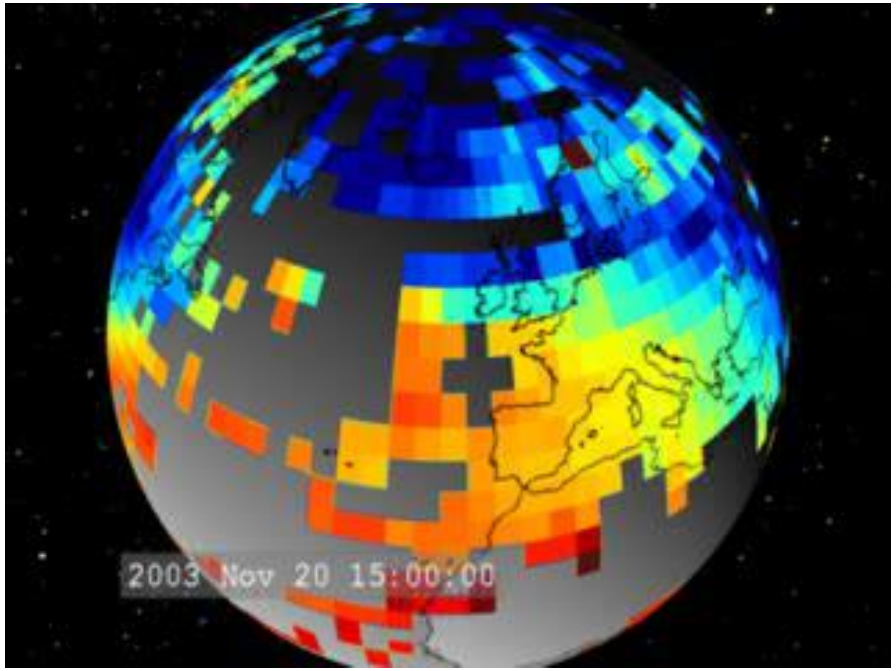
First maps small network 1991, US 1993

Outline

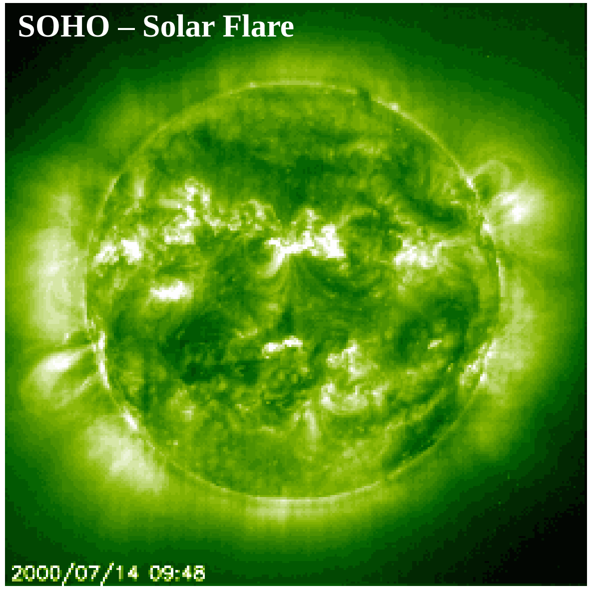
History – mine

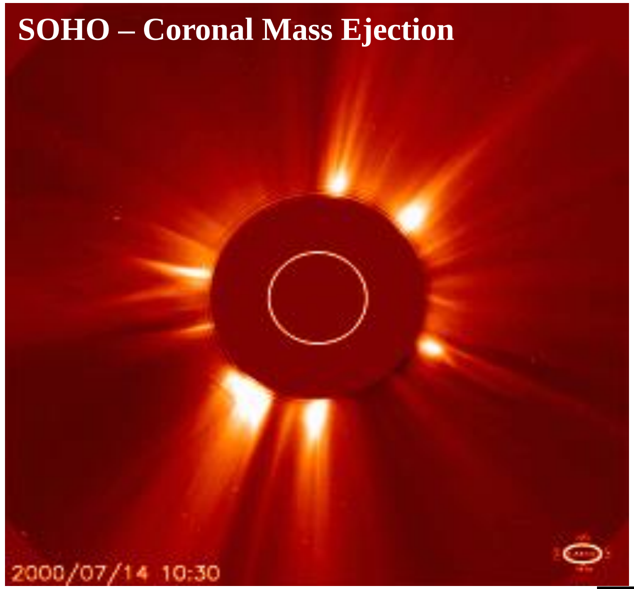
System Science

- **Past (pre and post-GPS)**
- **Current (2000-now)**
- **Future**



Solar Flare of 14 July 2000

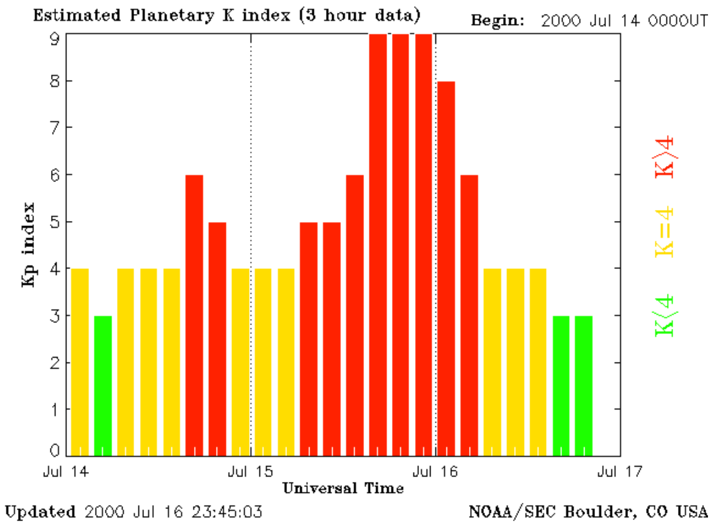


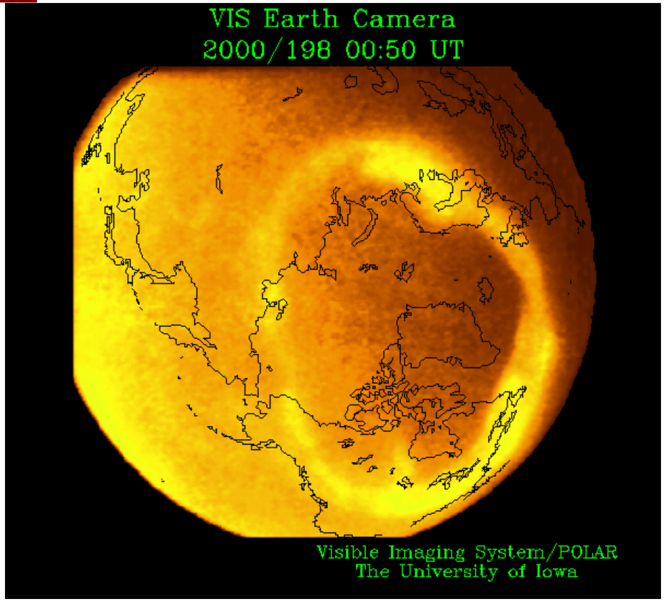


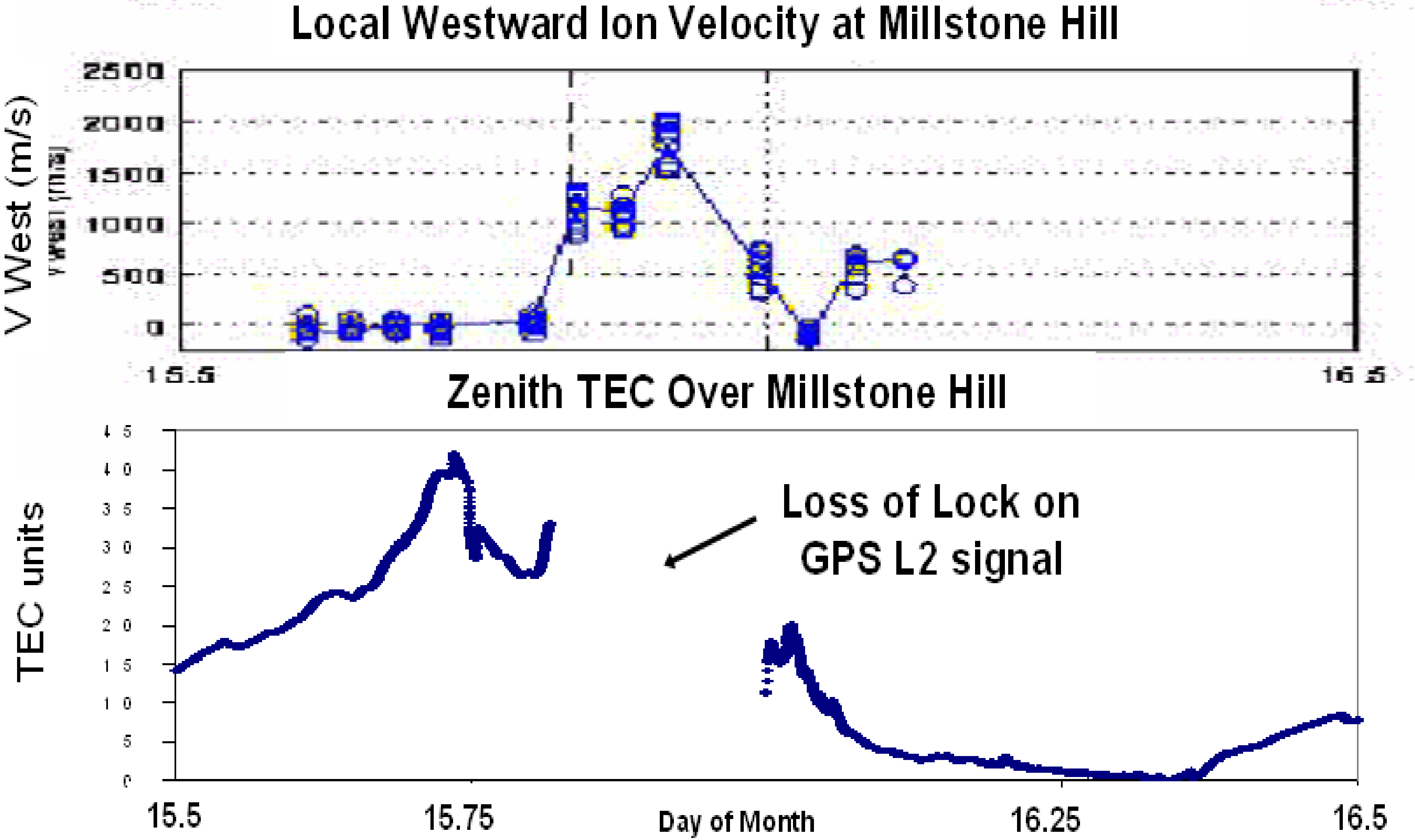
Solar Flare of 14 July 2000

Biggest Solar Storm in Nine Years

Caused very large magnetic storm and ionospheric effects

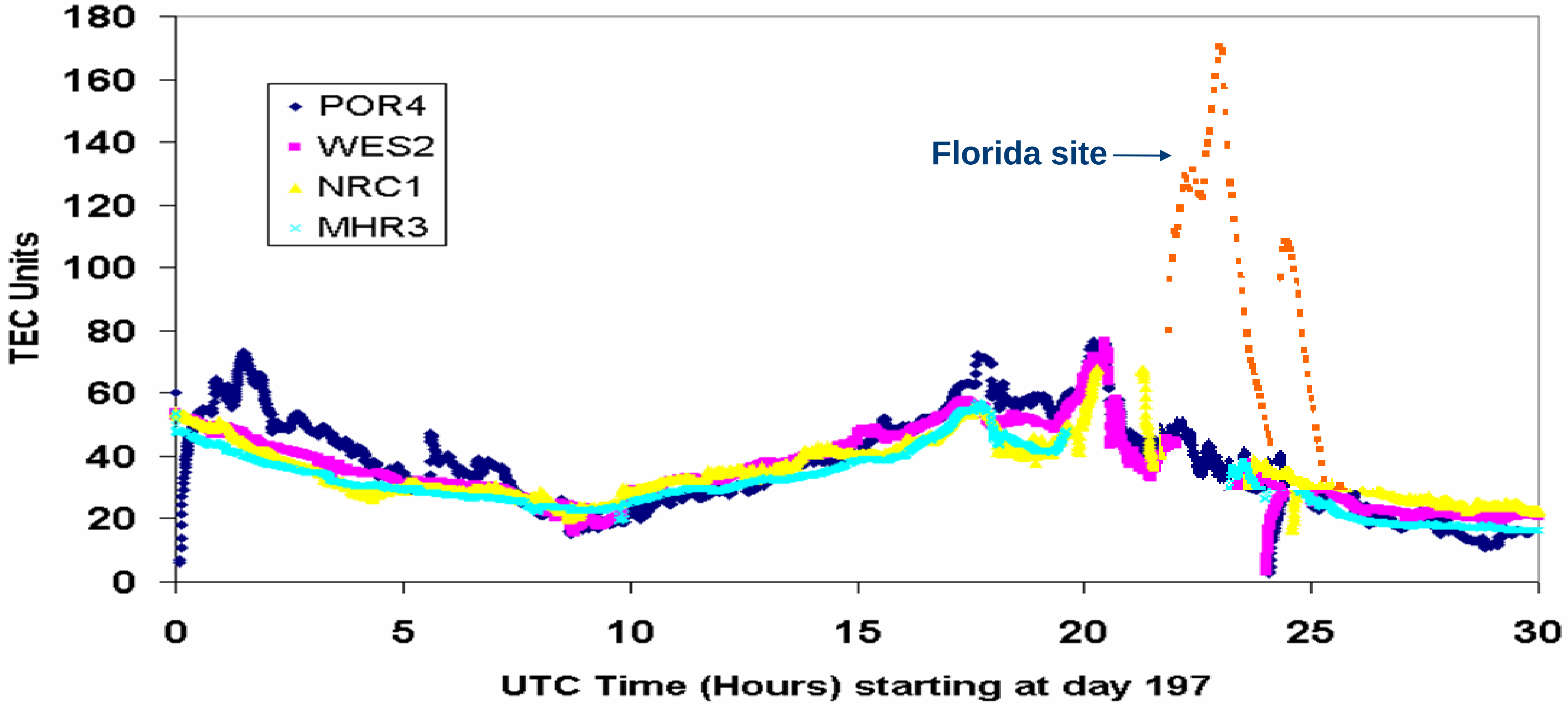






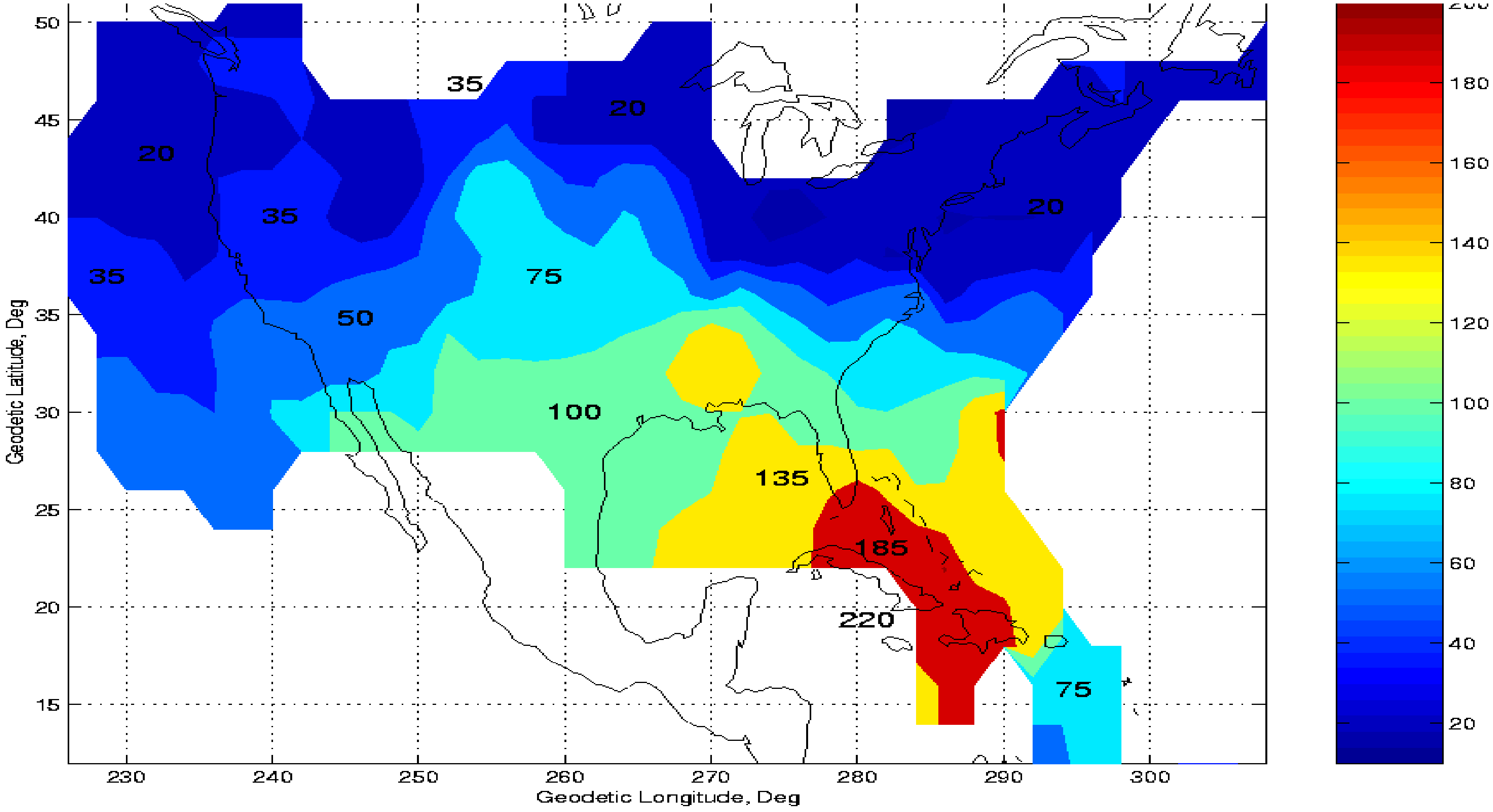
Local Westward Ion Velocity at Millstone Hill
V West (m/s)
2500
2000
1500
1000
500
0
15.5
16.5
Zenith TEC Over Millstone Hill
TEC units
45
40
35
30
25
20
15
10
5
0
Loss of Lock on GPS L2 signal
15.5
15.75
Day of Month
16.25
16.5

TEC Disturbances on 15 July 2000



GPS Total Electron Content Map

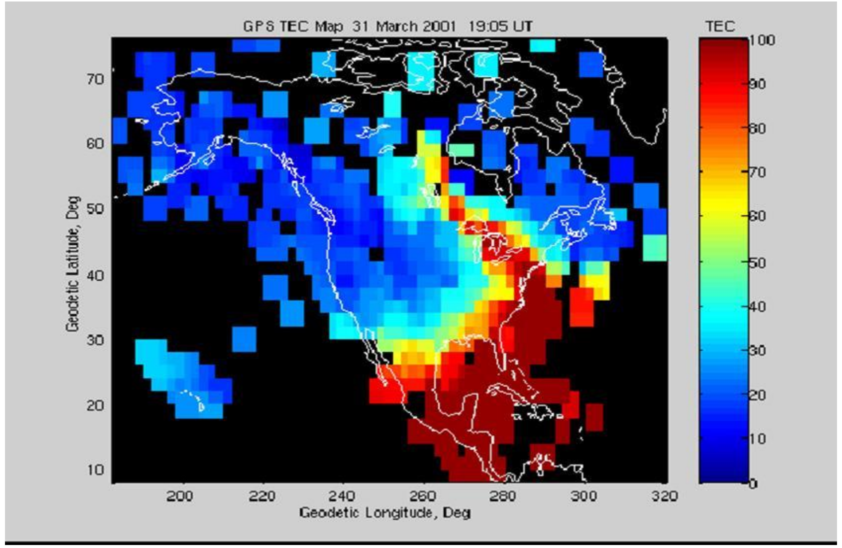
Illustration of Storm Enhanced Density

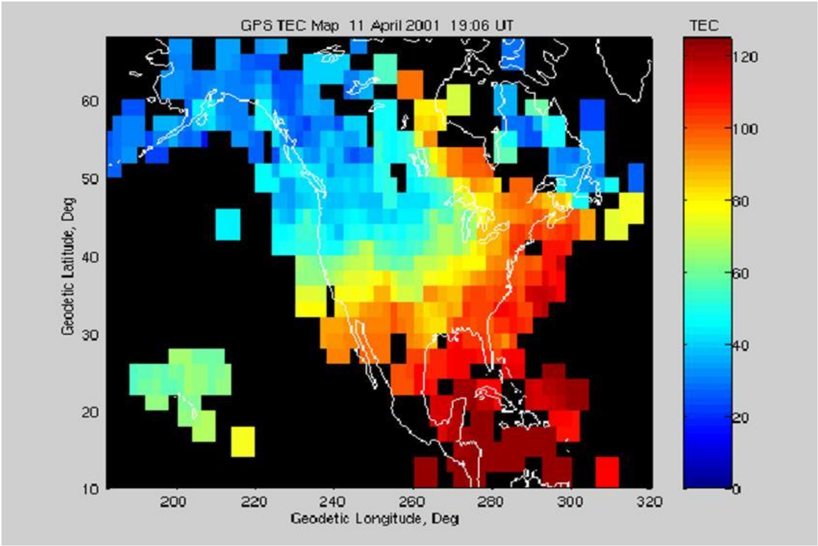


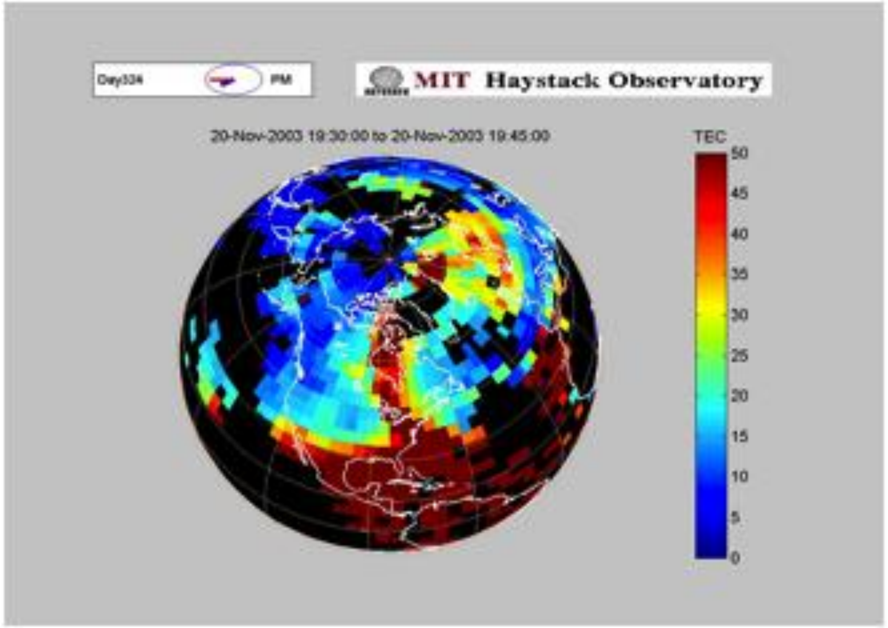
Coster, Foster, Erickson, Rideout, 2000

Day 90, 2001

Day 101, 2001





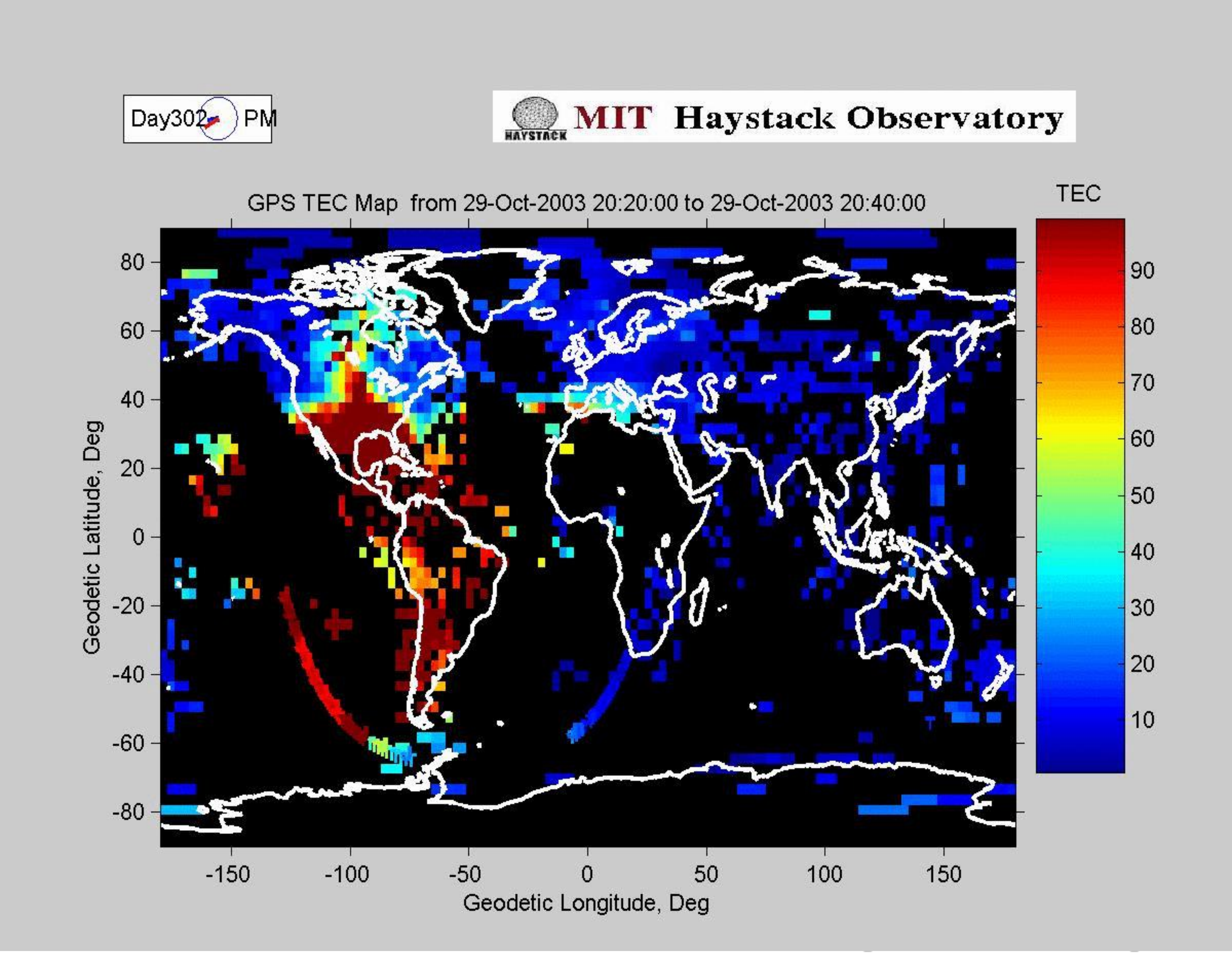


Distributed vs. single point measurements

Wide Area Distribution of 'Raw' Information

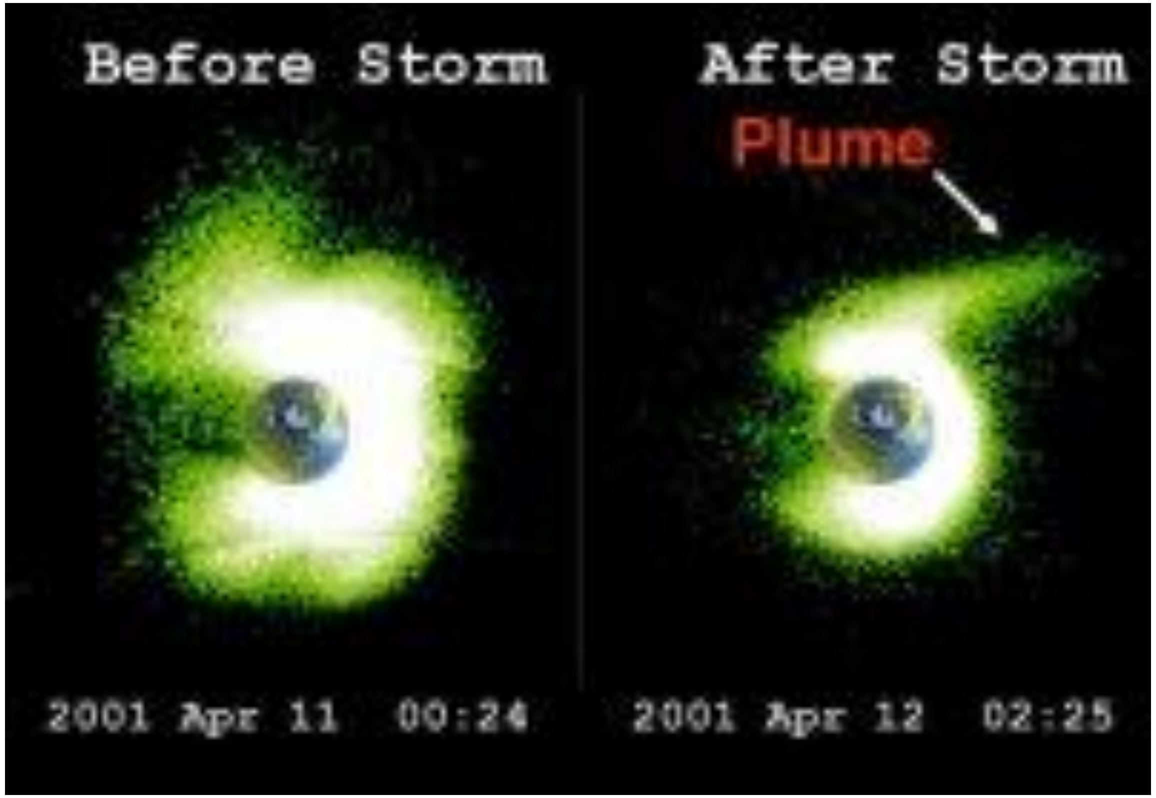
Distributed networks of sensors yield global physics unattainable with single-point measurements

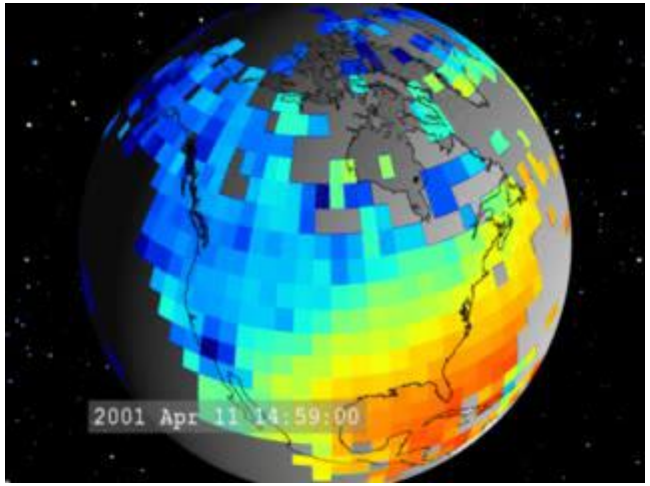
Example :
Global GPS-derived ionospheric mapping during geomagnetic disturbances




Before Storm
2003 Oct 28 02:59
After Storm
2003 Oct 31 01:38

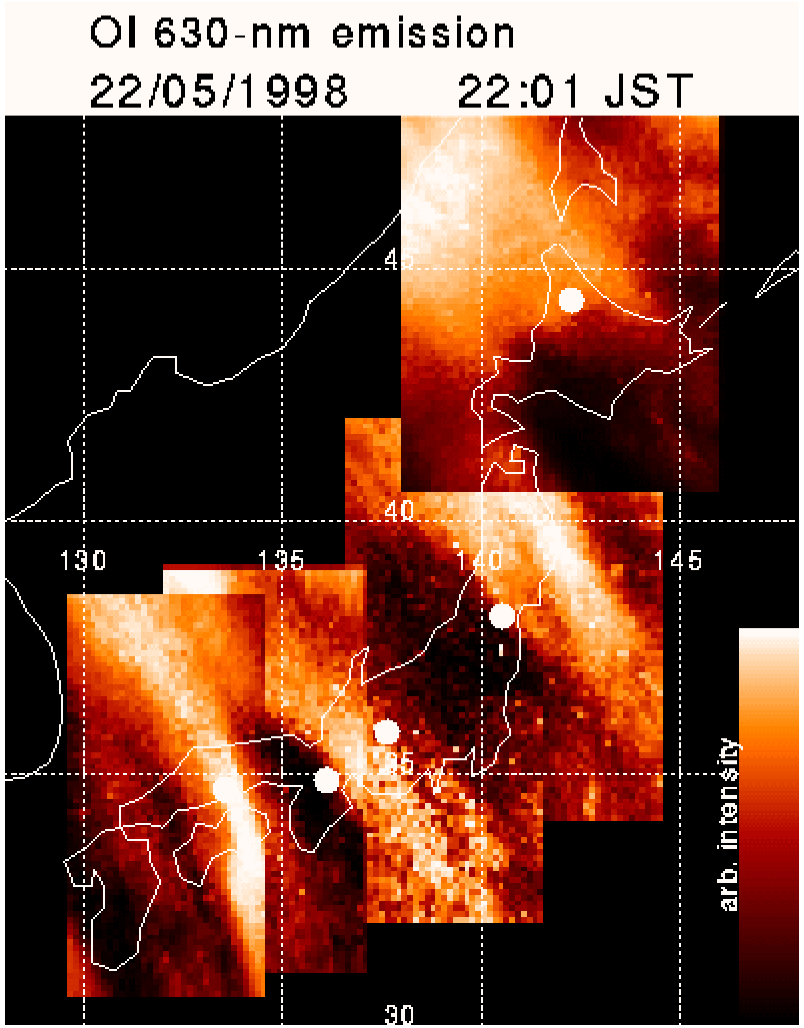
IMAGE Data of Plasmasphere

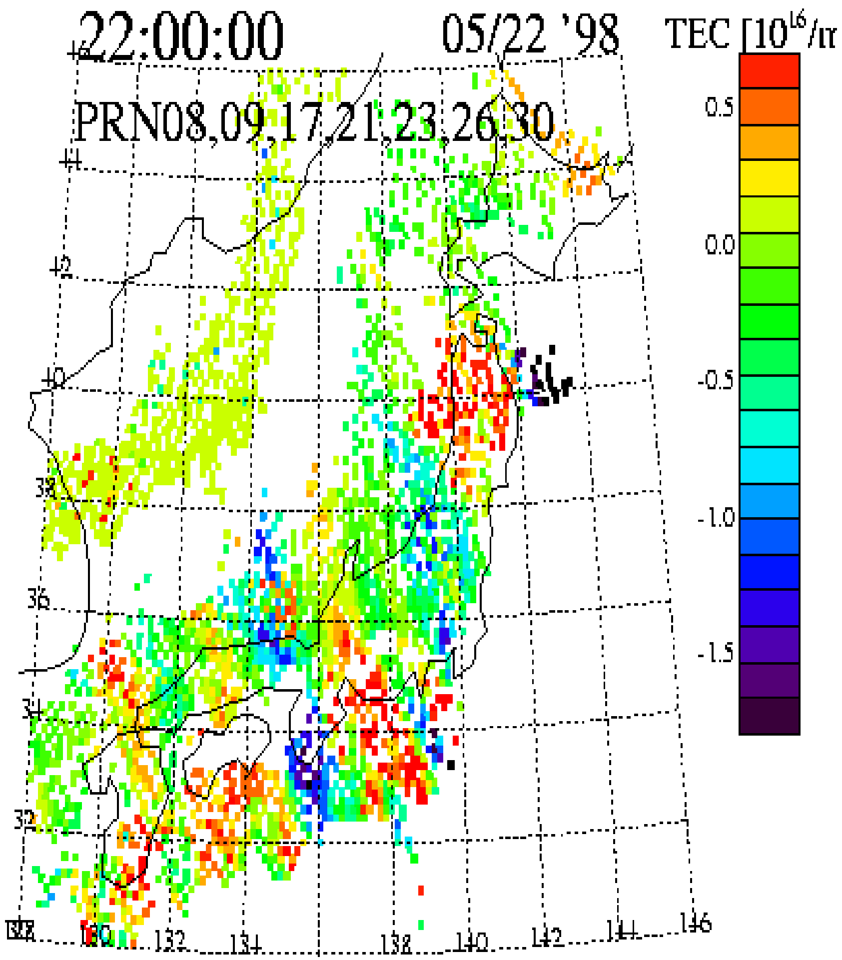


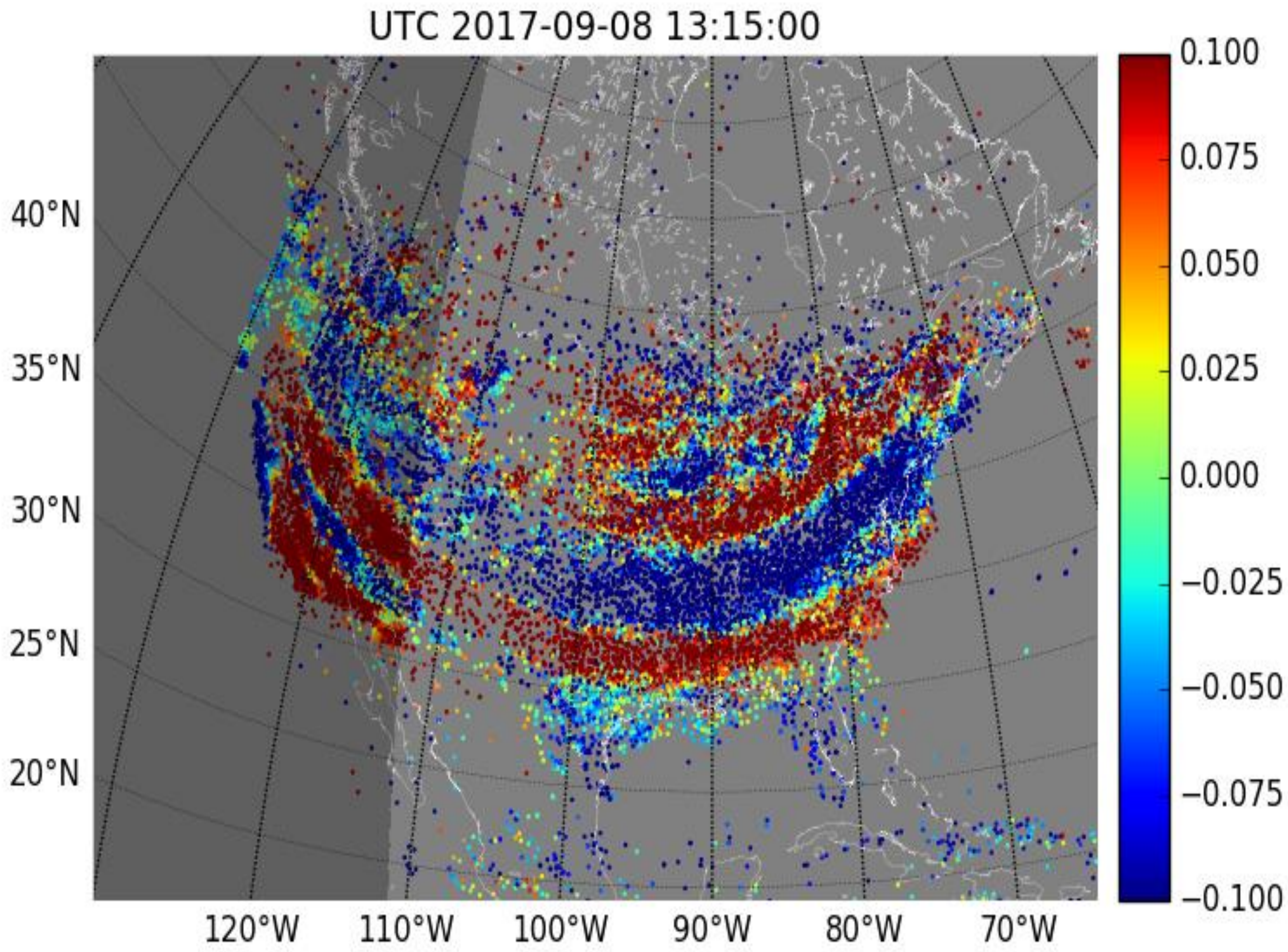


Foster, Coster, Erickson, Rideout, 2003

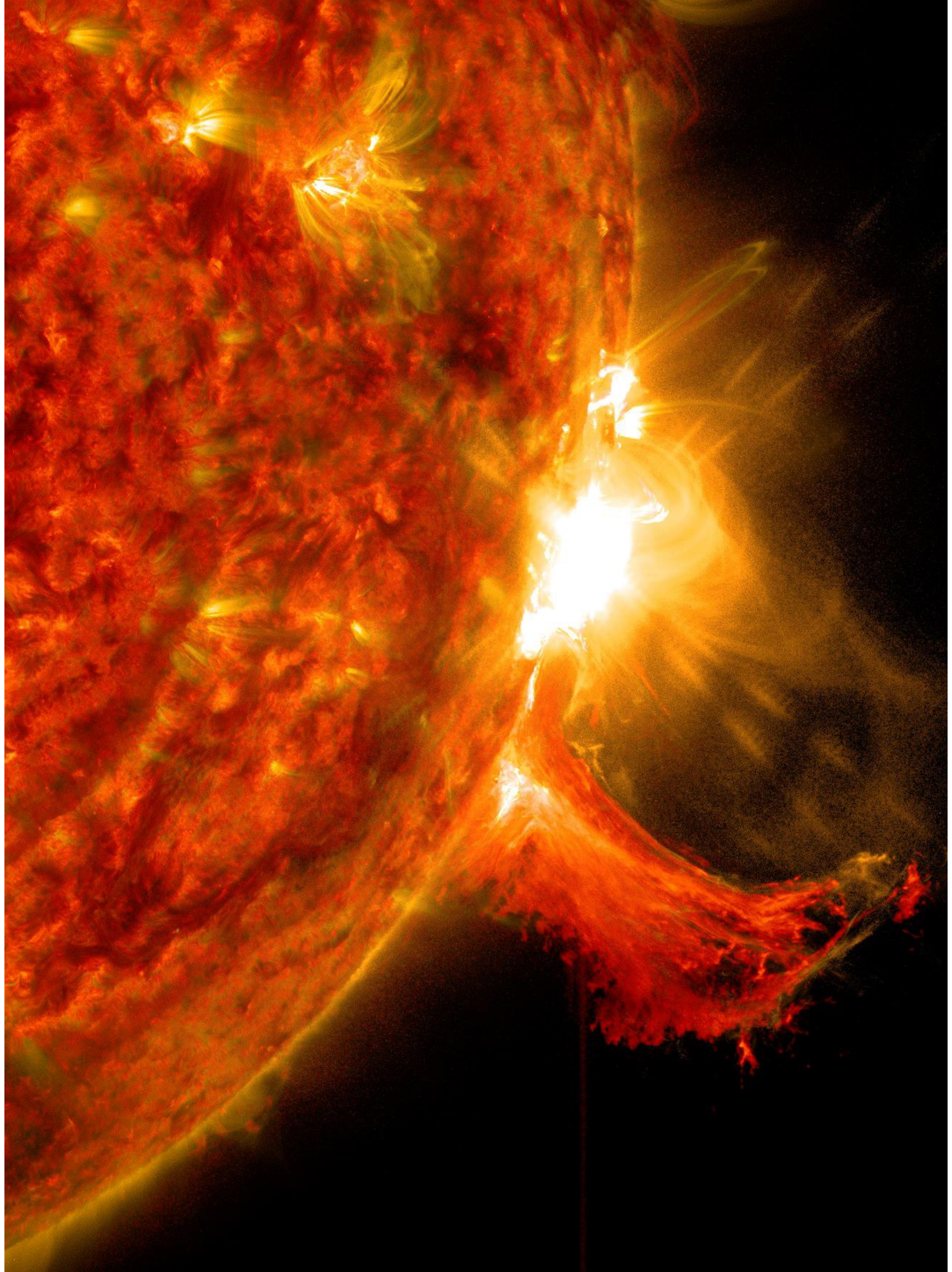
Nighttime MSTID Observations (TEC, Airglow) [*Saito et al.*, 2001]







UTC 2017-09-08 13:15:00
40°N
35°N
30°N
25°N
20°N
120°W
110°W
100°W
90°W
80°W
70°W
0.100
0.075
0.050
0.025
0.000
−0.025
−0.050
−0.075
−0.100

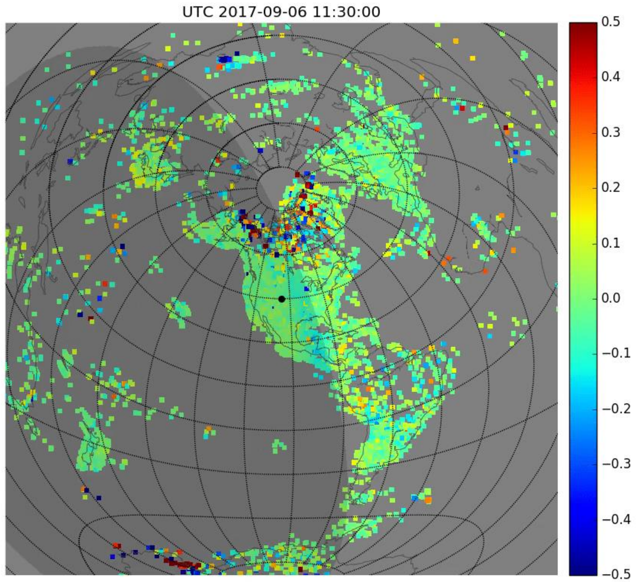


Solar Flare

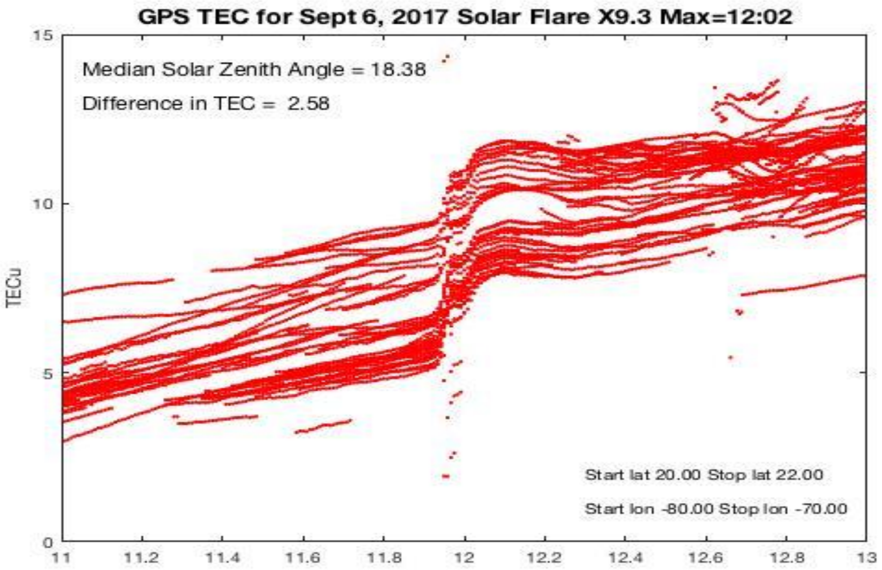
A violent explosion in the Sun's atmosphere; energy equivalent of a hundred million hydrogen bombs. Giant bursts of X-rays and energy which travel at the speed of light

- **Arrival: 8 min from Sun to Earth (149.6 million km)**
- **Duration: minutes to 3 hrs**
- **Daylight-side impact**

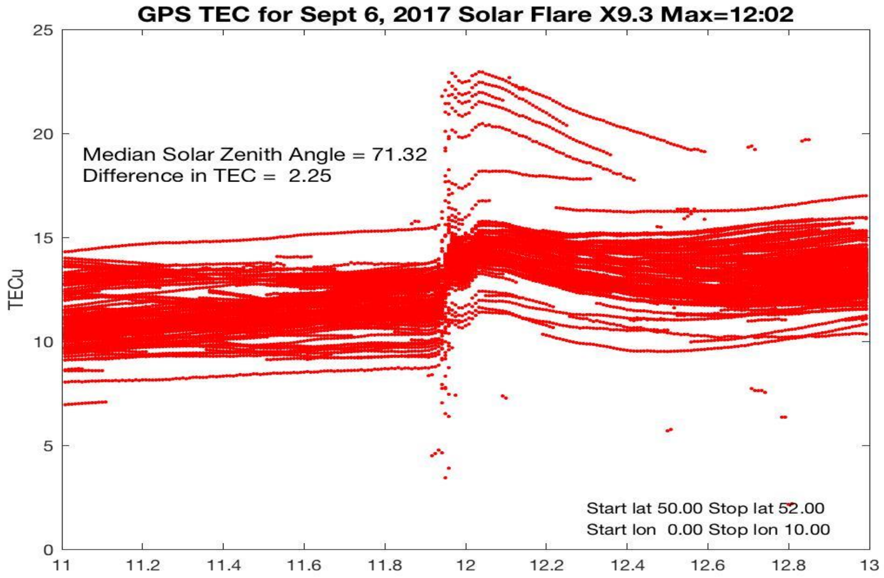
Sept 6, 2017



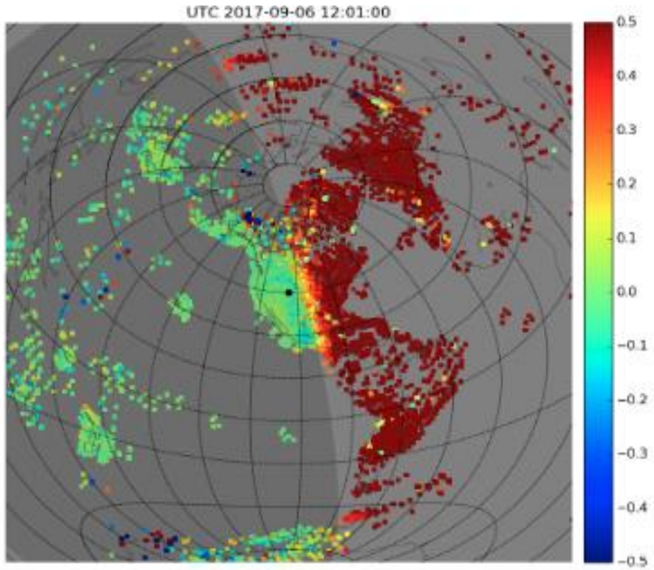
UTC 2017-09-06 11:30:00
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5



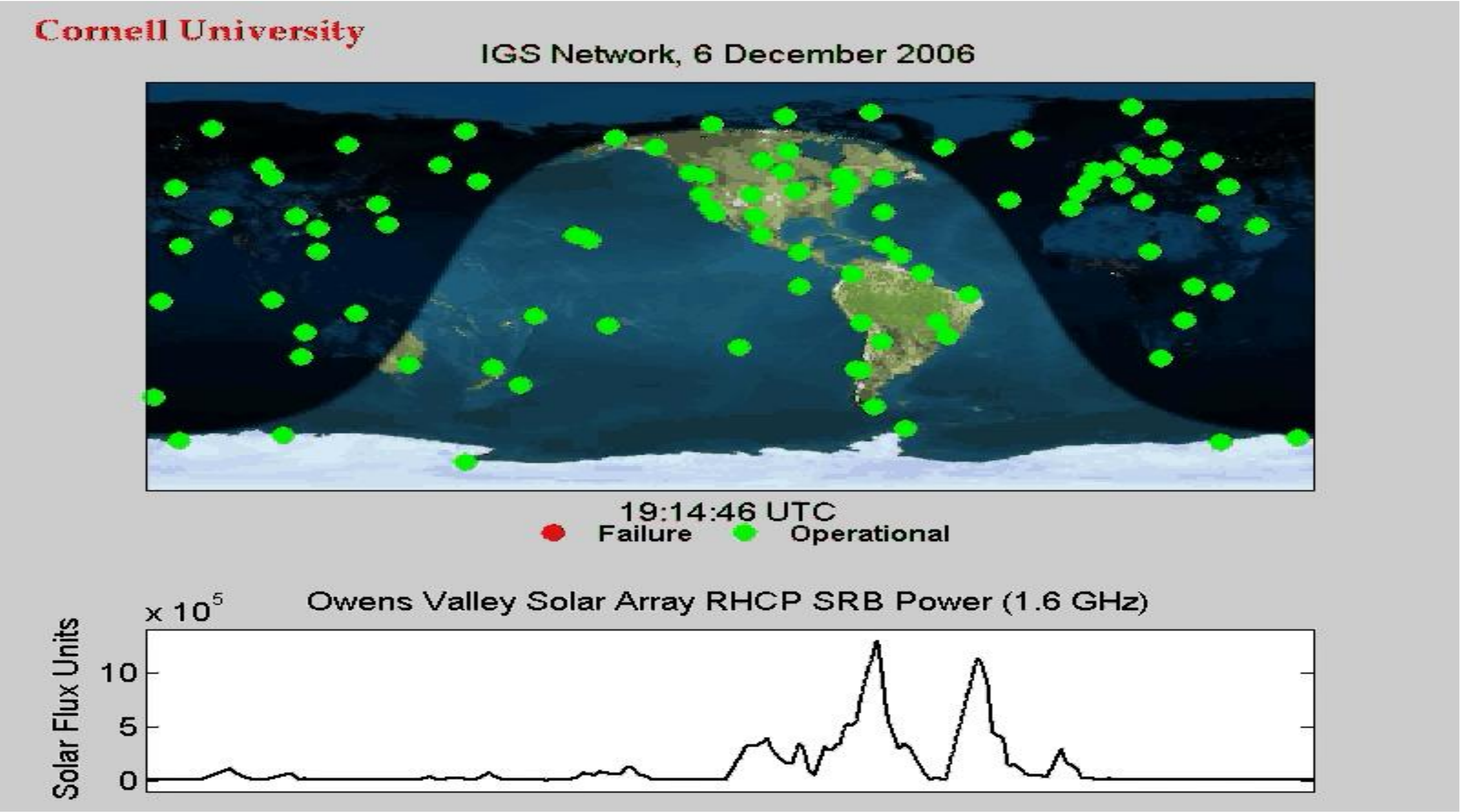
GPS TEC for Sept 6, 2017 Solar Flare X9.3 Max=12:02
Median Solar Zenith Angle = 18.38
Difference in TEC = 2.58
Start lat 20.00 Stop lat 22.00
Start lon -80.00 Stop lon -70.00
TECu



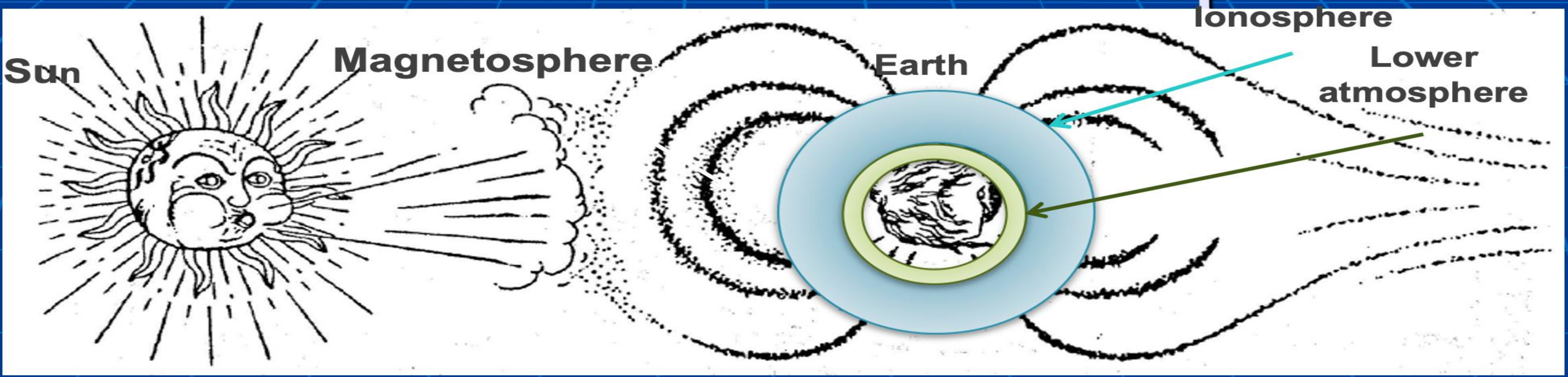
GPS TEC for Sept 6, 2017 Solar Flare X9.3 Max=12:02
Median Solar Zenith Angle = 71.32
Difference in TEC = 2.25
Start lat 50.00 Stop lat 52.00
Start lon 0.00 Stop lon 10.00
TECu



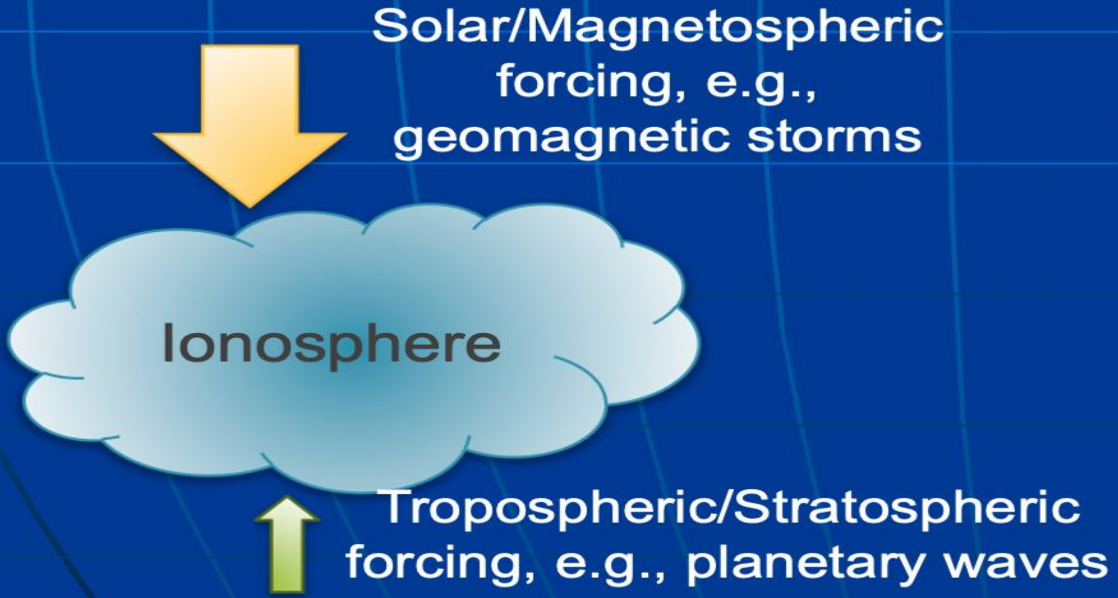
UTC 2017-09-06 12:01:00


Cornell University
IGS Network, 6 December 2006
19:14:46 UTC
Failure
Operational
Owens Valley Solar Array RHCP SRB Power (1.6 GHz)
x 10^5
Solar Flux Units
10
5
0

Forces that act on the Ionosphere



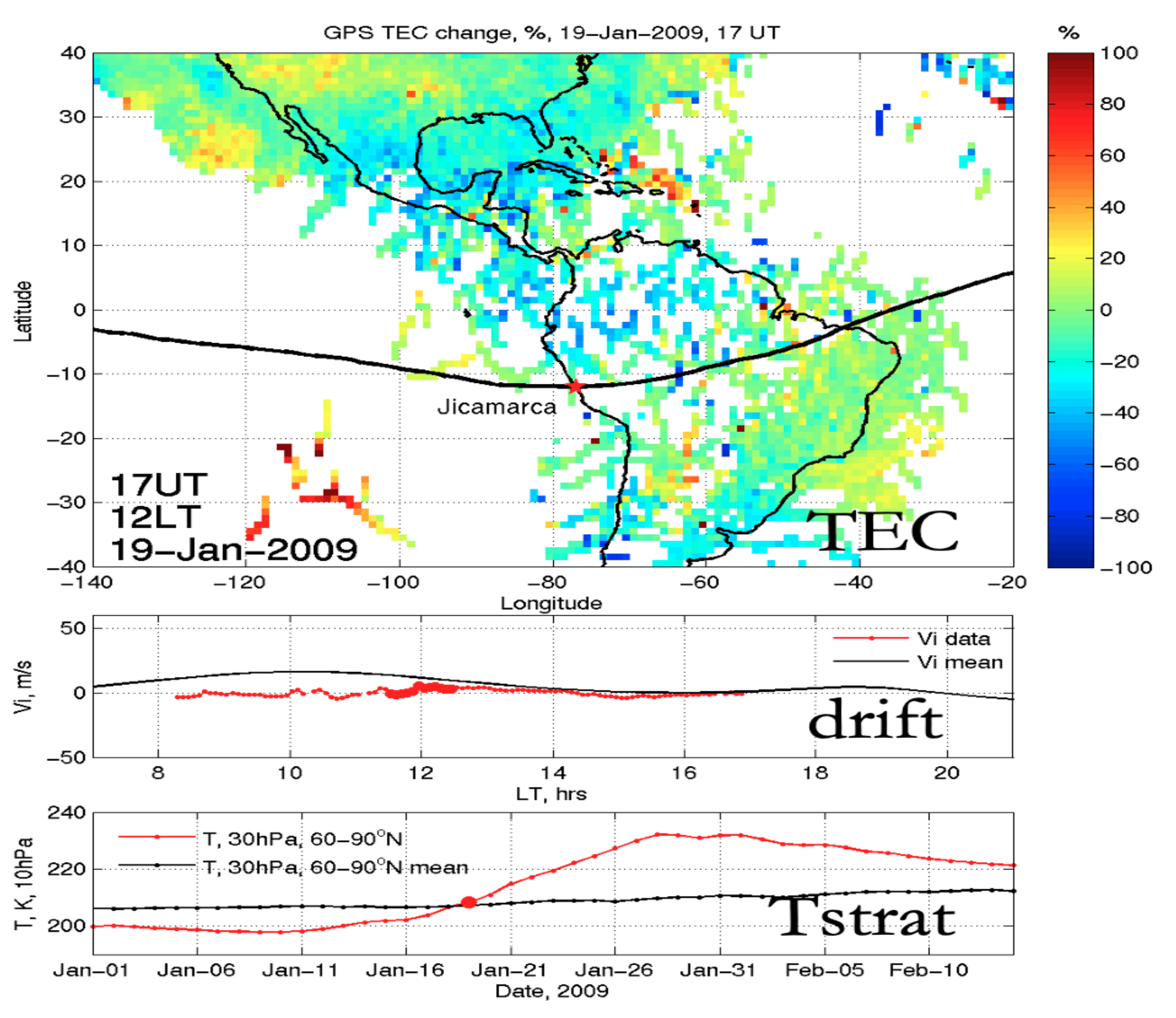
[adapted from *Marchavilas*, 2007]



- These forces produce ionospheric changes: electric fields, electron density, temperature, composition,.

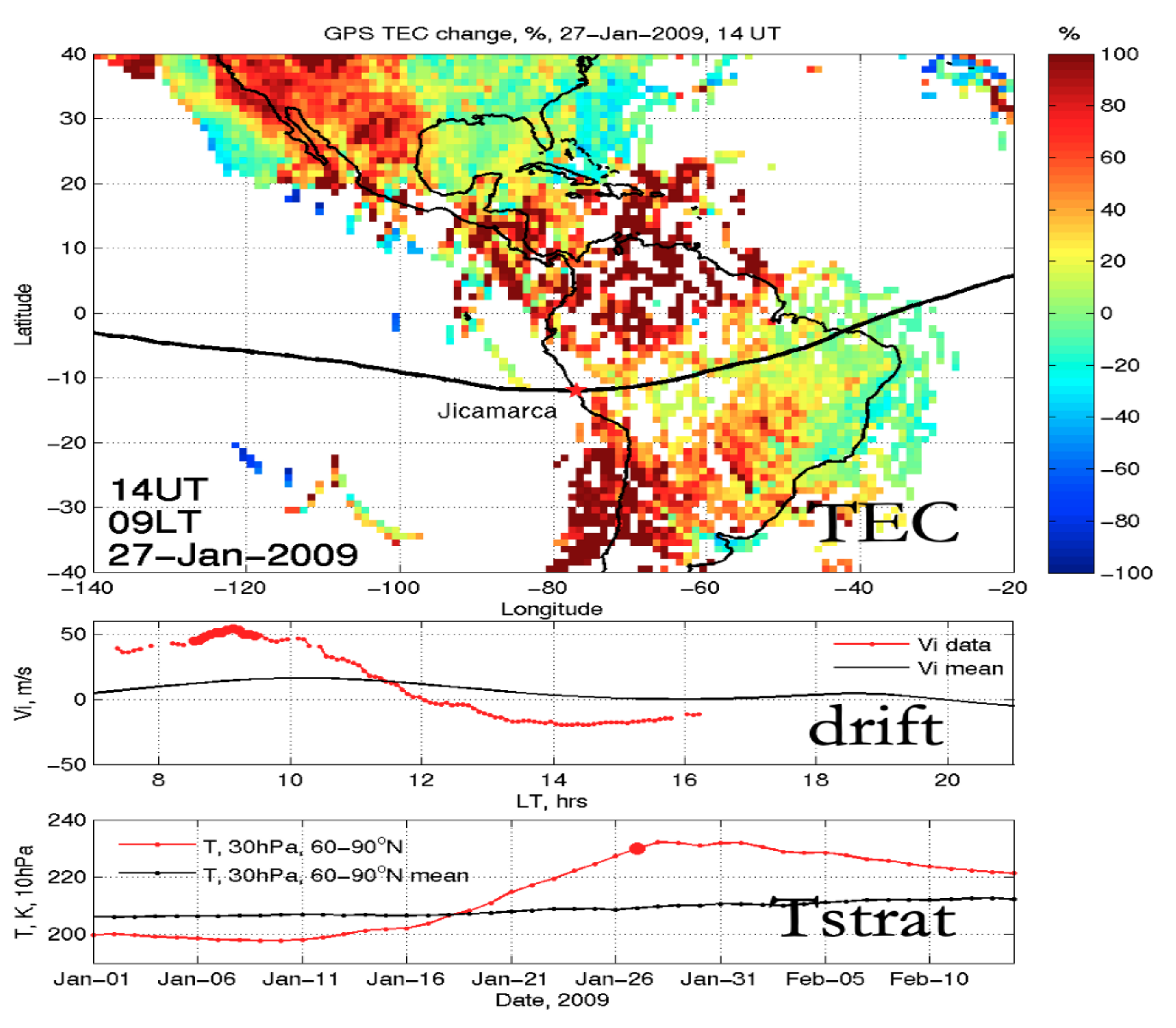
Courtesy L. Goncharenko

GPS TEC change – no warming

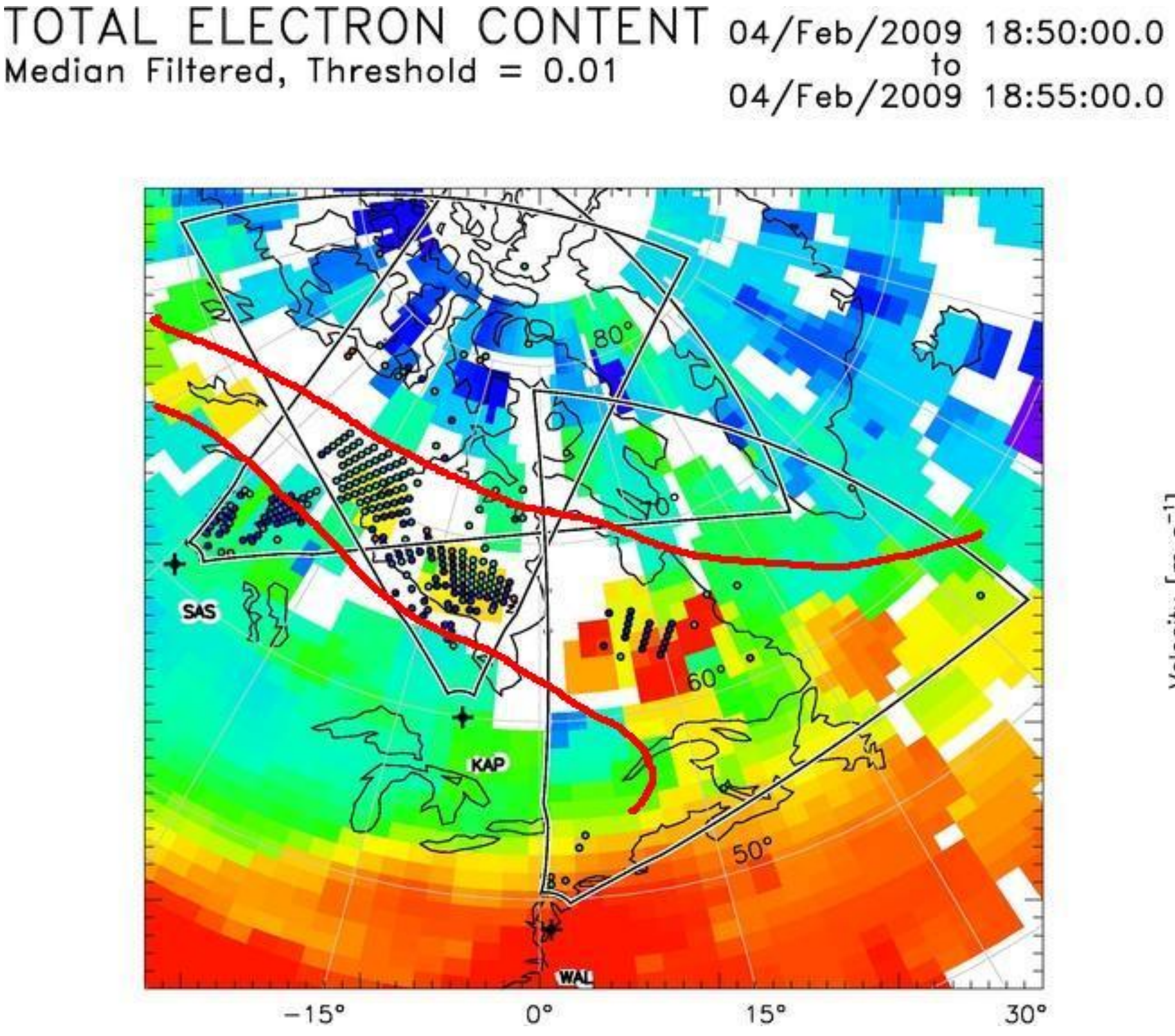


- GPS TEC (Total Electron Content) data show large-scale picture of ionospheric behavior
- Before the warming, TEC change is 10-20% from mean and vertical drift is small
- The mean is Jan 1-14, 2009

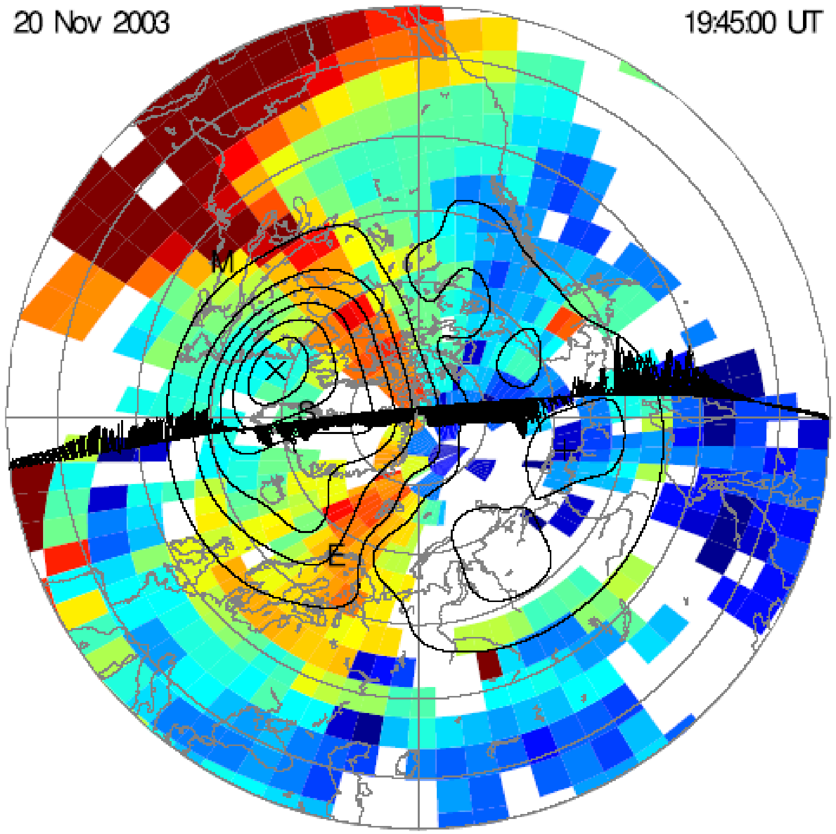
GPS TEC during warming: morning sector



- During stratwarming, TEC increases in excess of 50-100% in the morning
- Large upward drift at Jicamarca
- The magnitude of increase is similar to effects of severe geomagnetic storms


TOTAL ELECTRON CONTENT
Median Filtered, Threshold = 0.01
04/Feb/2009 18:50:00.0
to
04/Feb/2009 18:55:00.0
80°
70°
60°
50°
SAS
KAP
WAL
−15°
0°
15°
30°
150
100
50
0
−50
−100
−150
Velocity [m s⁻¹]
13
11
9
7
5
3
1
Total Electron Content [TECU]

SuperDarn Convection Patterns merged with DMSP and Global TEC



Outline

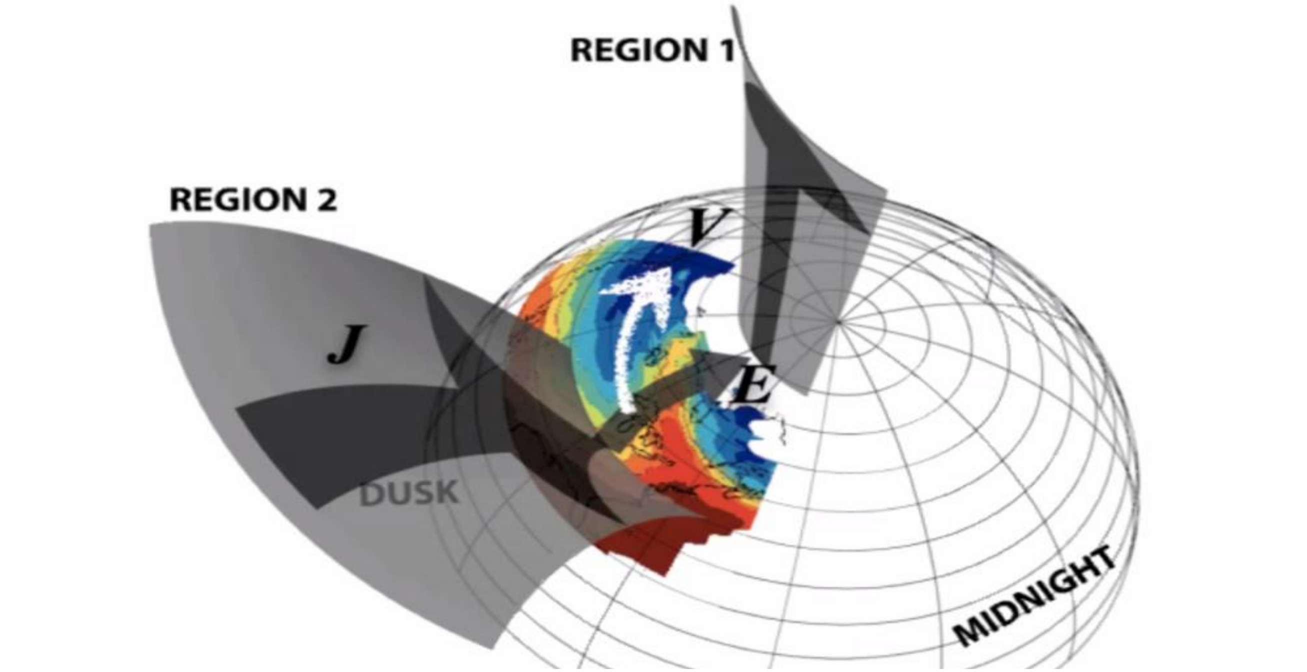
History – mine

System Science

Past (pre and post-GPS)

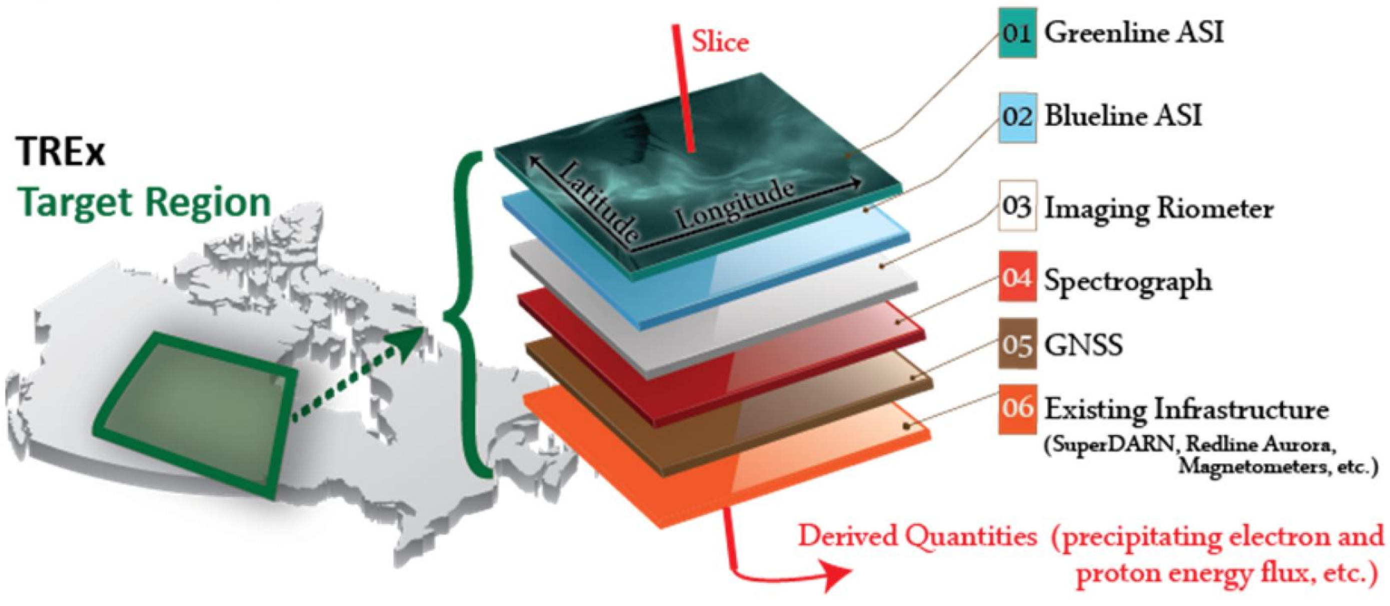
Current

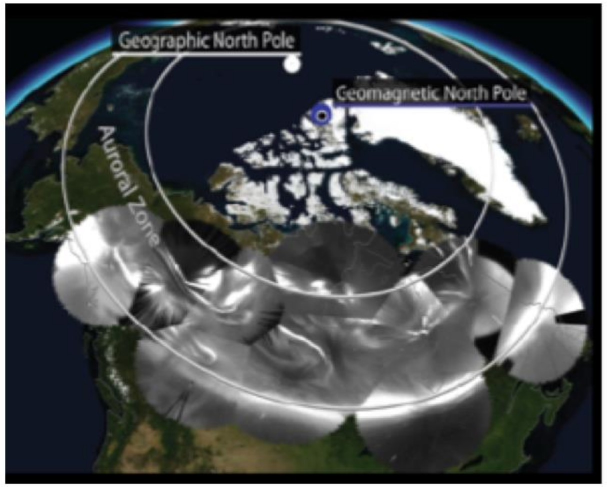
Future

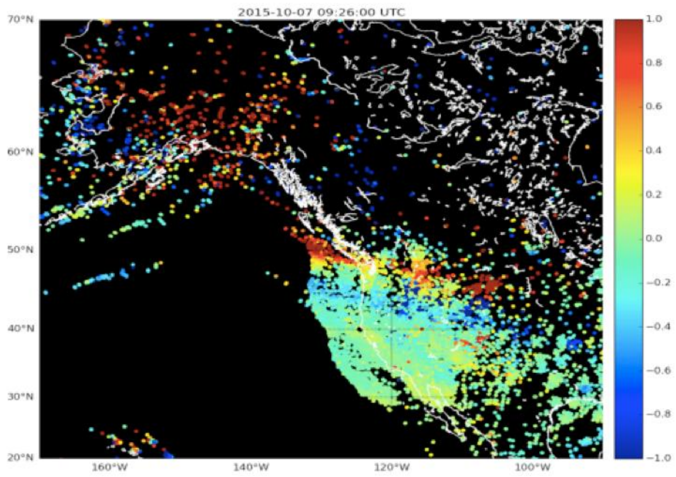


Big Data: Example - Transition Region Explorer (TREx) sites

Development of a sensor web





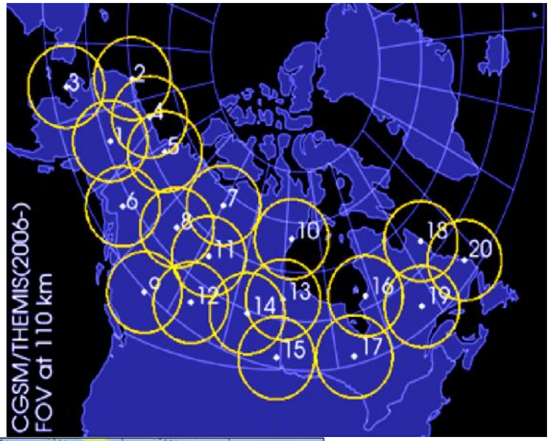


MERGE DATA FROM DIFFERENT SENSORS

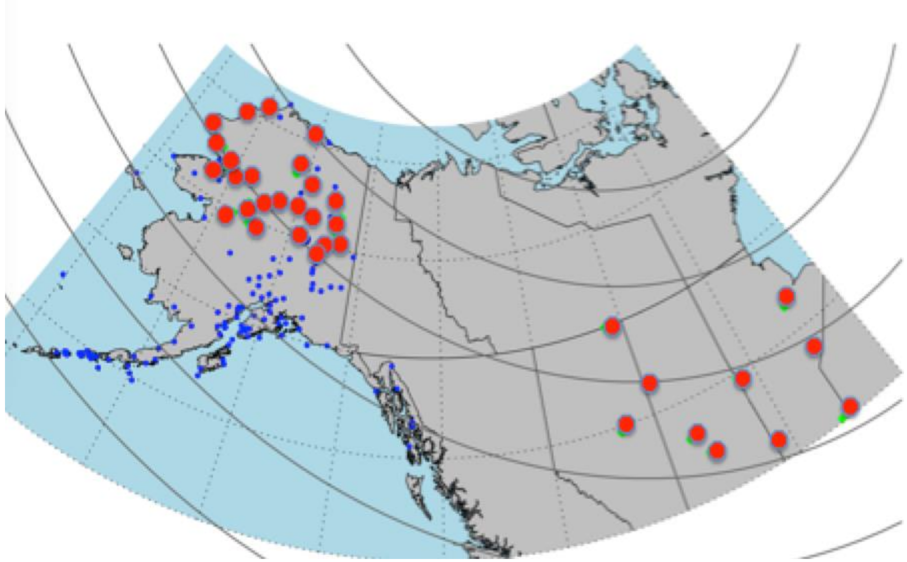
MACAWS and CHAIN networks with GNSS TEC and scintillation parameters combined with THEMIS All-sky imager data

- <u>NSF MRI Collaborative:</u> Development of **M**onitors for **A**laskan and **C**anadian **A**uroral **W**eather in **S**pace (MACAWS) plus **C**anadian **H**igh **A**rctic **I**onospheric **N**etwork (CHAIN)
- World-wide network GNSS TEC receivers
- THEMIS All-sky imagers

THEMIS

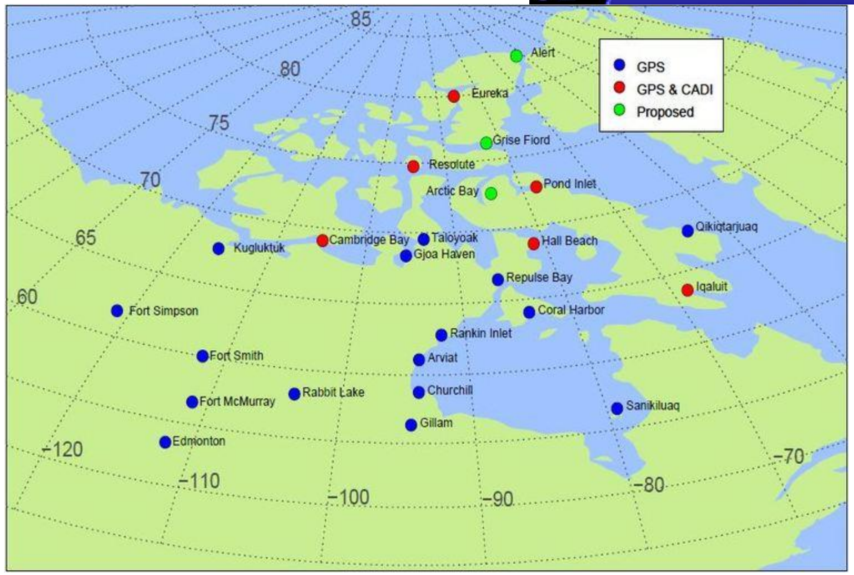


MACAWS



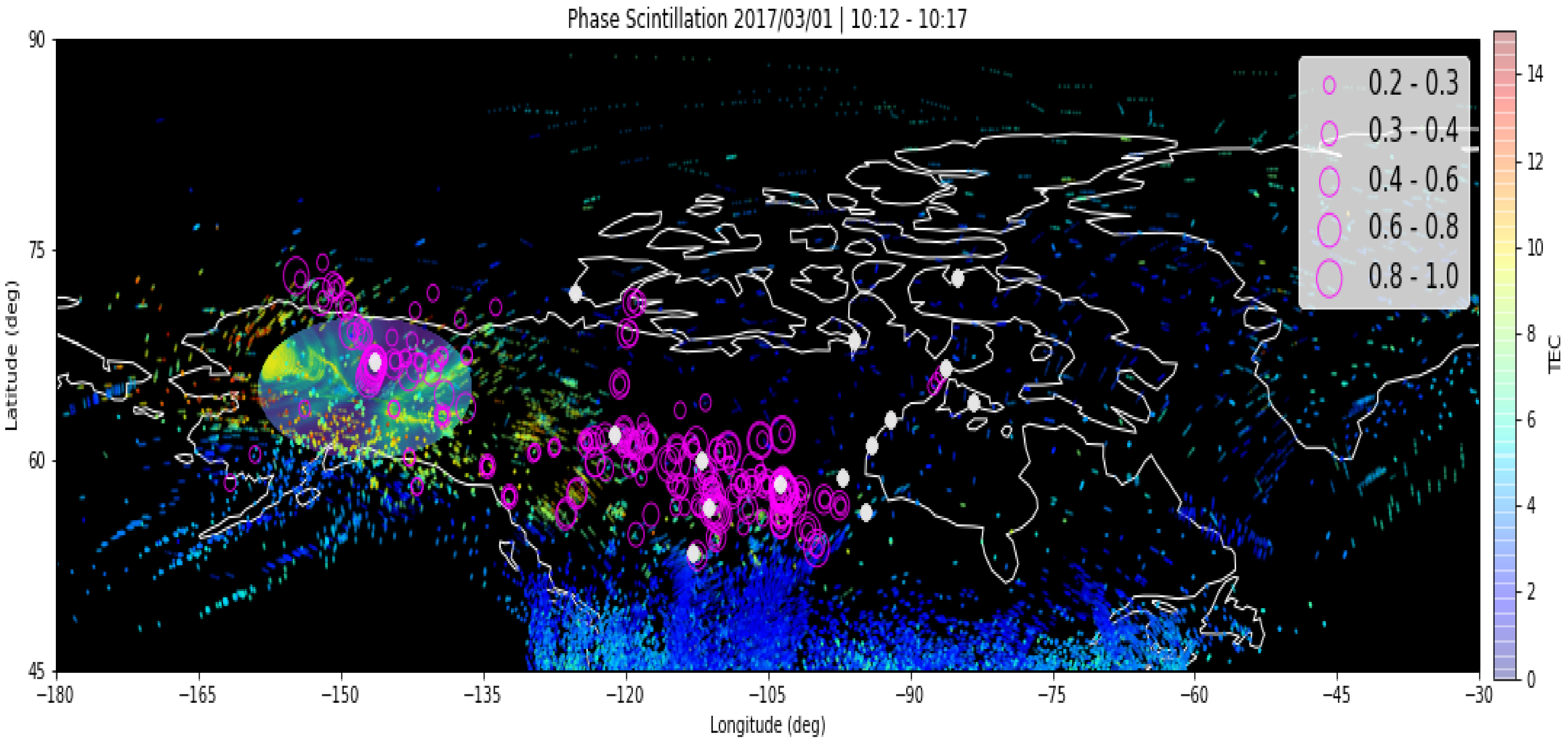
MIT Haystack Observatory, U. Calgary, U of Alaska

CHAIN



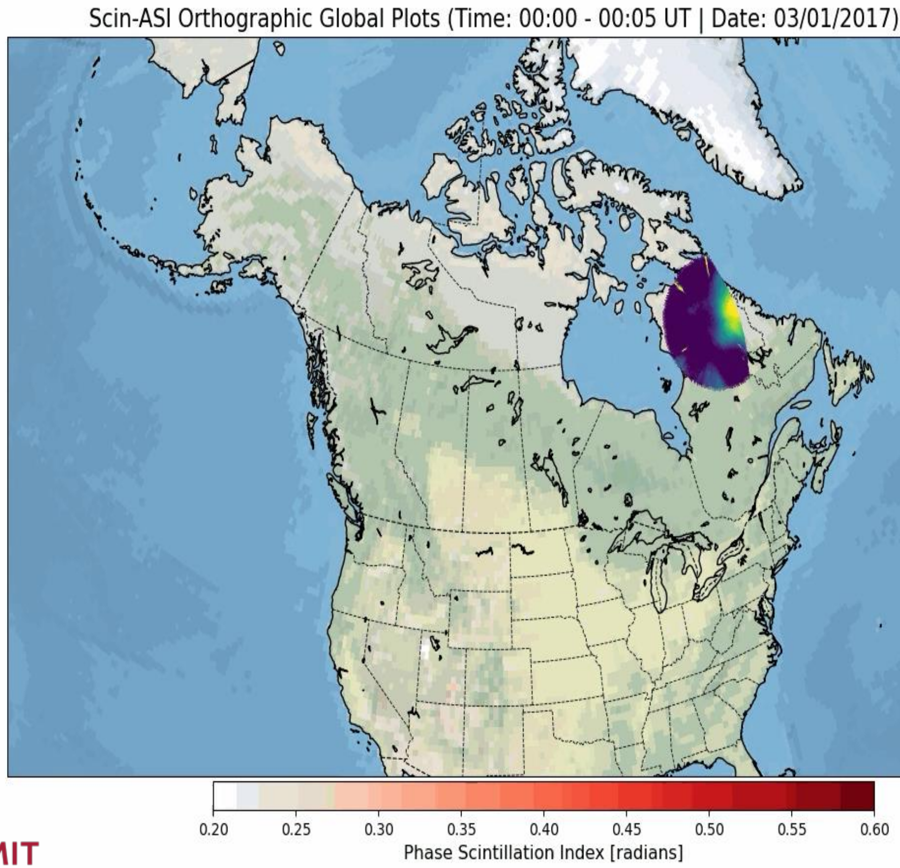
University of New Brunswick

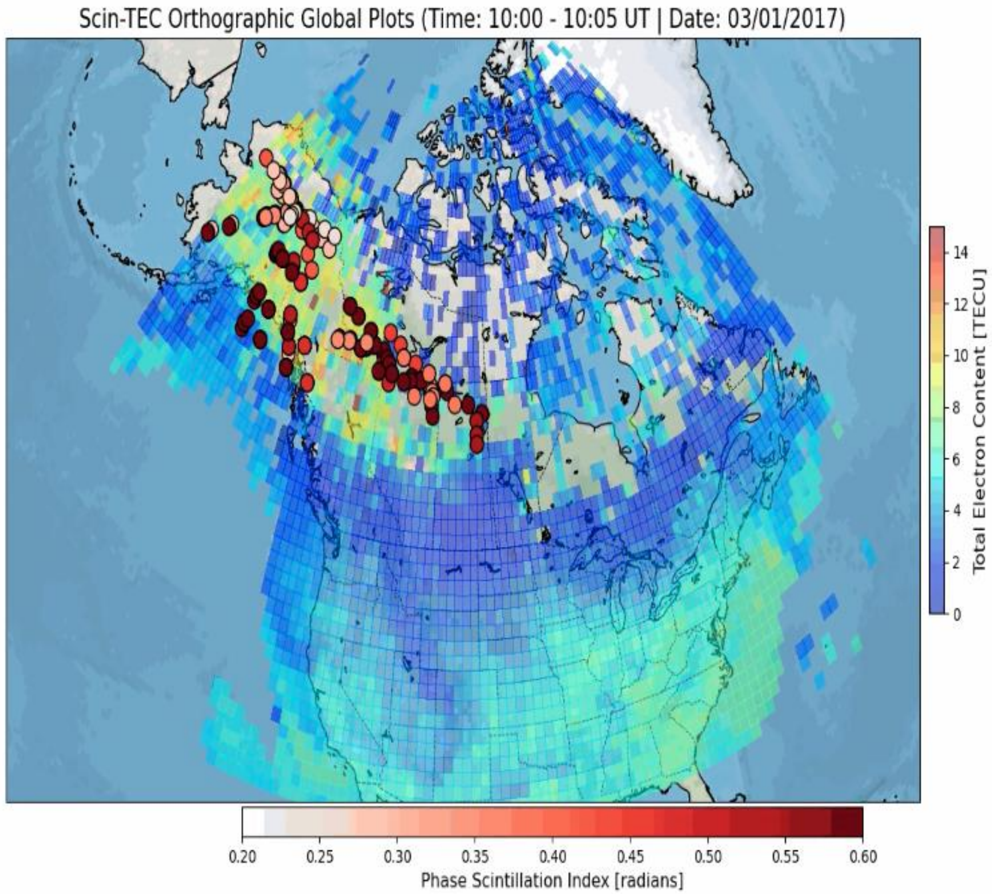
MIT
HAYSTACK
OBSERVATORY



Phase Scintillation 2017/03/01 | 10:12 - 10:17
Latitude (deg)
Longitude (deg)
90
75
60
45
−180
−165
−150
−135
−120
−105
−90
−75
−60
−45
−30
0.2 - 0.3
0.3 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
TEC
0
2
4
6
8
10
12
14

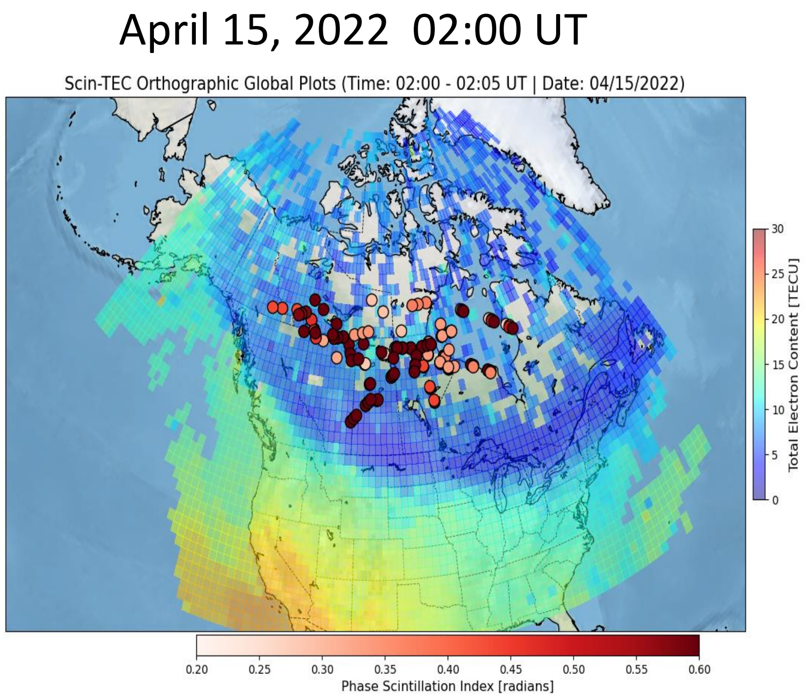
Merged All-sky imagers, GNSS Scintillation, and GNSS Total Electron Content (TEC) maps – March 1, 2017

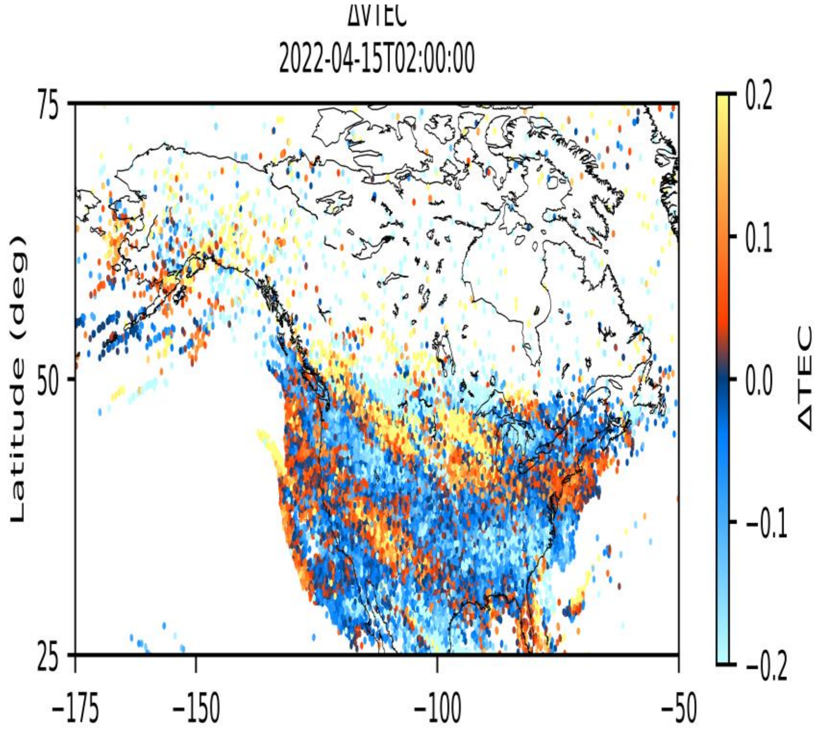




MIT
HAYSTACK
OBSERVATORY

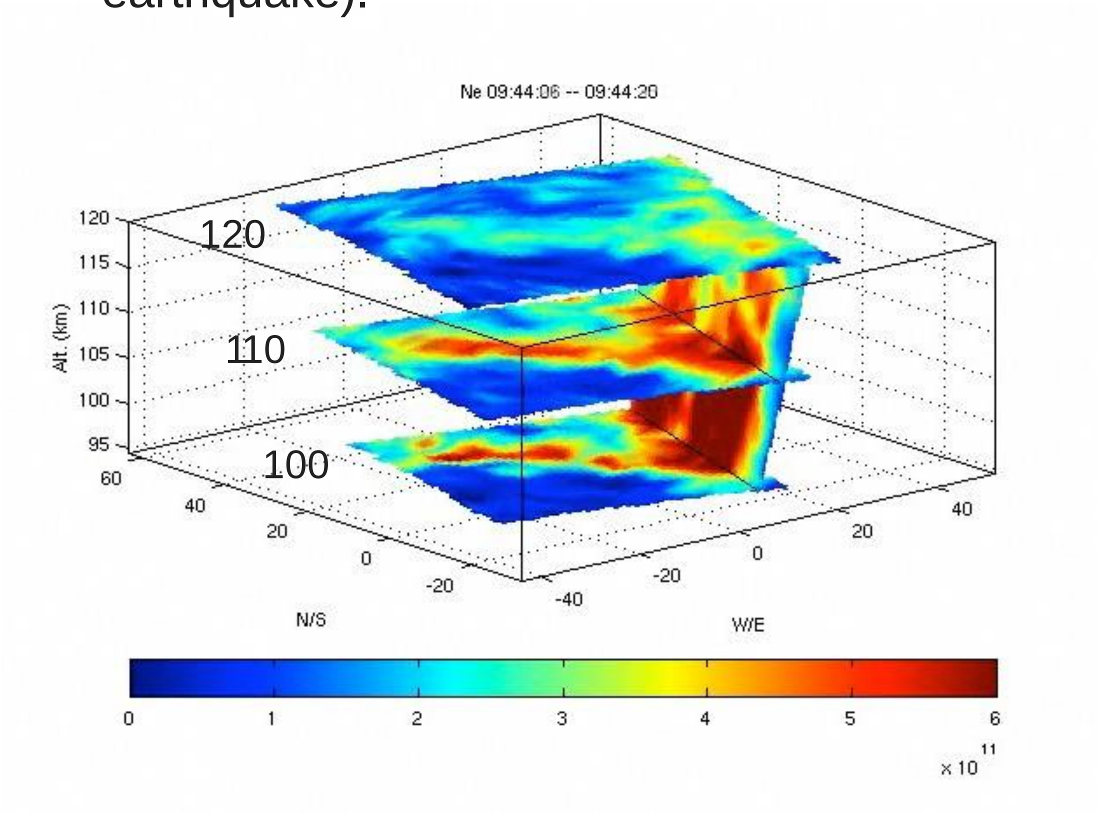
April 15, 2022 02:00 UT

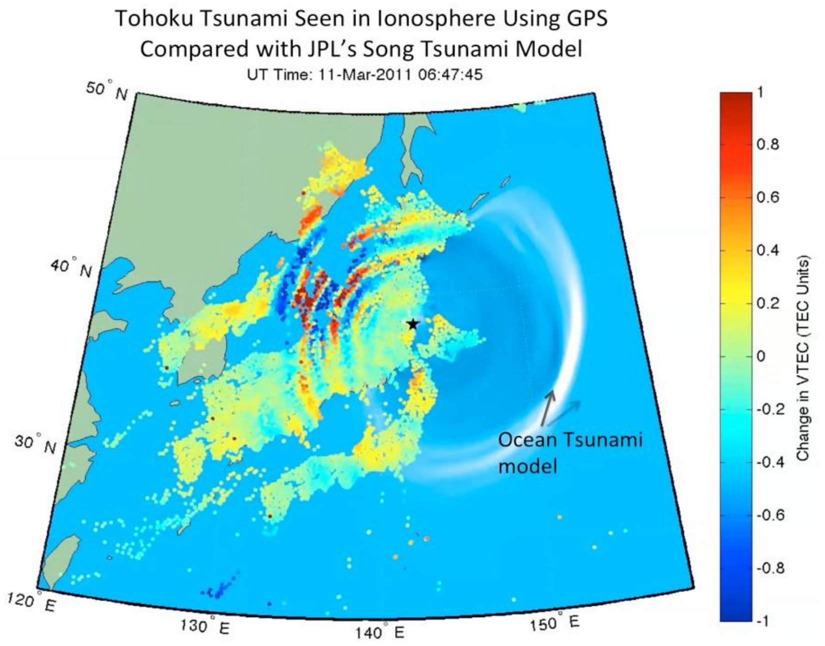




The ionosphere as Earth system sensor

Space-time variations in the ionospheric density field provide a projection of dynamics drivers above (left, magnetospheric substorm) and below (right, Tohoku earthquake).

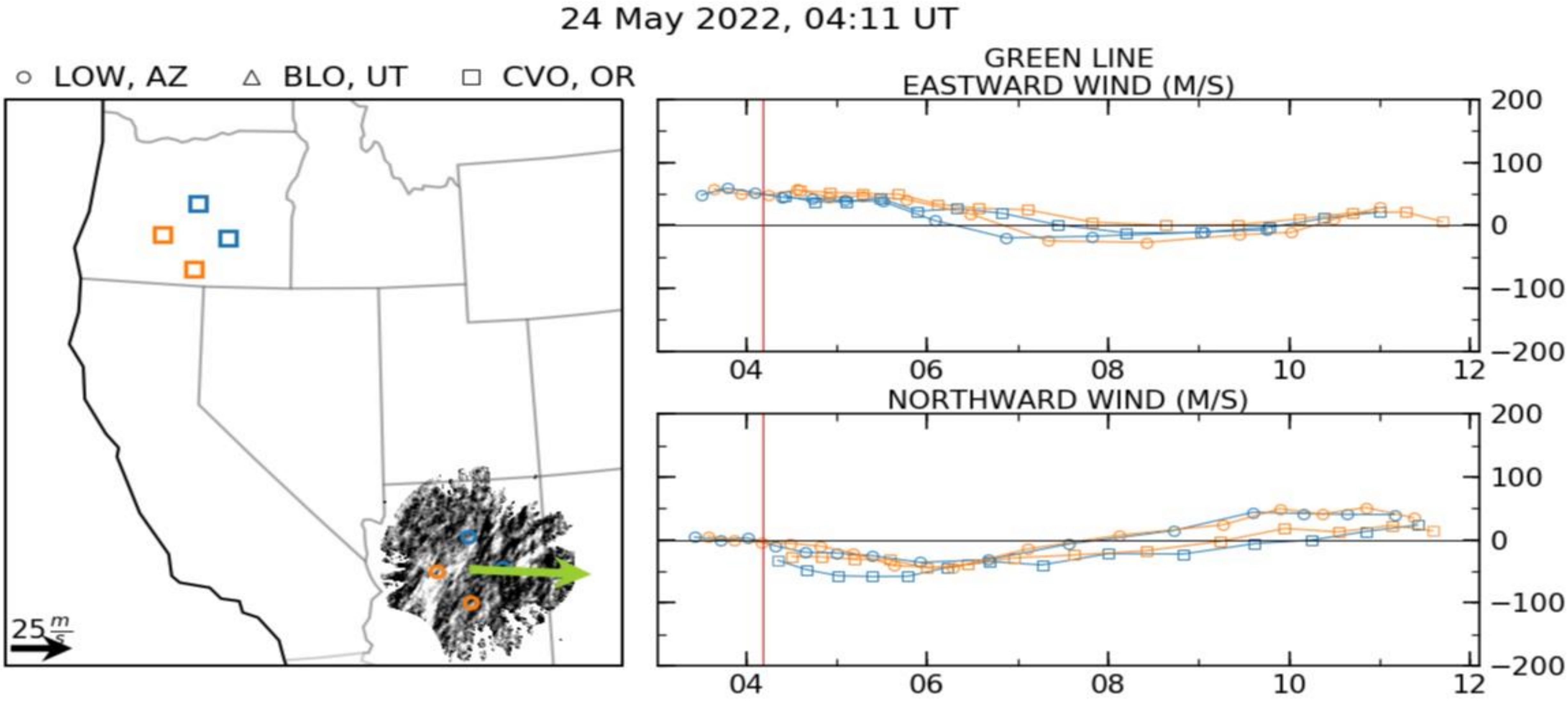




Semeter, J., T. Butler, C. Heinselman, M. Nicolls, J. Kelly, and D. Hampton, Volumetric imaging of the auroral ionosphere: Initial results from PFISR, J. Atmos. Sol. Terr. Phys., 71, 738–743. doi: 10.1016/j.jastp.2008.08.014, 2009.

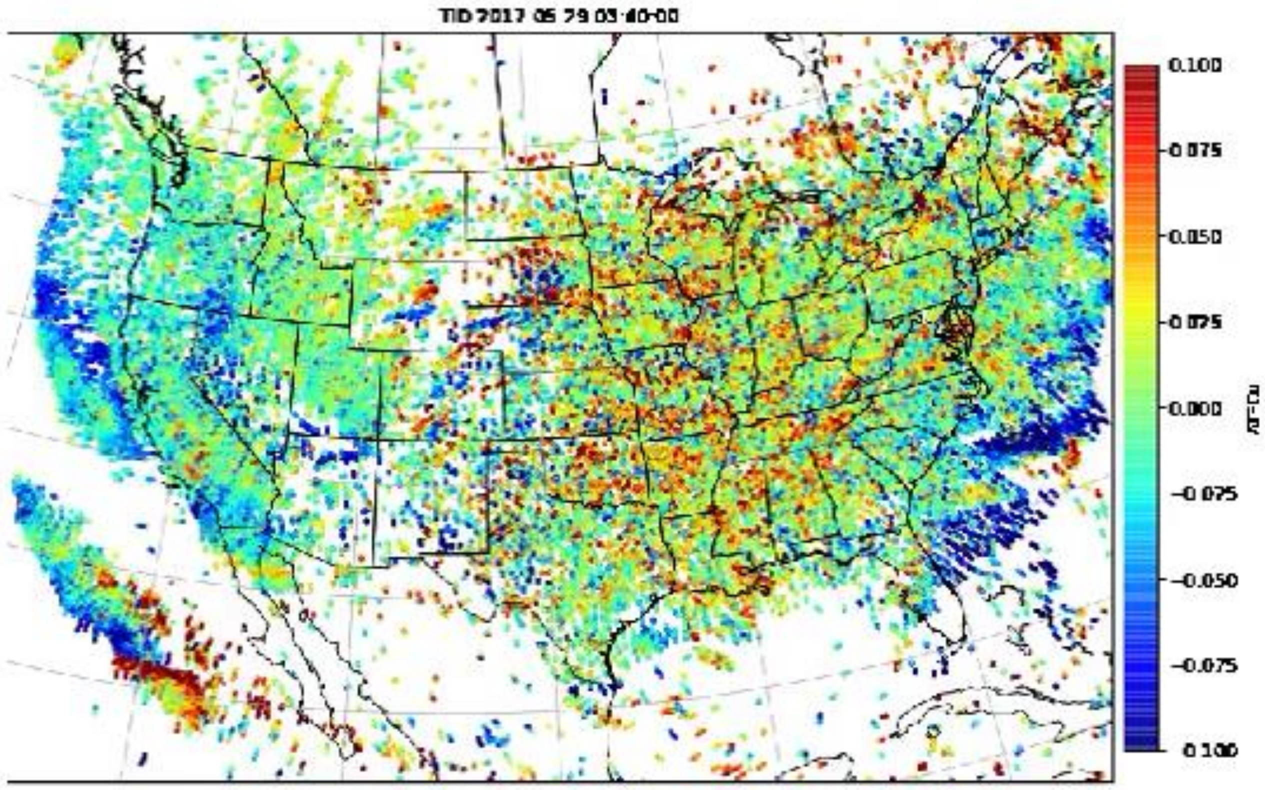
Song, Y. T., et al (2007), Detecting tsunami genesis and scales directly from coastal GPS stations, Geophys. Res. Lett., 34, L19,602, 10.1029/2007GL031681.

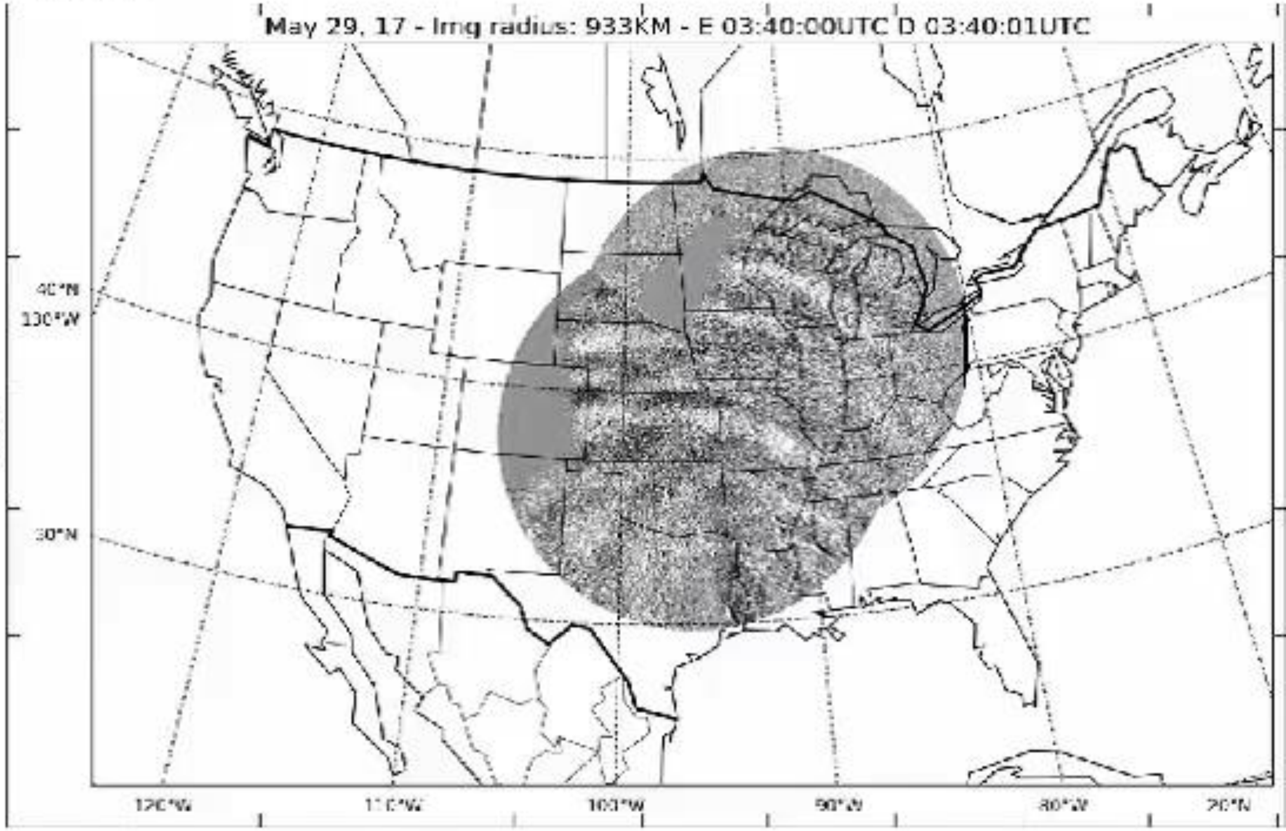
MANGO ASI – Jonathan Makala, Asti Bhatt, Brian Harding



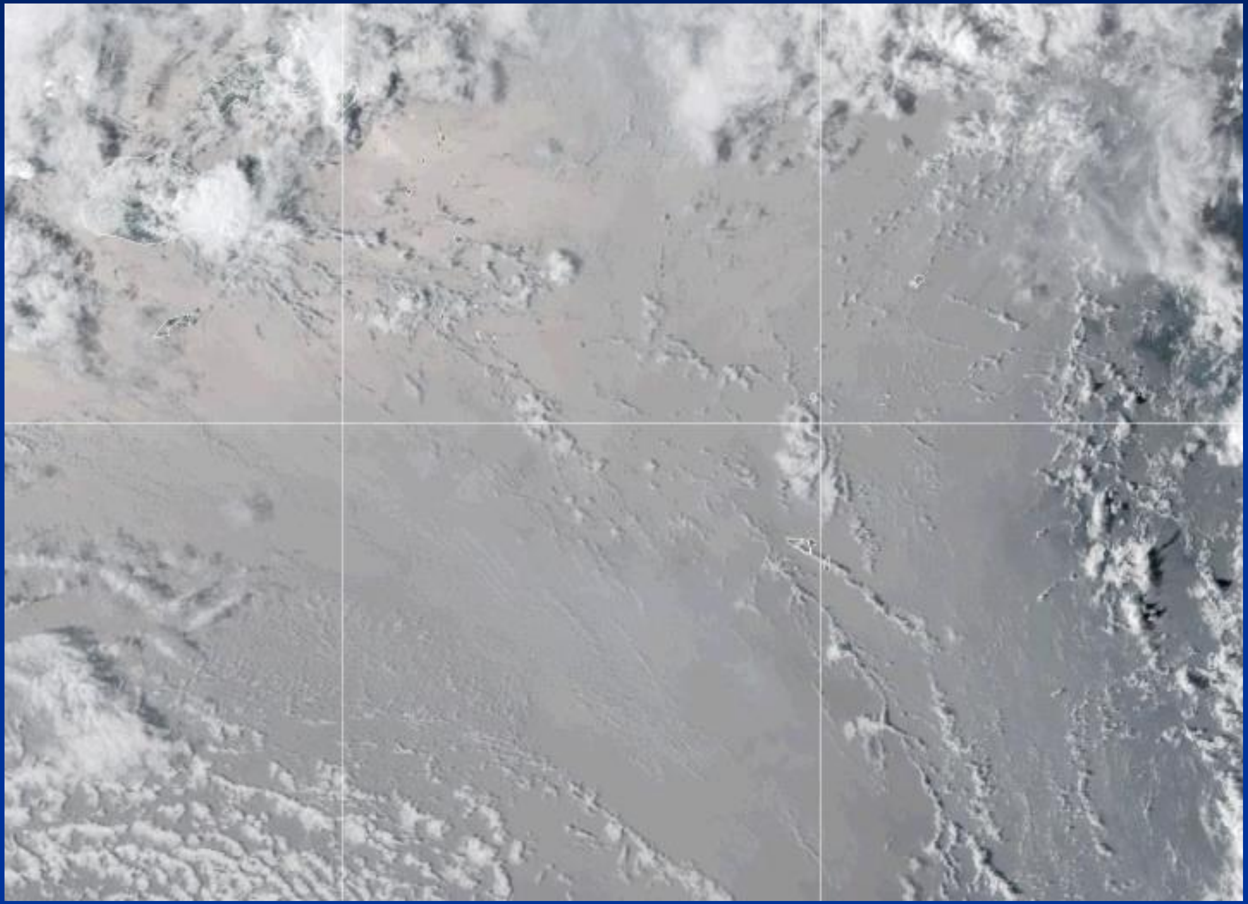
MANGO DATA compared to GNSS TID data 05/29/2017

05/29/2017 @ 03:40





2022 Tonga volcanic eruption induced TID global propagation



This looping video shows a series of GOES-17 satellite images that caught an umbrella cloud generated by the underwater eruption of the Hunga Tonga-Hunga Ha'apai volcano on Jan. 15, 2022.

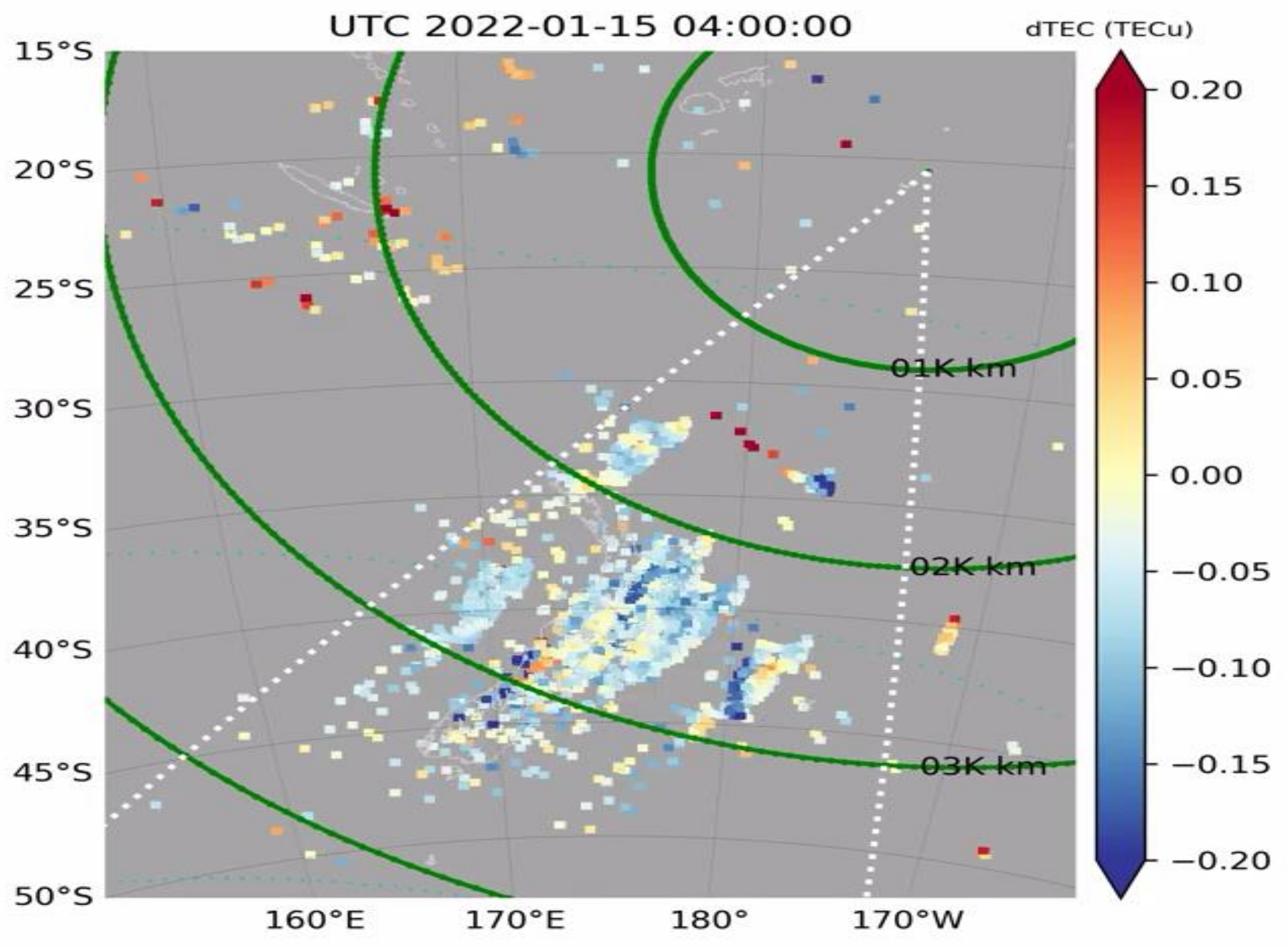
Crescent-shaped bow shock waves and numerous lighting strikes are also visible.

Credit: NASA Earth Observatory image by Joshua Stevens using GOES imagery courtesy of NOAA and NESDIS words from https://www.jpl.nasa.gov/news/tonga-eruption-sent-ripples-through-earths-ionosphere)

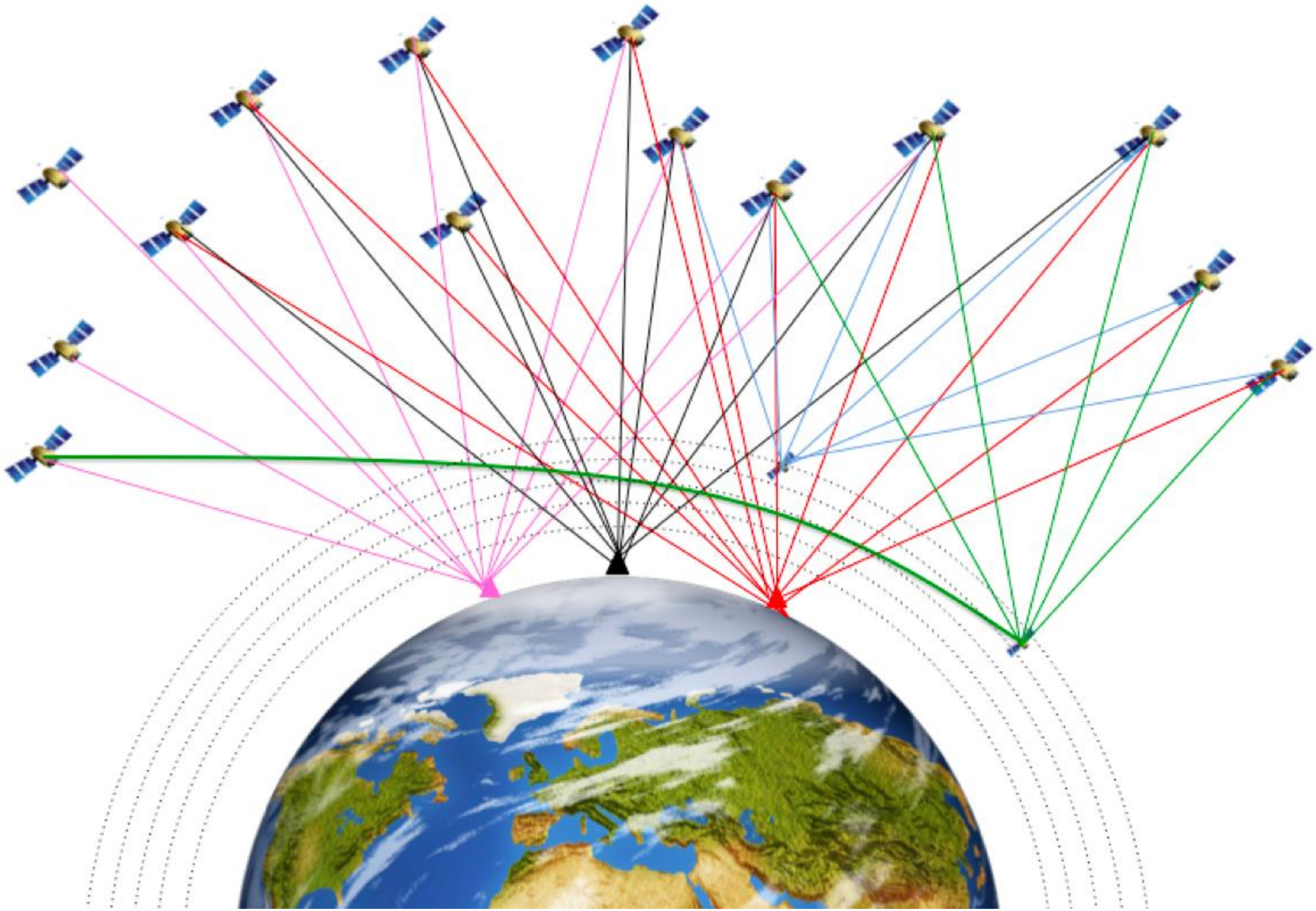
New Zealand (Animation)

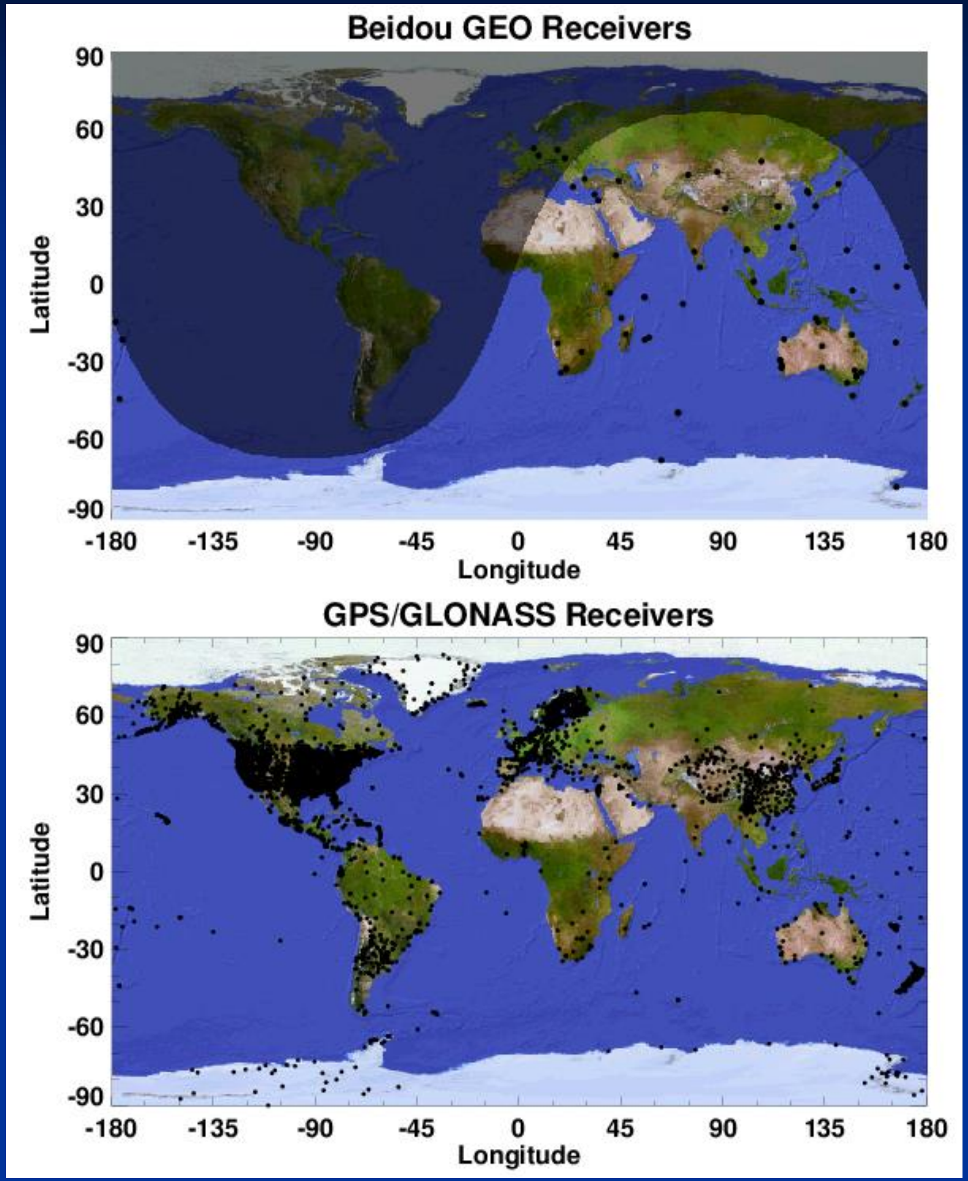
Initial waves had huge amplitudes and wavelengths (~ 2K km!)

Subsequent waves had 300-500 km wavelengths

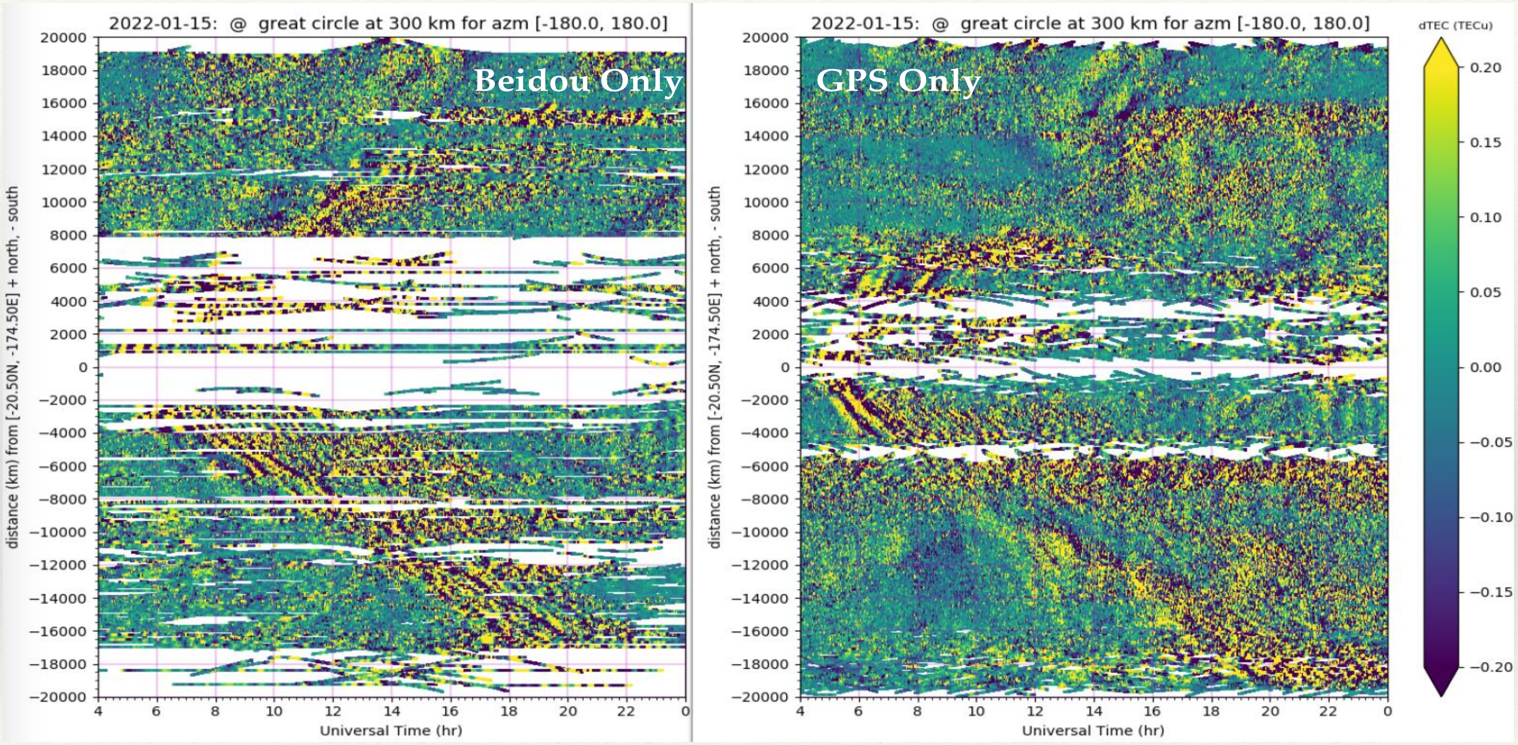


MIT HAYSTACK OBSERVATORY





Beidou and GPS data coverage for Tonga eruption study



MIT HAYSTACK OBSERVATORY

Distance-Time plot to show eruption induced global TID propagation https://www.frontiersin.org/articles/10.3389/fspas.2022.871275/full

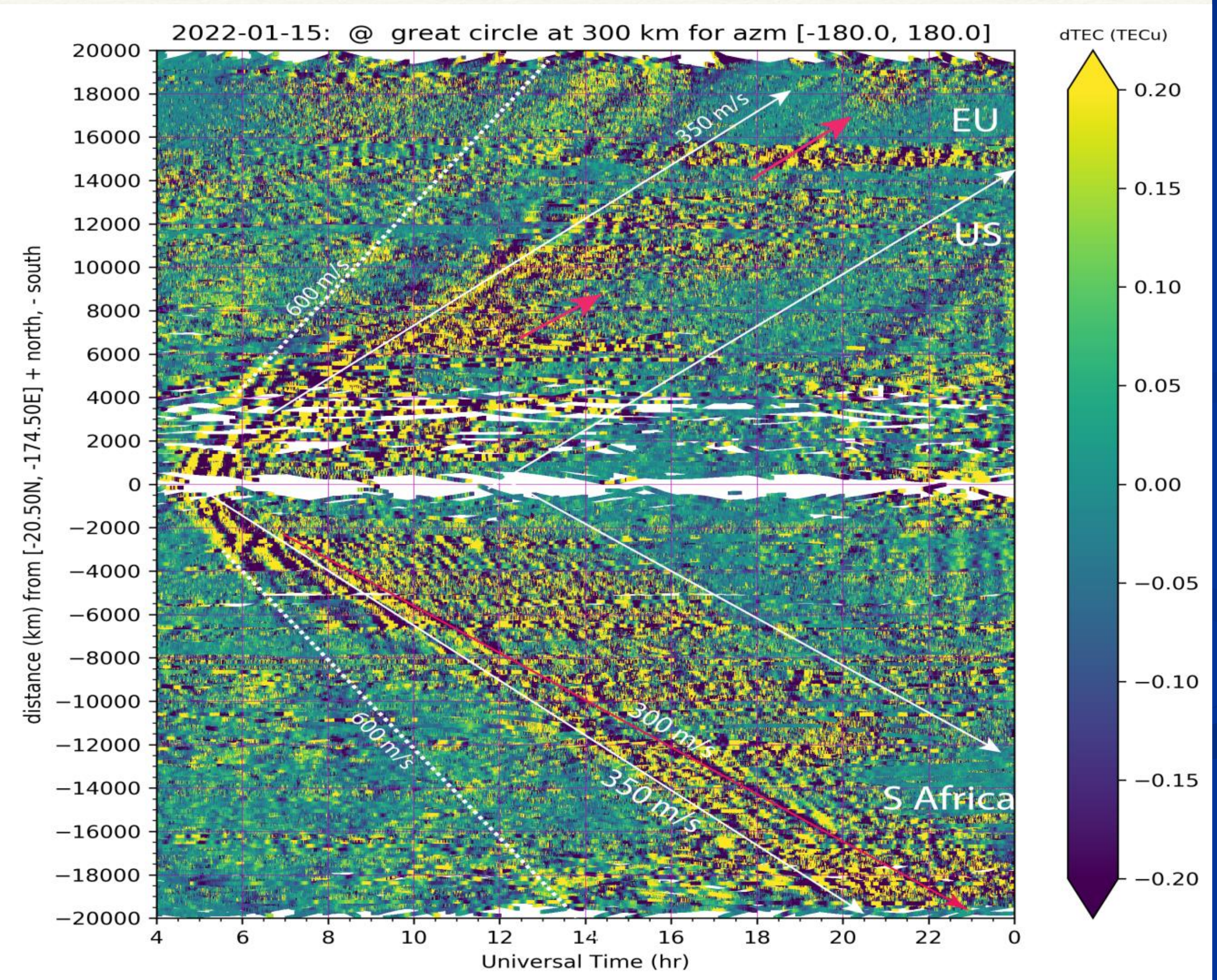
Global View: N-S Propagation

Evident TID occurrence was based on the distance from the epic center;

TIDs reached 20K km distance 17 hrs after the eruption;

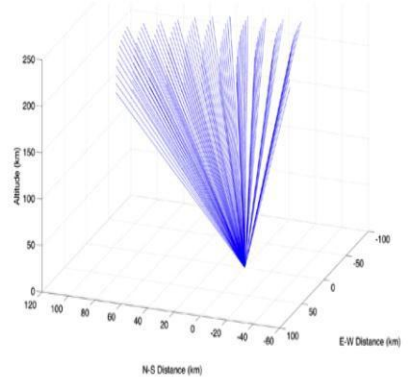
Shock fronts travled at ~ 350 m/ s

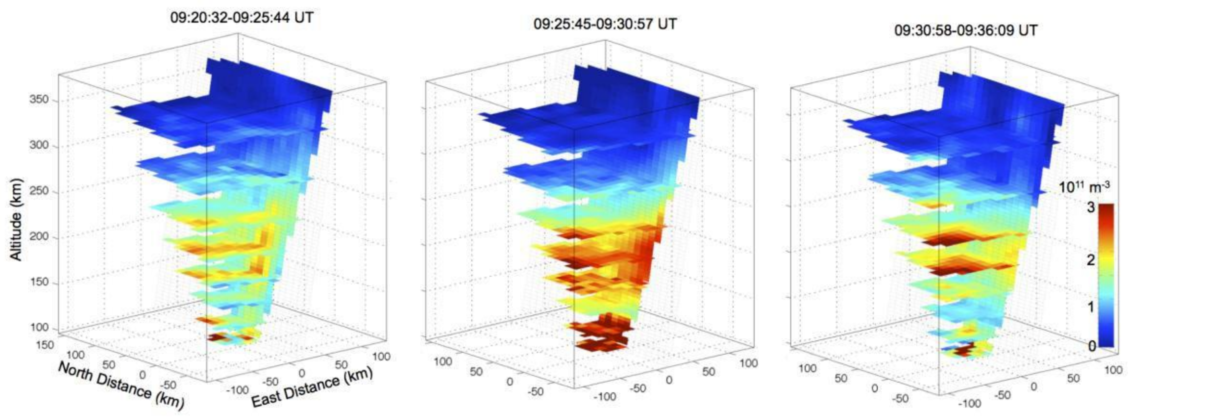
Regional disturbances lasted for 8-10 hrs



MIT HAYSTACK OBSERVATORY

Big Data and Computational Reconstruction





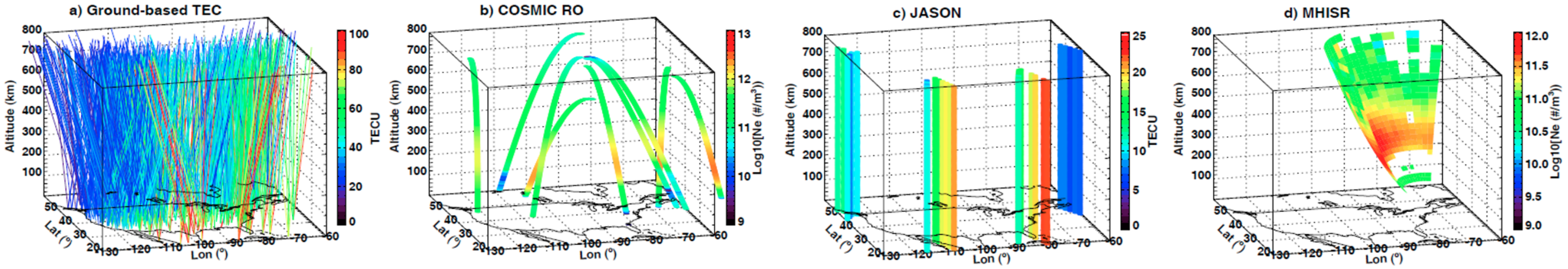
Consecutive 5-minute images of three-dimensional ionospheric density patterns observed with the Poker Flat Incoherent Scatter Radar (PFISR) during a geomagnetically active period. (After Semeter et al. „09, „10)

MERGE DATA FROM DIFFERENT SENSORS

Regional 3-D electron density specification with a new TEC-based Ionospheric Data Assimilation System (TIDAS)

Region: the continental U.S.; Data assimilation Method: En3DVAR; Background: NeQuick

1. Ground-based and Space-borne Datasets: GNSS TEC + COSMIC RO + JASON TEC + Millstone Hill ISR



2. Ensemble-based background error covariance

3. Three-Dimensional Variation (3DVAR) Approach

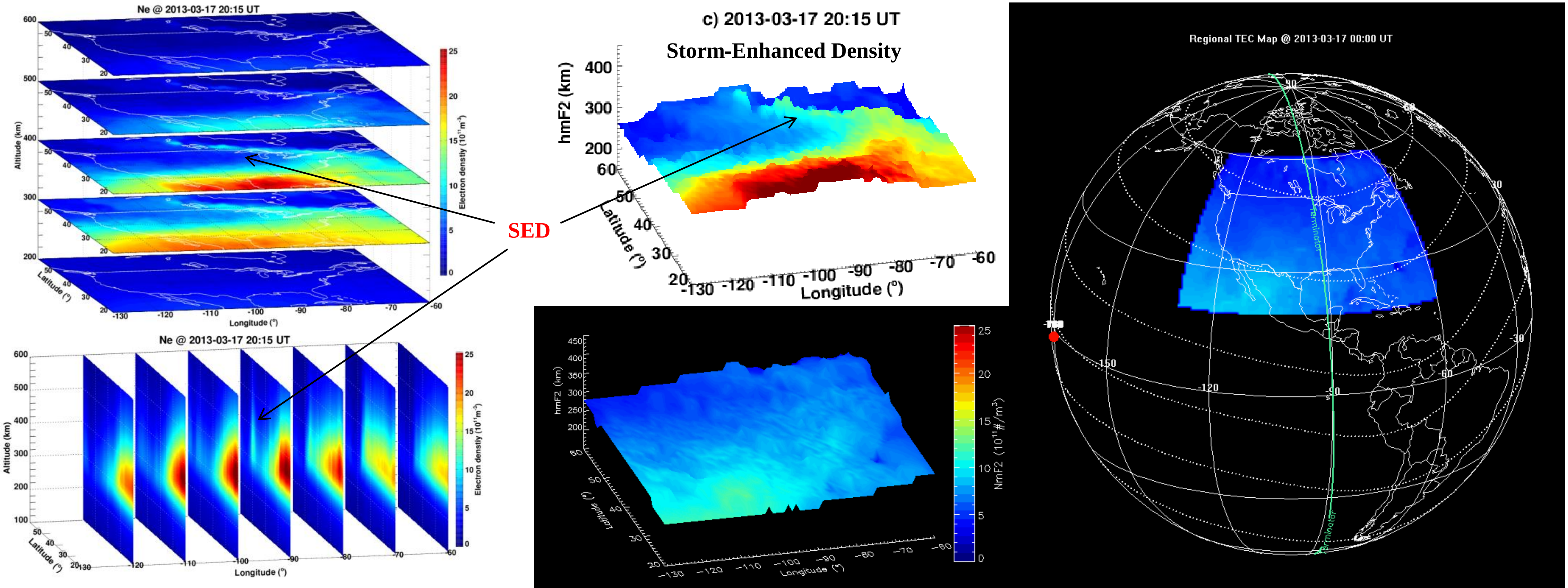
4. Sparse-Matrix Storage

MIT HAYSTACK OBSERVATORY

Regional 3-D electron density specification with a new TEC-based Ionospheric Data Assimilation System (TIDAS)

Resolution: 1° (Latitude) x 1° (Longitude) x 20 km (Altitude) x 5 min

- TIDAS data assimilation results provide a reasonable representation of the morphology and evolution of well known large-scale ionospheric characteristics, such as the equatorial ionization anomaly (EIA) at low latitudes, mid-latitude storm-enhanced density (SED) containing a remarkable density gradient, and the main ionospheric trough with TEC depletions at subauroral
- **In particular, TIDAS data assimilation product captures well the 3-D fine structures and dynamic evolution of SED**



HMONG Guide in North Vietnam has more sophisticated cell phone than Cornell-educated Mechanical Engineer.

West Texas 15 Sept 2000 near El Paso Texas
Aurora In West Texas Skies

Credit & Copyright: [Chris Grohusko](). Astronomy Picture of the Day

(from astronomy picture of the day)

Courtesy Shunrong Zhang

Summary:

- *Find easier ways to integrate differe*Summary – the future
- *Utilize all signals*
- *Improve visualizationnt data sets; Standardize data formats*
- *Modelers, data scientists, experimentalists: collaborate*