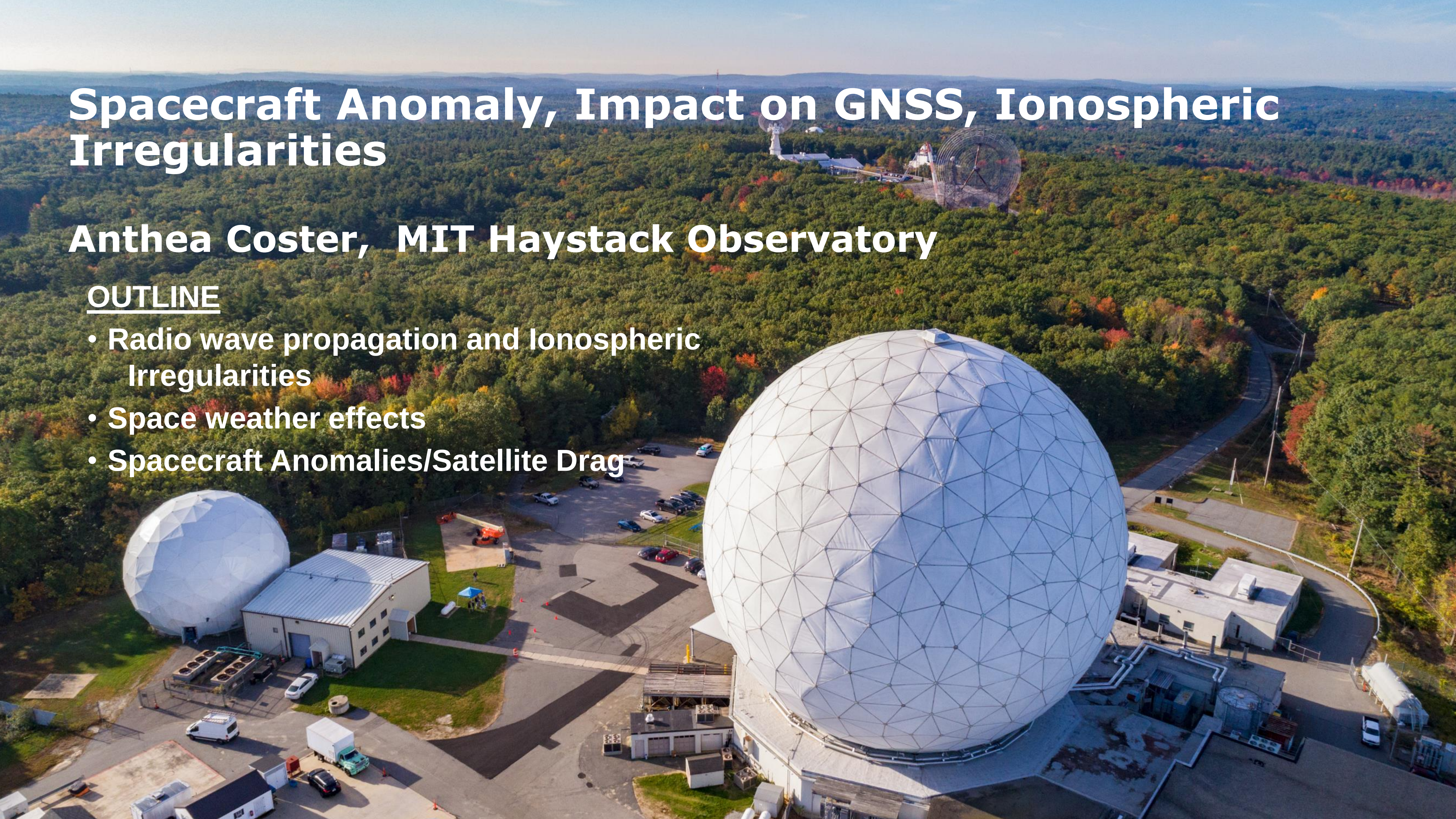
# Spacecraft Anomaly, Impact on GNSS, Ionospheric Irregularities

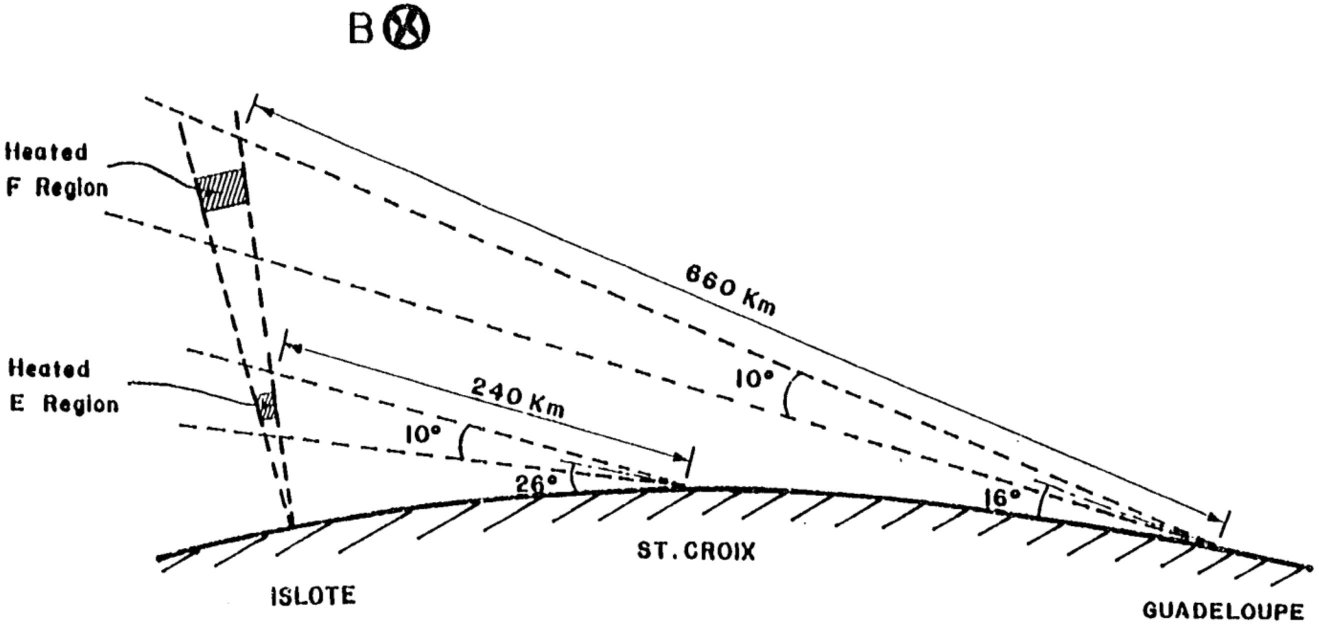

## Anthea Coster,  MIT Haystack Observatory

OUTLINE

- Radio wave propagation and Ionospheric Irregularities
- Space weather effects
- Spacecraft Anomalies/Satellite Drag

# PhD Research in 1980 : Time Synchronization Hard

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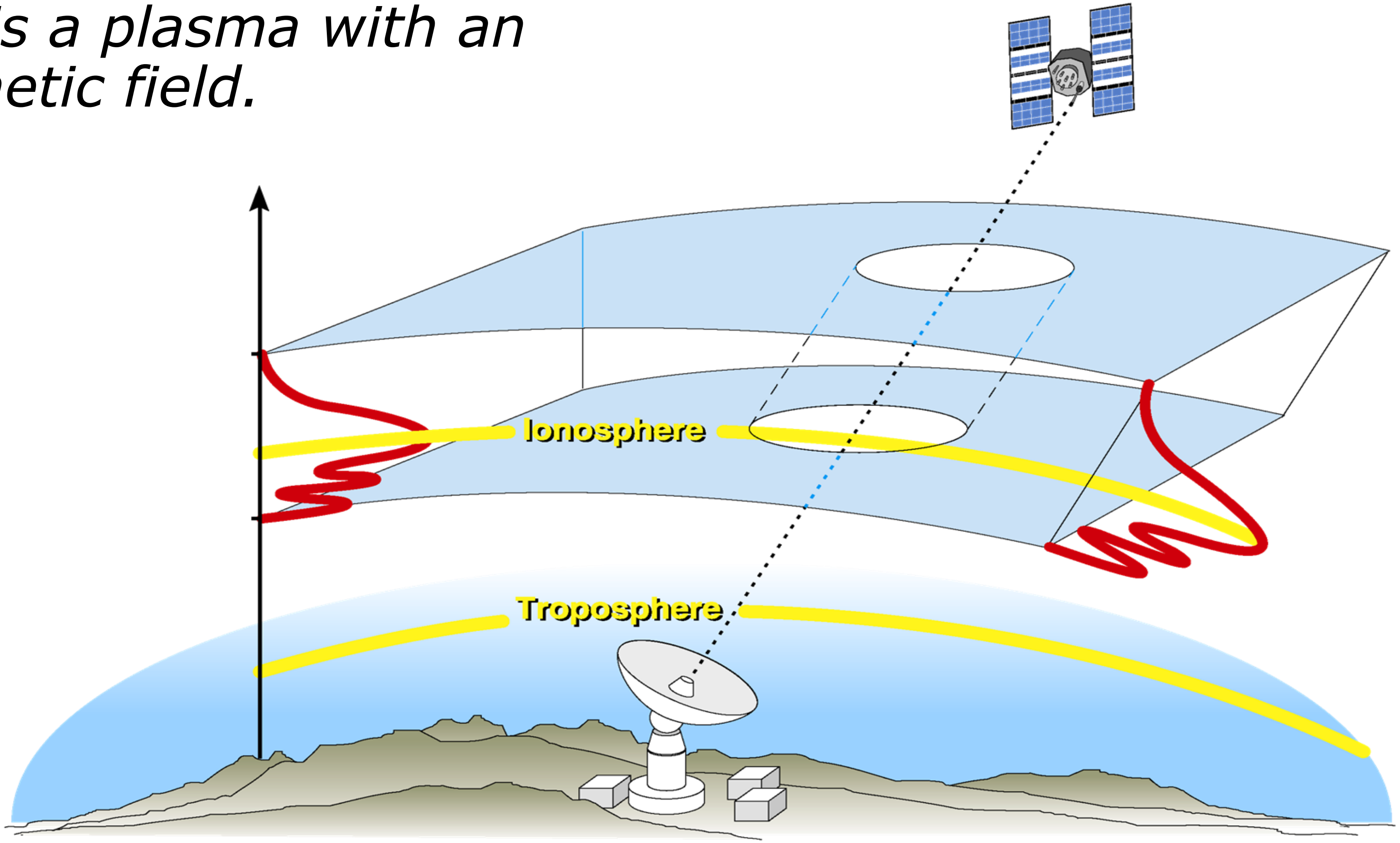
# Radio Wave Propagation

*The ionosphere is a plasma with an embedded magnetic field.*




From Attila Komjathy, JPL

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# 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

$i = \sqrt{-1}$

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

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

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

$\varepsilon_0$ = permittivity of free space

$\mu_0$ = permeability of free space

$B_0$ = ambient magnetic field strength

$e$ = electron charge

$m$ = electron mass

$\theta$ = angle between the ambient magnetic field vector and the wave vector

$\nu$ = electron collision frequency

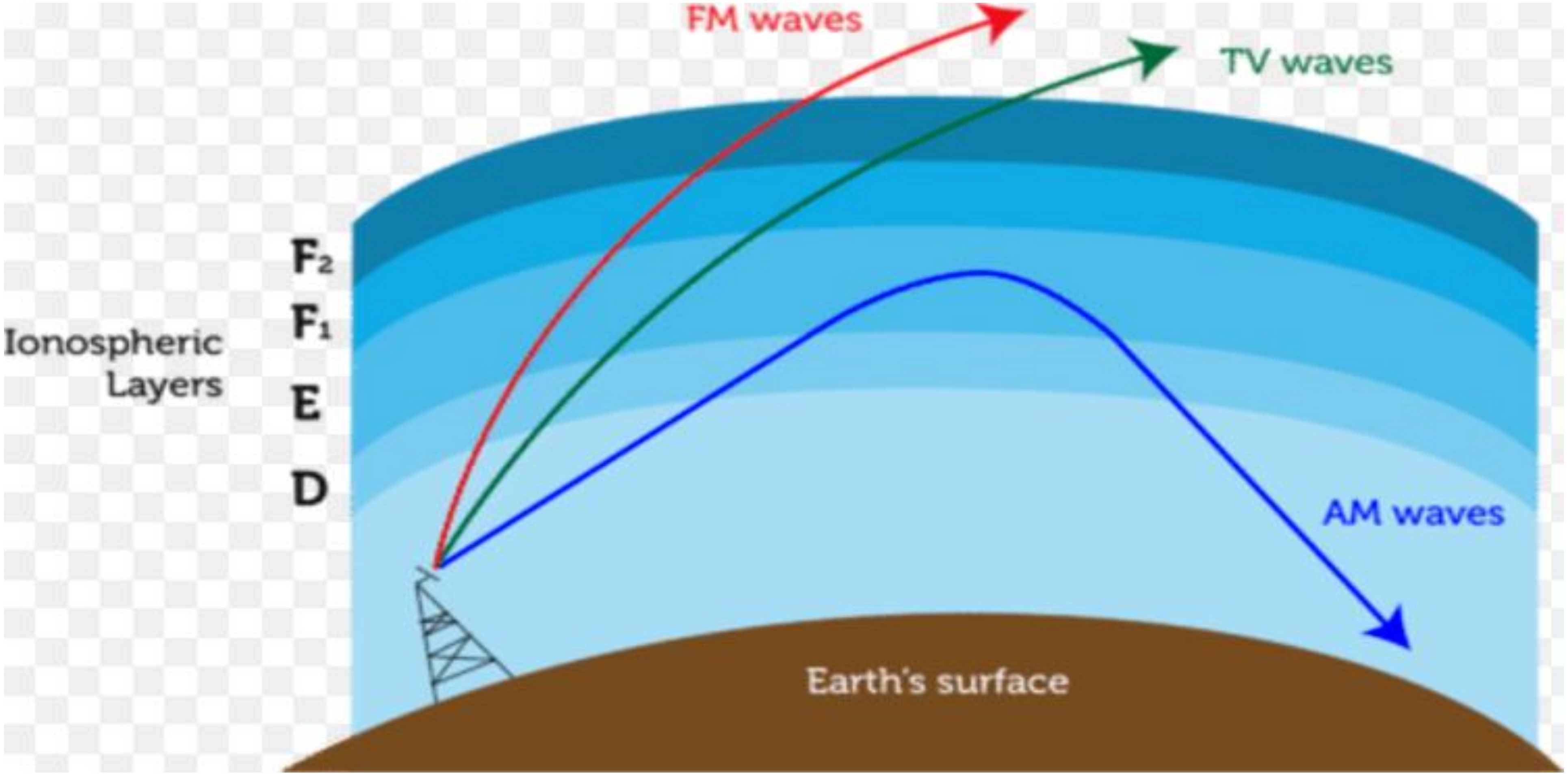
$\omega = 2\pi f$ (radial frequency)

$f$ = 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

# Some Radio Waves are Reflected

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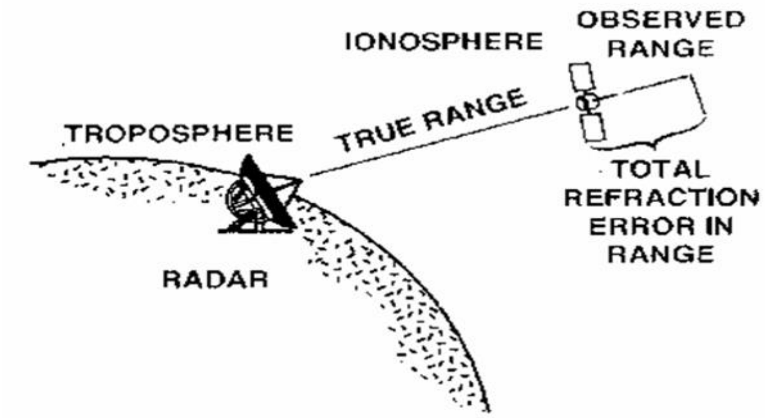
# Ionospheric Range Delay




$$\Delta R_{ion}(meters) = \frac{40.3}{f^2} \underbrace{\int_0^R N_e \, dr}_{\text{TEC}}$$

**TEC**

Range Delay

| TEC | S-Band | L-Band | UHF | VHF | Elev | Mapping Function |
|---|---|---|---|---|---|---|
| 50 | 2.4 m | 12 m | 104 m | 787 m | 90 ° | x 1 |
| 110 | 5.1 m | 26 m | 223 m | 1.7 km | 20 ° | x 2.12 |

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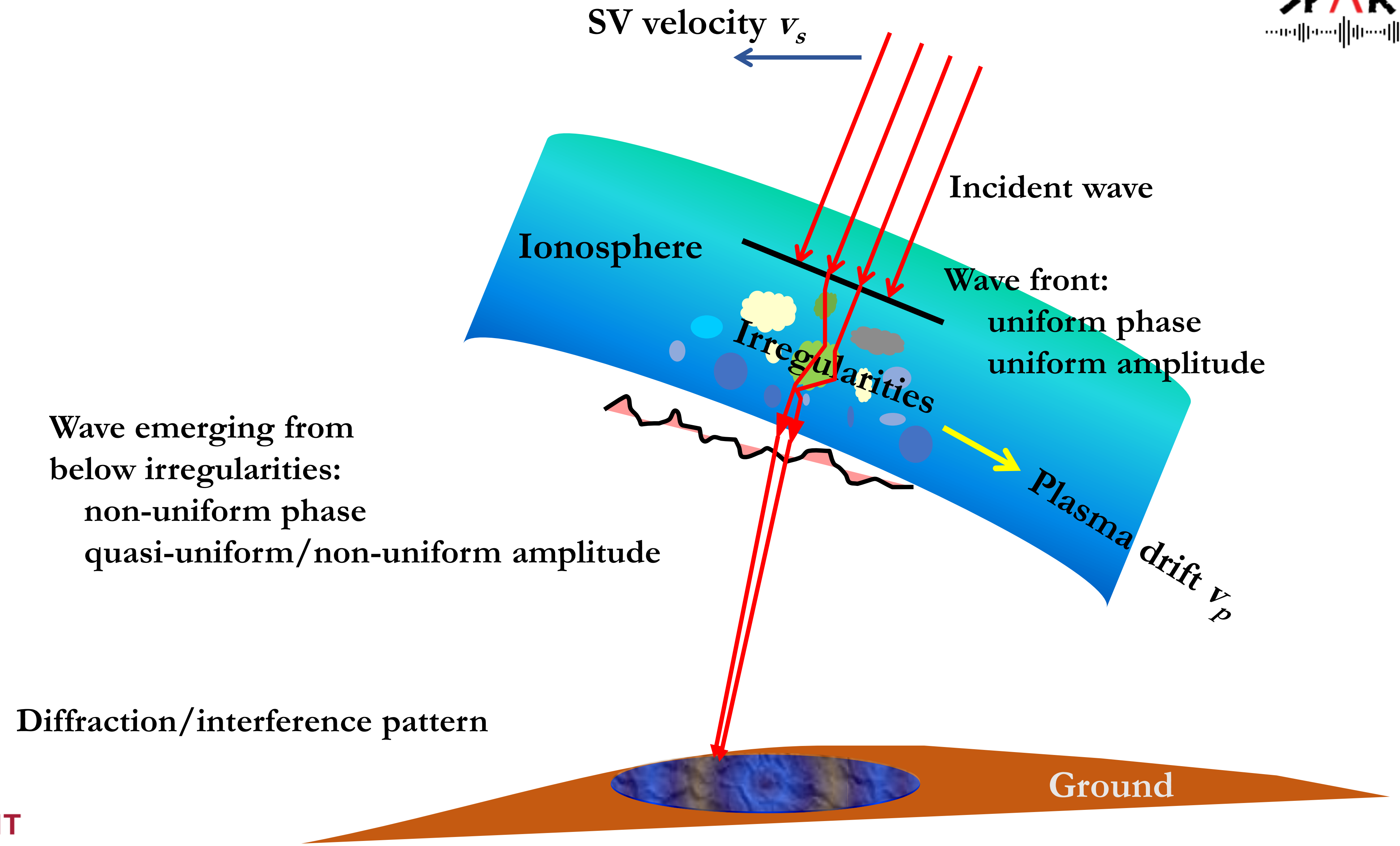
# Space Weather - Scintillation

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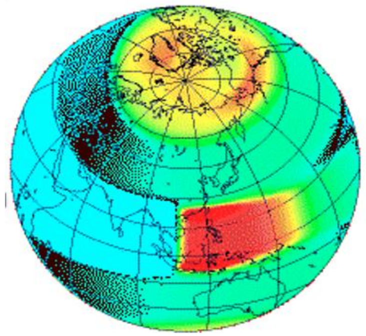
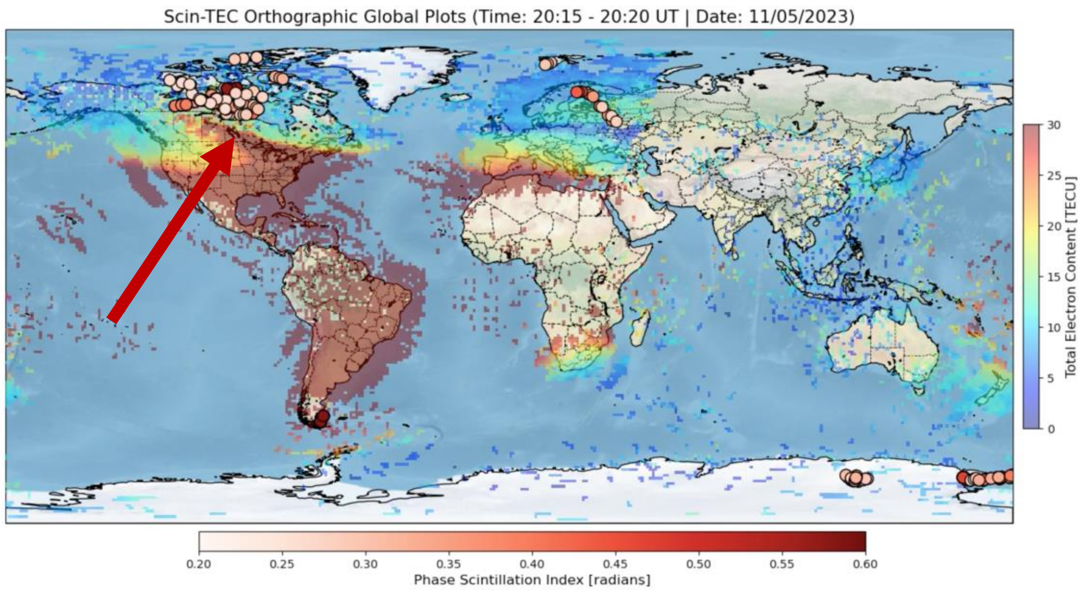
Courtesy of Jade Morton

# High Latitude GNSS Scintillation

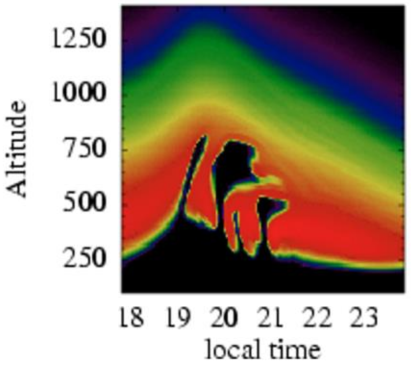
Associated with aurora and precipitation,
Storm-enhanced density features (SED),
polar cap patches, Tongues of Ionization (TOI)

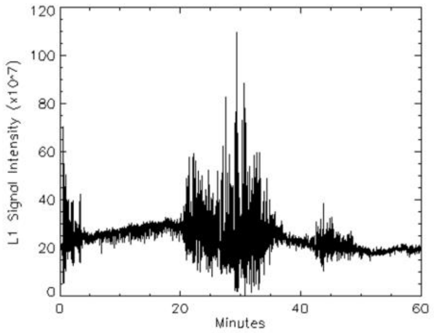





# Low-Latitude GNSS Scintillation

Associated with Equatorial Spread-F, "bubbles"

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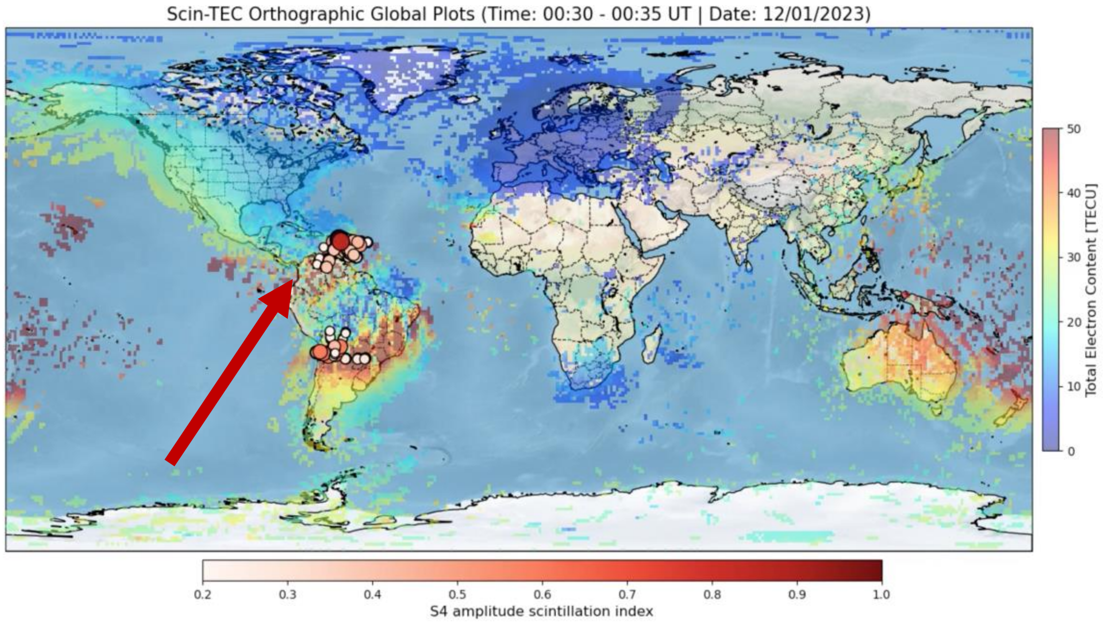

# Scintillation Impacts

- GNSS loss of lock due to phase or amplitude scintillation
- Radars lose ability to coherently track objects in space
- Loss of or difficulty in receiving communication channels

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## OUTLINE

- Radio wave propagation and ionospheric irregularities
- Space weather effects
- Spacecraft Anomalies/Satellite Drag

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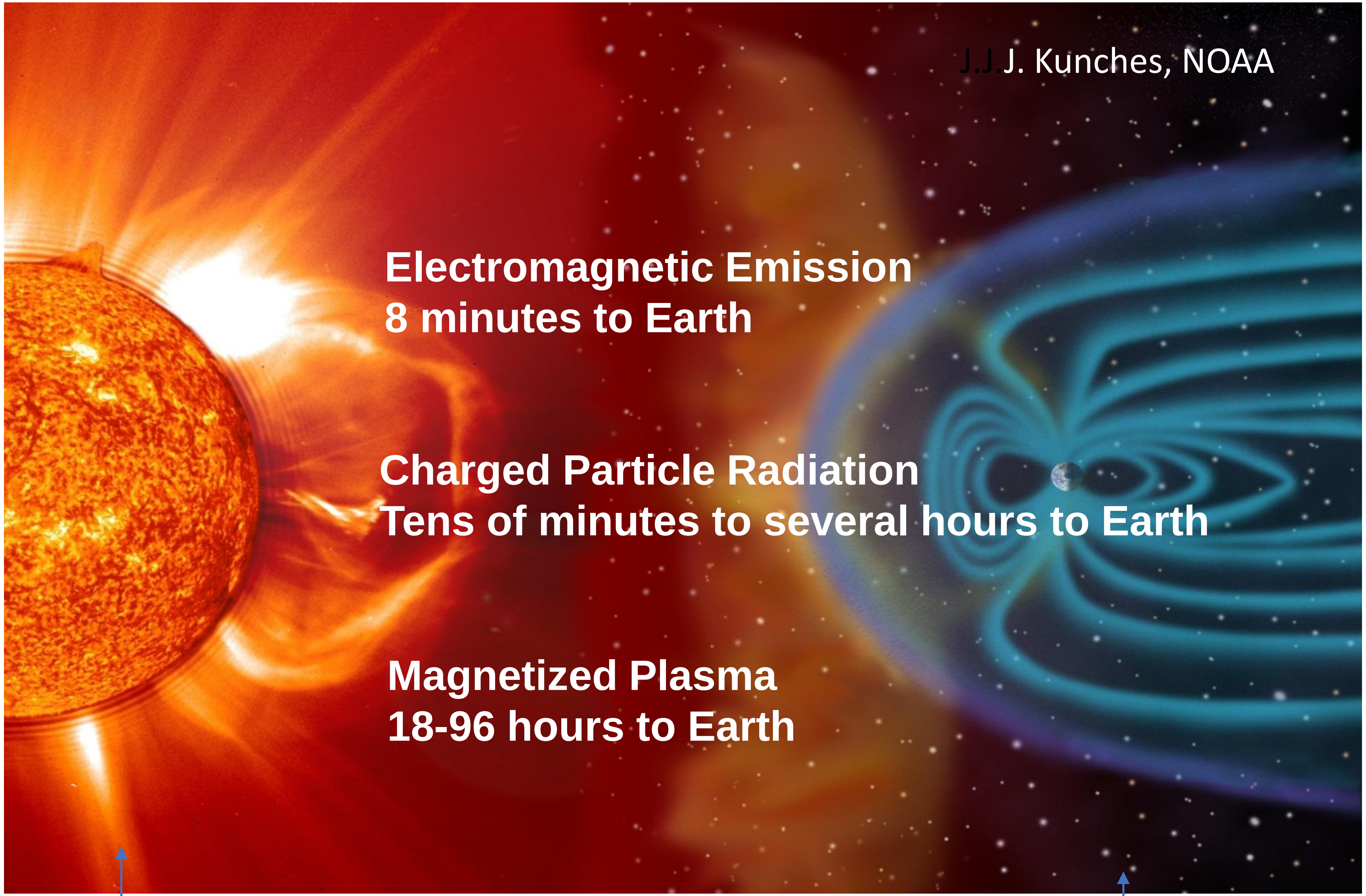
# Three Agents of Space Weather

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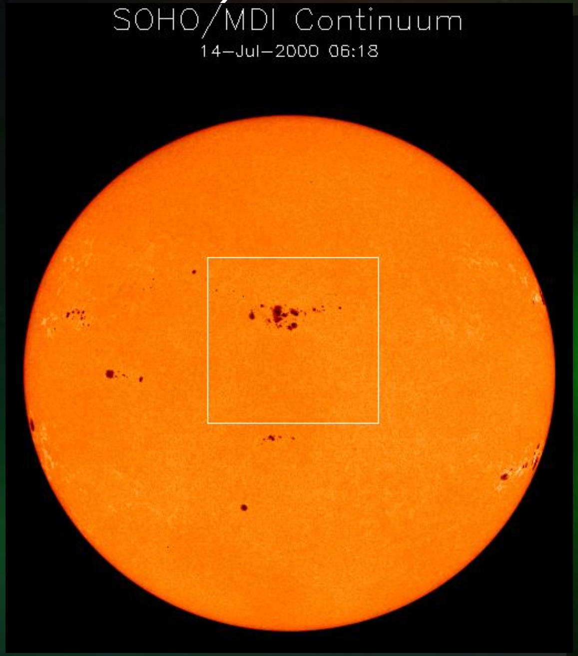
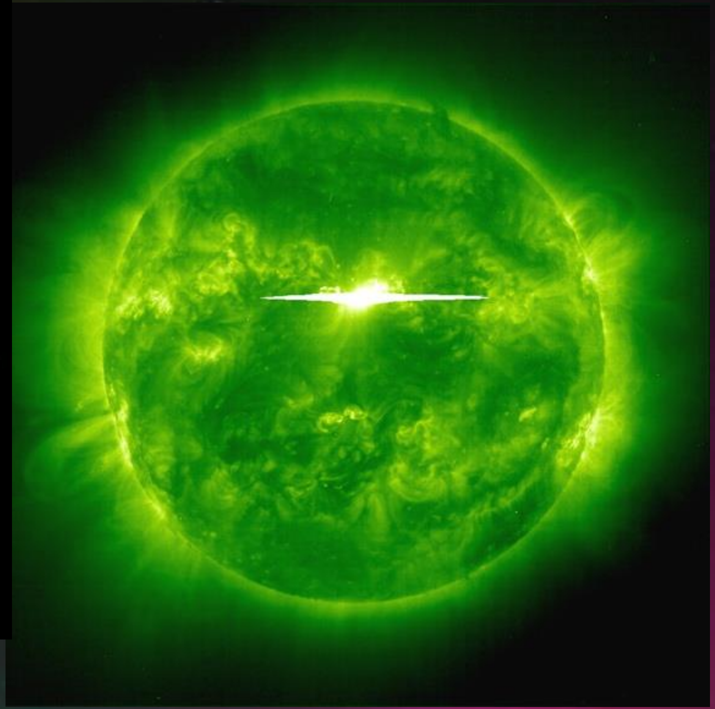
# Solar Flares/Solar Radio Bursts *(Radio Blackouts – R Scale)*



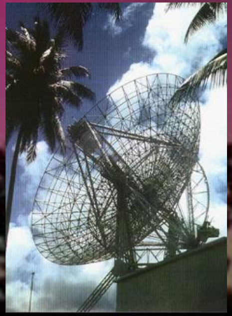
J. Kunches, NOAA

***Solar Flare –***
***A violent* explosion in the Sun's atmosphere; energy equivalent of a hundred million hydrogen bombs.**

- Arrival: 8 min from Sun to Earth
- Duration: minutes to 3 hrs
- Daylight-side impact

## *Impacts*

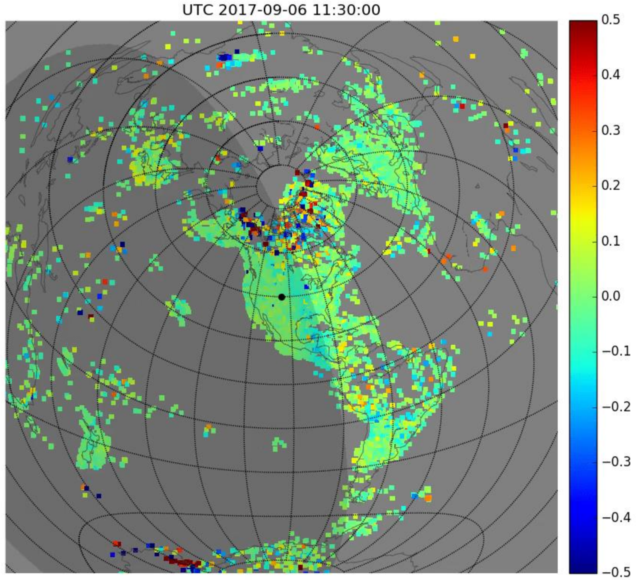
GPS Network

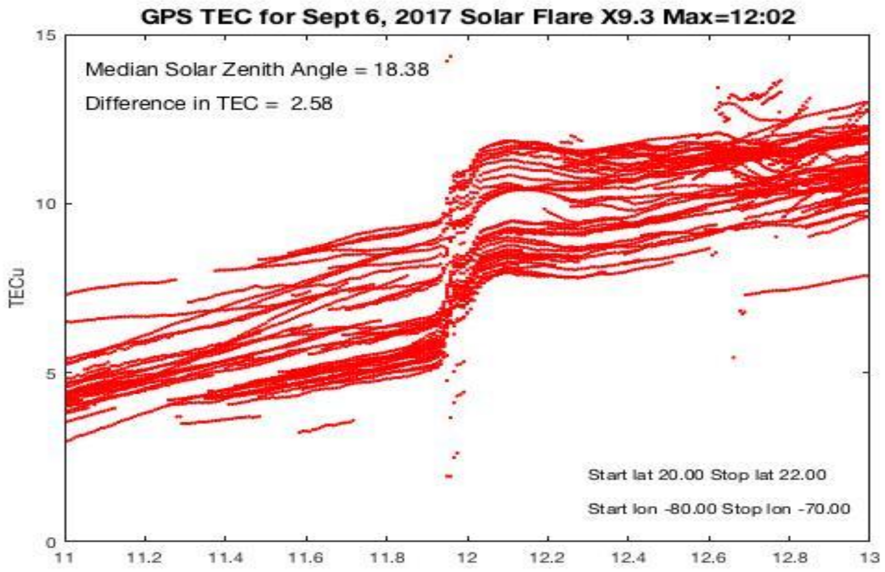


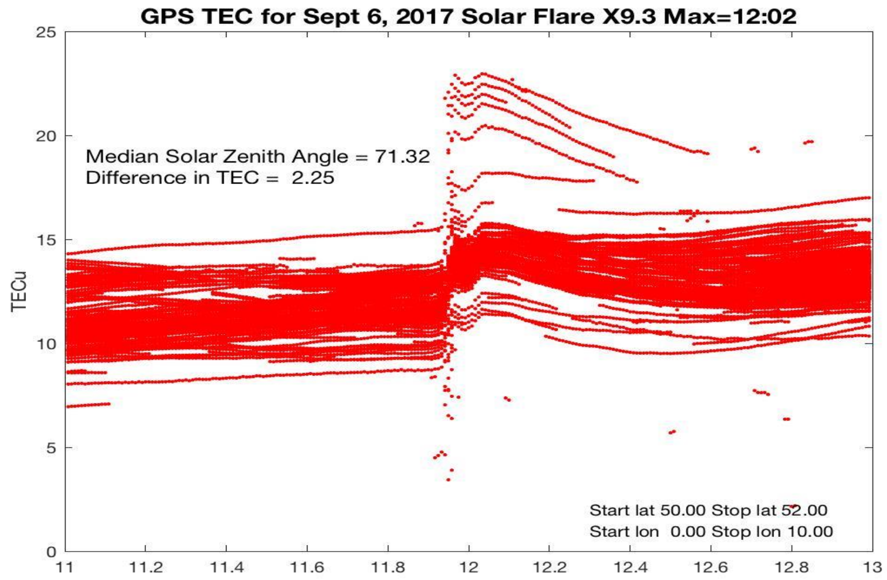
Communications
Ground and Space-based

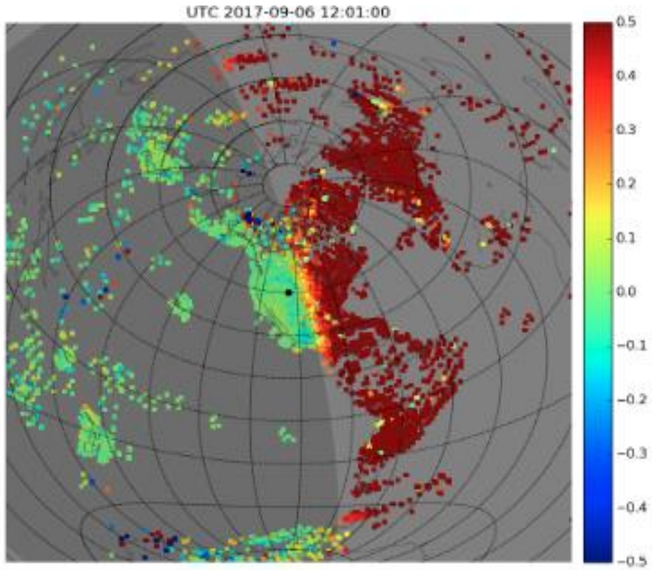
Radar

# Sept 6, 2017
## X9.3 Solar Flare

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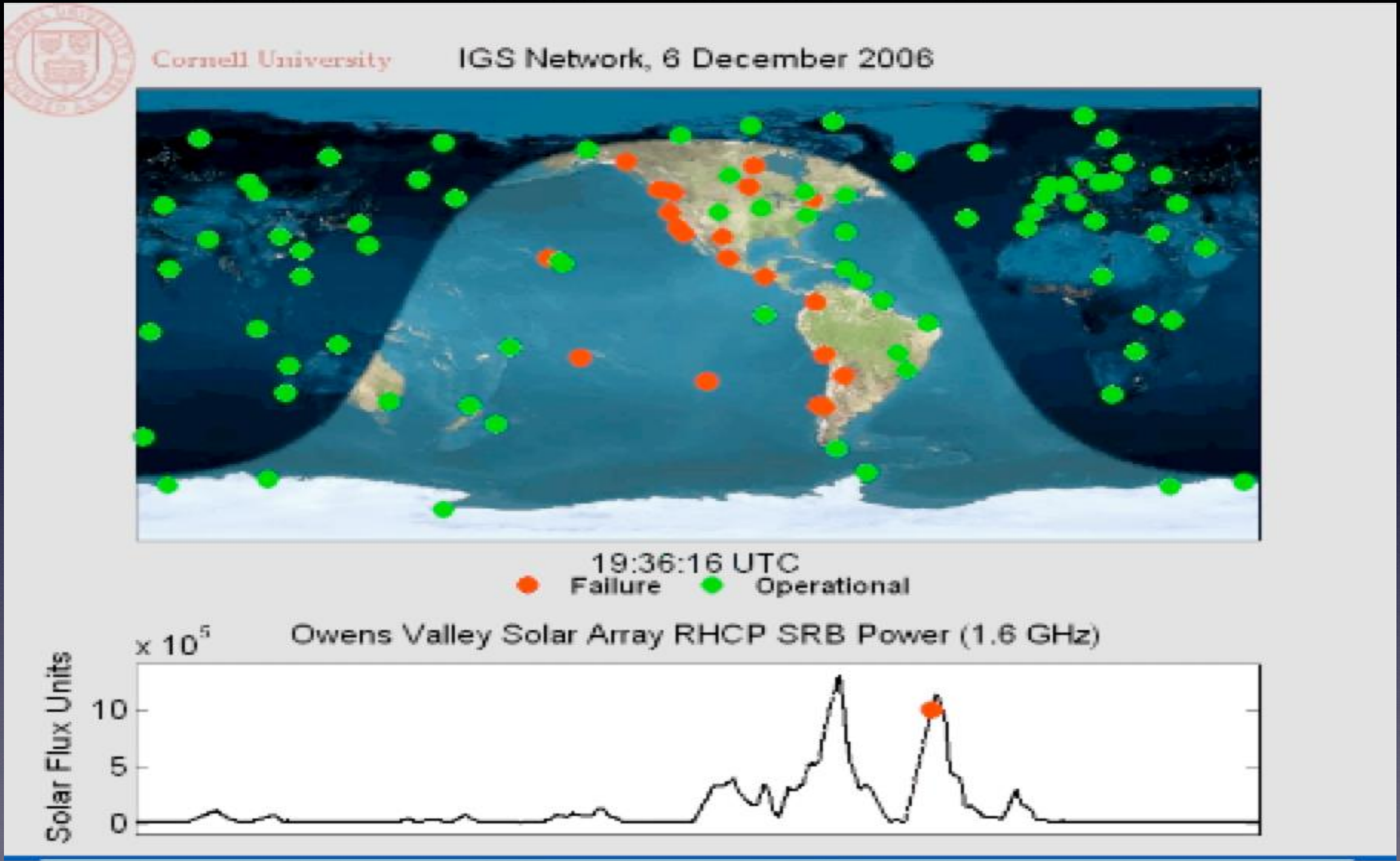
# Increase in background noise level due to Solar Radio Bursts

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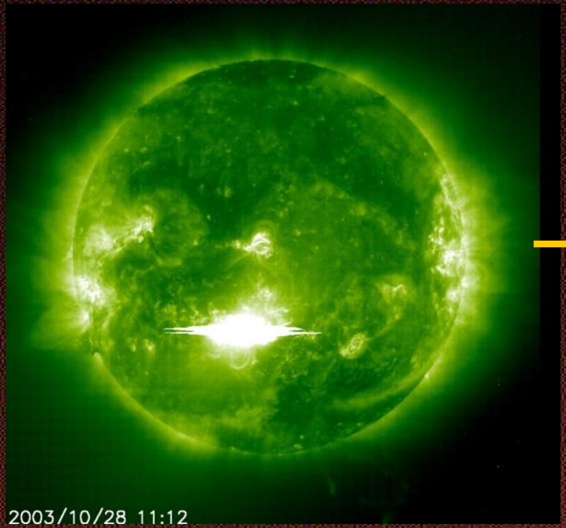
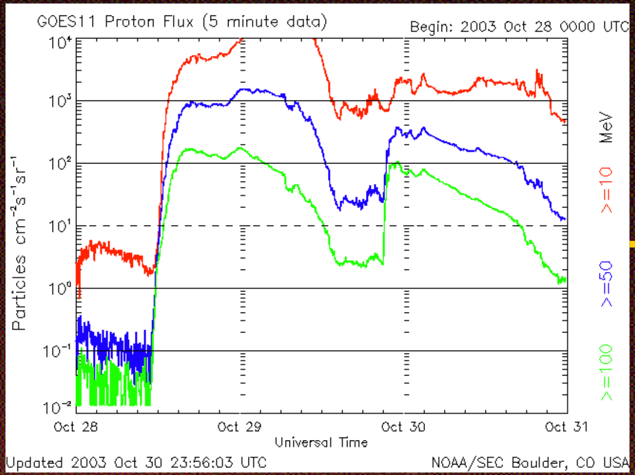
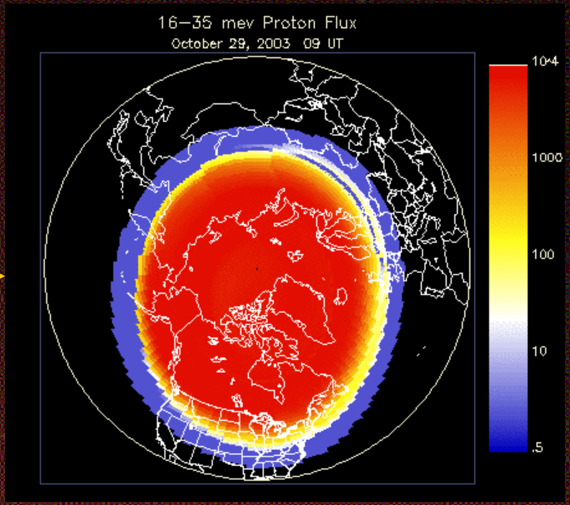
# Solar Radiation Storms *(S Scale)*



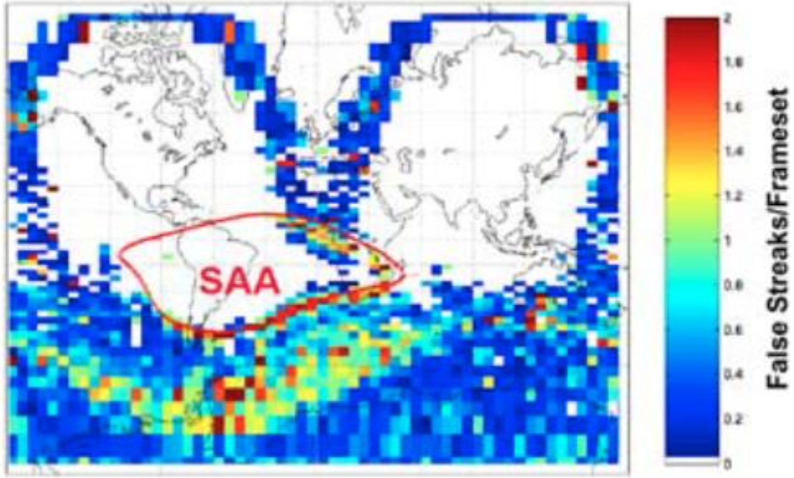

- Arrival: 30 minutes to several hours
- Duration: hours to days

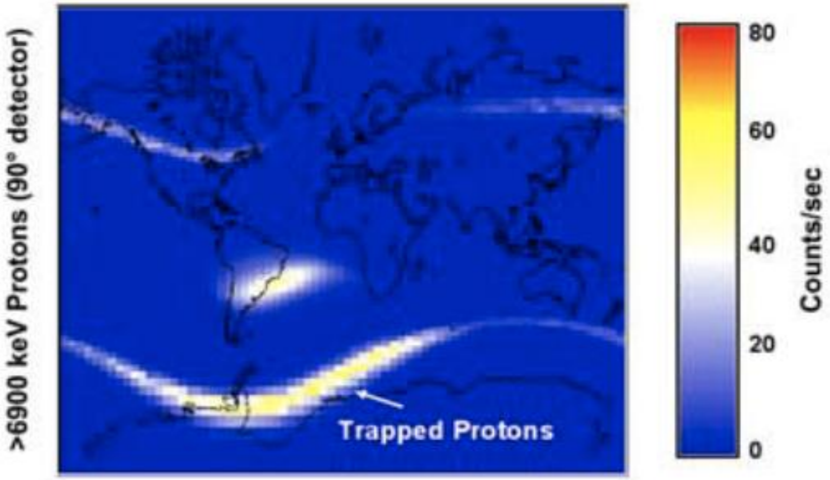
## *Impacts…*

- Satellite Operations (range from loss of data to loss of satellite)
- Aviation (communications and exposure concerns)
- High latitude HF comm outage
- Manned Spaceflight

# Optical Tracking from Space

- Subtract background stars and look for streaks; calculate angular position

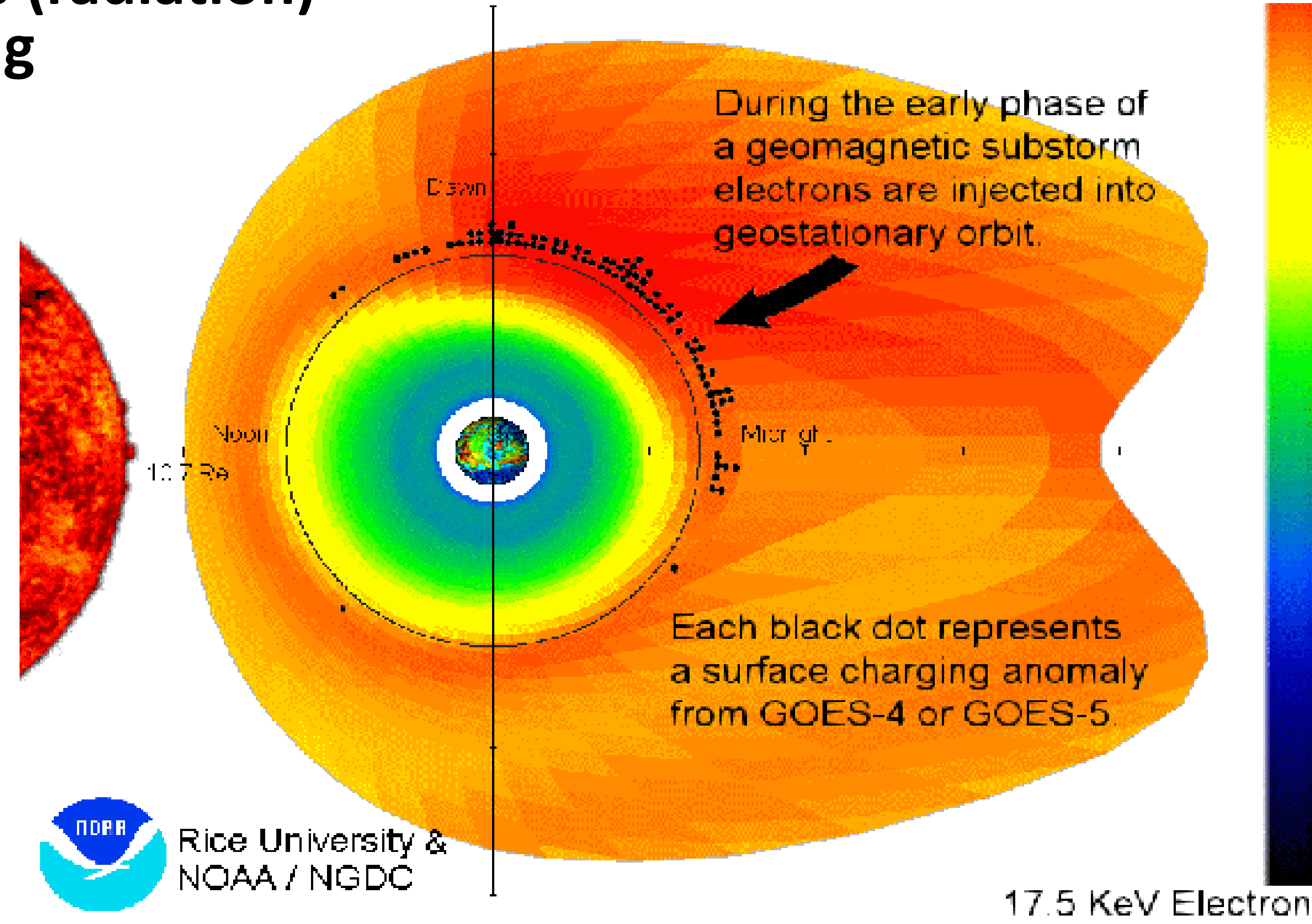


# Space environment effects on GEO satellites

Electron and ion particle effects (radiation)
    Internal and Surface Charging
Magnetic field variability
    Affects attitude control

*Certain places known to be regions of enhanced satellite anomaly occurrence*

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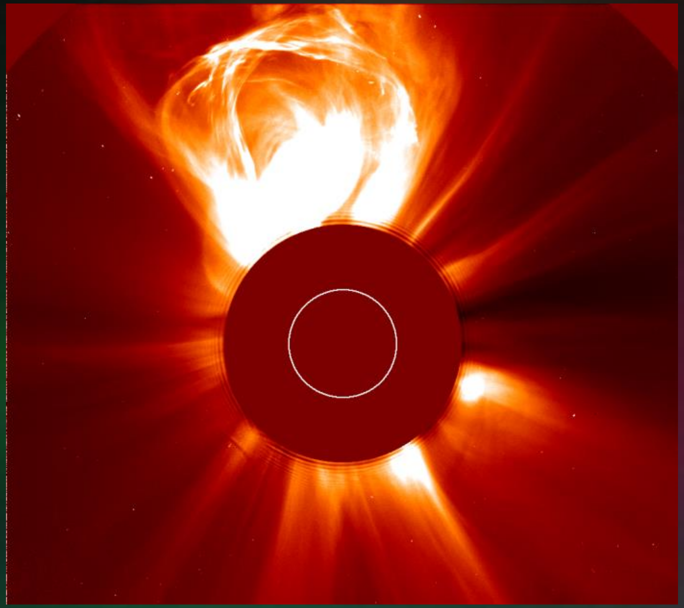
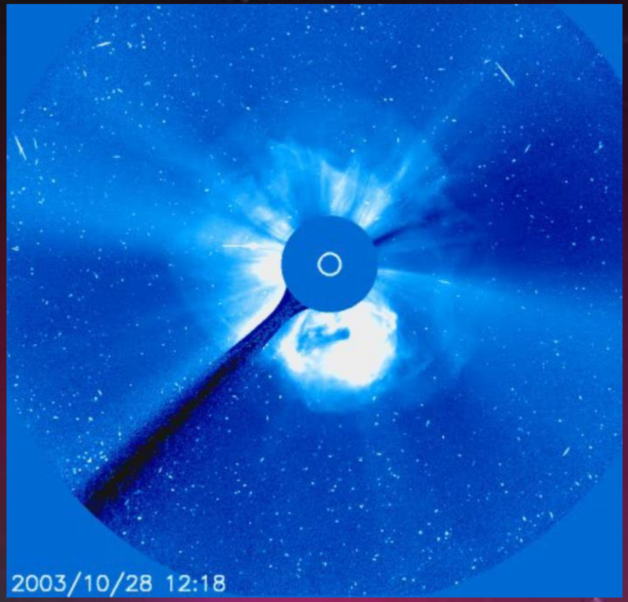
# Geomagnetic Storms *(G Scale)*

Coronal Mass Ejections (CMEs)
create geomagnetic storms



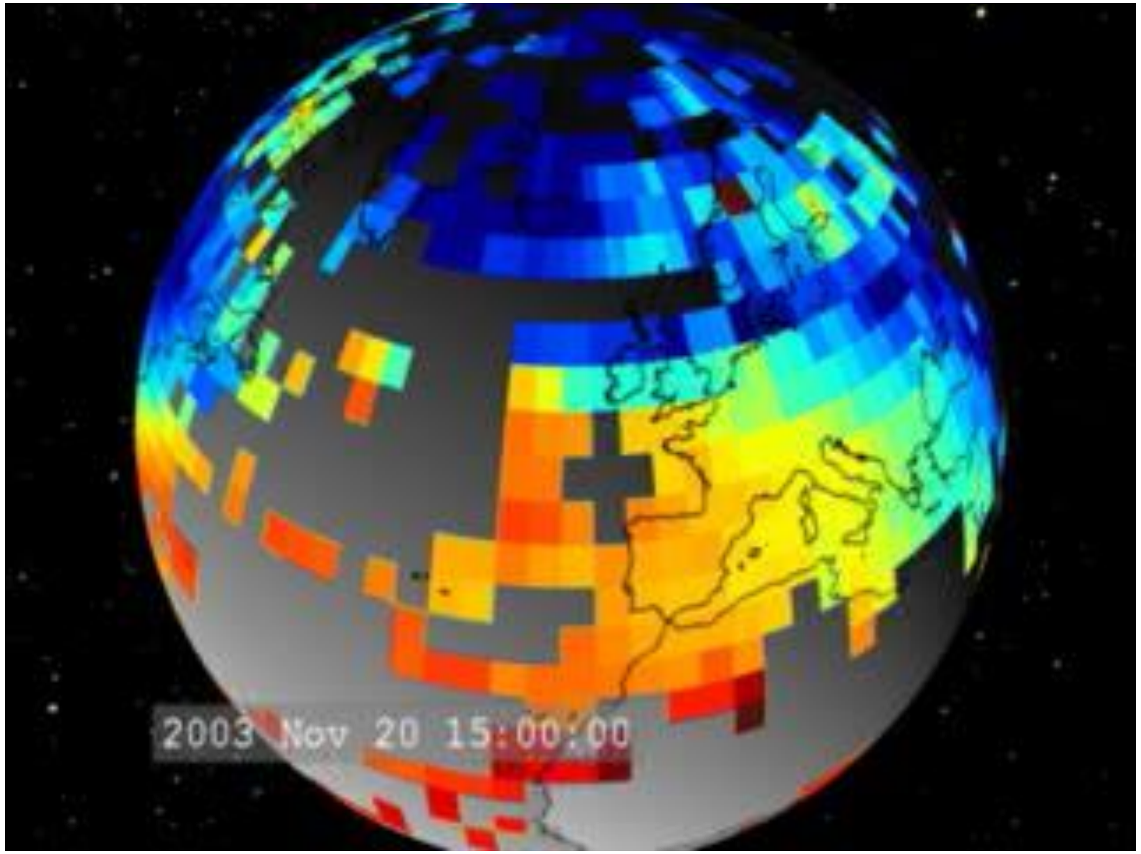


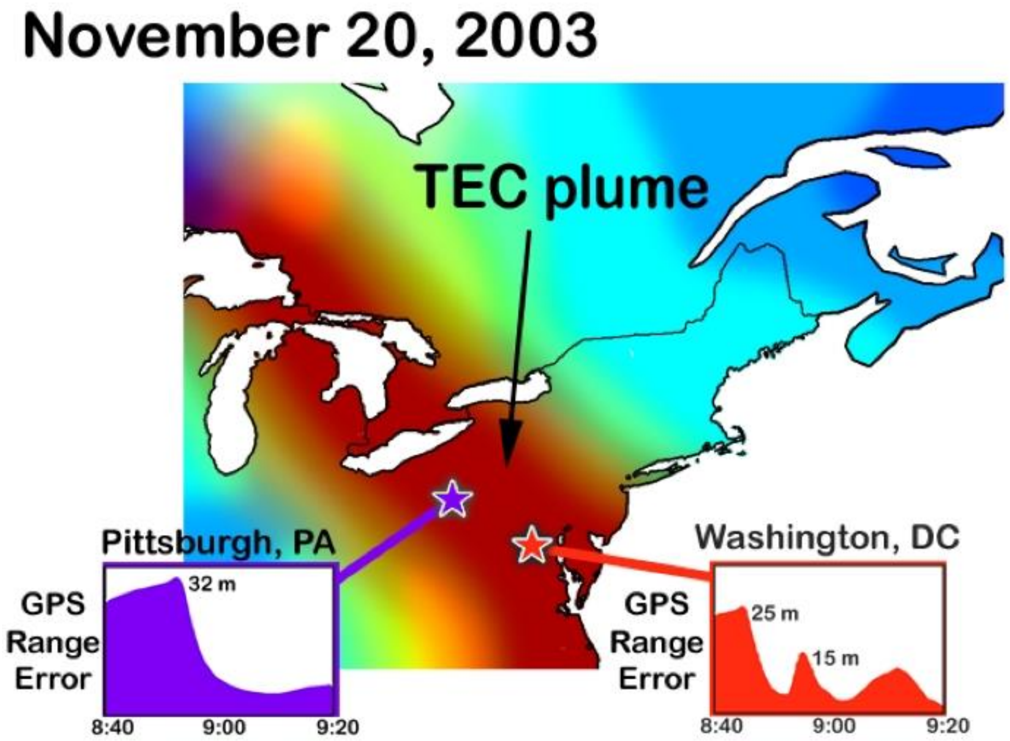

- Arrival: ~20 – 90 hours
- Duration: hours to a day
- Creates Ionospheric storms

## Impacts…

- Satellite Operations
- Aircraft operations
- Power grid operations
- GNSS operations
- Pipelines

# Large Gradients in the TEC lead to GNSS range errors




Courtesy of A. Mannucci

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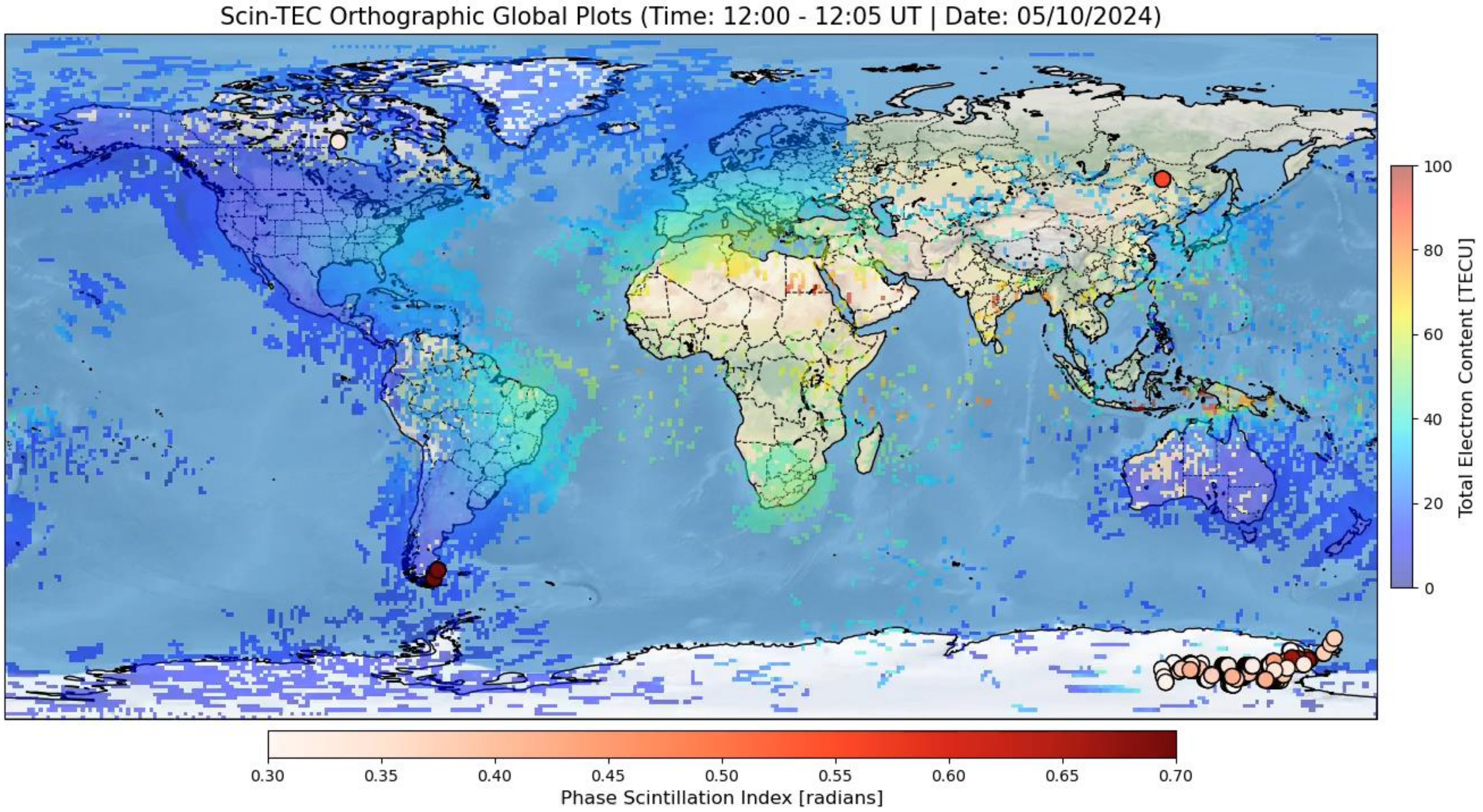
# *SigmaPhi/TEC May 10, 2024*

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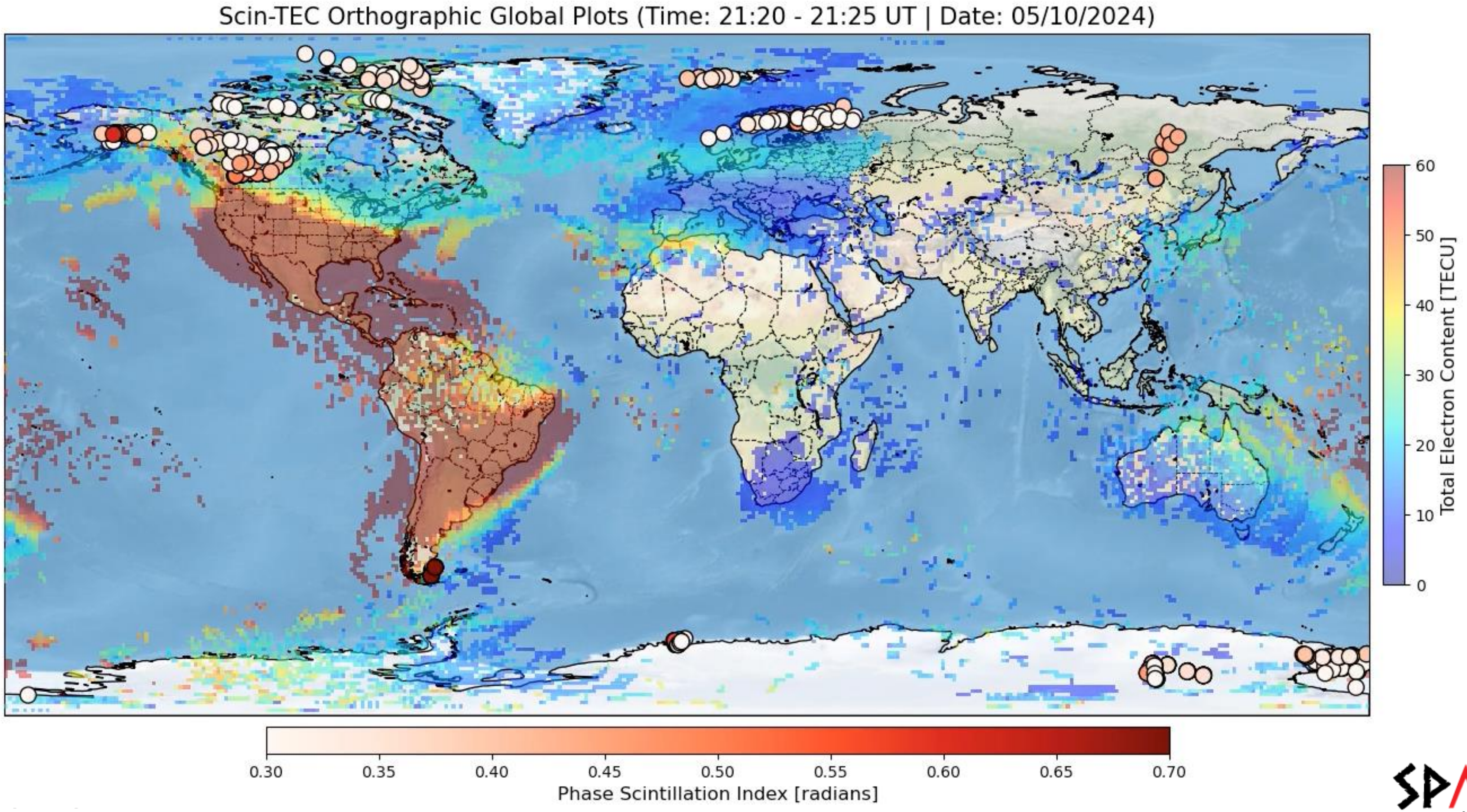
# *SigmaPhi/TEC May 10, 2024*

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# Outline

Overview – space weather

Radio wave propagation (GNSS)

Ionospheric Irregularities

Spacecraft Anomaly/ Satellite Drag

# Atmospheric drag

- **Satellites in Low Earth Orbit (LEO) (<2,000 km altitude) are significantly impacted by atmospheric drag**
- **Atmospheric drag is largest source of error in orbit prediction:**

$$F_i = \tfrac{1}{2}\rho A C_i v^2$$

$F_i =$ Force, $N$

$i =$ d(drag), l(lift), and s (side slip)

$A =$ area, $m^2$

$C_i =$ coefficient

$v =$ spacecraft speed with respect to the atmosphere, $m/s$

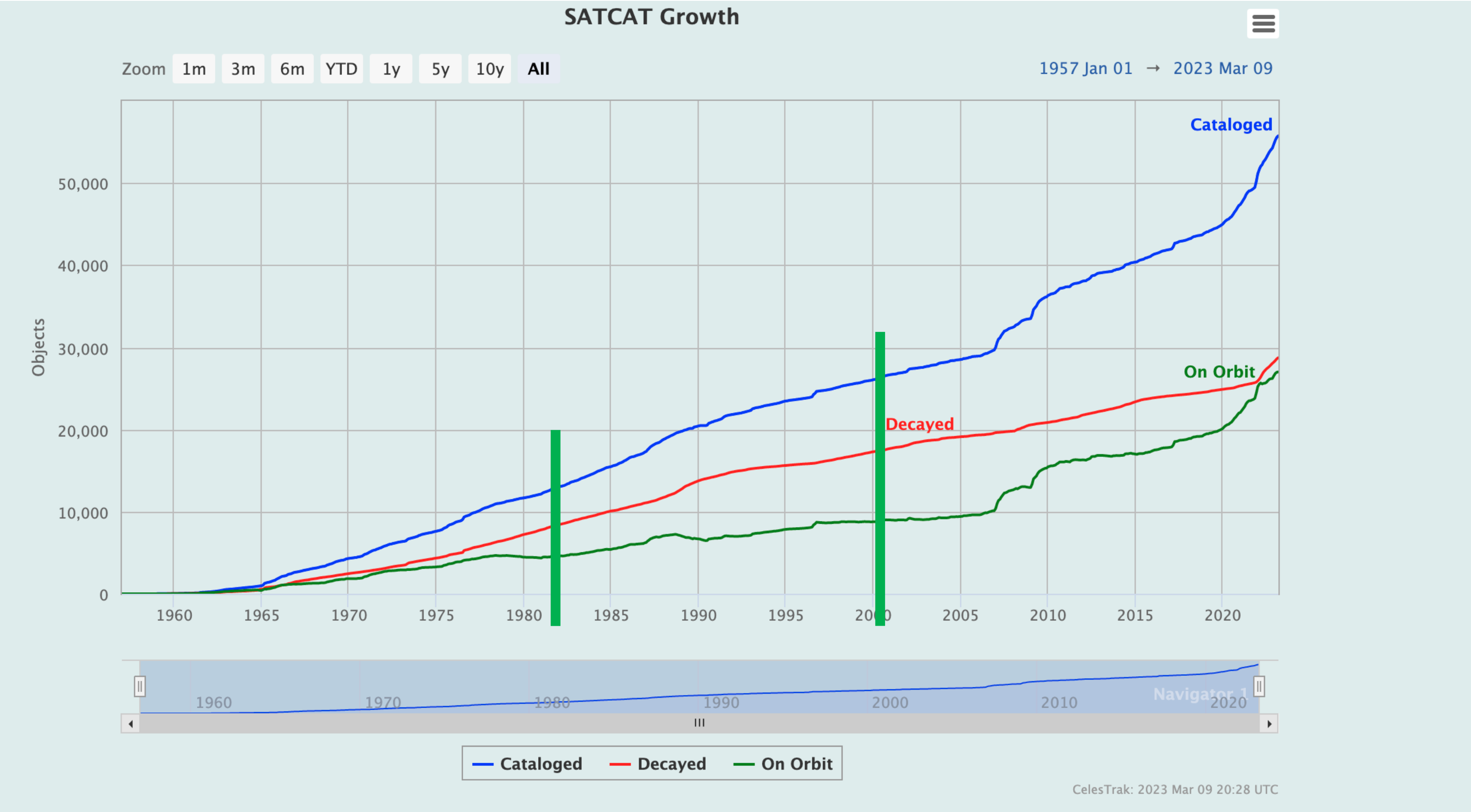
$\rho =$ atmospheric mass density, $kg/m^3$

The largest error is generally due to inaccurate estimates of the thermospheric density $\boldsymbol{\rho}$

Courtesy of Julia Briden, MIT


Video Courtesy: NASA
GEOSPATIAL WORLD

# Historical SATCAT Growth, 1957 to Present

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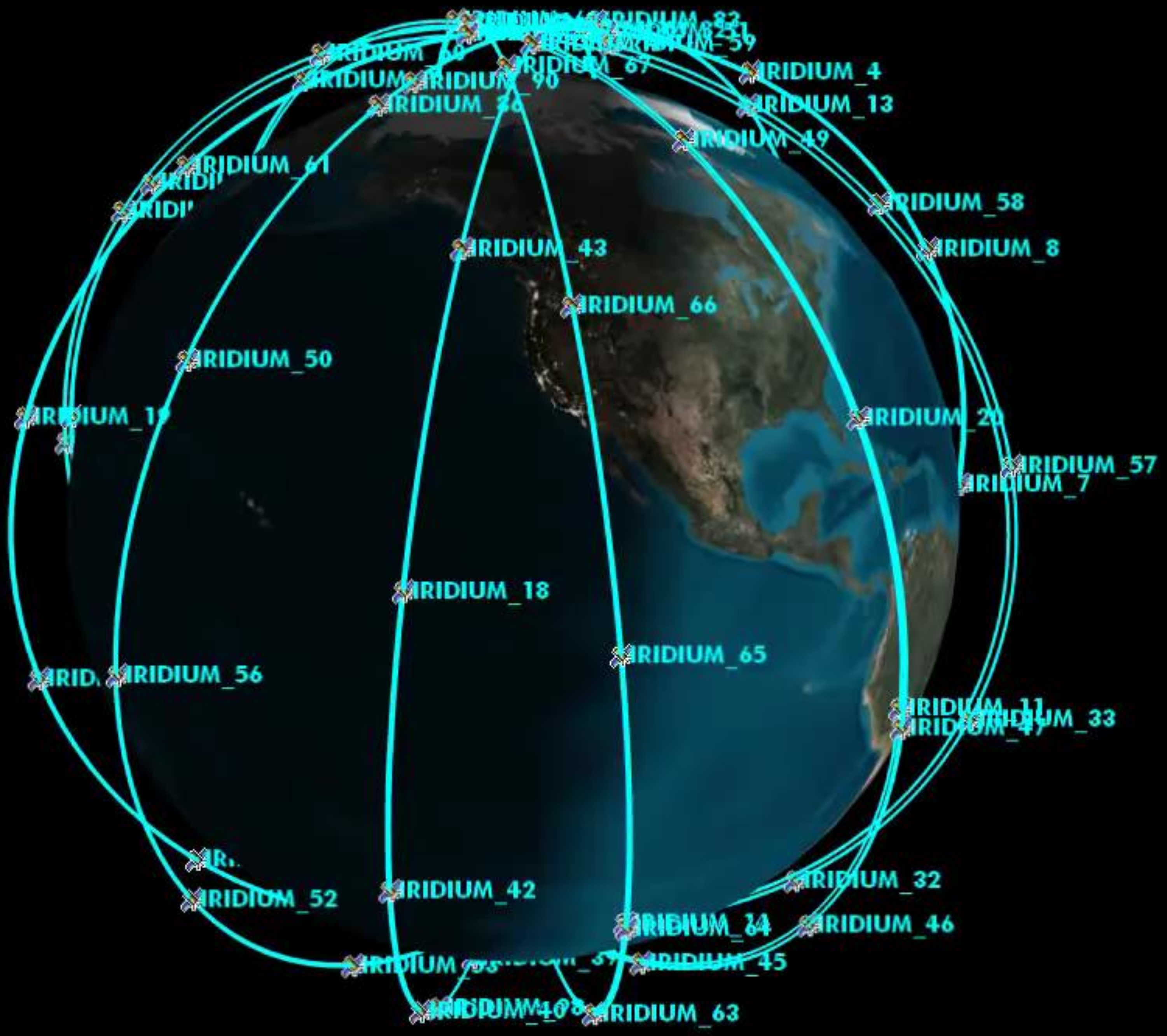
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Aurora May 10, Westford, MA

# Summary

- Space Weather Impacts:
  - Radiation hazards satellites (not necessarily advertised)
  - HF comm outages (noticed May 10-12, 2024)
  - Satellite tracking issues (not necessarily advertised)
  - GNSS degradation – some noted
- Correct estimation of Atmospheric Drag measurements more significant as number of satellites in LEO grows

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