# Space Weather Effects on GPS Systems

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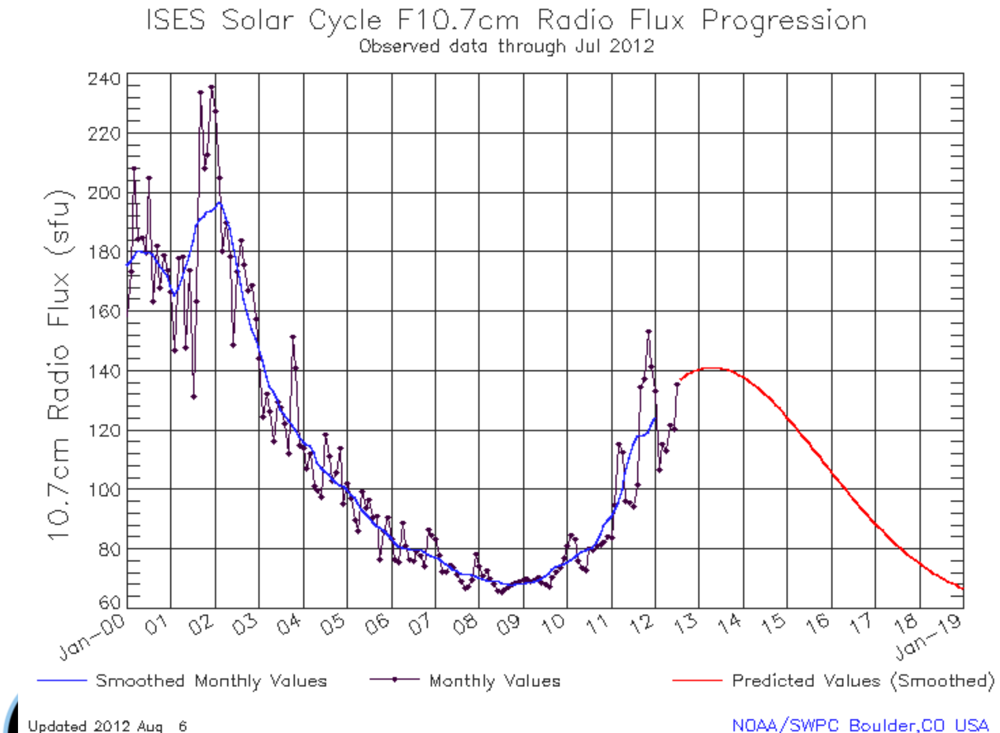
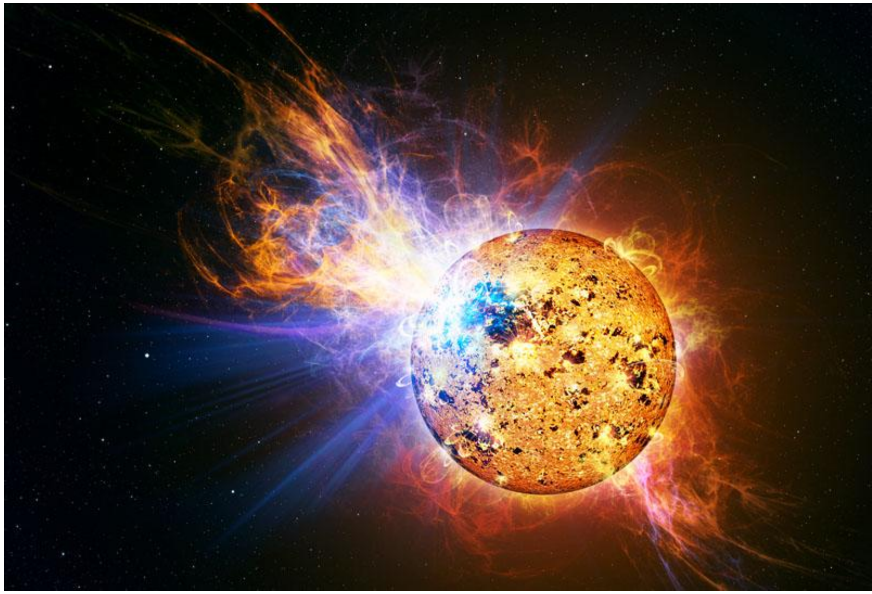
# Outline

- Space Weather Effects on GPS
  - Solar Radio Bursts
  - Relevant Phenomenology
  - Delay and Total Electron Content
- Scintillation
  - Equatorial Impacts
  - DMSP/SSUSI Scintillation Maps
- IDA4D Data Assimilation
- Polar Cap GPS Scintillation

# Why Care About Space Weather?

***Each of the next 5 years is expected to have higher solar activity than any year since 2003. So if you are used to space weather being a non-factor in your operations, that is about to change.***



***March 7, 2012 – The sun unleashed an X5.4-class solar flare, the largest in 6 years. A warning shot at the beginning of the new solar maximum?***

# Space Weather Effects

## X-Rays, EUV, Radio Bursts

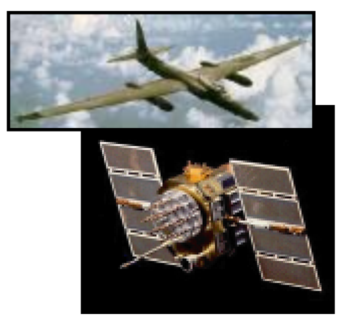
- SATCOM Interference
- Radar Interference
- HF Radio Blackout
- Geolocation Errors
- Satellite Orbit Decay

## Scintillation

- Degraded SATCOM
- Dual-Frequency GPS Error
  - Positioning
  - Navigation
  - Timing

## SEP Events

- High Altitude Radiation Hazards
- Spacecraft Damage
- Satellite Disorientation
- Launch Payload Failure
- False Sensor Readings
- Degraded HF Comm (high latitudes)



## Geomagnetic Storms

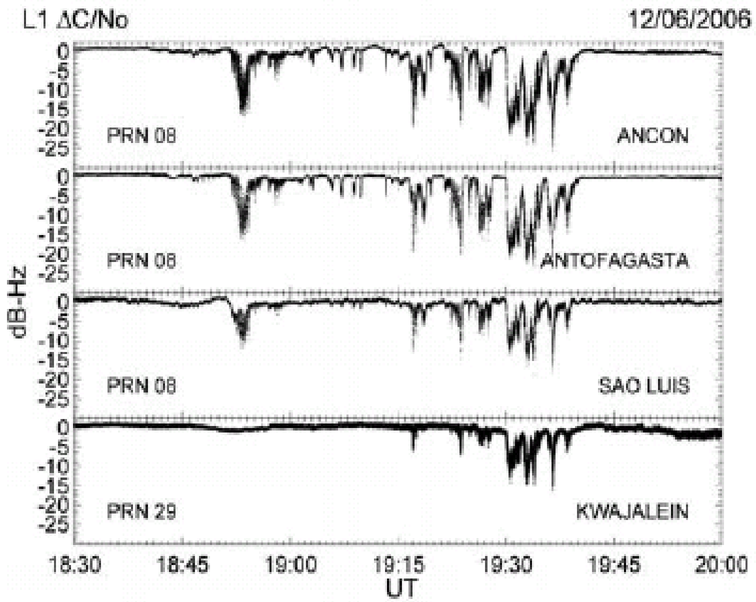
- Spacecraft Charging and Drag
- Geolocation Errors
- Space Track Errors
- Launch Trajectory Errors
- Radar Interference
- Radio Propagation Anomalies
- Power Grid Failures

CS APL NSS

# Effects of Solar Radio Bursts on GPS

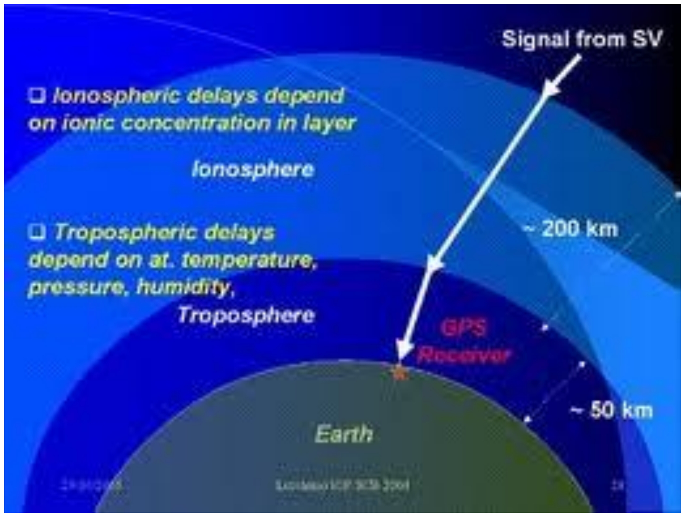
- Sun produces radio waves during solar flare eruptions
- Reduces the signal-to-noise ratio of relatively weak GPS signal
- Solar radio waves cover a broad frequency range and interfere with frequencies L1, L2 (among many other) channels used by GPS

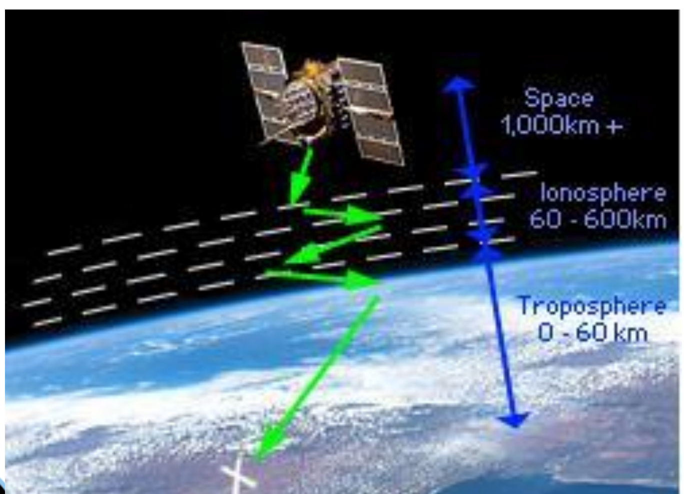
**GPS SNR**

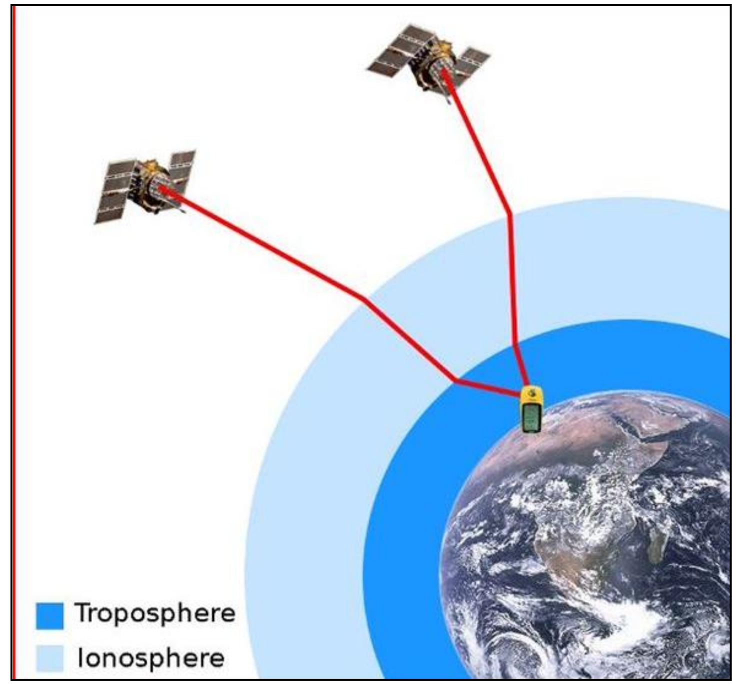



**Carrano et al. 2009**

# Atmospheric Effects on GPS Ranging




- Refraction lengthens the path of the wave compared to a geometric line of sight

# Error-Producing Time Delays

$\rho = R + c(t_u - \delta t + \delta t_D)$

- $\rho$ is pseudo-range
- $R$ is actual range
- $c$ is the speed of light
- $t_u$ is the receiver clock offset
- $\delta t$ is the satellite clock offset
- $\delta t_D = \delta t_{atm} + \delta t_{noise+resolution} + \delta t_{mp} + \delta t_{hw}$

- Concentrate on $\delta t_{atm}$ which is a group delay due to the ionosphere and troposphere
- Signal information delayed (e.g. PRN code and navigation data)
- Carrier phase advanced

# Atmospheric Delays

- $\delta t_{atm} = \delta t_{trop} + \delta t_{iono}$
- Physical reason for delays is refraction due to changes in indices of refraction for ionosphere and troposphere

$$\Delta S = c * \delta t_{atm} = \int_{SV}^{User} n\, ds - \int_{SV}^{User} dl$$

ΔS is the path length difference due to refraction by the Ionosphere or troposphere

$\omega^2_{pe}$= plasma frequency
Can be equated with
total electron content (TEC)

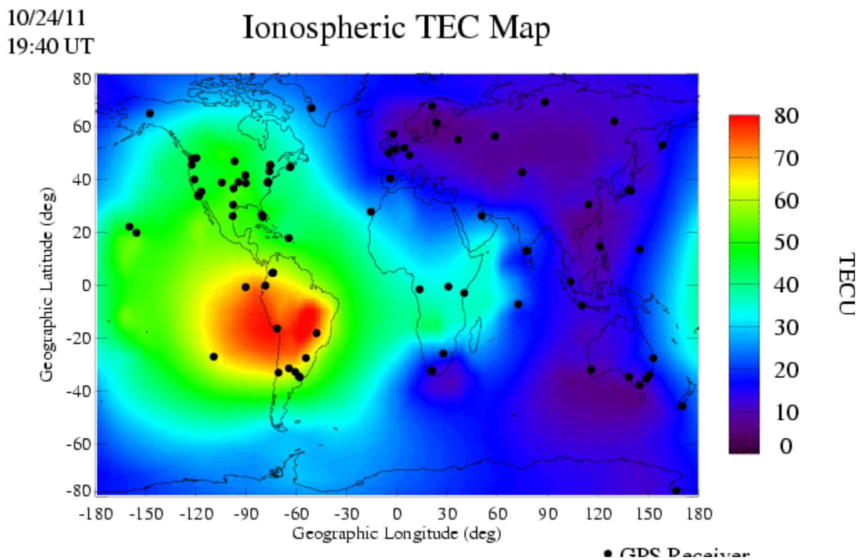
$$\Delta S = c * \delta t_{iono} = \int_{SV}^{User} \frac{\omega_{pe}^2}{\omega^2} ds$$

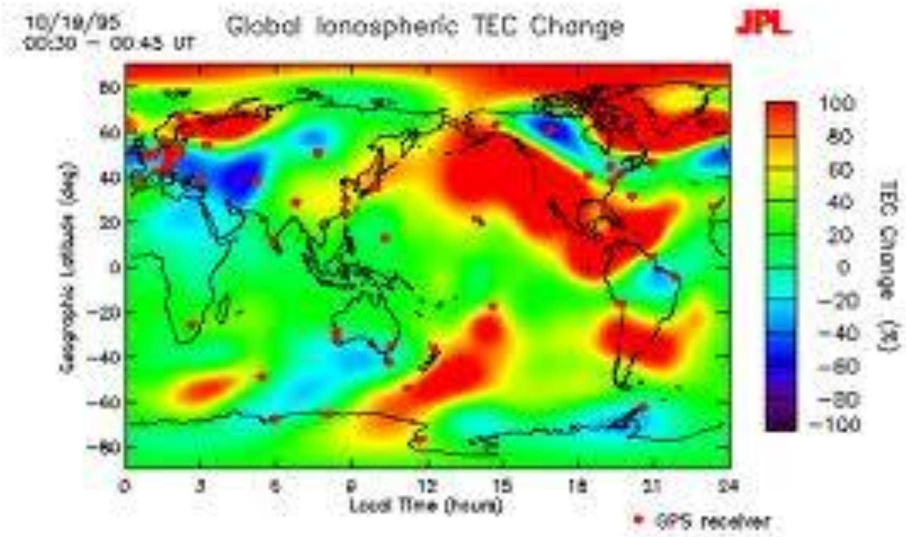
$$\Delta S = c * \delta t_{iono} = \frac{40.3}{f^2} \int_{SV}^{User} n_e\, ds$$

$$\Delta S = c * \delta t_{iono} = \frac{40.3}{f^2} * TEC$$

APL

# Ionospheric Total Electron Content Map

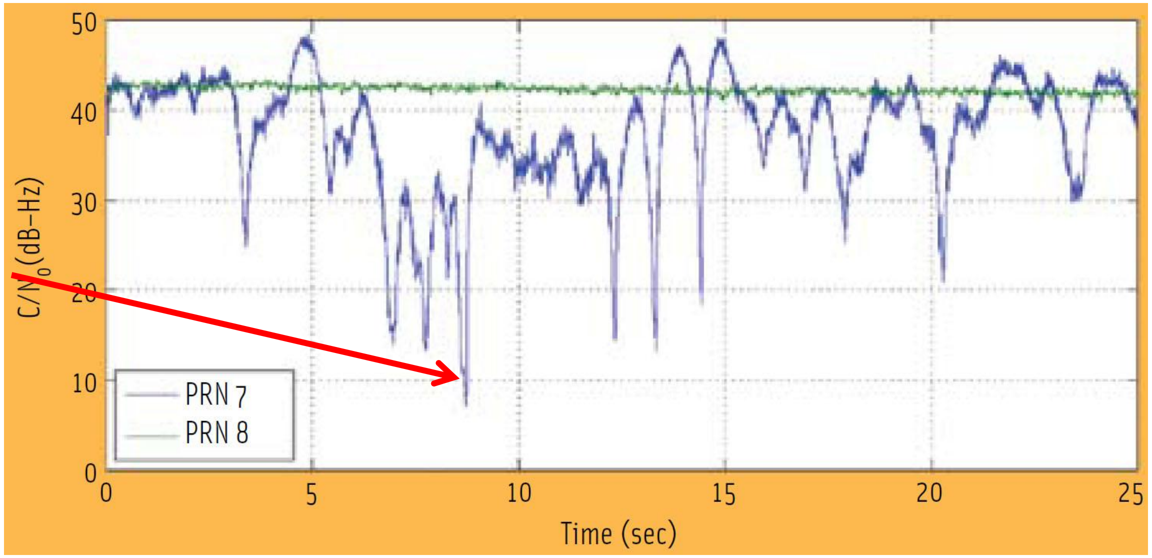



- Ionospheric TEC maps (left), 60 TECU → 10 m (33 ns delay)
- During geomagnetic storms, TEC values can increase by more that 100% (effectively doubling the error)
- Ionospheric storms occur within first hours of a geomagnetic storm
- TEC “walls” (Dehel, 2004); TEC falls by 130 TECu over 50 km; 30 m GPS delay; walls move 100 to 500 m/s

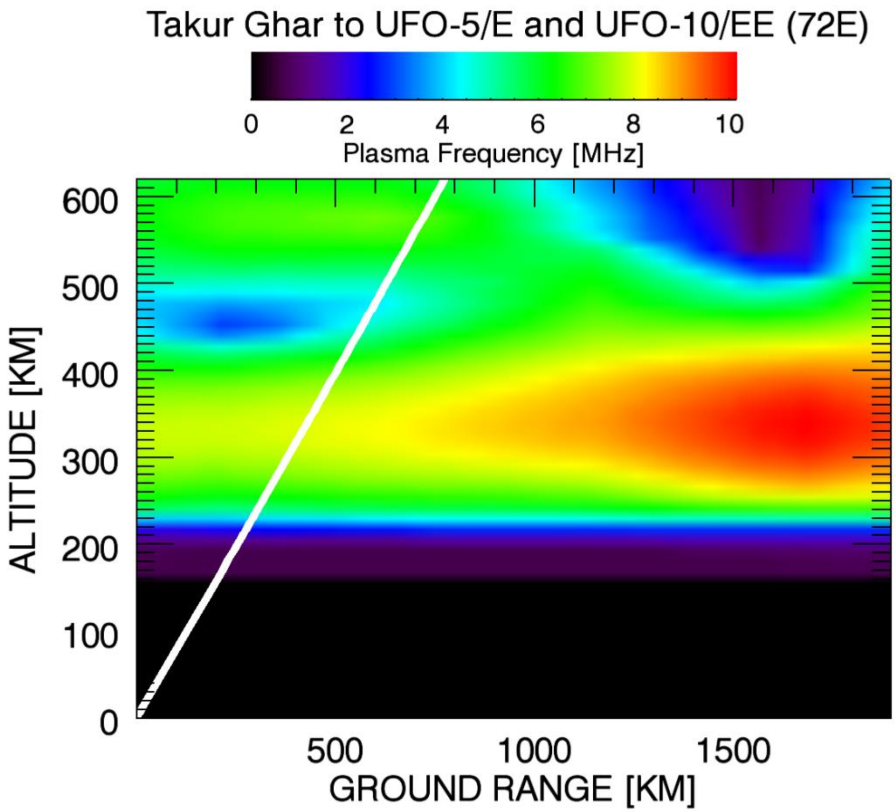
# Ionospheric Scintillation Affects GPS and Other RF Signals

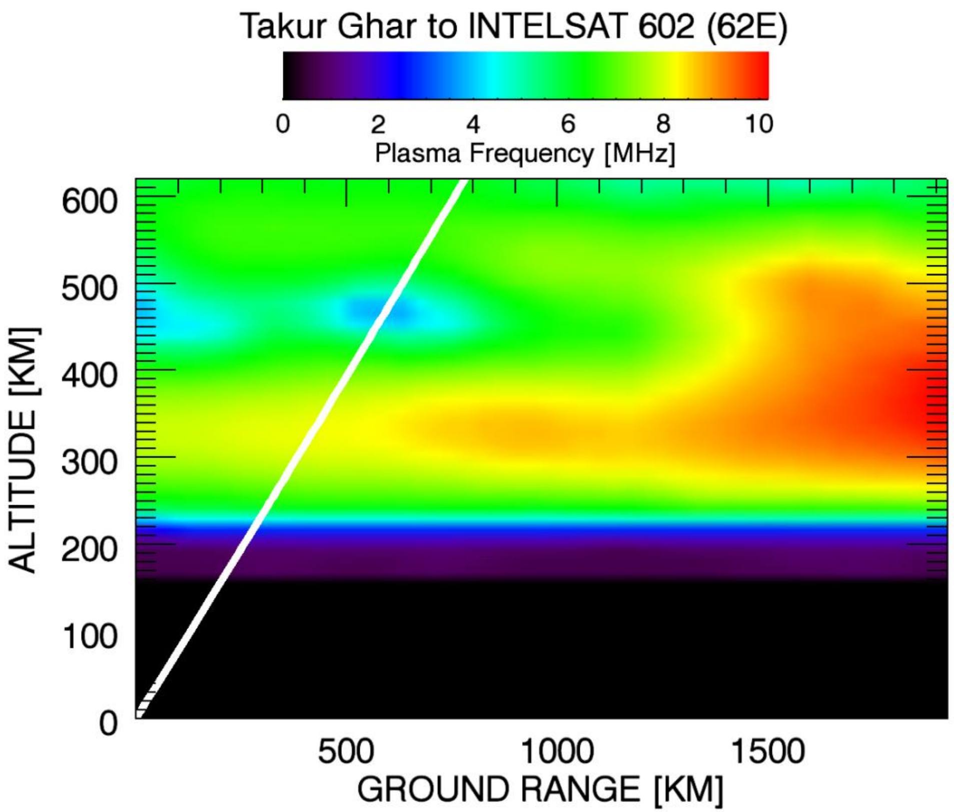
Loss of lock
Loss of information




- Scintillations (“twinkling” ) in GPS signals arise from spatial and temporal variations in the ionosphere.
- These ionospheric variations occur under quiet and disturbed conditions.
- They are difficult to forecast accurately.

# Scintillation Near Bubbles

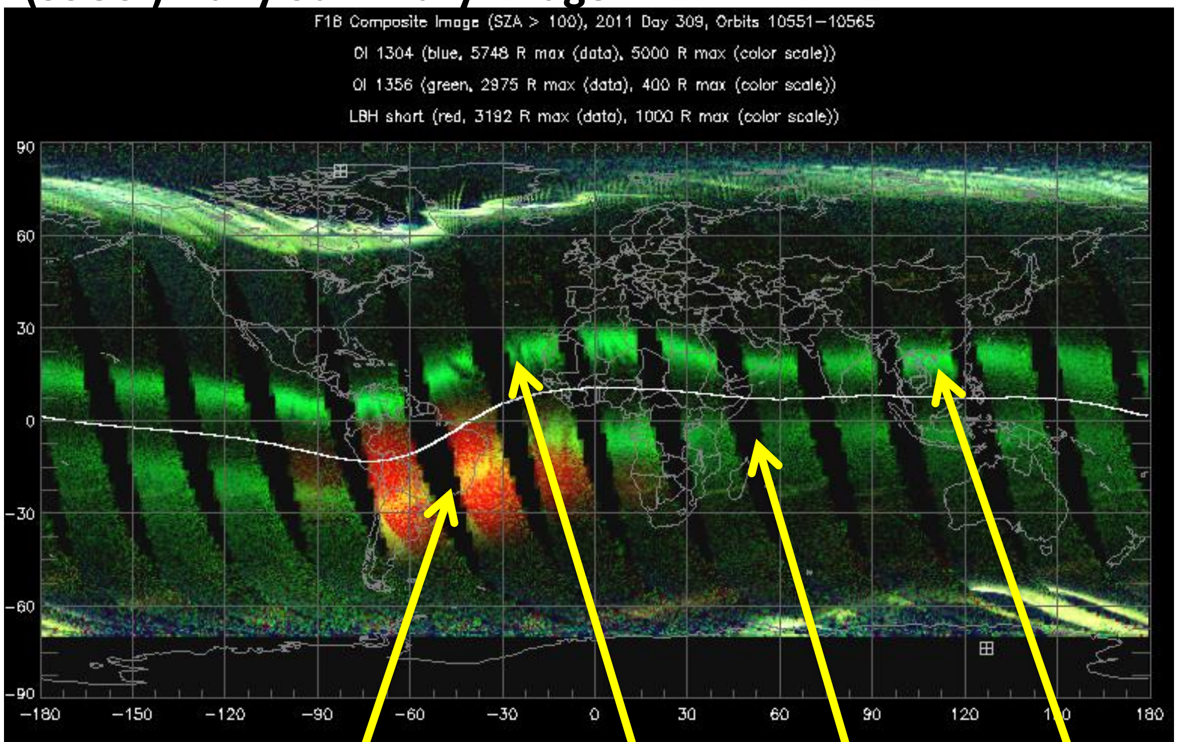



- Lines of sight all pass through regions of depleted ionospheric electron density
- Depleted regions known as bubbles (equatorial spread F)

# Equatorial Region Space Weather Impacts

**Special Sensor Ultraviolet Spectrographic Imager (SSUSI) Daily Summary Image**




South Atlantic Anomaly

Bubbles

Orbit gaps

Ionization Arcs

## Scintillation

- Degraded SATCOM
- Dual-Frequency GPS Error
  - Positioning
  - Navigation
  - Timing

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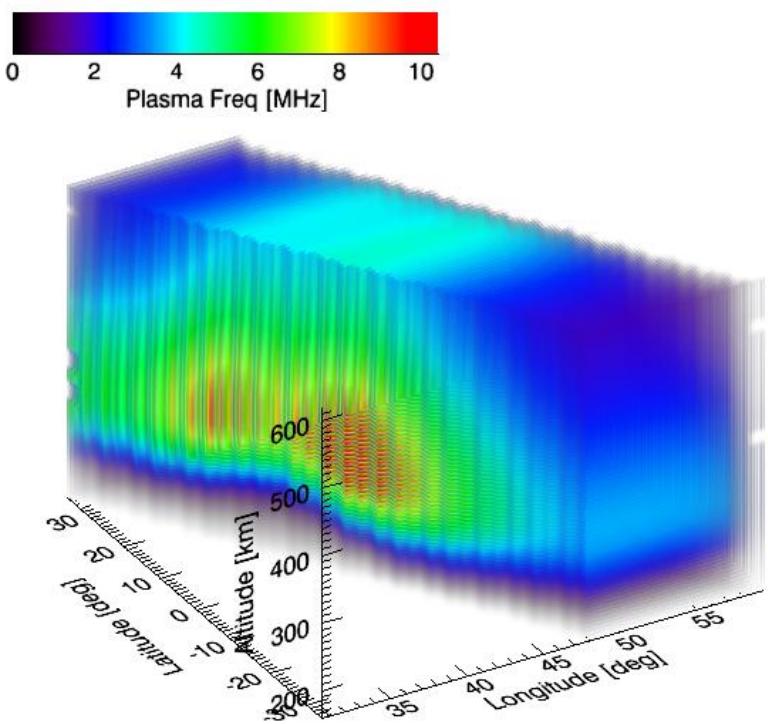
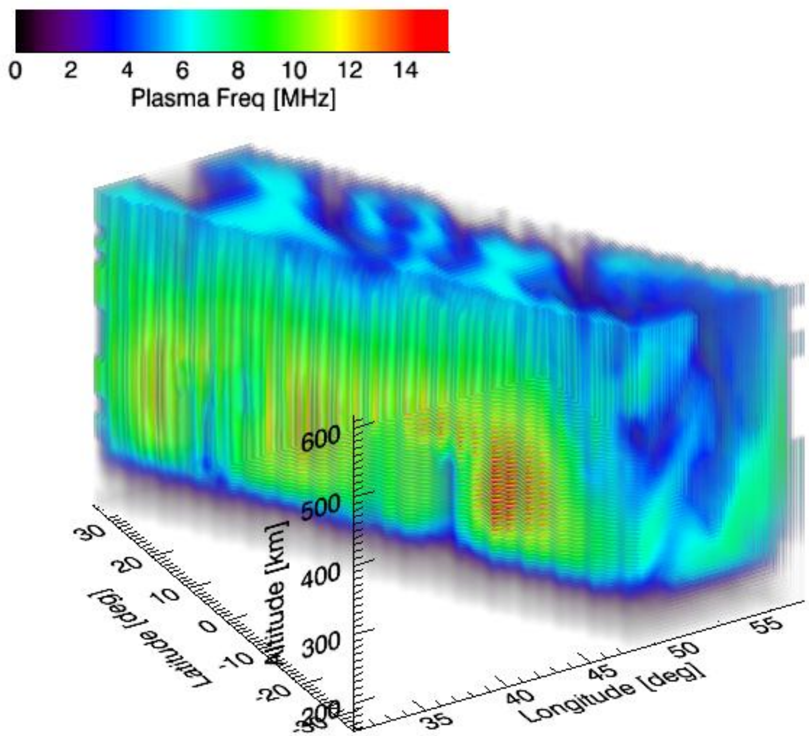
# SSUSI imagery shows locations of irregularities

2004 Day 94 (April 3)

IRI-2001 model



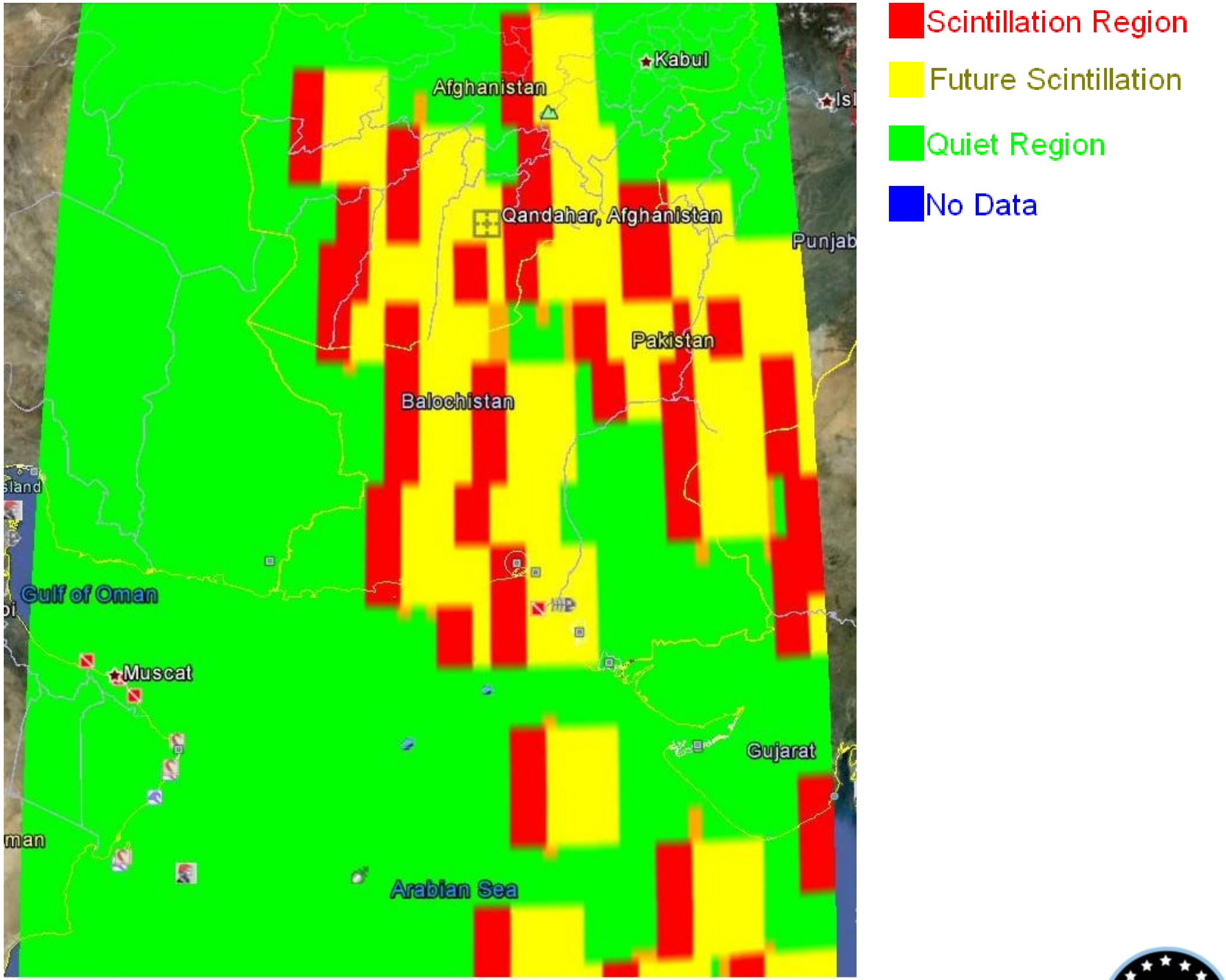

SSUSI data



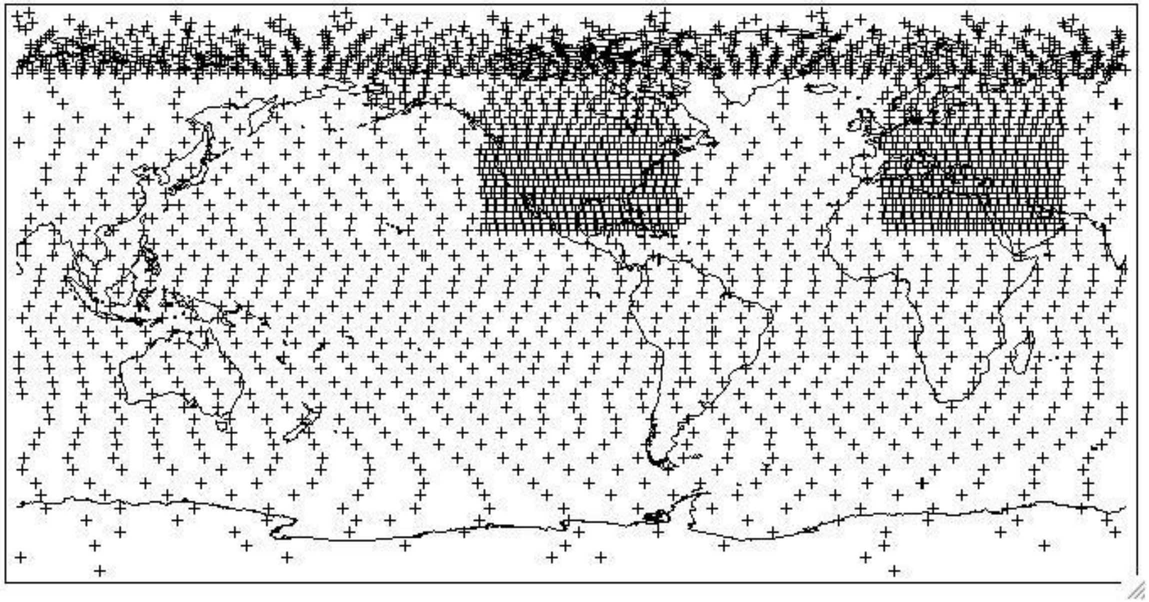

- 2D tomographic inversion is performed for each altitude vs. longitude slice, 12 combined to make 3D profile
- 3D grid (12x24x30), 5 deg lat., 0.33 deg lon., 20 km alt. resolution

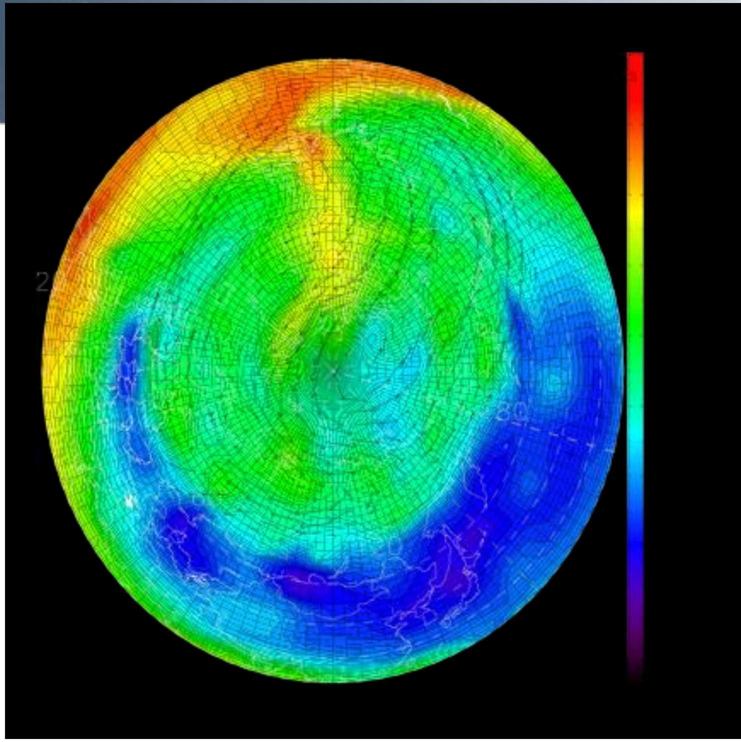
# Mesoscale Ionosphere Model – Assimilate SSUSI, GPS, SCINDA Data

- Model assimilates SSUSI, GPS, and SCINDA data using Kalman Filter
- 20° lat. x 15° lon., available at all longitudes
- Background ionospheric physics and propagation model eliminates data gaps
- Fixed grid, updates every 15 minutes



# Ionospheric Data Assimilation Four Dimensional (IDA4D)



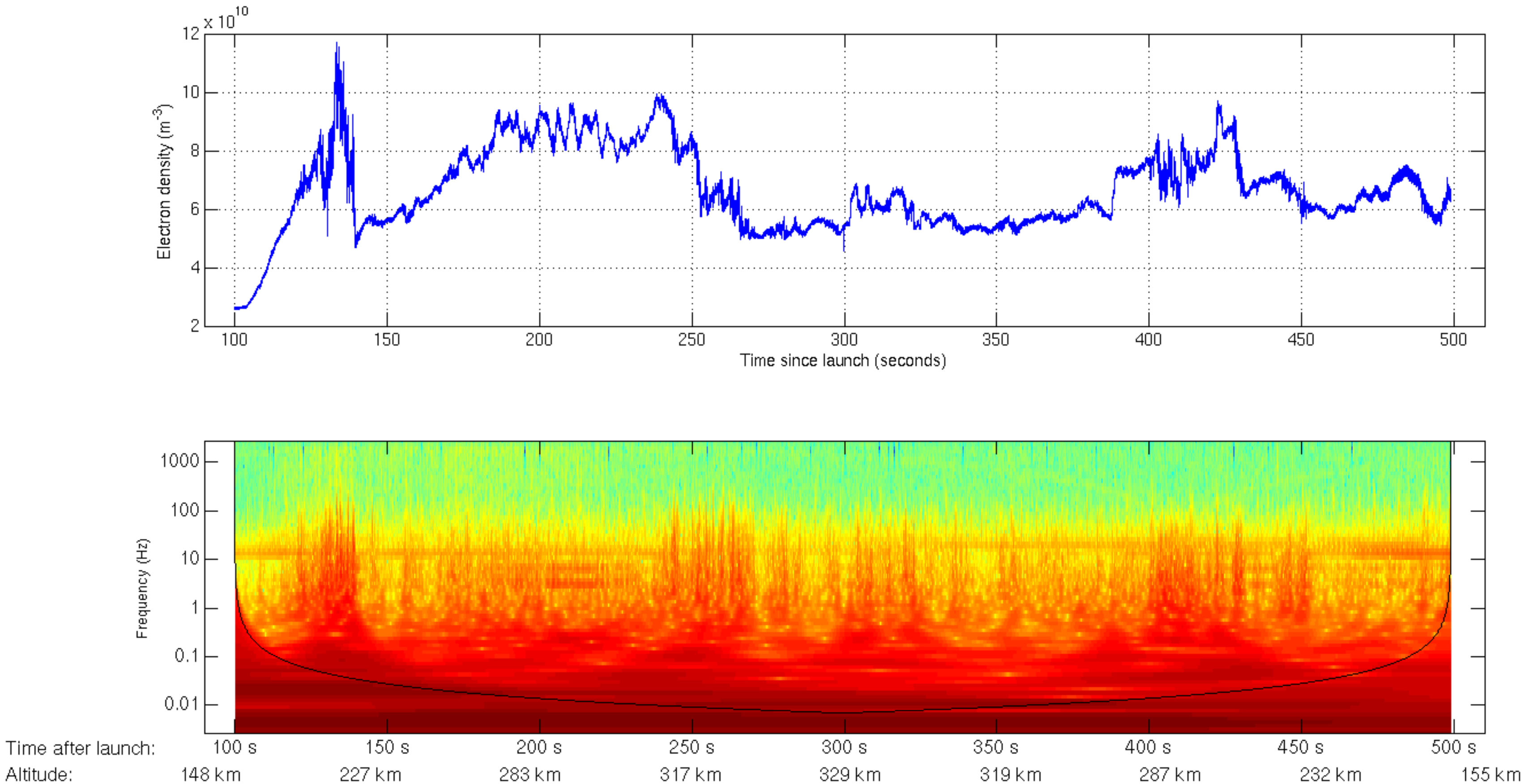


- Global 3D time-evolving imaging of the ionosphere electron density
  - Gauss Markov Kalman Filter predicts forward in time
- *Solves for log of electron density*
  - *Guarantees positivity*
  - *Errors are more log normal distribution*
- *Completely irregular horizontal grid, vector of vertical grid points*
  - User selectable
  - High resolution where desired
  - Can be dynamically chosen based on data

# Polar Cap GPS Scintillation

- Polar cap GPS scintillation is a typical occurrence often caused by ionization patches immersed in convection flow
- Interferes with increasing human activity at high latitudes
- Present simulated GPS scintillation based on ICI-2 Langmuir probe measurements of F-region density fluctuations
- Finding- Scintillation for this case caused primarily but F-region gradient drift waves.
- NEW  RESULT- Scintillation fluctuations mimic TEC fluctuations which leads to position error and scientific uncertainty

# ICI-2 Langmuir Probe Data




- ICI-2 sampled F-region density with sufficient resolution (<10 m) for phase screen modeling of GPS scintillation

# Summary

- Solar max is approaching – ionospheric disturbances will likely increase interference with GPS (signal fading and precision errors)
- Ionosphere affects GPS through time delays associated with TEC gradients and scintillation associated with ionospheric irregularities
- GPS susceptible to scintillation particularly at low latitudes
- Satellite UV (SSUSI) imagery can map irregularities
- APL data assimilation models (IDA4D) can identify scintillation over regions of interest
- New models at APL reveal sources of polar cap GPS scintillation and positioning errors


- **Space Environment Applications, Systems, and Operations for National Security (SEASONS) Conference**
- **Purpose: To discuss impacts of space environment on DoD and IC systems, and the applications and requirements for sensors and algorithms to mitigate these impacts and enhance operations**
- **2012 Theme: *Operating through solar max***
  - **Lessons learned from last solar max**
- **Confirmed Keynote Speakers:**
  - **Brig. Gen. Coffin (*Deputy Commanding General for Operations, USASMDC/ARSTRAT* )**
  - **Dr. Fred Lewis (Director Air Force Weather)**
  - **Ms. Aurea Rivera (Senior Intelligence Engineer, NASIC)**
- **Open to US Citizens with a Secret clearance**
- **SCI sessions**
- **For more information:**
  - **Contact Dr. Erin Taylor at 240-228-9525 or Erin.Taylor@jhuapl.edu**
  - **Visit the website at https://secwww.jhuapl.edu/SEASONS/**