Ionospheric Effects on GNSS Augmentation Systems

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OCTOBER 30, 2024

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African Capacity Building Workshop on Space Weather and Ionospheric Research

Introduction

- The Global Positioning System (GPS) requires augmentation in order to meet the strict requirements necessary to support the guidance of aircraft
  - This is also true for the other core constellations

- The main challenges for GNSS are:
  - Integrity – is it safe to use?
  - Continuity – will there be interruptions?
  - Availability – can you count on it when you need it?

- Augmentation systems fill in the gaps that GPS and the other constellations cannot meet by themselves

“**GNSS**. *A worldwide position and time determination system that includes one or more satellite constellations, aircraft receivers and system integrity monitoring, augmented as necessary to support the required navigation performance for the intended operation.”* [ICAO Annex 10, Volume I]

Parameters Used to Evaluate Aviation Performance

- **Accuracy**: characterize typical behavior of the system in the presence of nominal errors

- **Integrity**: limit risk from abnormal behavior affecting the system
  - Integrity risk
  - Maximum tolerable error
  - Time to alert (TTA)

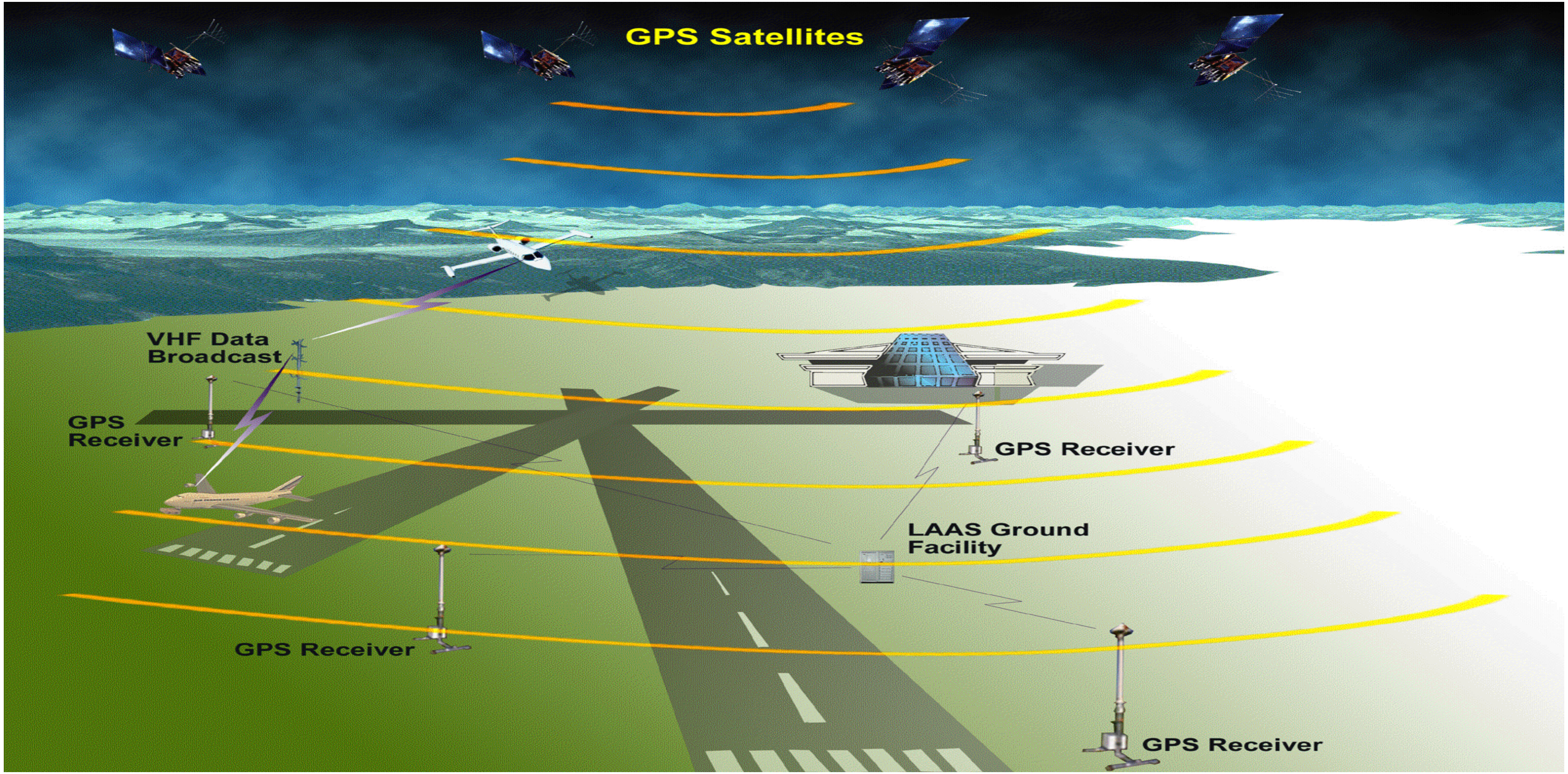
- **Continuity**: limit risk of losing the service unexpectedly

- **Availability**: fraction of time that one has the accuracy, integrity, and continuity required to perform the desired operation

200’ Decision Height (DH) Requirements

- **Accuracy:** < 4 m 95% horizontal & vertical positioning error
- **Integrity:**
  - Less than 10^{-7} probability of true error larger than 40 m horizontally or 35 m vertically
  - 6 second time-to-alert
- **Continuity**: < 10^{-5} chance of aborting a procedure once it is initiated
- **Availability:** > 99% of time

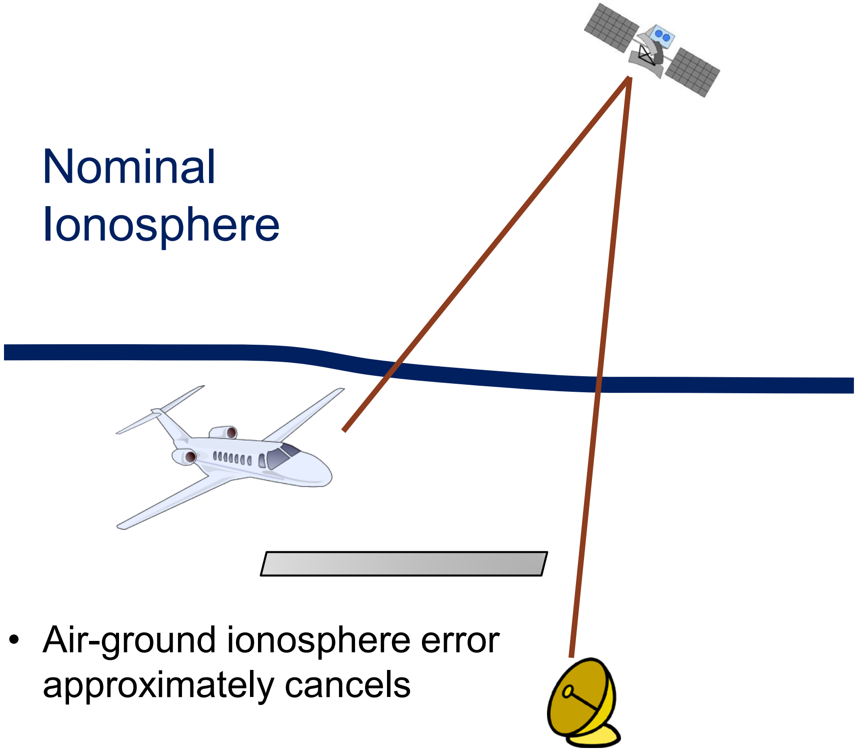
Ground Based Augmentation System (GBAS)



Courtesy: FAA

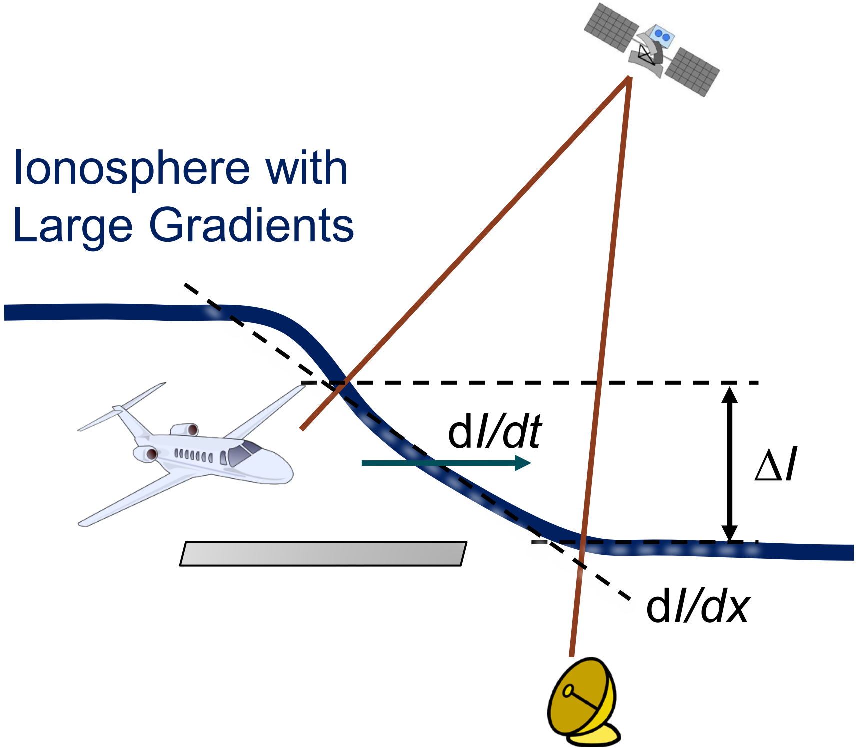
GBAS Ionospheric Effects

Nominal Ionosphere



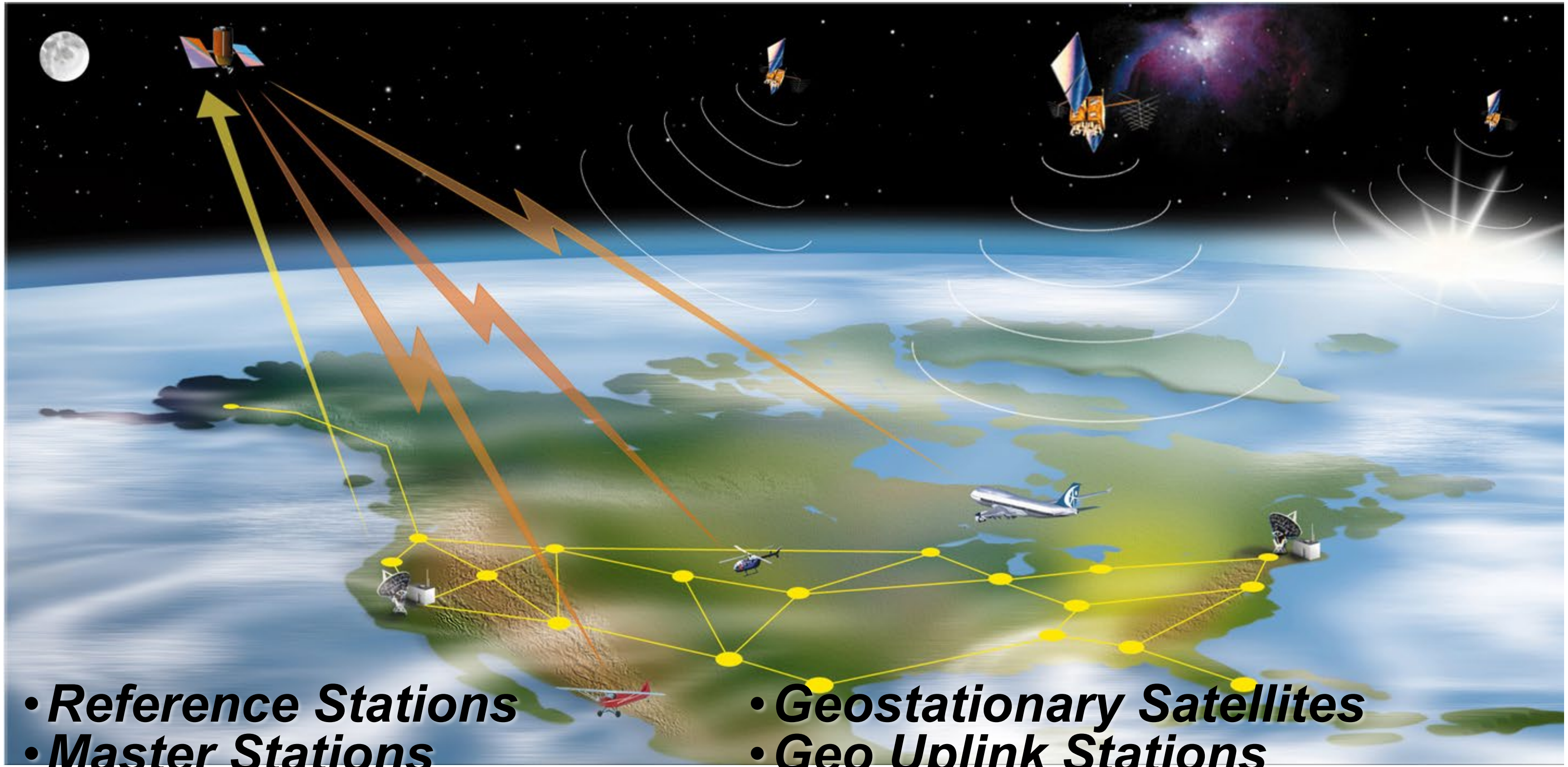
- Air-ground ionosphere error approximately cancels

Ionosphere with Large Gradients



- Air-ground ionosphere error, Δ*I*, is large
- Spatial & temporal gradients induce errors in single frequency carrier-smoothed code filters

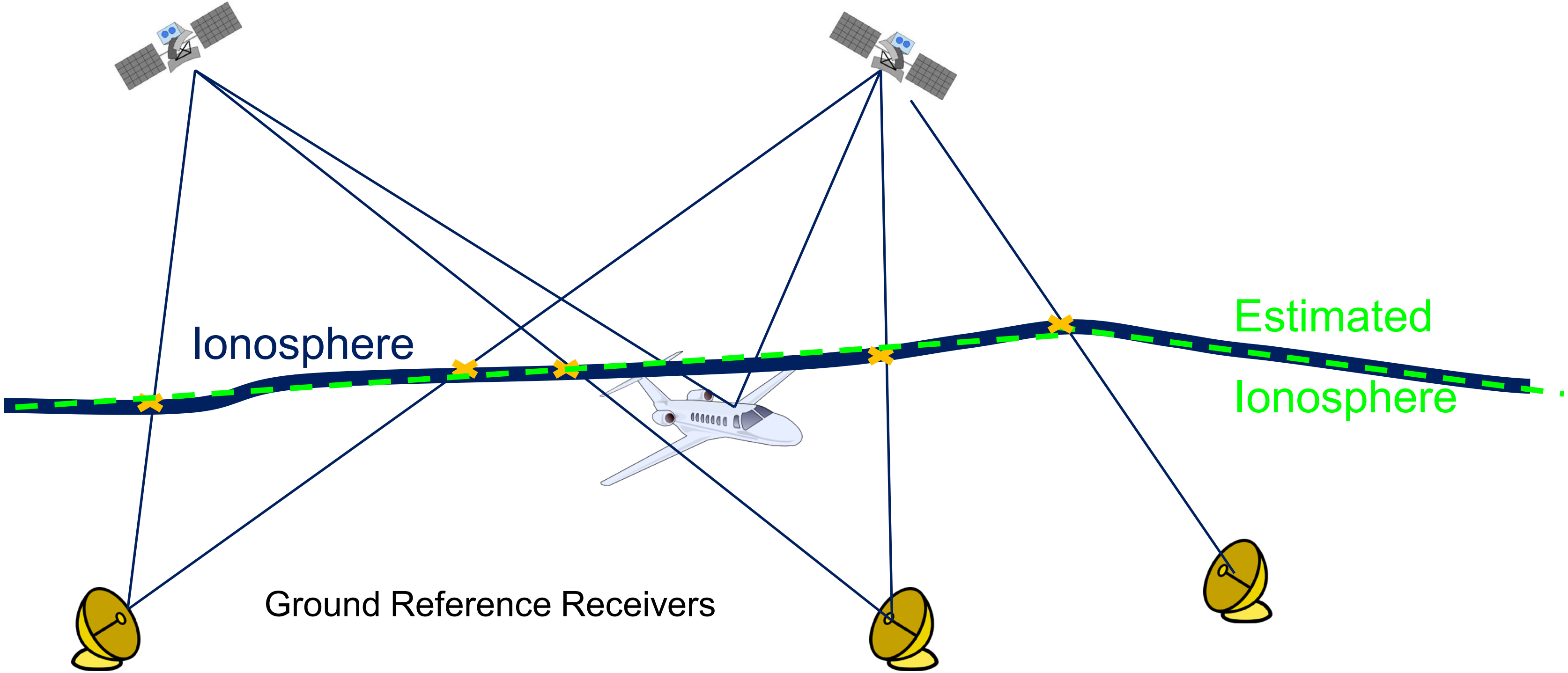
Satellite Based Augmentation System (SBAS)



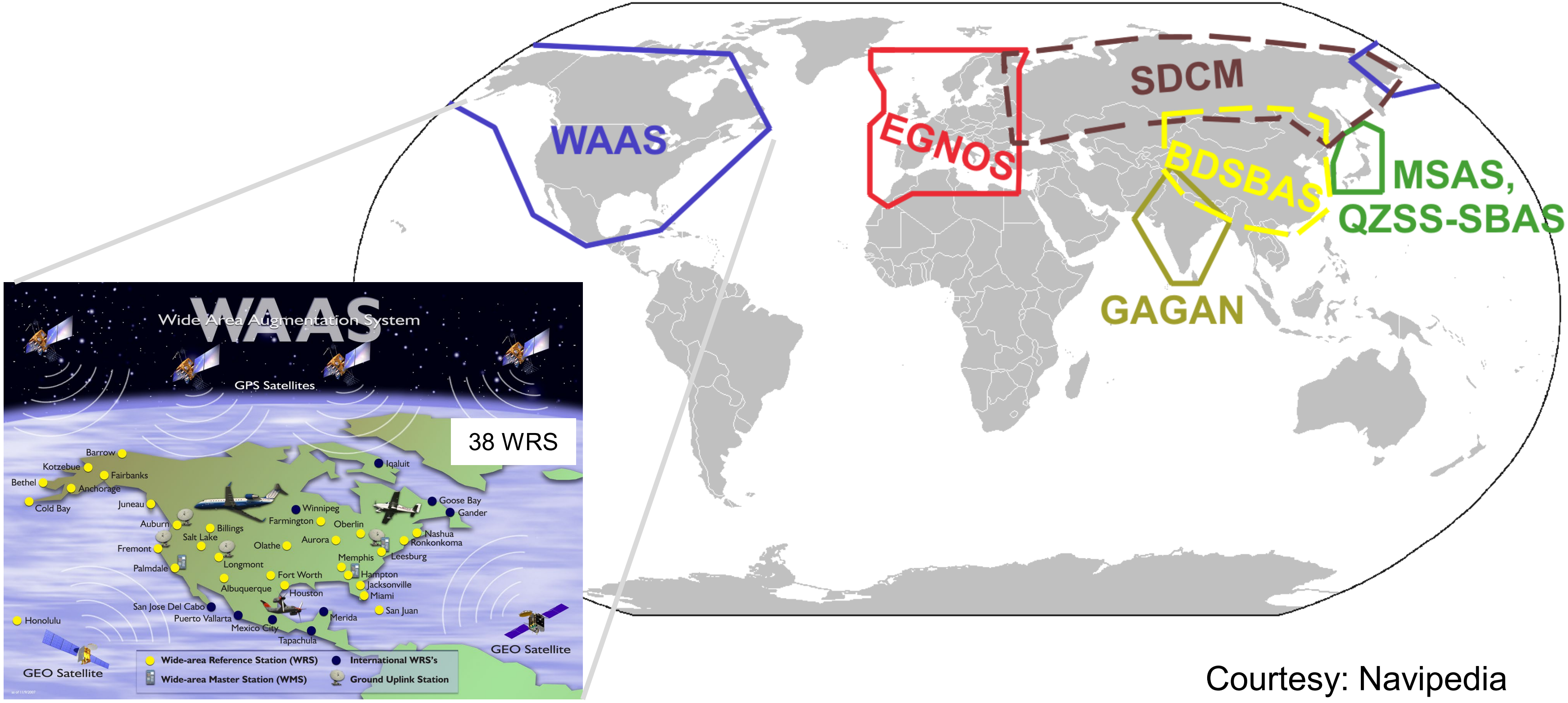
- *Reference Stations*
- *Master Stations*
- *Geostationary Satellites*
- *Geo Uplink Stations*

Courtesy: FAA

SBAS Models Ionospheric Delay on a Continental Scale



Current SBAS Implementations

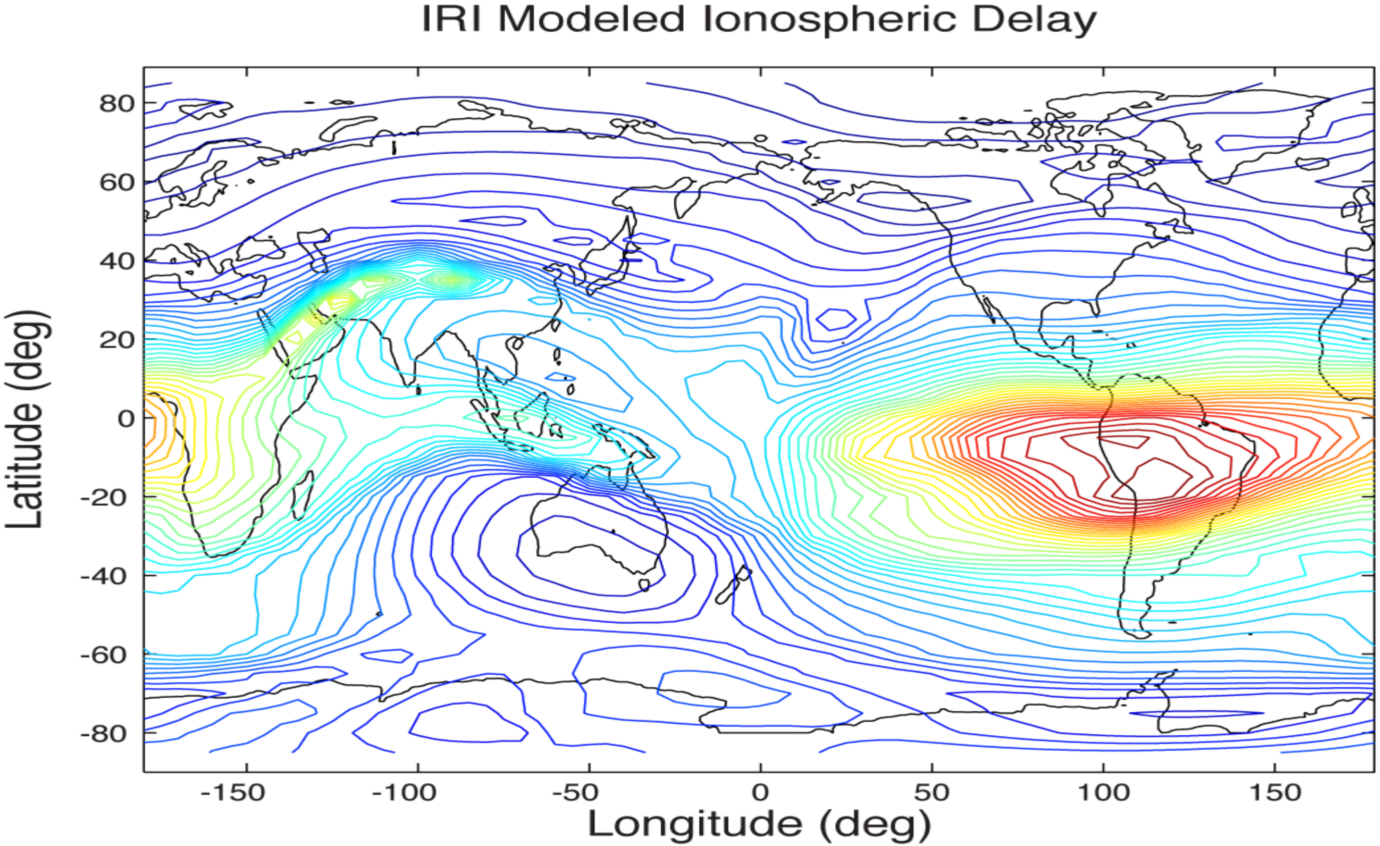


Courtesy: Navipedia

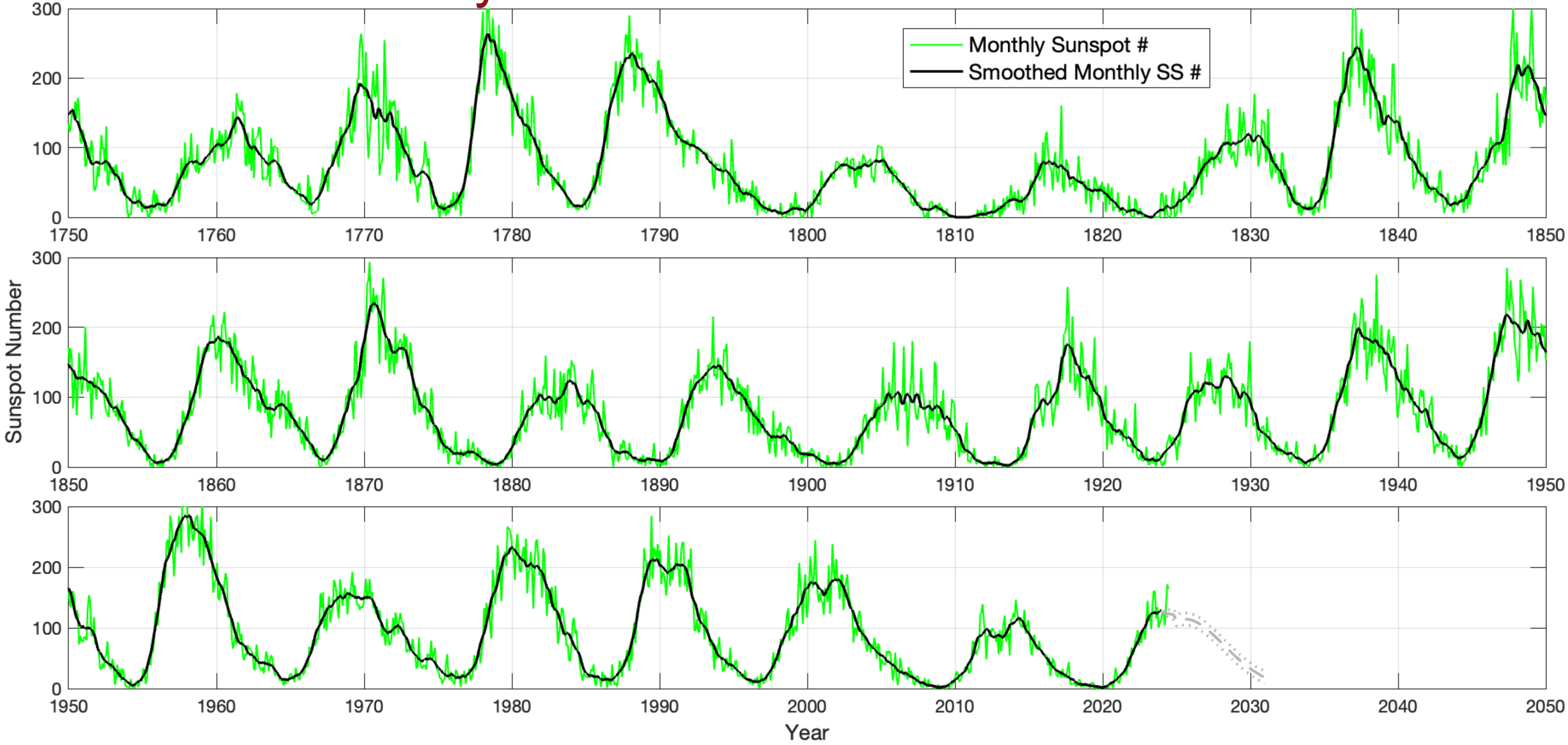
Ionospheric Related Threats to Augmentation Systems

- Poor quality and/or erroneous measurements lead to inaccurate ionospheric corrections
  - Measurement uncertainty must be accurately described and accounted for
  - Faulty measurements must be contained
- Ionospheric delay at the user location is different than the ionospheric delay measured by ground systems
  - Spatial variation of the ionosphere must be fully modelled
- Ionospheric delay changes from when the correction was generated
  - Temporal variation of the ionosphere must be well characterized
- Nominal vs. Disturbed
  - Ionosphere is often well behaved and accurately modelled locally
  - Disturbances can lead to very different phenomena that are very difficult to accurately model

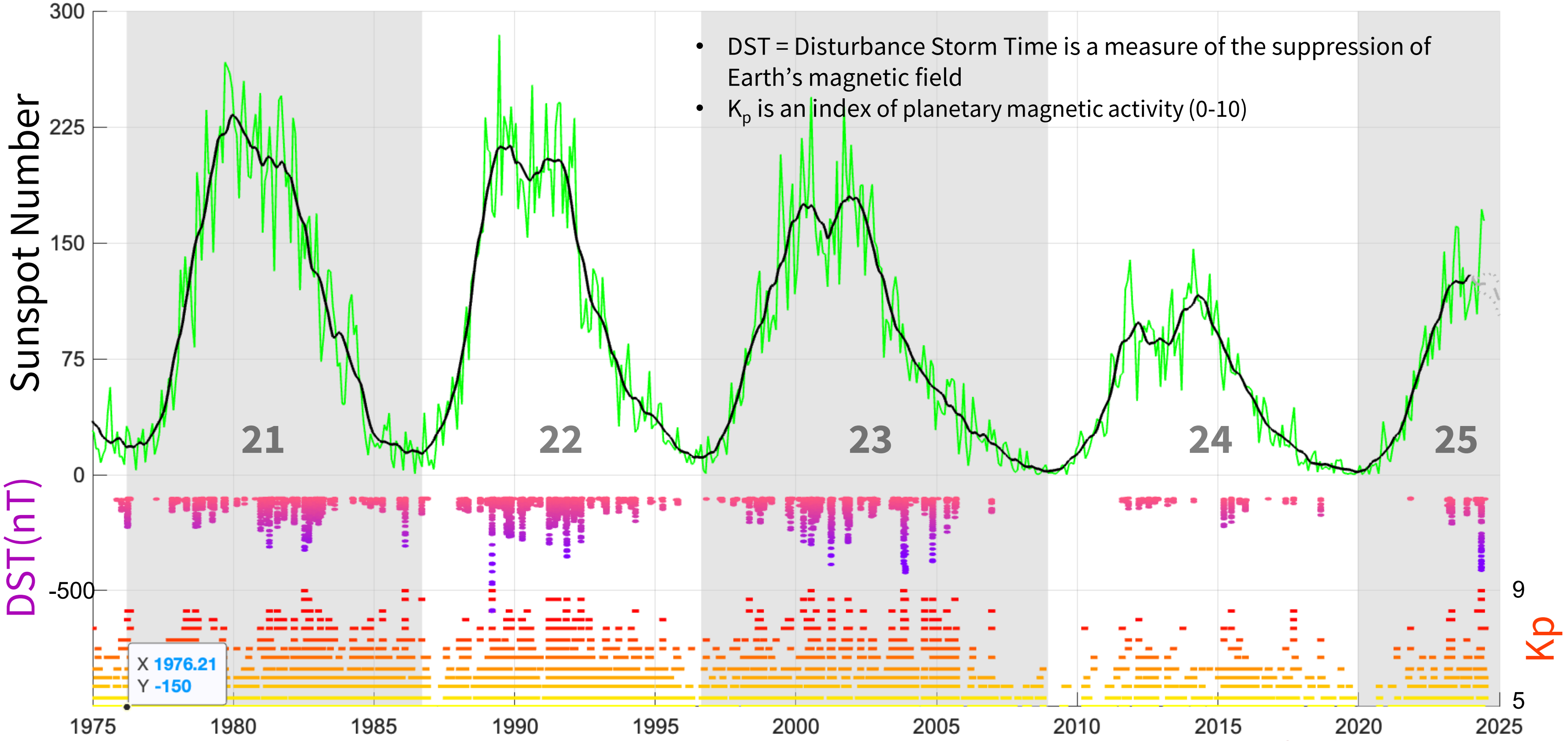
Ionospheric Delay



11-Year Solar Cycles



11 Year Solar Cycle



- DST = Disturbance Storm Time is a measure of the suppression of Earth's magnetic field
- K_p is an index of planetary magnetic activity (0-10)

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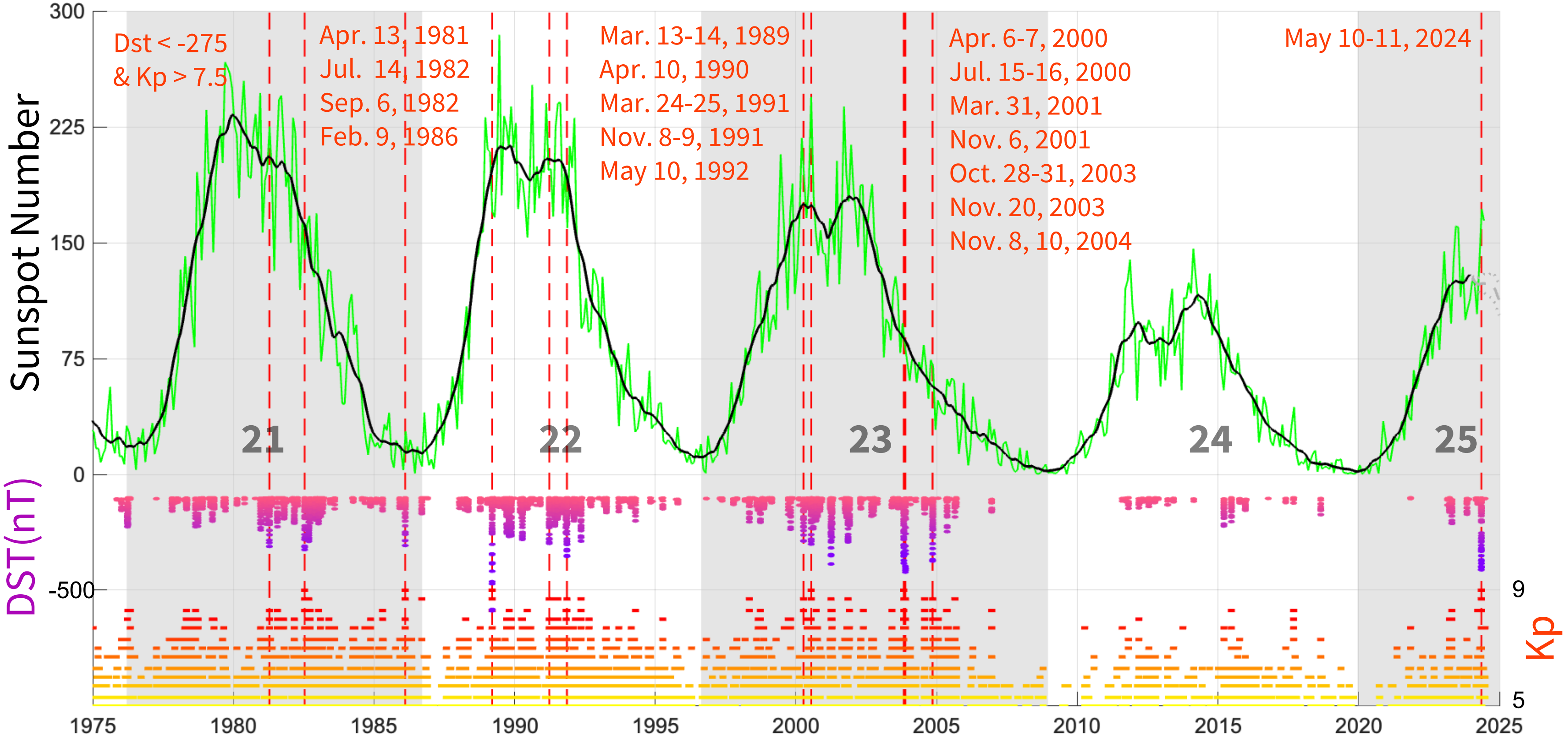
Major Ionospheric Storms



Dst < -275
& Kp > 7.5

Apr. 13, 1981
Jul. 14, 1982
Sep. 6, 1982
Feb. 9, 1986

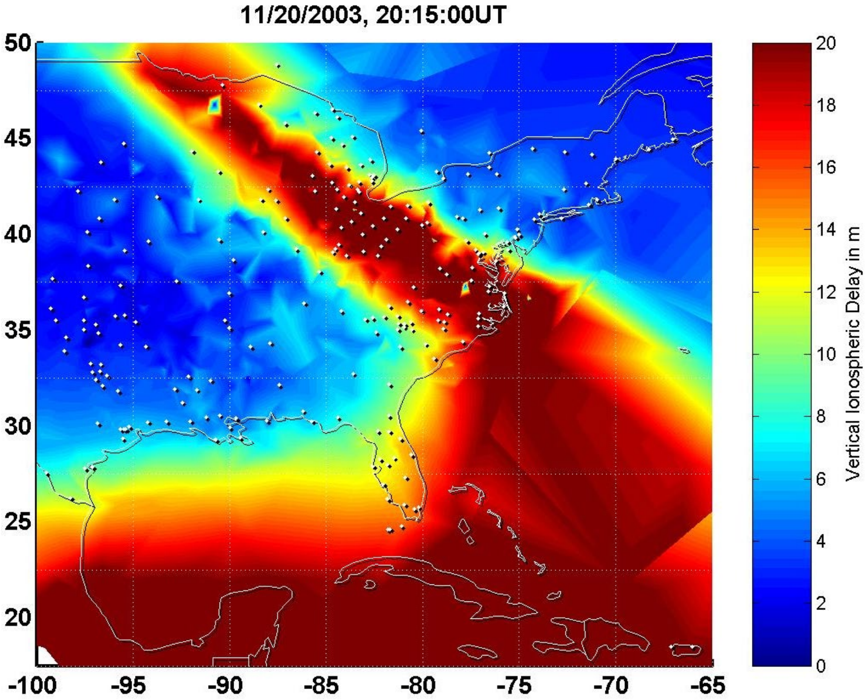
Mar. 13-14, 1989
Apr. 10, 1990
Mar. 24-25, 1991
Nov. 8-9, 1991
May 10, 1992

Apr. 6-7, 2000
Jul. 15-16, 2000
Mar. 31, 2001
Nov. 6, 2001
Oct. 28-31, 2003
Nov. 20, 2003
Nov. 8, 10, 2004

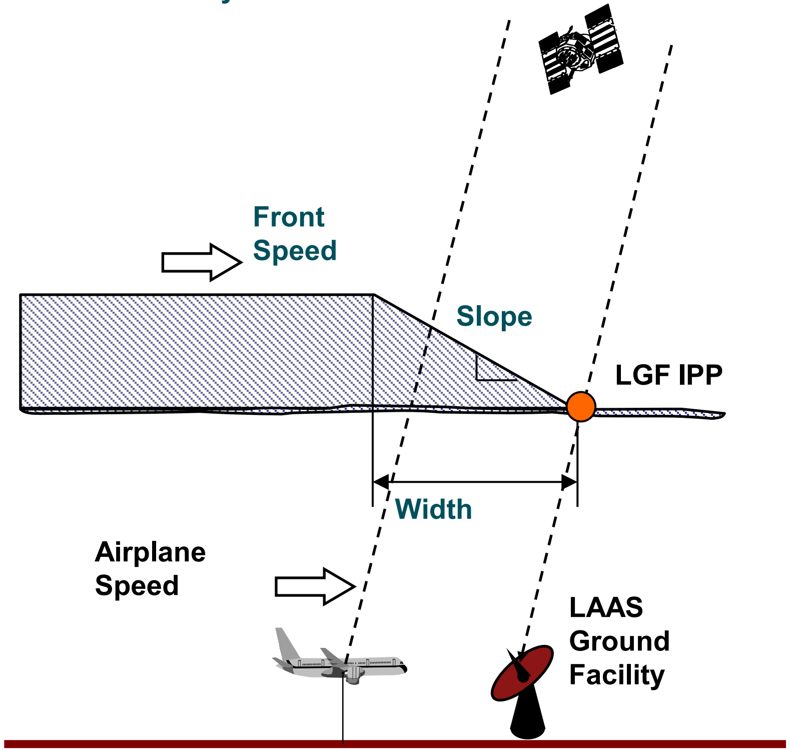
May 10-11, 2024

GBAS: Gradient Threat

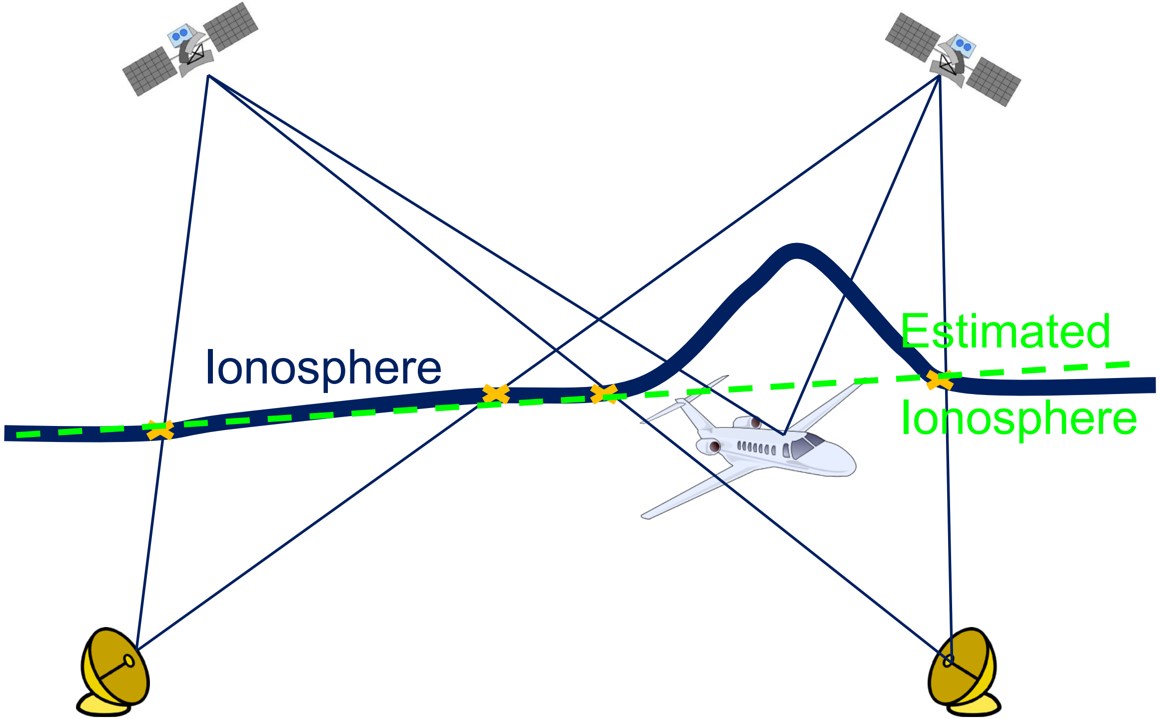
Observed Data



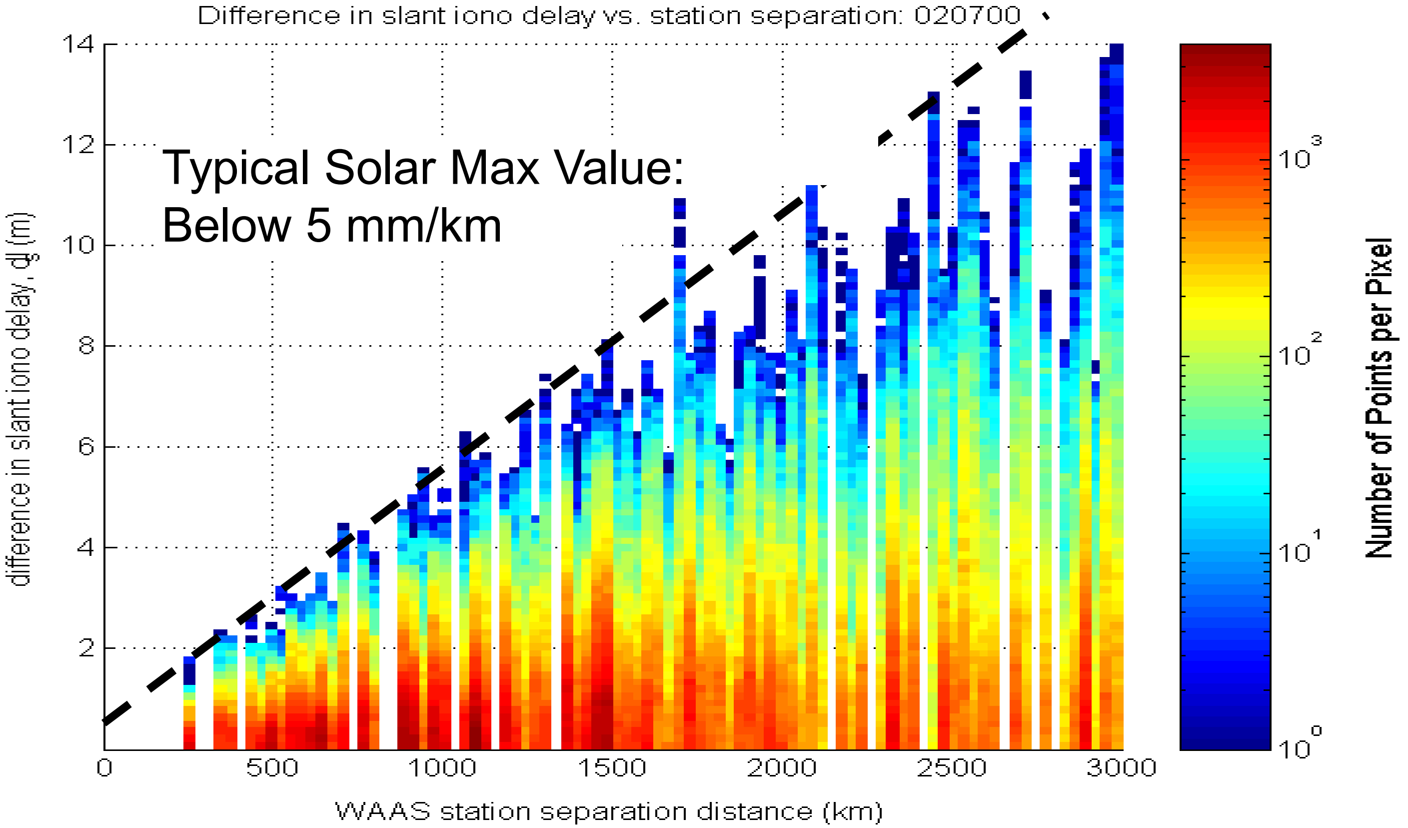
Analysis Model



SBAS: Under-sampled Threat



Nominal Day Spatial Gradients Between WAAS Stations



Typical Solar Max Value:
Below 5 mm/km

Slide Courtesy Seebany Datta-Barua

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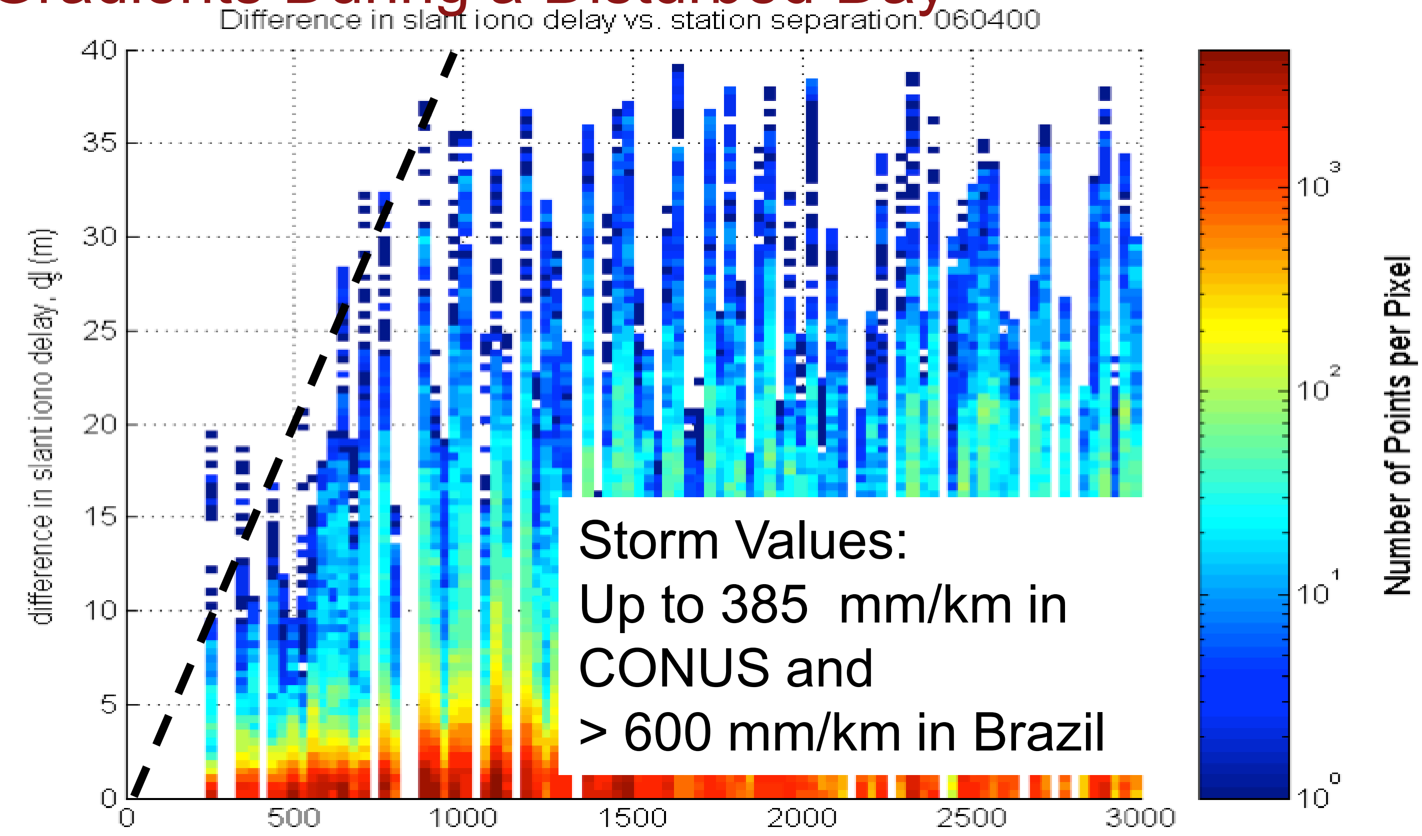
Spatial Gradients During a Disturbed Day

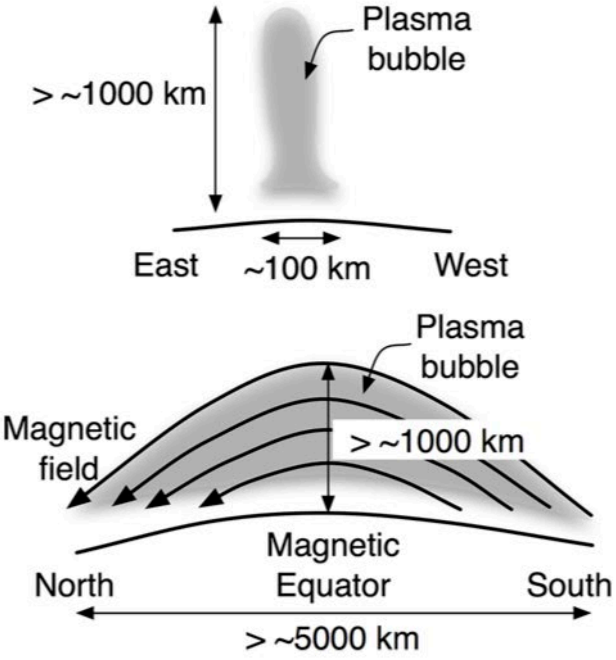


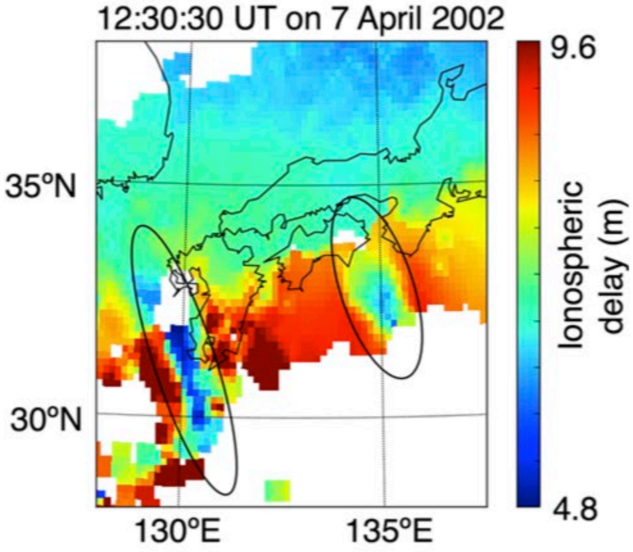
Storm Values:
Up to 385 mm/km in CONUS and
> 600 mm/km in Brazil

Slide Courtesy Seebany Datta-Barua

Characteristics of Plasma Bubble

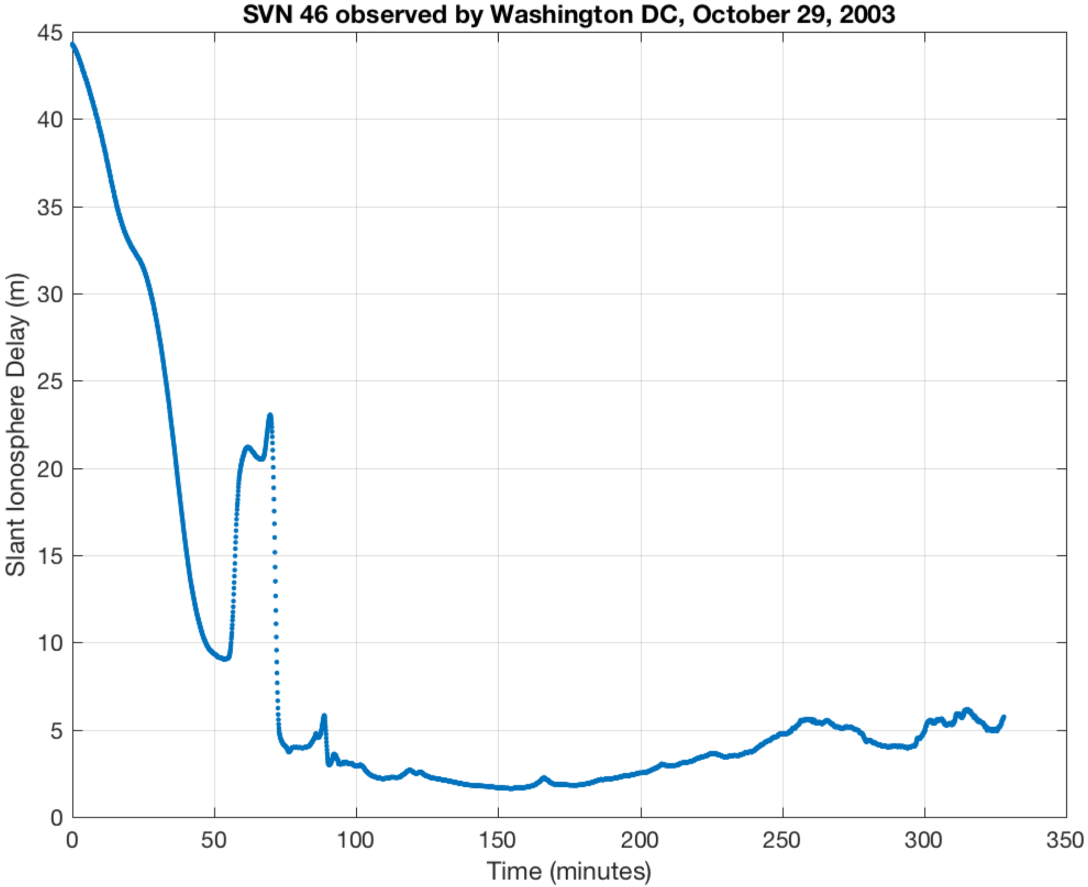
- Multiple plasma bubbles often occur with separation of about several hundred kilometers [*Saito et al., 2009*].
- Drift eastward typically with a velocity of 50-150 m/s [*Saito et al., 2009*].





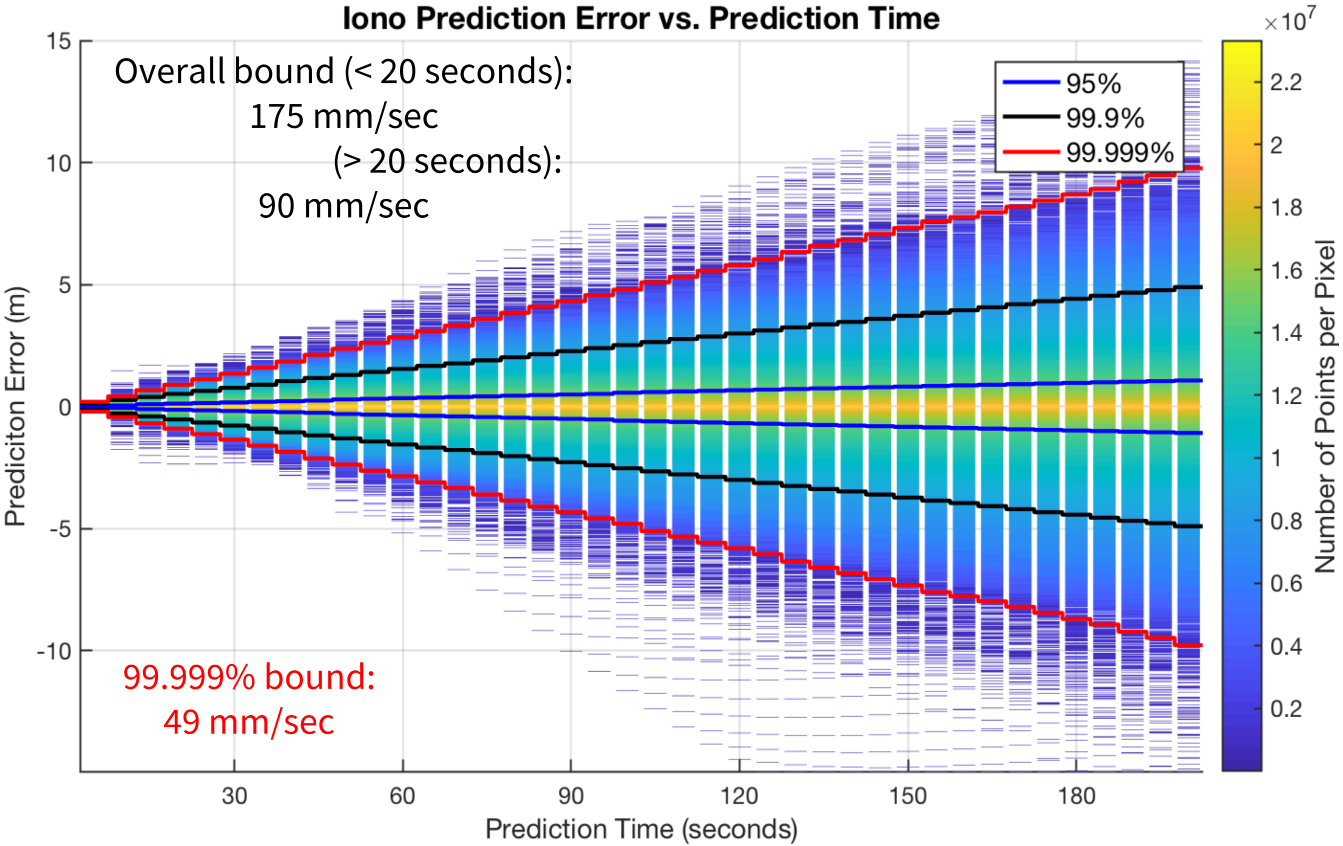
(Saito et al., 2009)

Worst Track



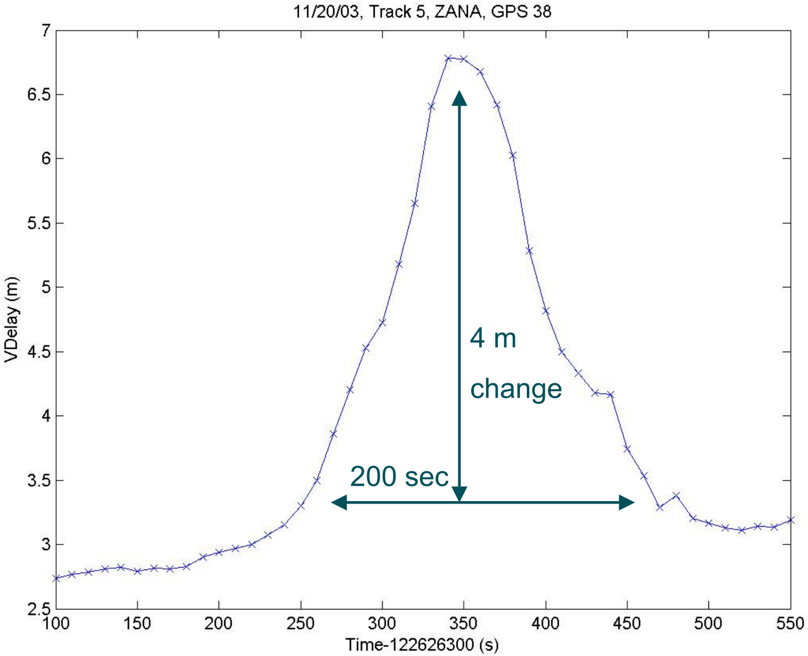
- October 29, 2003
  - During a severe ionospheric storm
- Observed from Washington DC to PRN 11

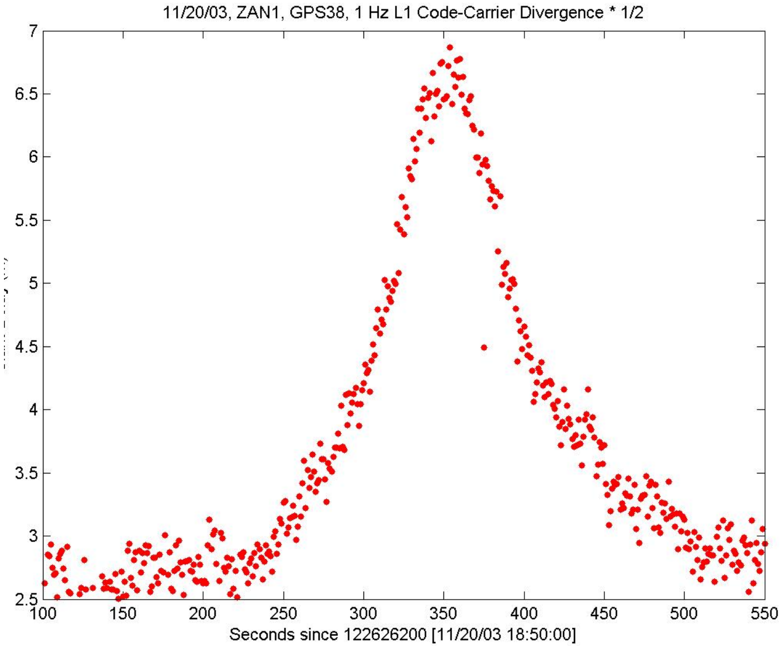
Error Growth



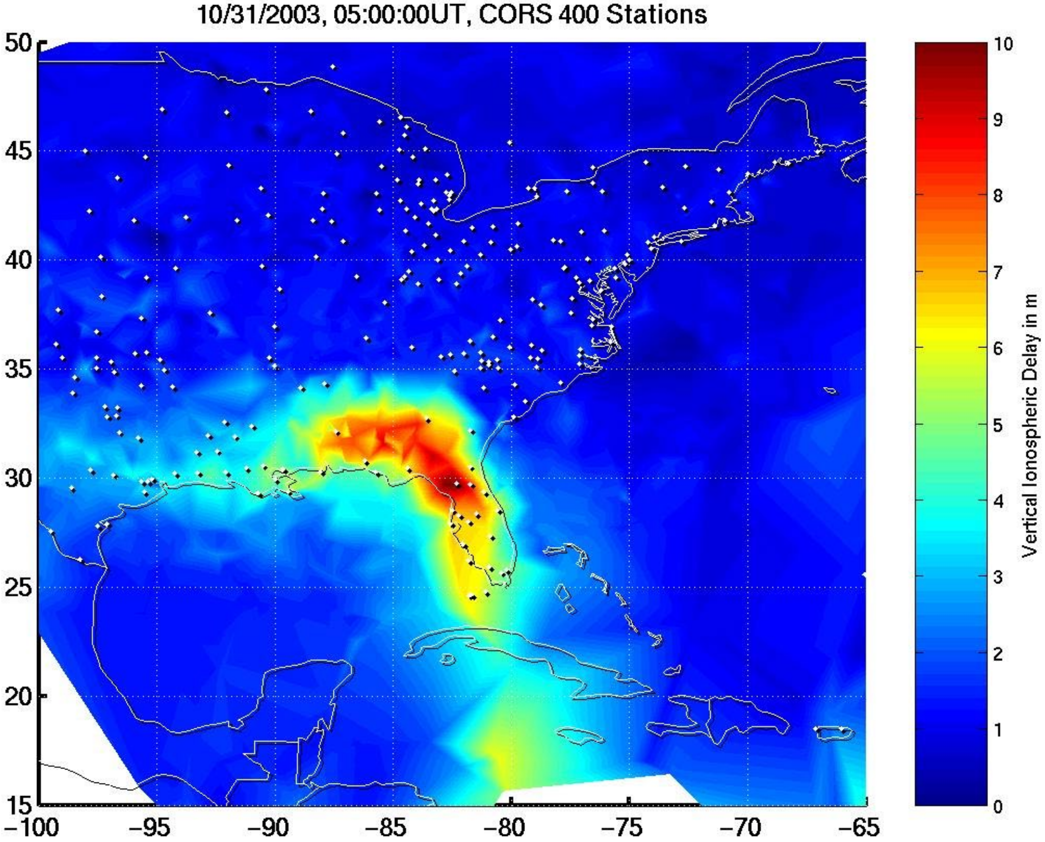
- Typical values
  - Solar minimum
    - < 1 mm/sec 95%
  - Solar maximum
    - < 3 mm/sec 95%
- Maximum value
  - < 175 mm/sec

Disturbance in Polar Region





Small-scale Irregularity



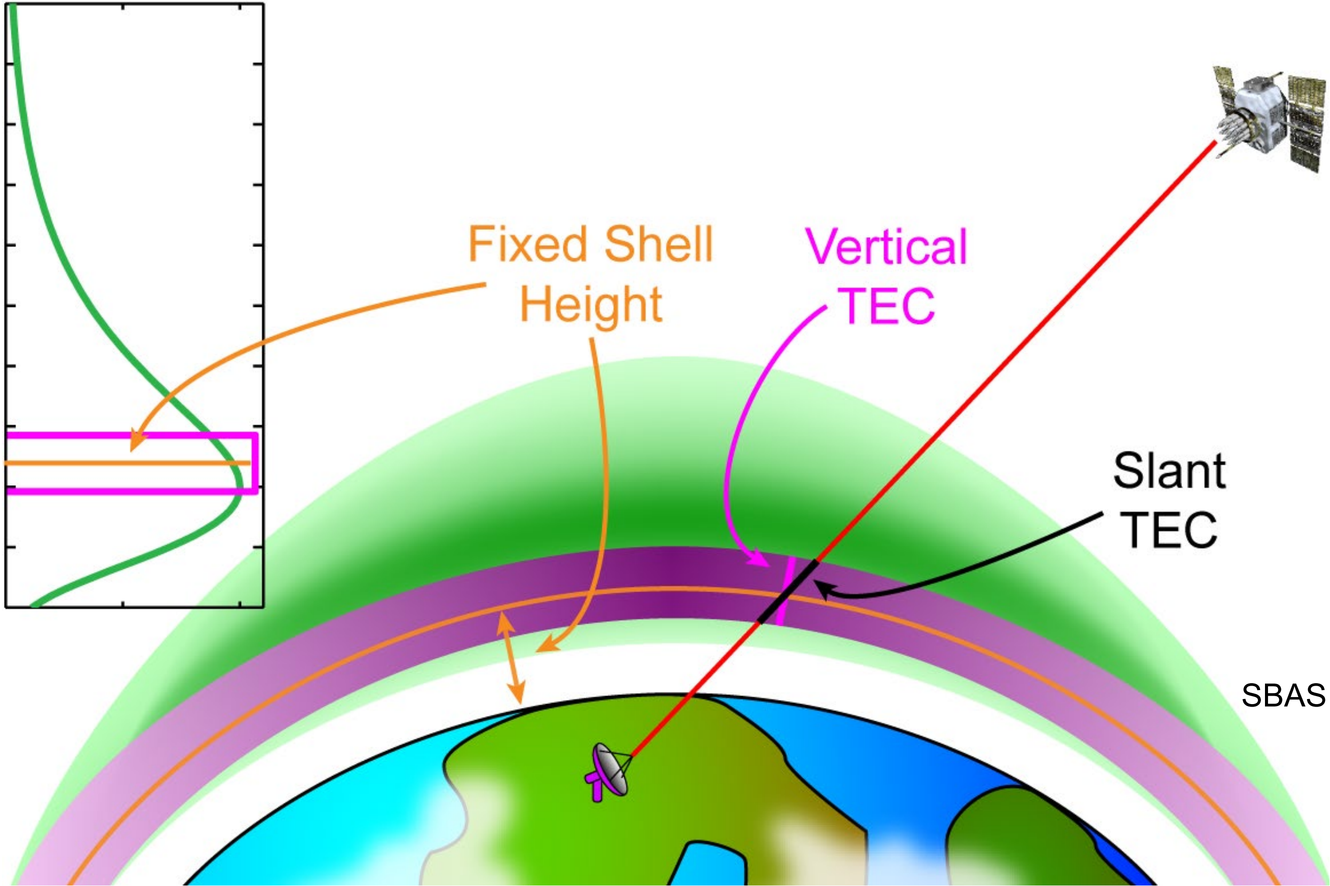
Ionospheric Delay Threats Summary

- Spatial gradients nominally below 4 mm/km
  - Extreme values up to ~400 mm/km in disturbed mid-latitude conditions
  - Extreme values greater than 500 mm/km observed in equatorial regions

- Temporal gradients nominally below 1 mm/sec
  - Temporal gradients up to 175 mm/sec in disturbed mid-latitude conditions

- Localized variations observed after storm events
  - ~10 m vertical delay difference over ~ 200 km
  - Otherwise surrounded by smooth ionosphere

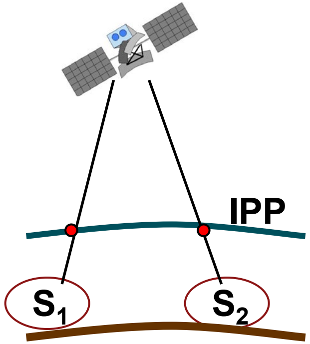
Thin Shell Model



SBAS Shell Height = 350 km

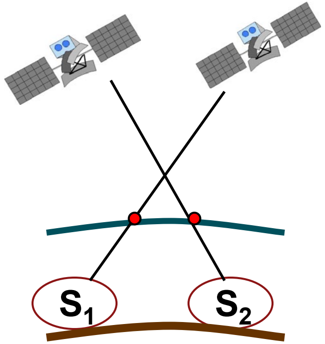
Estimation of Ionospheric Gradients

Station Pair Method



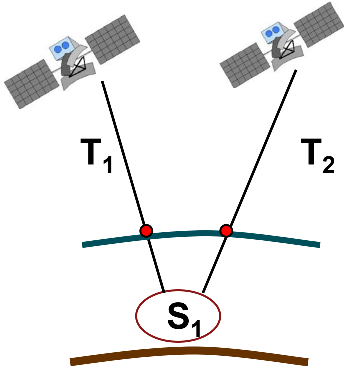
- *Long baselines*
- *Free from satellite IFB calibration error*

Mixed Pair Method



- *Long and short baselines*
- *IFB calibration error on both SV and RR*

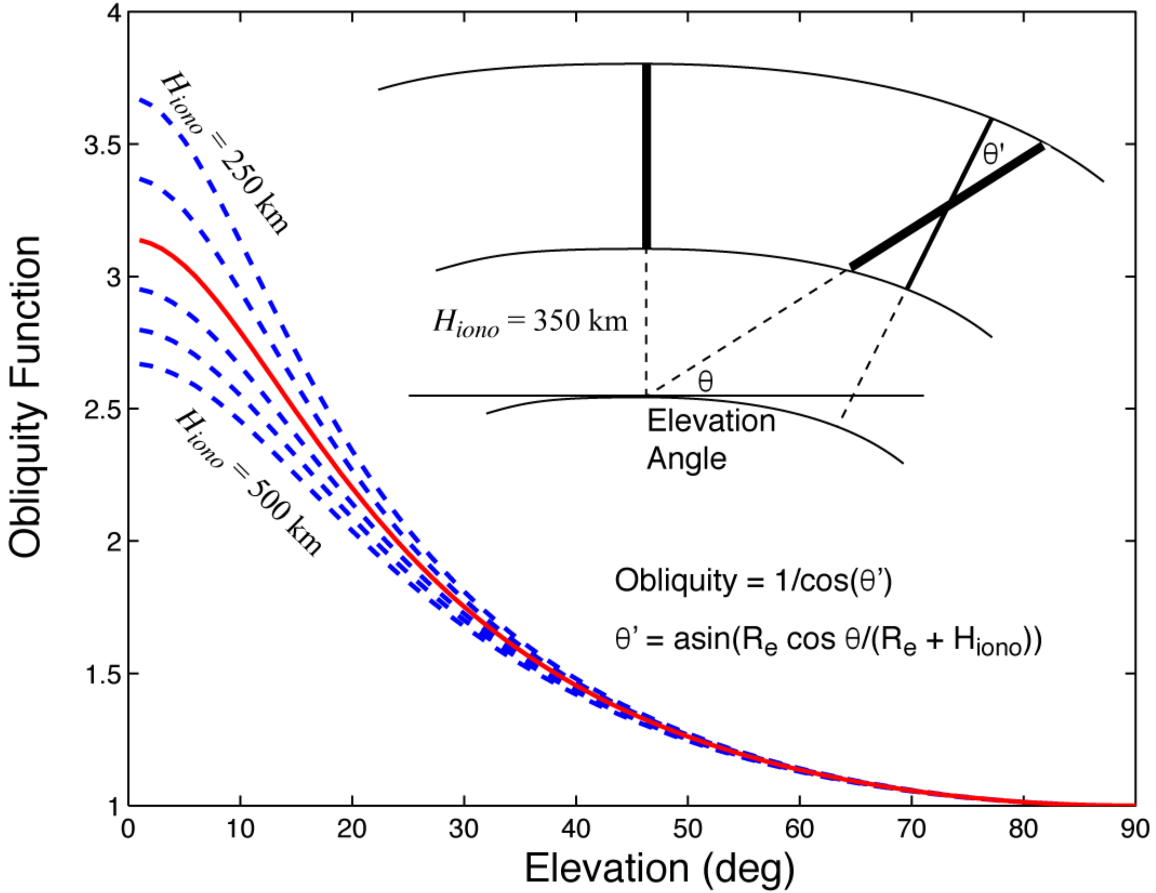
Time Step Method



- *Short baselines*
- *Free from IFB calibration error*
- *Corrupted by iono. temporal gradients*

Slide Courtesy Jiyun Lee

Obliquity Factor



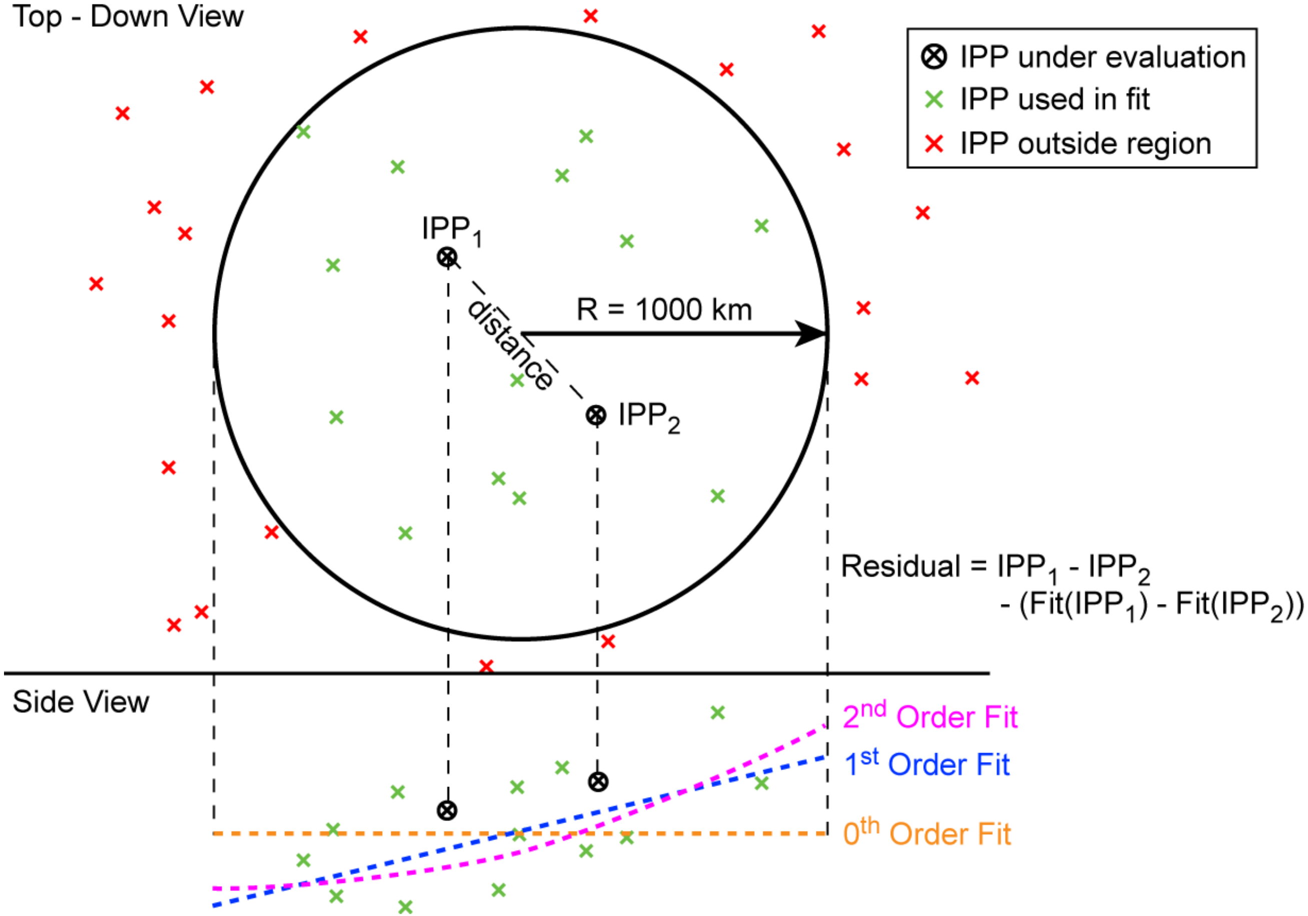
Obliquity = 1/cos(θ')

θ' = asin(R_e cos θ/(R_e + H_{iono}))

Spatial Decorrelation Estimation

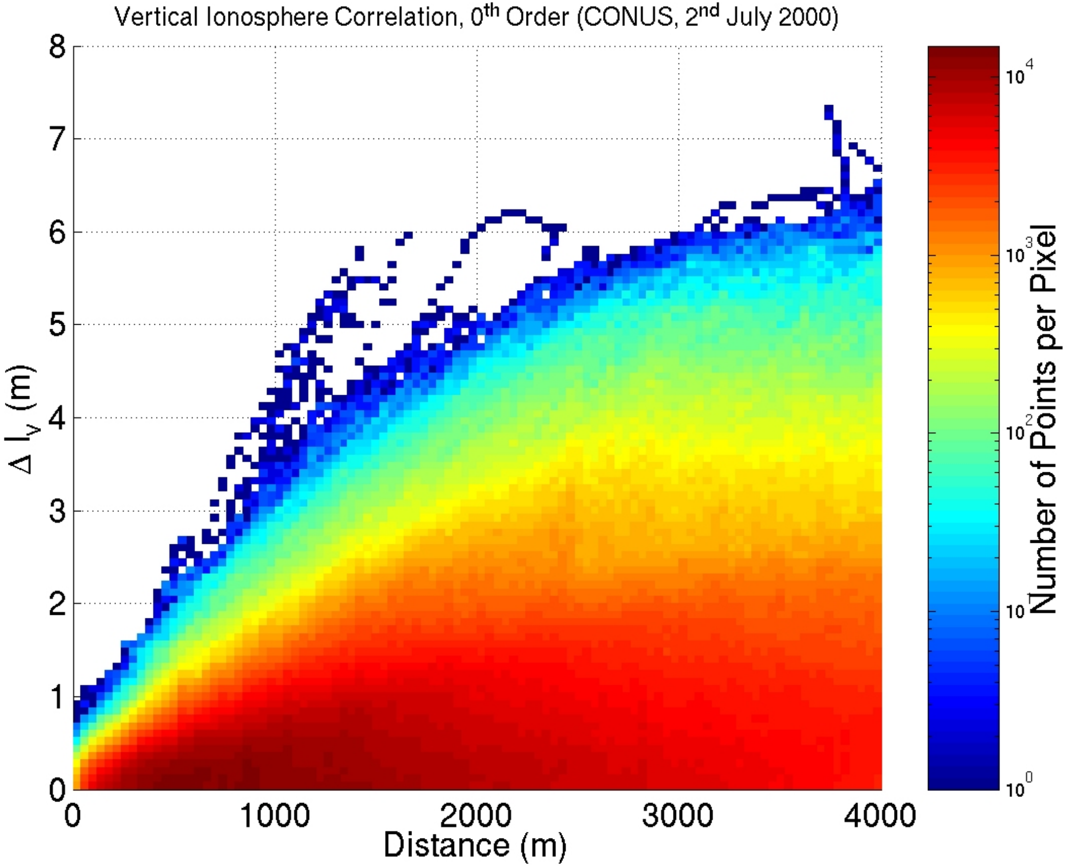
- Every IPP Is Compared to All Others
- The Great Circle Distance Between the IPPs Is Calculated
- The Difference in Vertical Ionosphere Is Calculated
- A Two-dimensional Histogram Is Formed: Each Bin Corresponds to a Distance Range and a Vertical Difference Range
- Histogram Contains the Counts for Each Time an IPP Pair Fell in a Particular Bin

Spatial Correlation Estimation Process

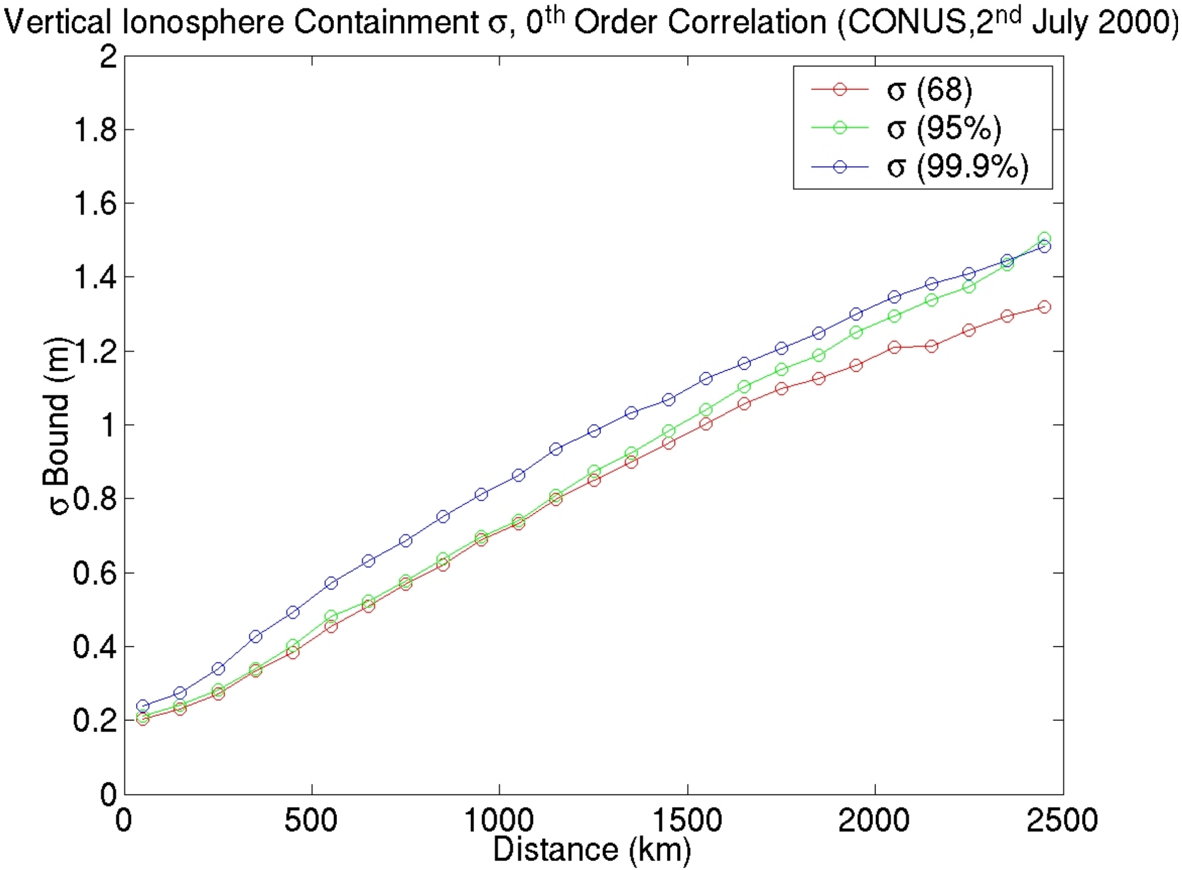


Residual = IPP$_1$ - IPP$_2$ - (Fit(IPP$_1$) - Fit(IPP$_2$))

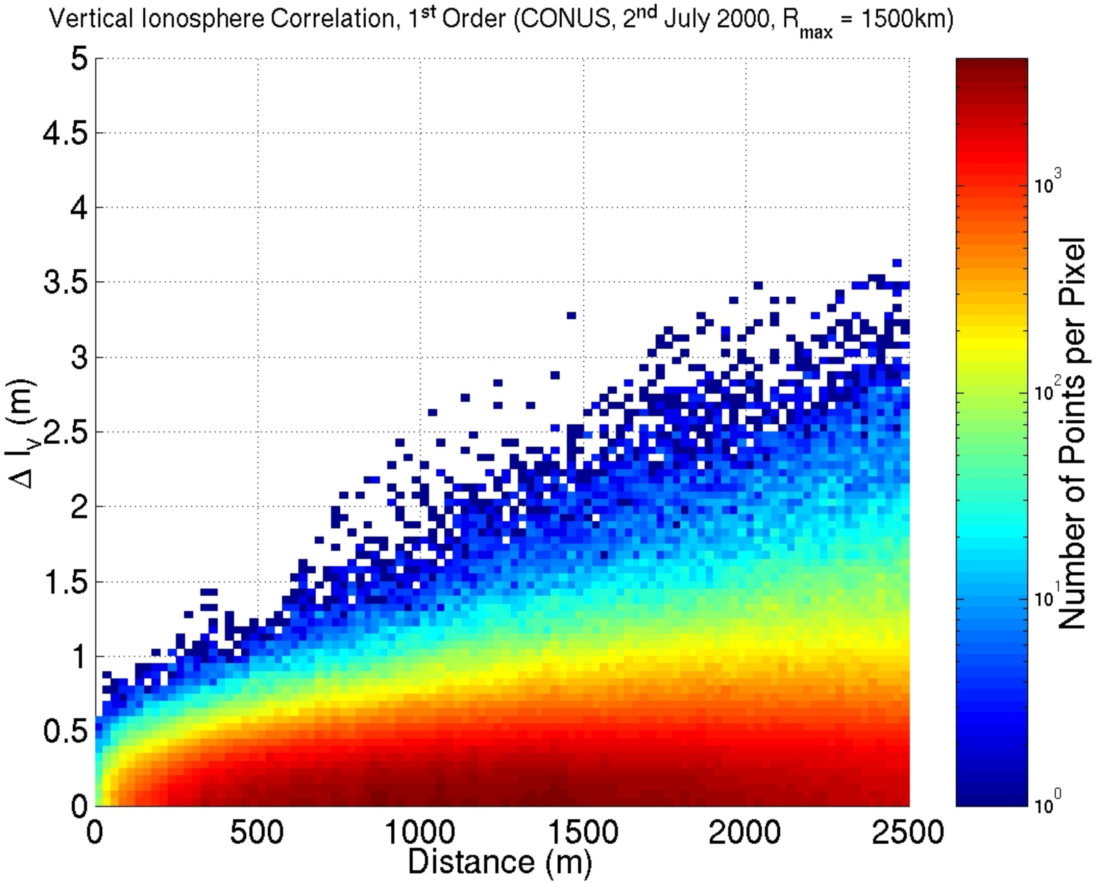
Ionospheric Decorrelation (0th Order)



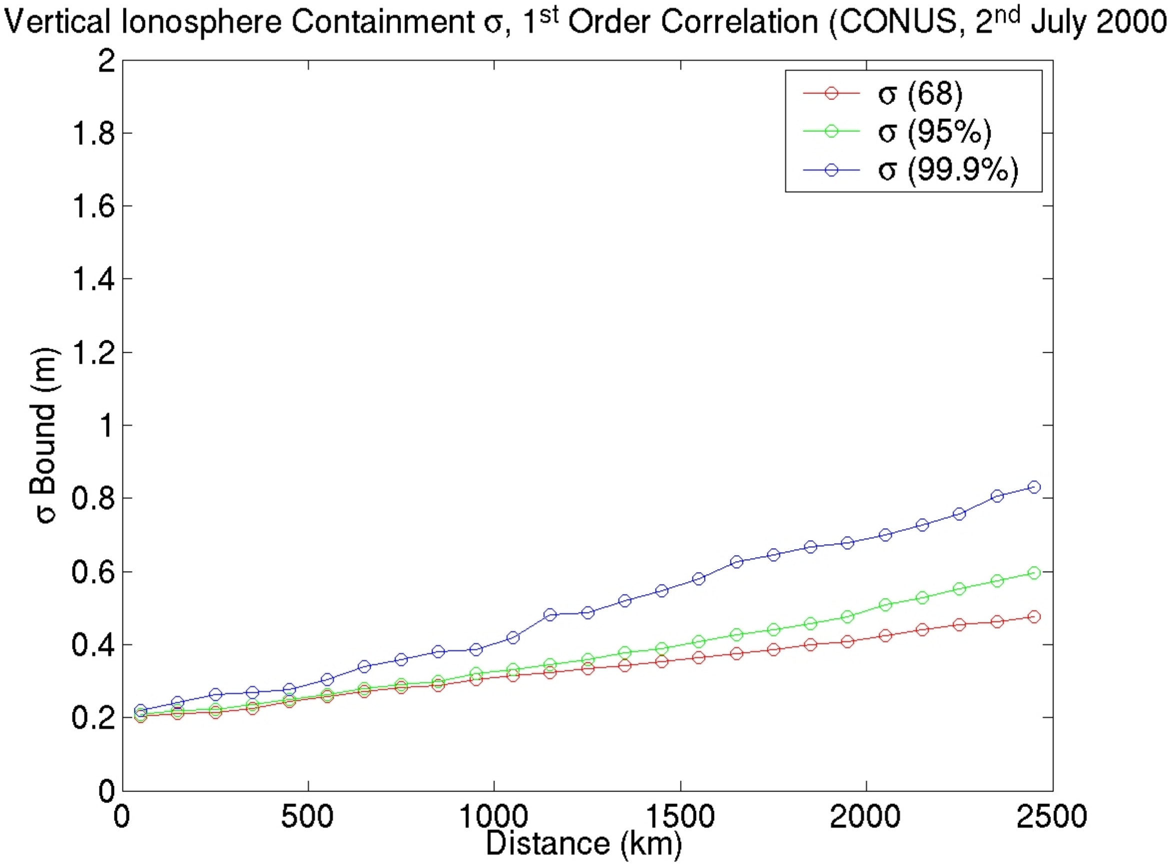
Ionospheric Decorrelation Function (0^{th} Order)



Ionospheric Decorrelation About a Planar Fit (1st Order)



Ionospheric Decorrelation Function (1st Order)



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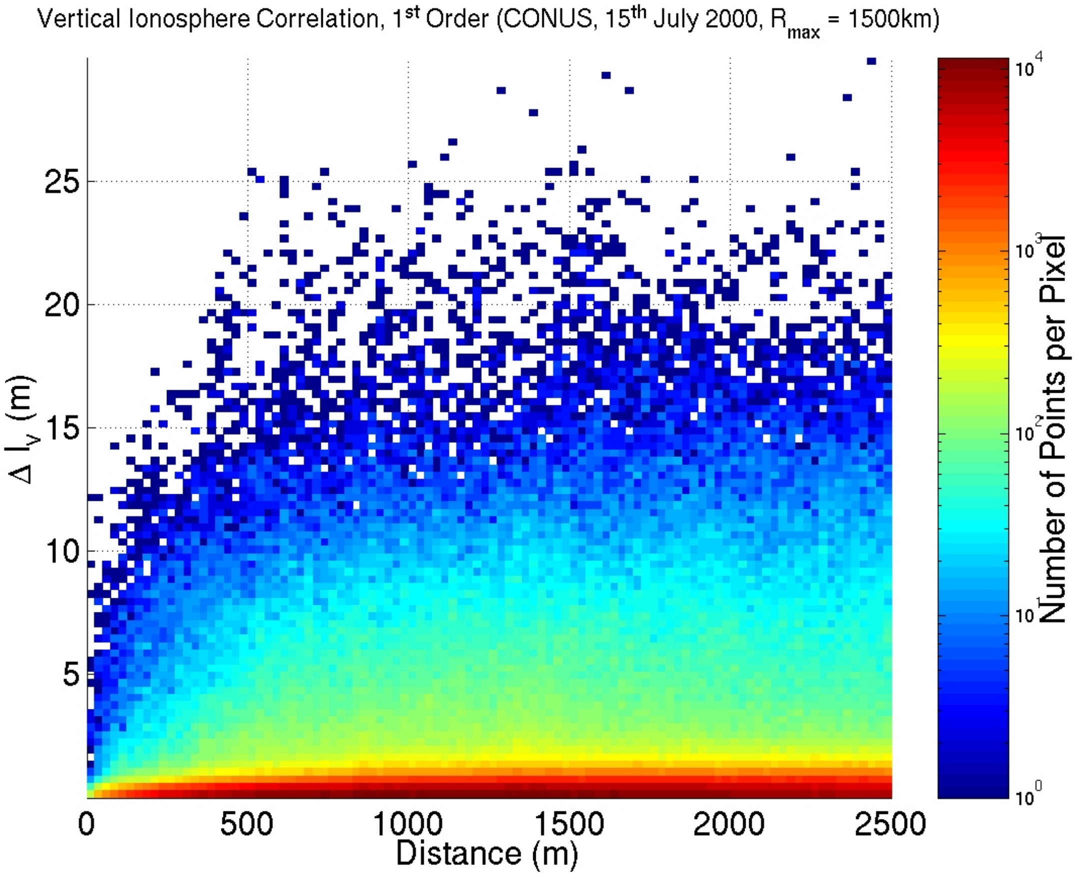
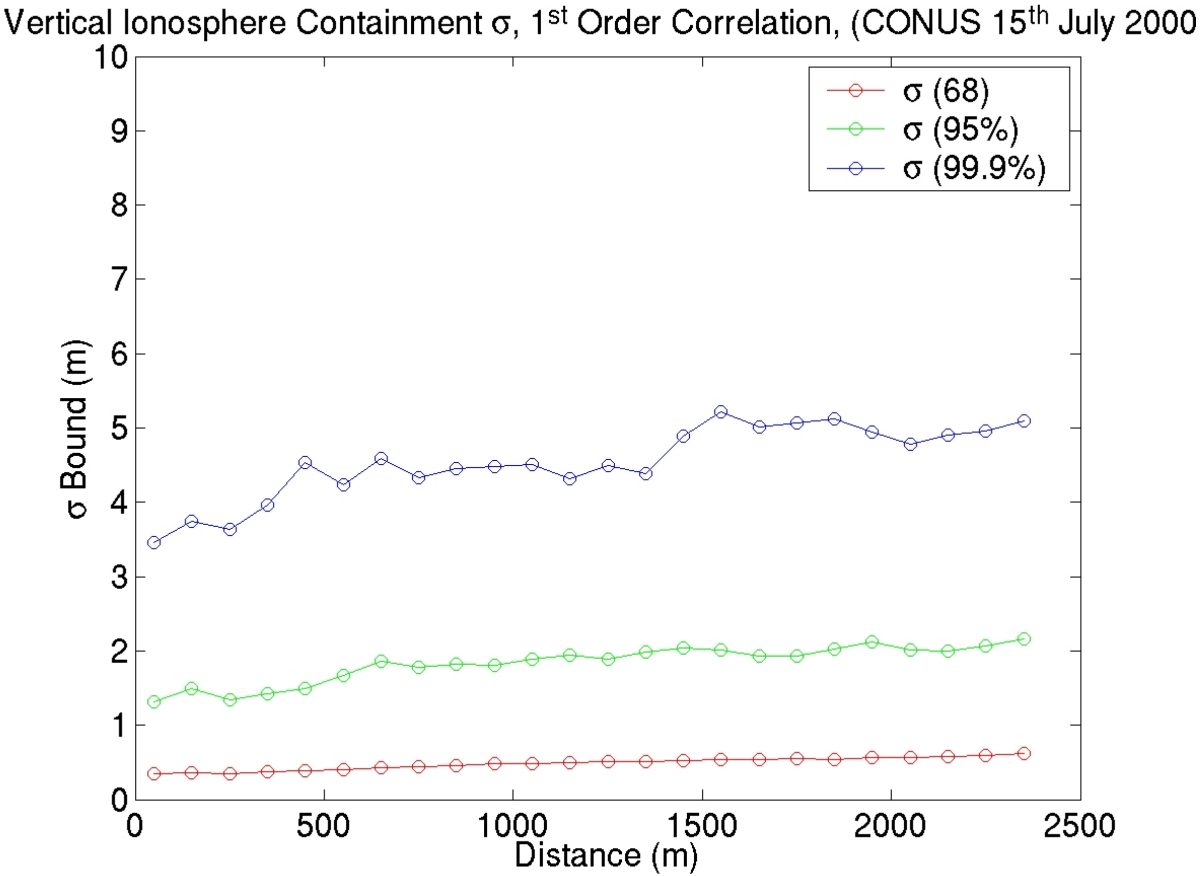
Disturbed Ionosphere

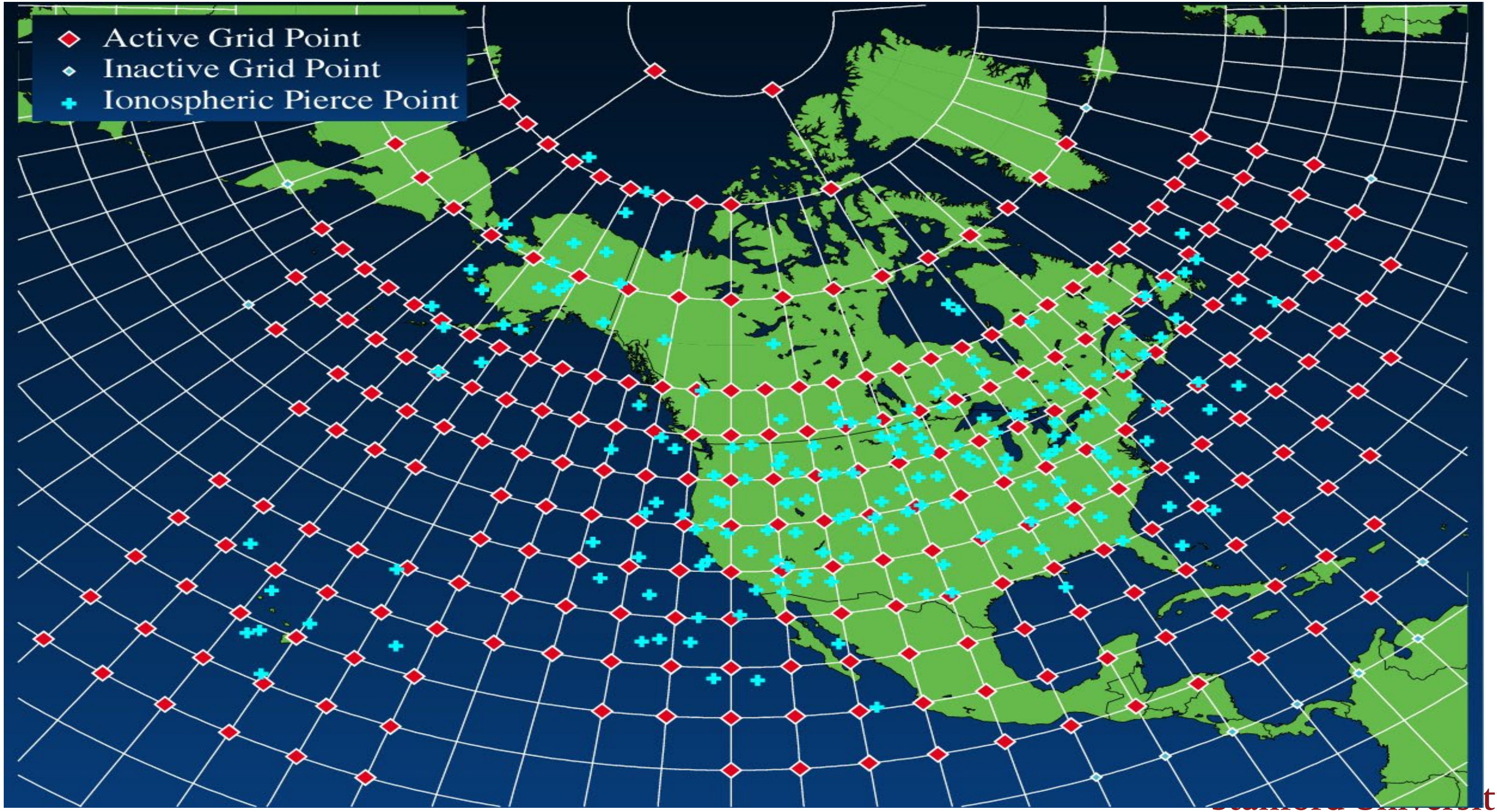


Stanford University

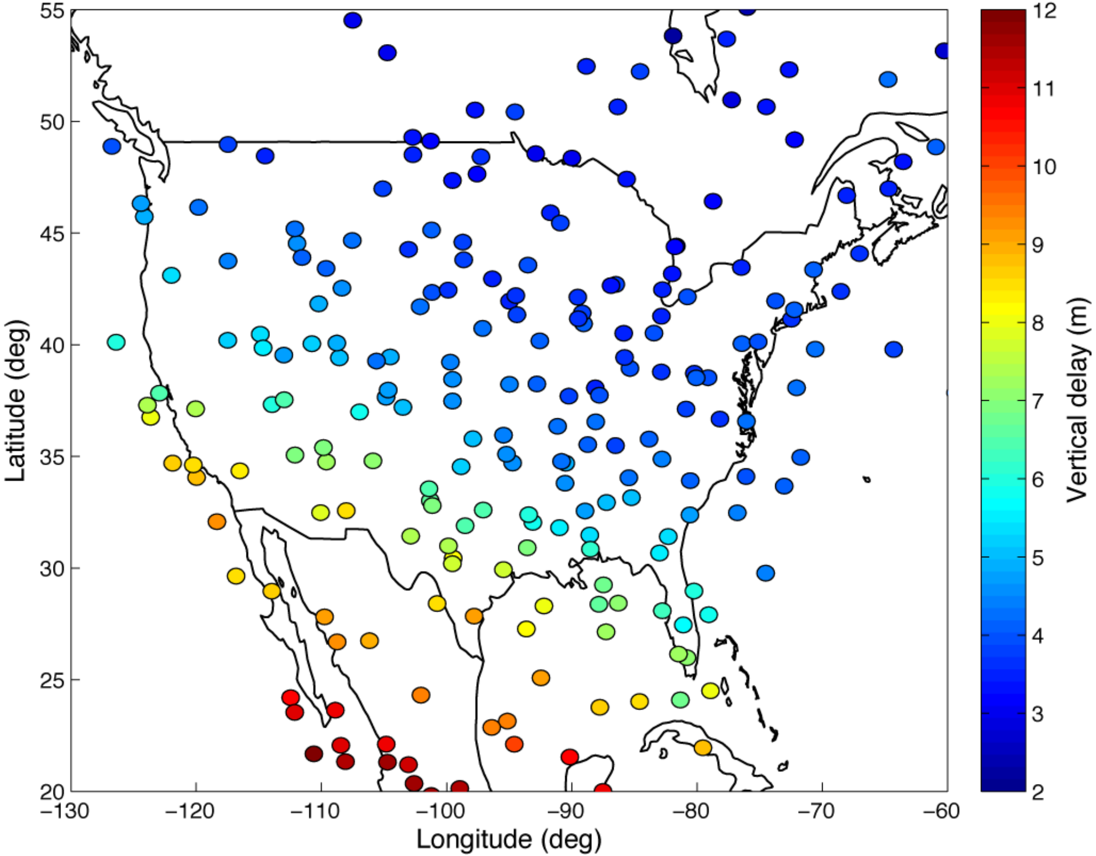
Disturbed Ionosphere



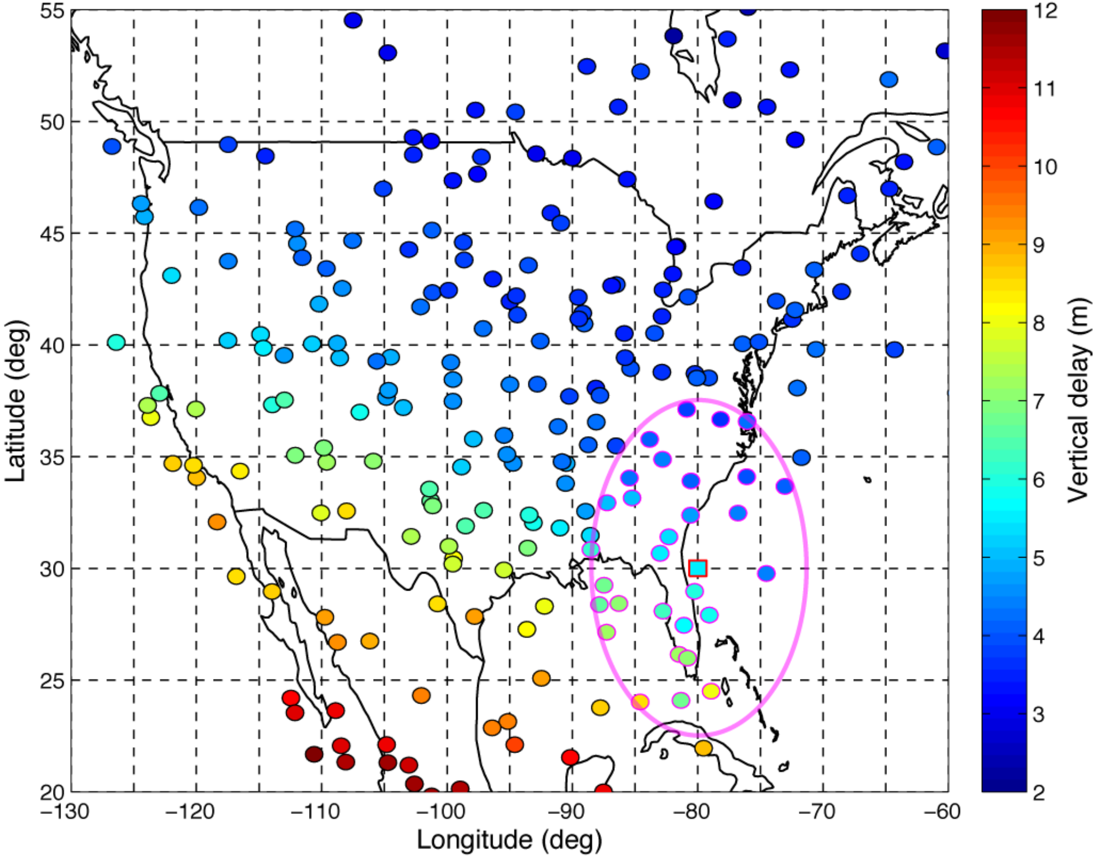
SBAS Ionospheric Grid (WAAS)



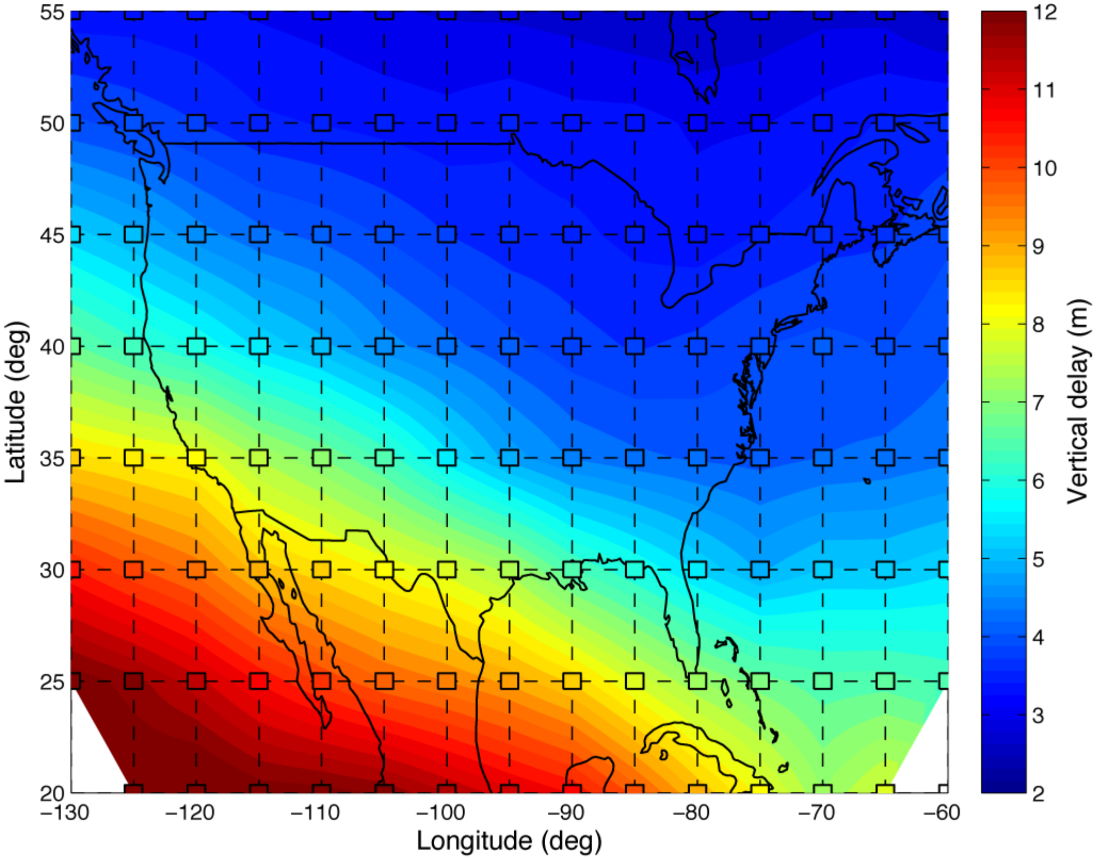
Nominal Ionosphere - IPPs



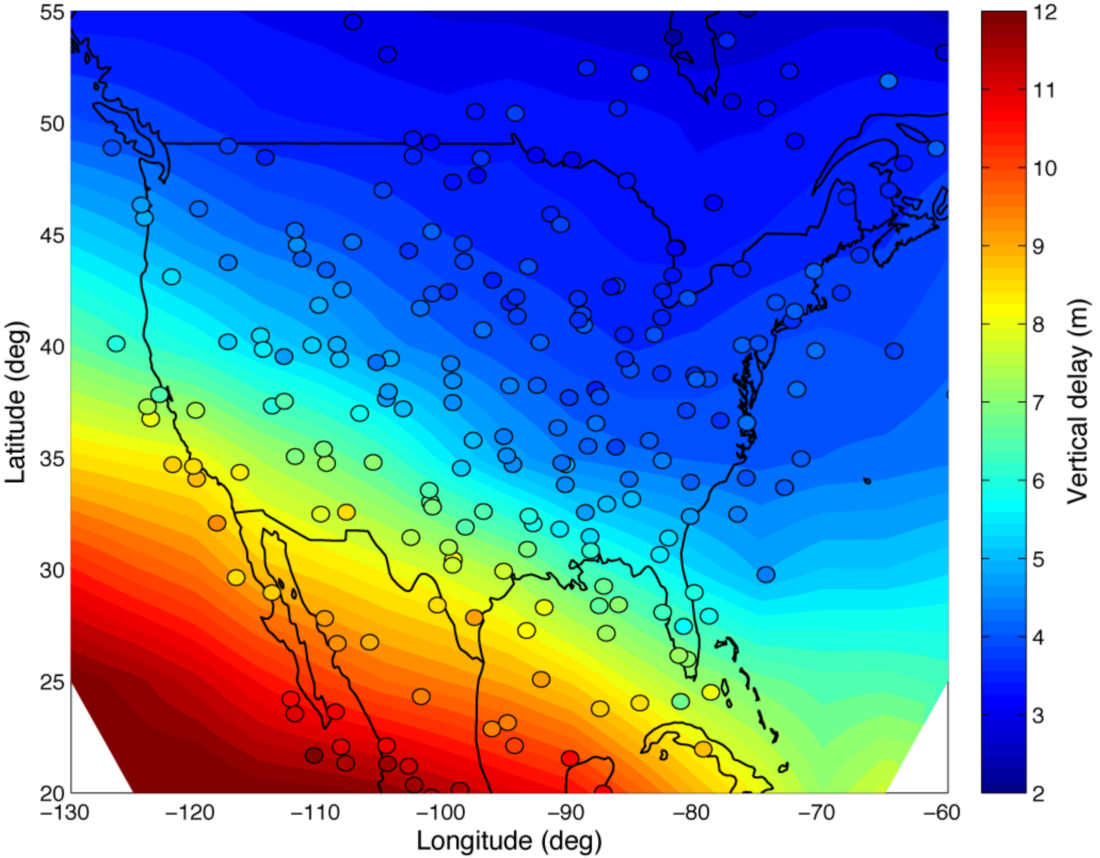
Fit to Local IPPs



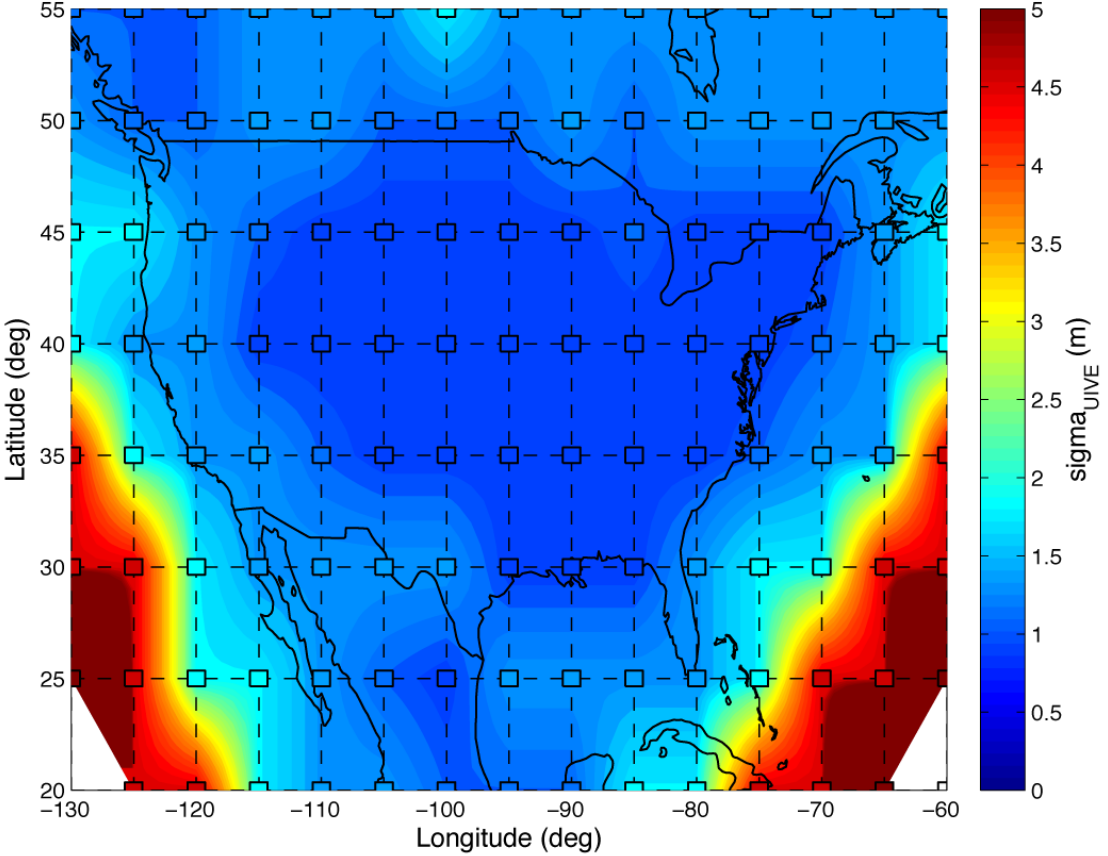
Nominal ionosphere – Grid Delays



Nominal Ionosphere – Grid Comparison to IPPs



Nominal Ionosphere – Confidence Values



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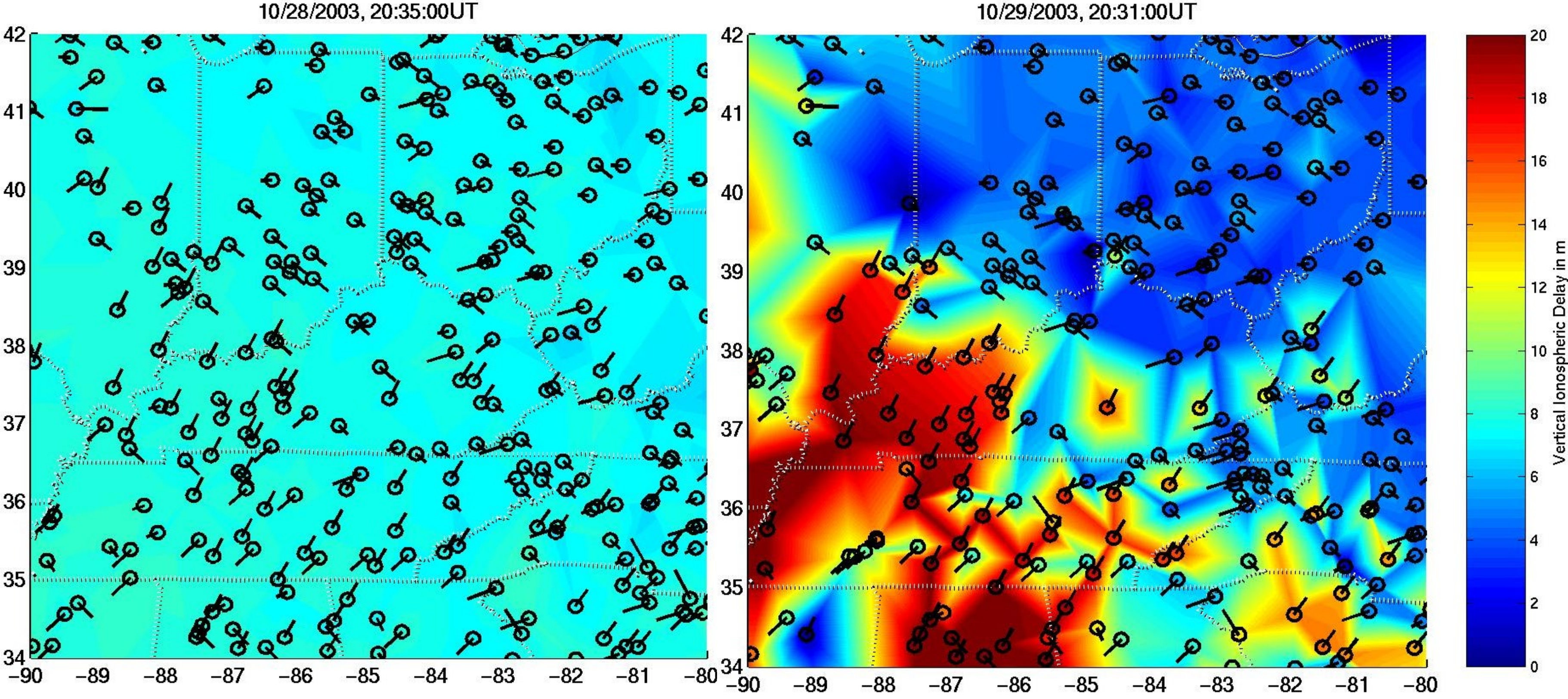
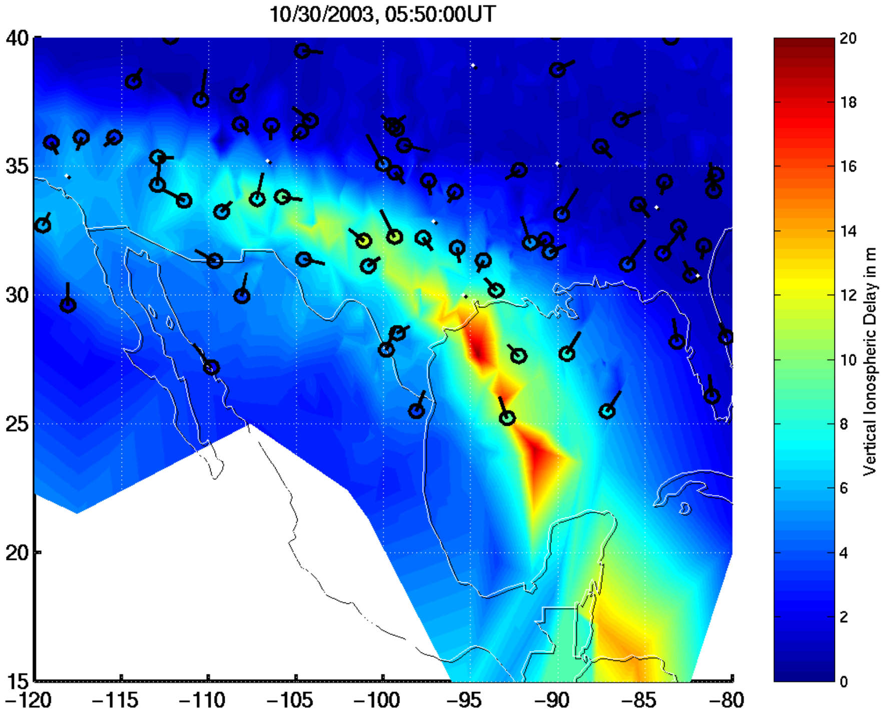
Limits of the Thin Shell Model

Disturbed Day



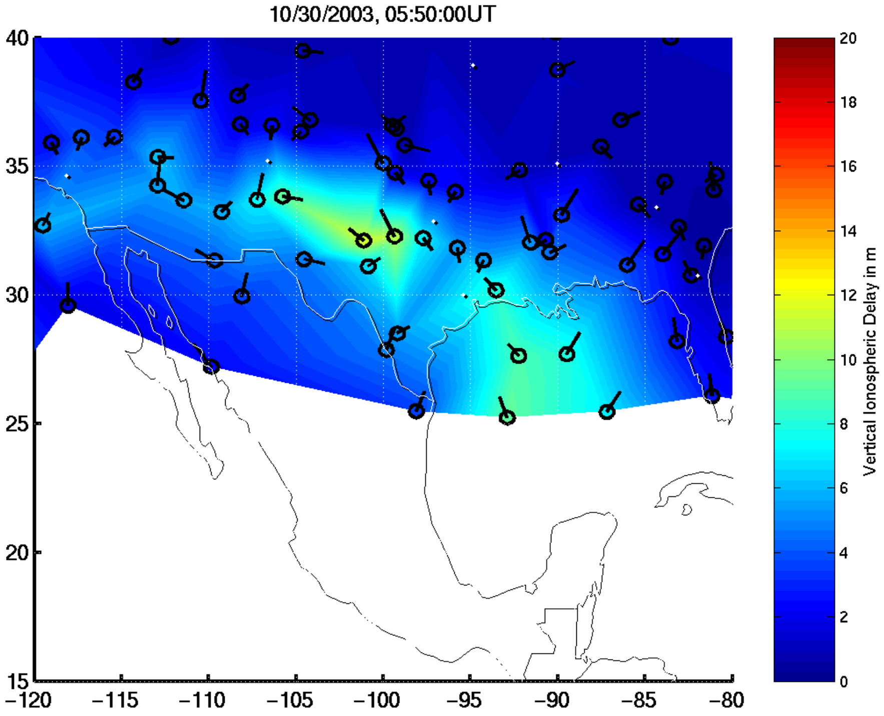
Quiet Day

Under-sampled Ionospheric Threat Condition



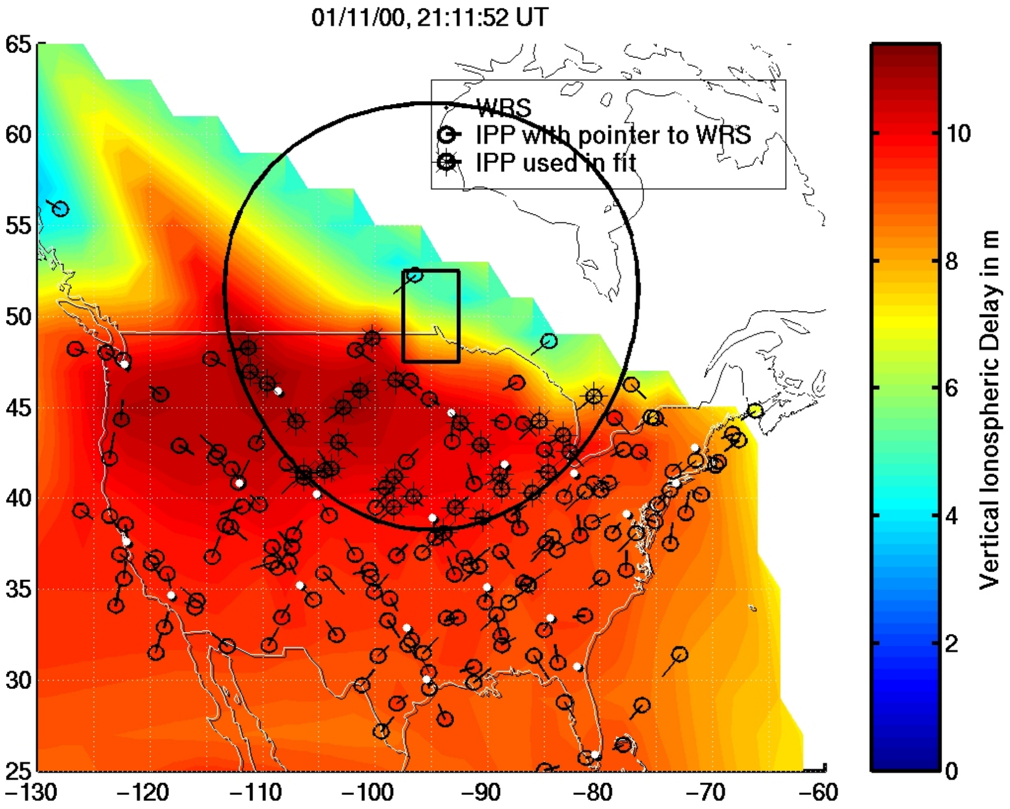
Courtesy:
Seebany
Datta-Barua

WAAS Measurements

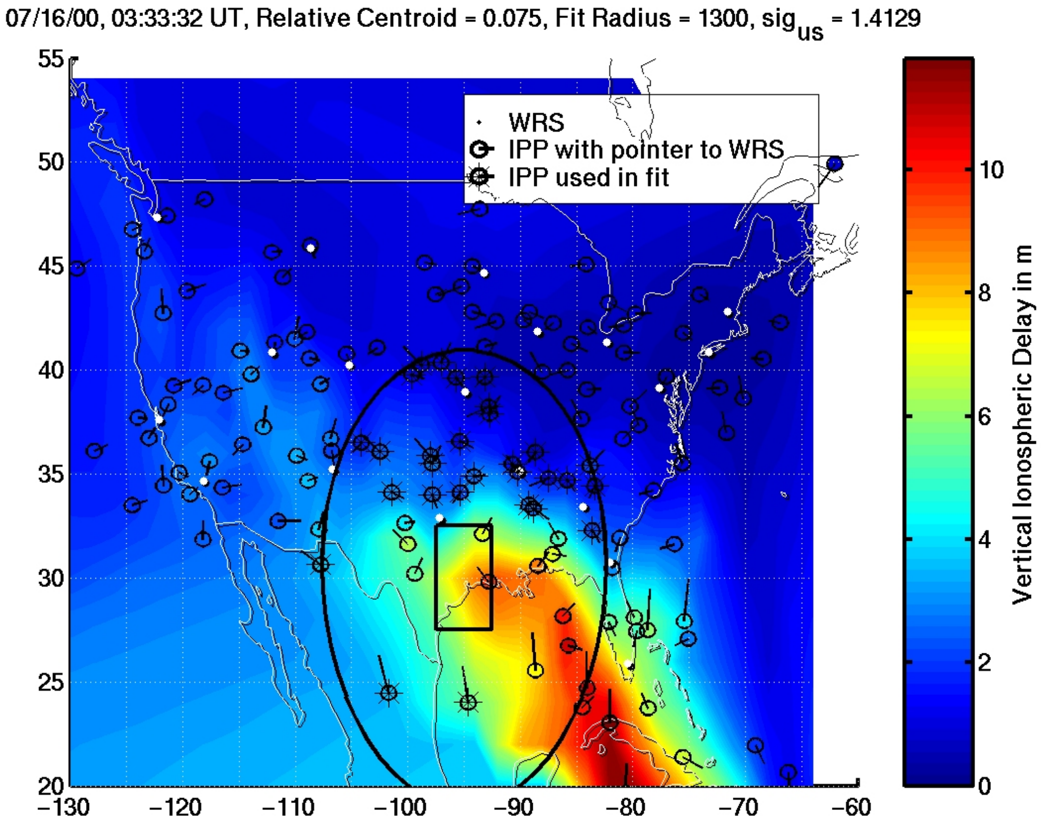


Courtesy:
Seebany
Datta-Barua

January 11, 2000

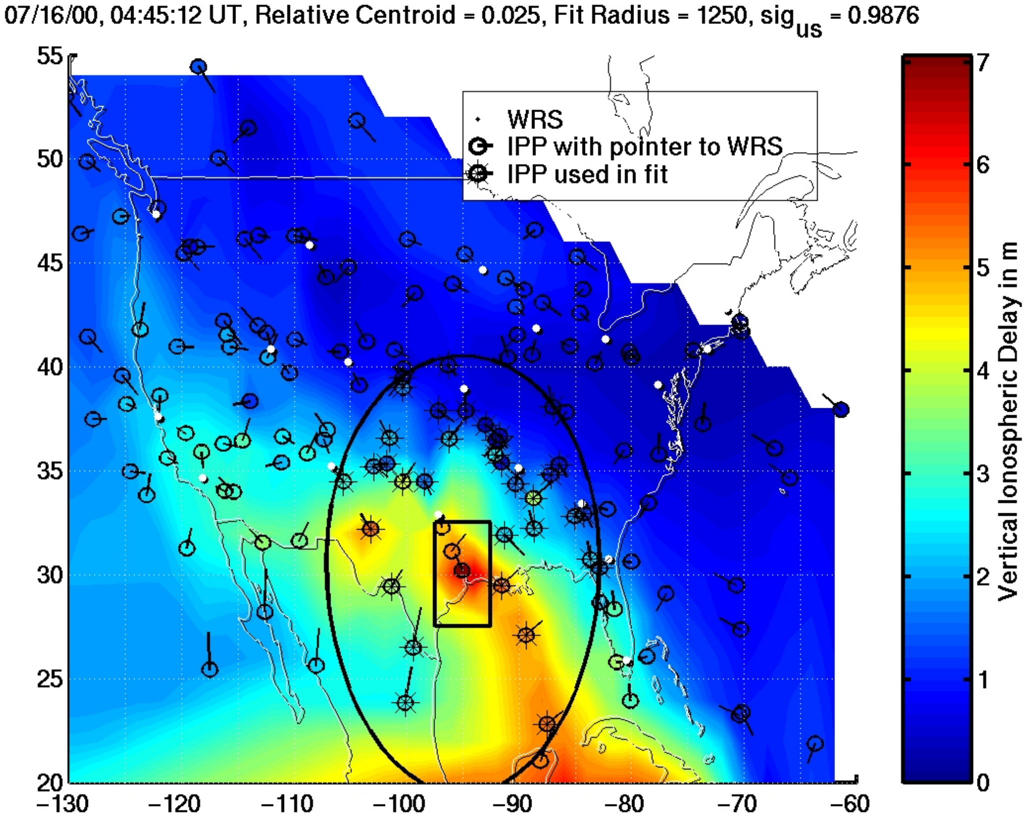


July 16, 2000



07/16/00, 03:33:32 UT, Relative Centroid = 0.075, Fit Radius = 1300, sig$_{us}$ = 1.4129
WRS
IPP with pointer to WRS
IPP used in fit
55
50
45
40
35
30
25
20
−130
−120
−110
−100
−90
−80
−70
−60
10
8
6
4
2
0
Vertical Ionospheric Delay in m

April 6, 2000



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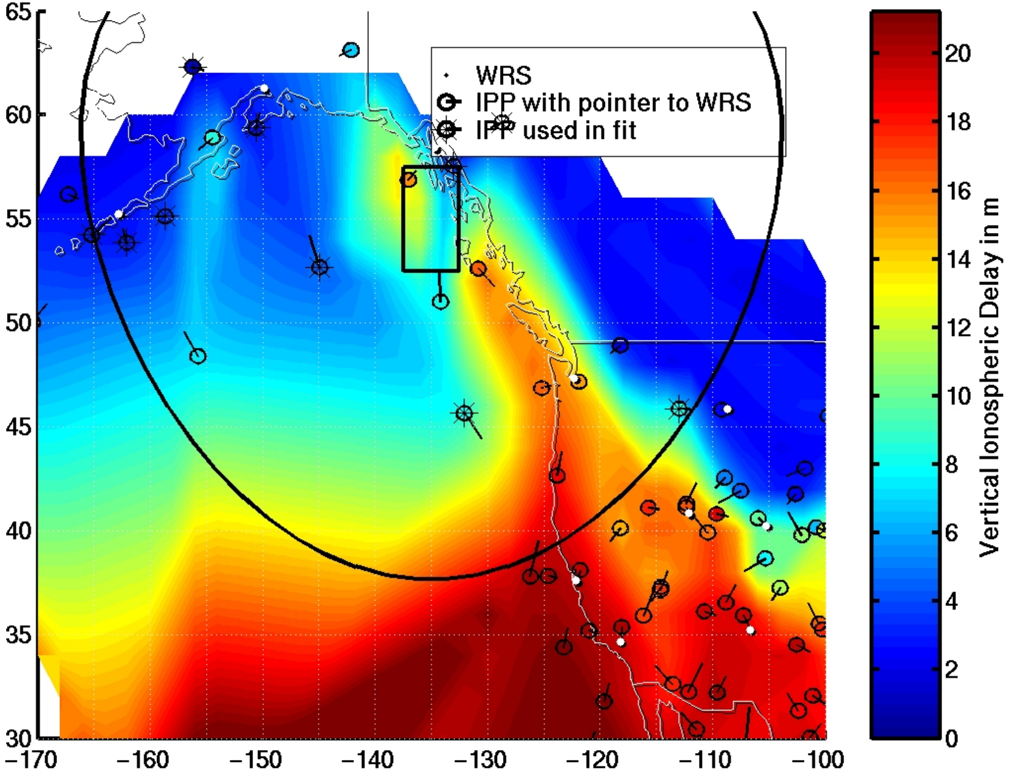
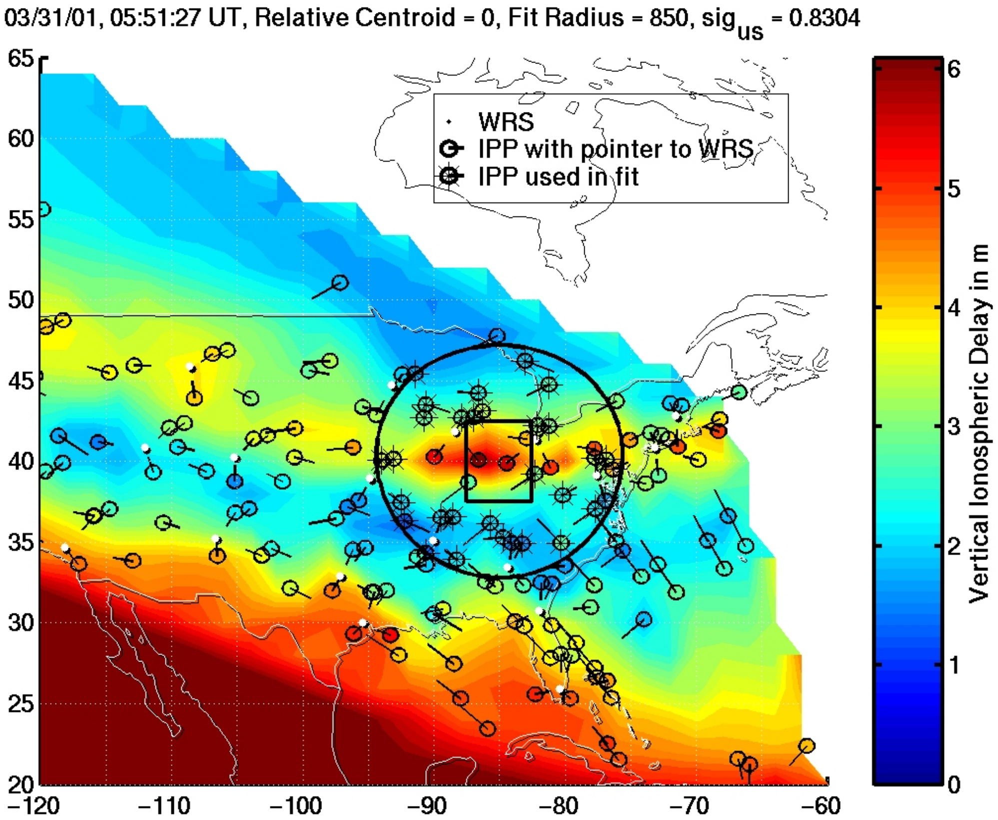
April 6, 2000

04/06/00, 23:15:12 UT, Relative Centroid = 0.175, Fit Radius = 2100, sig_{us} = 2.2128



March 31, 2001



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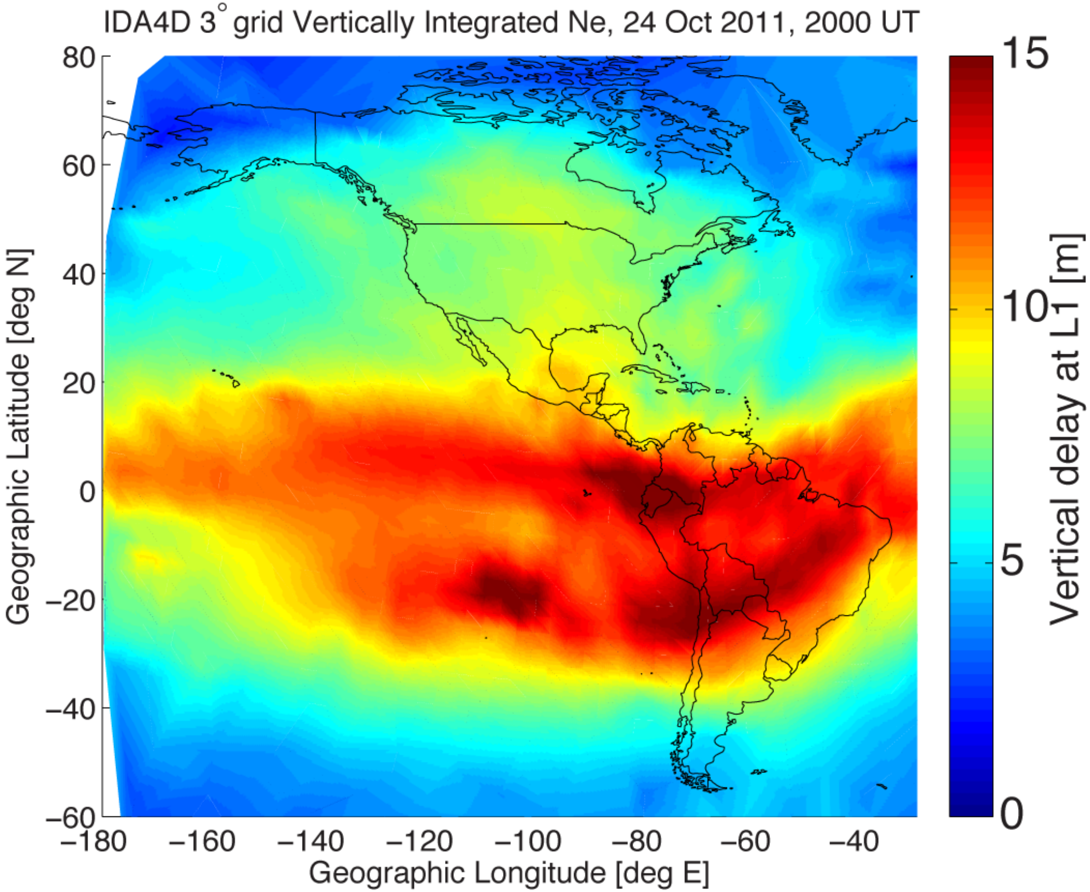
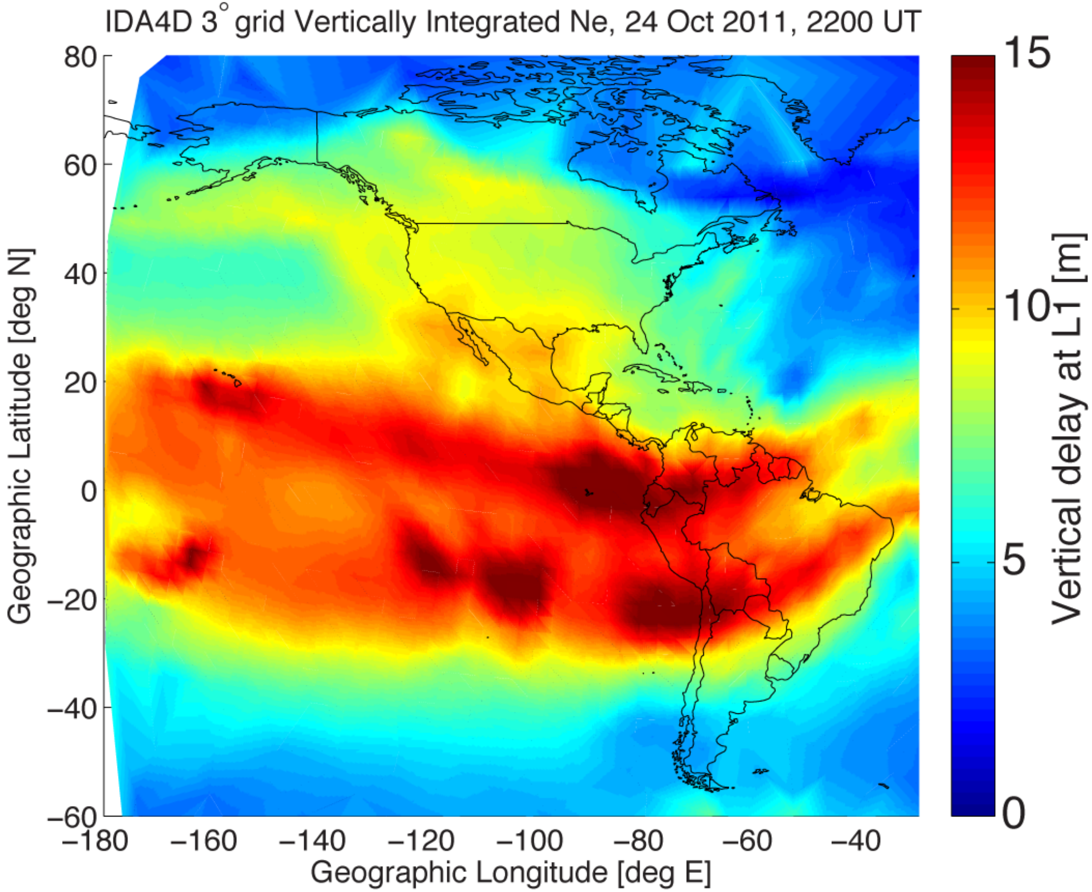
October 24-25, 2011



Iono Model Courtesy: Gary Bust & Seebany Datta-Barua

October 24-25, 2011



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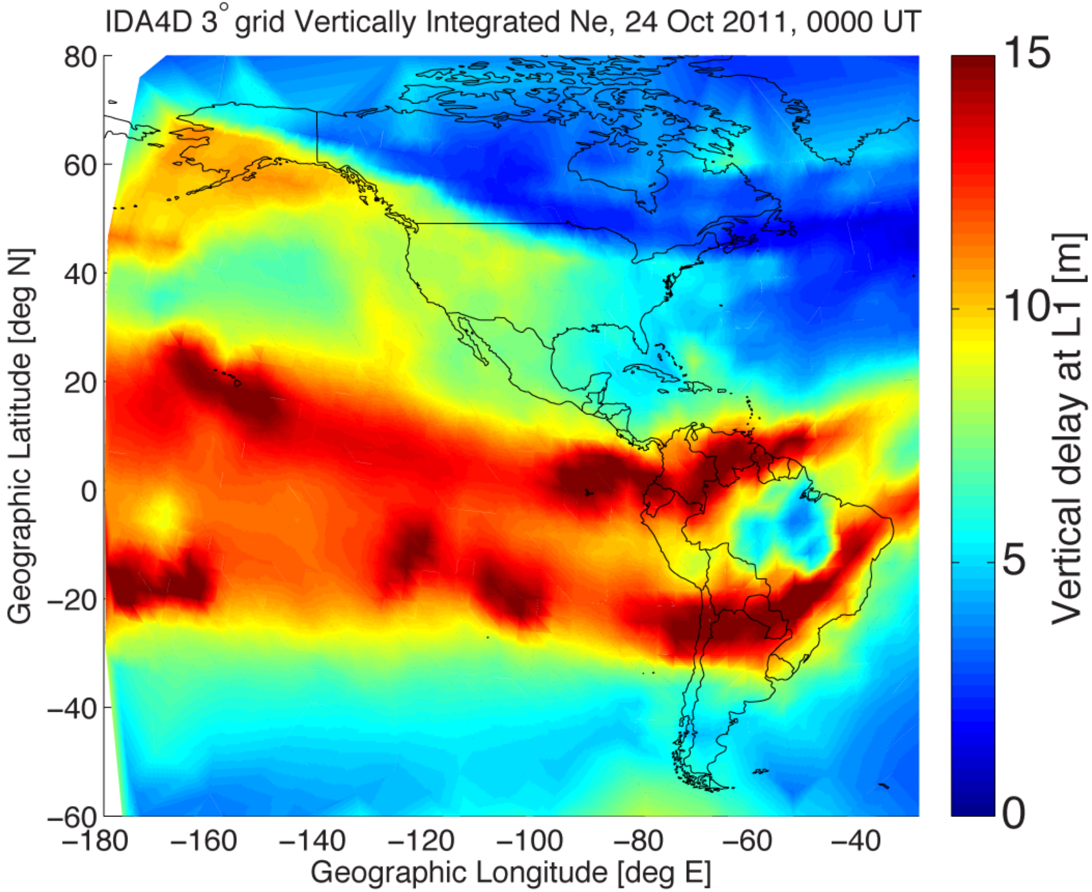

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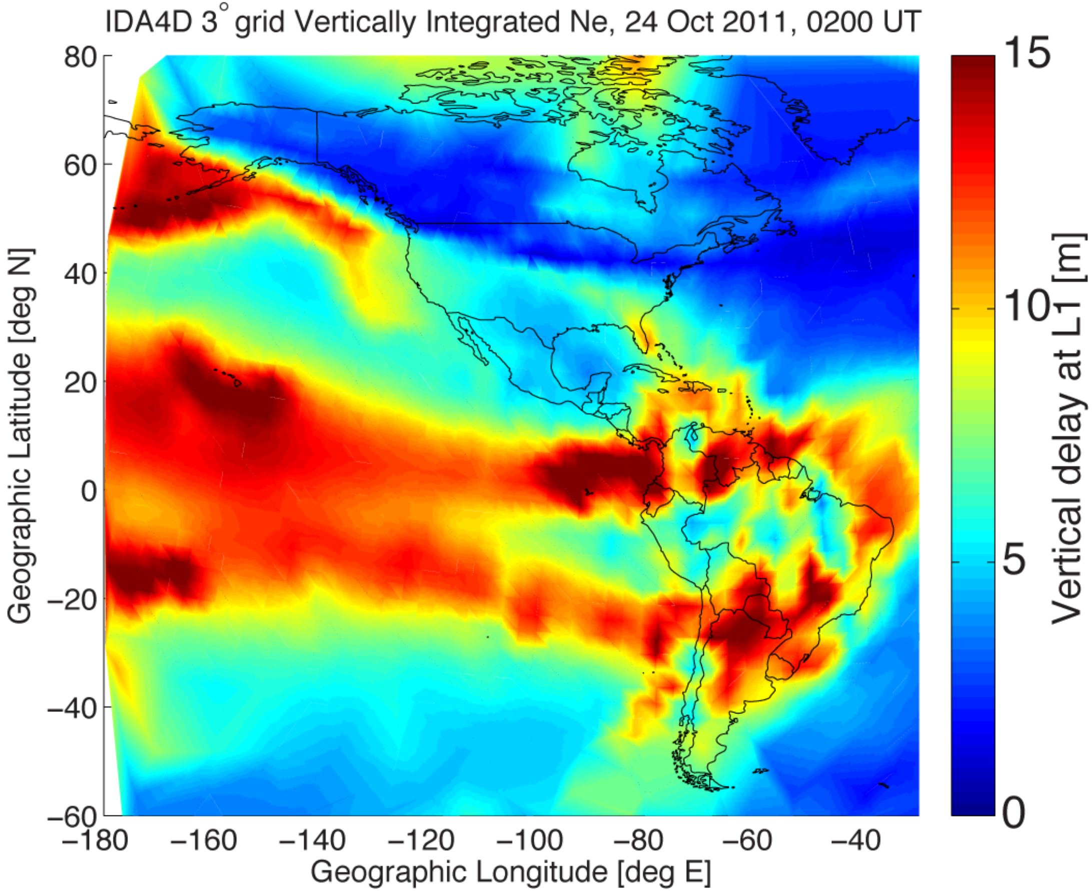

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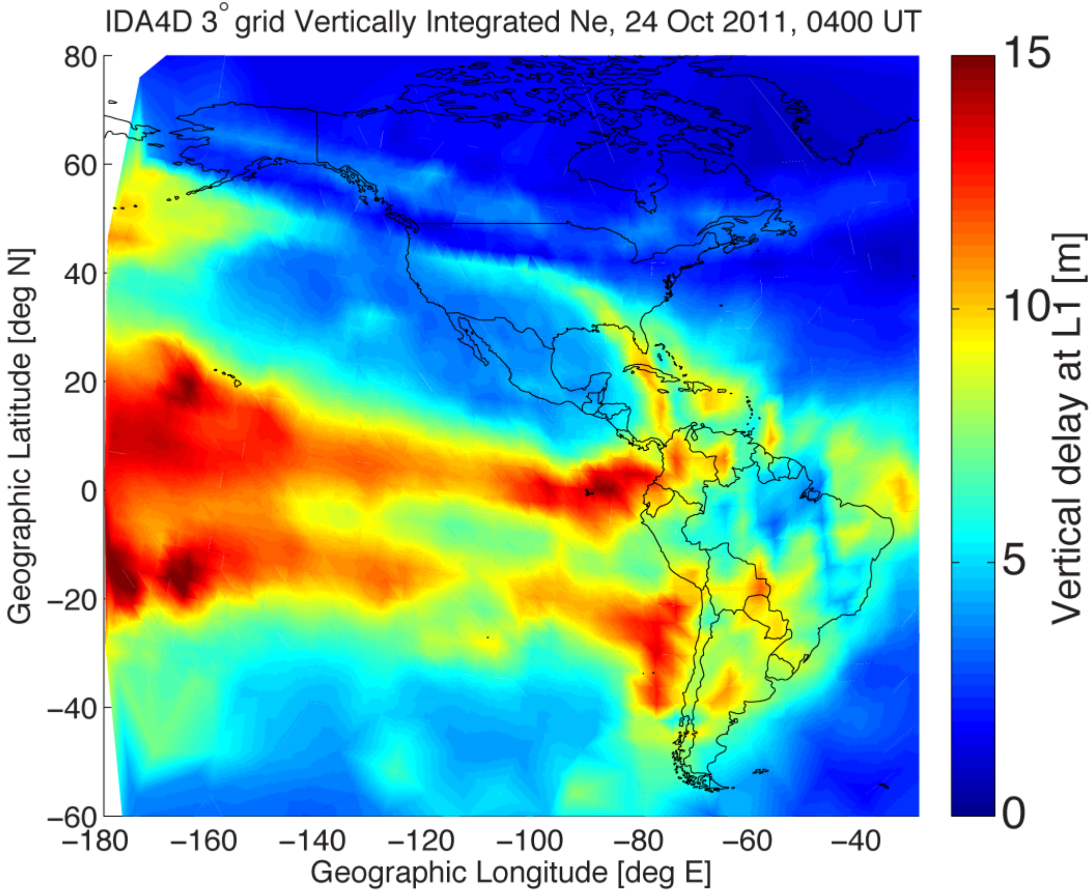

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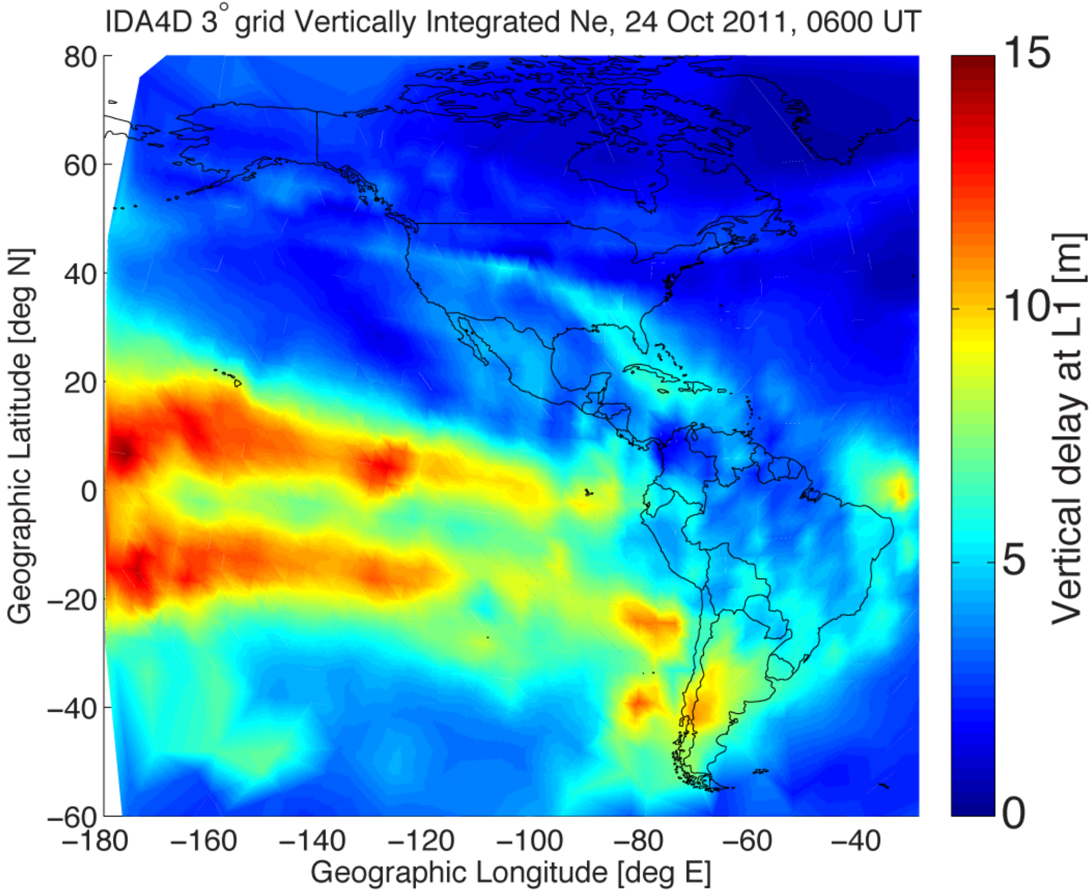


Iono Model Courtesy: Gary Bust & Seebany Datta-Barua

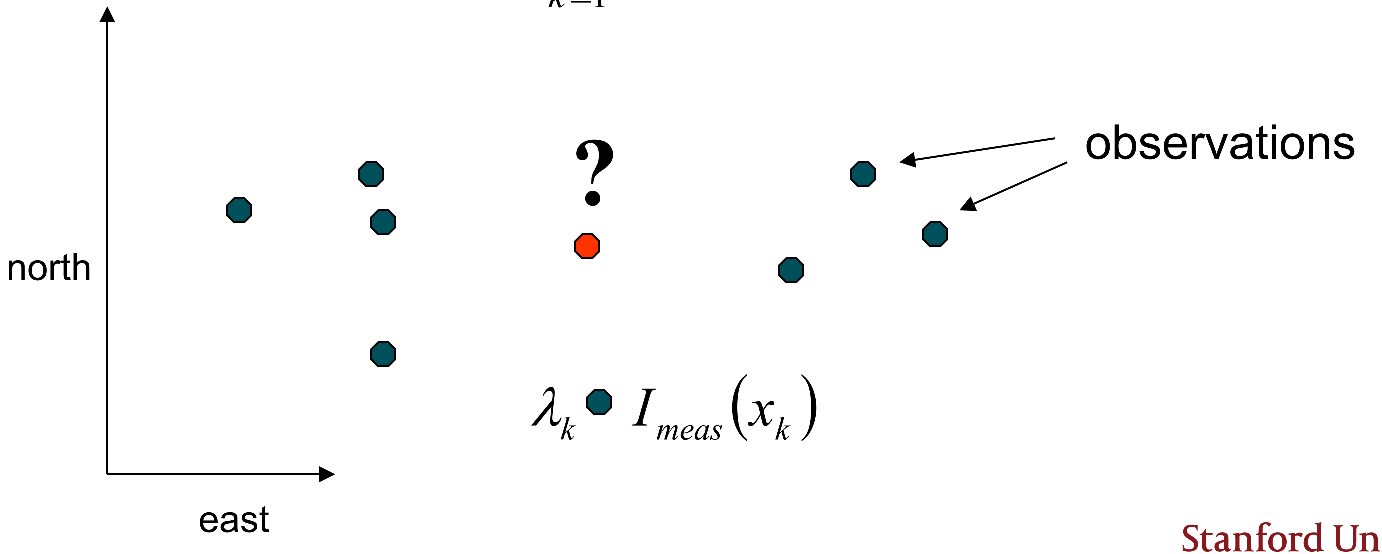
Grid Ionospheric Vertical Error (GIVE) Elements

- Formal error term
  - Measurement noise
  - Ionospheric modeling error
    - Accounts for sampled ionosphere and disturbance state
  - Antenna bias contribution
- Under-sampled threat term
  - Spatial & temporal threats
- Floor term
- Storm detector
  - Local at the IGP
  - Moderate storm detector (MSD)
  - Global extreme storm detector (ESD)

Linear estimator

- We choose a linear estimator:

$$I_{est} = \sum_{k=1}^{n} \lambda_k I_{meas}(x_k)$$



Unbiased estimator

- The measurements can be decomposed:

$$I_{meas}\left(x_k\right) = \underbrace{\underbrace{a_0 + a_1 x_{east,k} + a_2 x_{north,k}}_{\text{trend}} + r\left(x_k\right)}_{\text{Vertical Ionospheric Delay}} + n\left(x_k\right)$$

Measurement noise

- Assuming this form, an unbiased estimator is such that:

$$G^T \lambda = \begin{bmatrix} 1 \\ x_{east} \\ x_{north} \end{bmatrix} \qquad G = \begin{bmatrix} 1 & x_{east,1} & x_{north,1} \\ \vdots & \vdots & \vdots \\ 1 & x_{east,n} & x_{north,n} \end{bmatrix}$$

Confidence Computation

$$\hat{I}_{IGP} = \mathbf{w}^{\mathrm{T}} \cdot \mathbf{I}_{IPP}$$

Formal error due to ionospheric uncertainty

Undersampled threat term

$$\sigma_{IGP}^2 = R_{irreg}^2 \left[\mathbf{w}^{\mathrm{T}} \cdot \mathbf{C} \cdot \mathbf{w} - 2\mathbf{w}^{\mathrm{T}} \cdot \mathbf{c} + \left(\sigma_{decorr}^{total} \right)^2 \right] + \mathbf{w}^{\mathrm{T}} \cdot \mathbf{M} \cdot \mathbf{w} + \left(\sigma_{decorr}^{undersamp} \right)^2$$

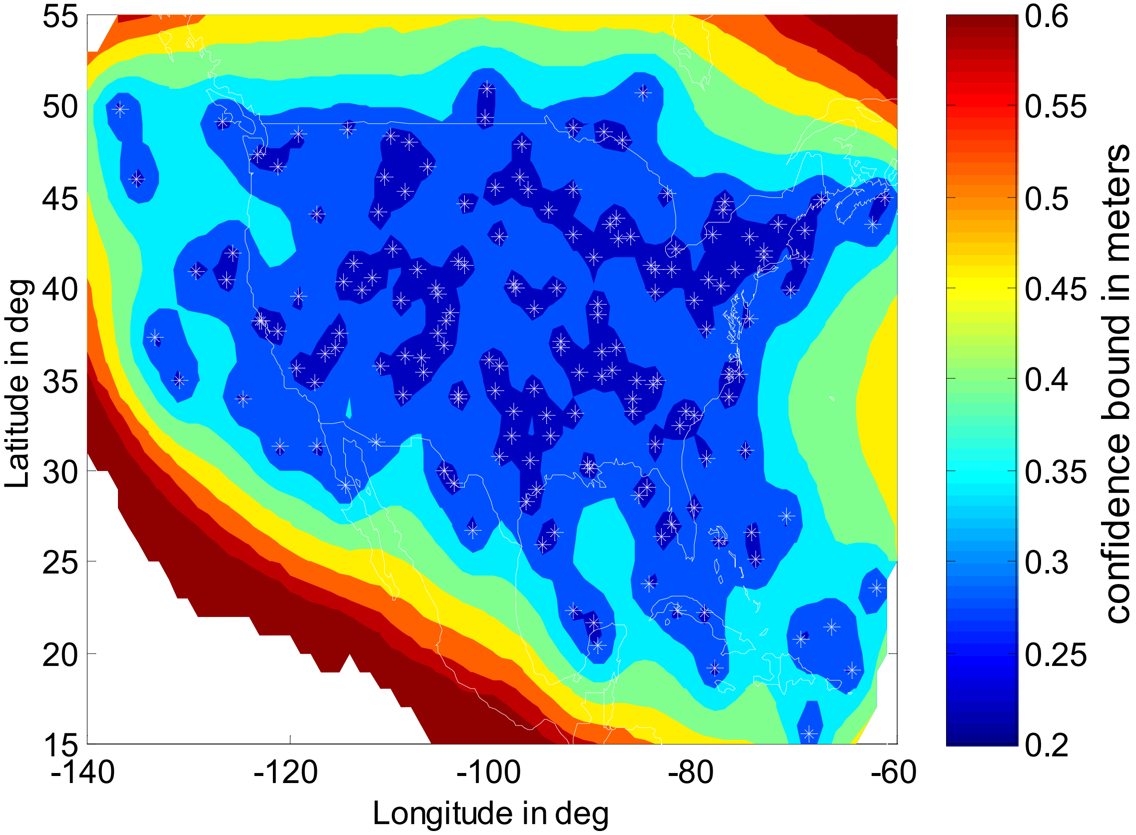
Measure of ionospheric state

$$R_{irreg}^2 = \frac{R_{noise} \chi^2}{\chi_{lowerbound}^2}$$

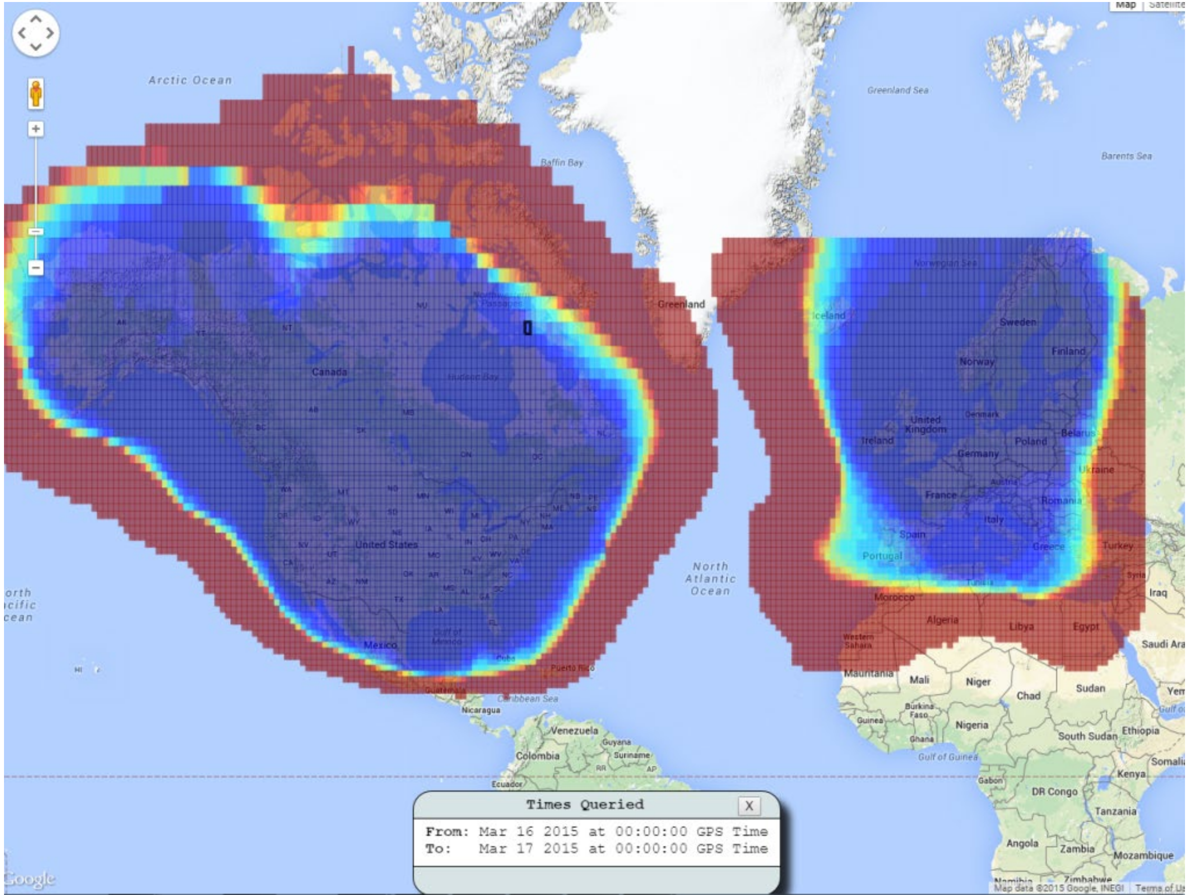
Formal error due to measurement noise

Sparks, L., Blanch, J., Pandya, N., “Kriging as a Means of Improving WAAS Availability,” *Proceedings of the 23rd International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2010)*, Portland, OR, September 2010, pp. 2013-2020.

Kriging variance



March 16, 2015



Times Queried

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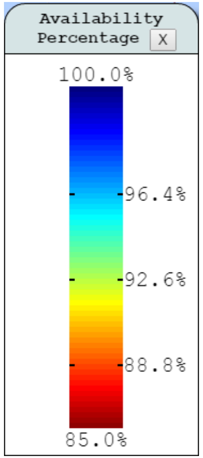
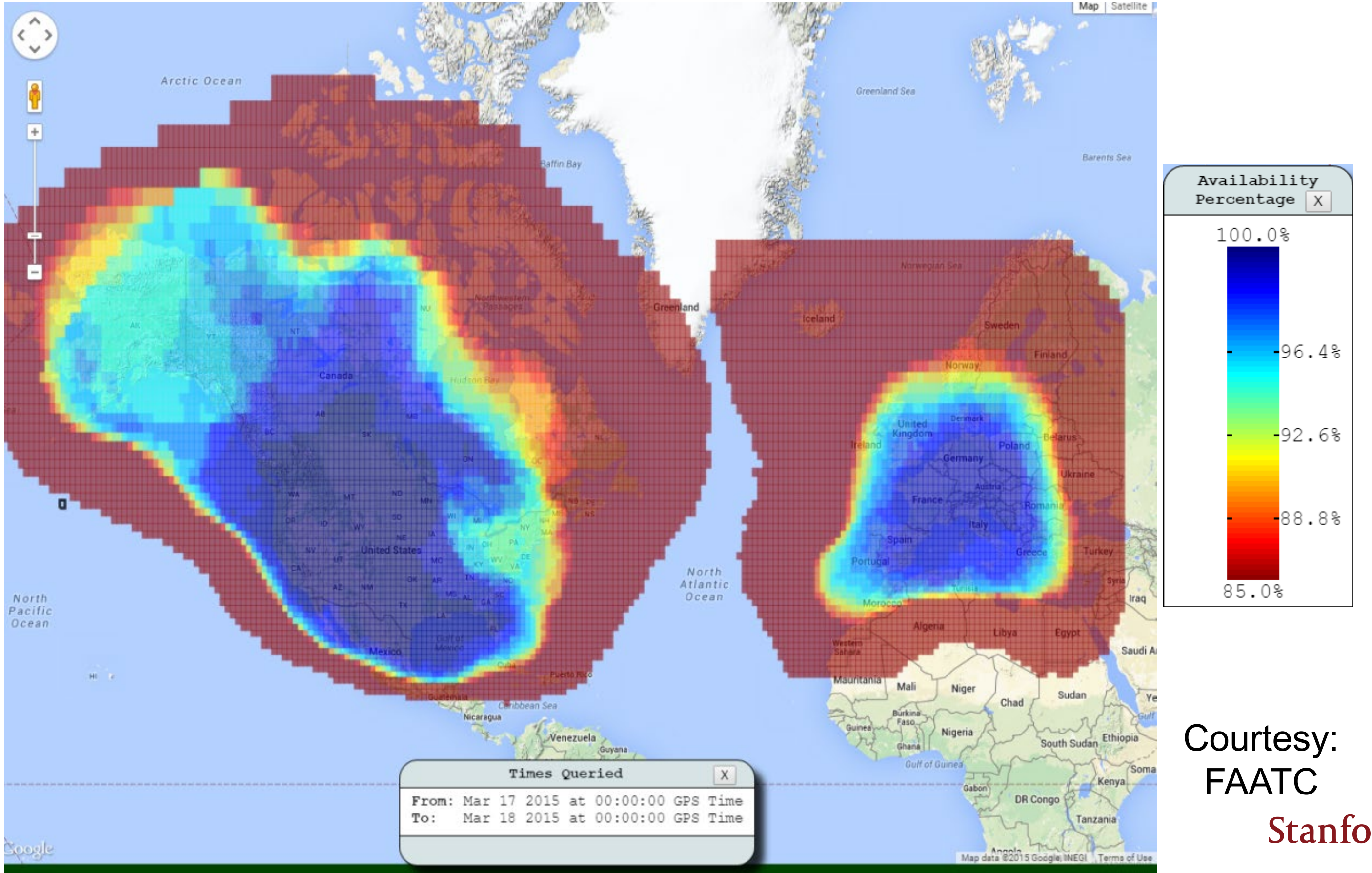
To: Mar 17 2015 at 00:00:00 GPS Time



Courtesy:
FAATC

March 17, 2015



Times Queried

From: Mar 17 2015 at 00:00:00 GPS Time
To: Mar 18 2015 at 00:00:00 GPS Time

Courtesy:
FAATC

GBAS Mitigation of Threats

- Ground station (GS) receiver network monitors and correct errors that originate on the satellites or in the atmosphere
  - Single correction and bound for each satellite
  - Monitoring accuracy limited by the effects multipath, noise, and GS geometry and antenna biases
  - Confidence bounds limited by ionosphere gradients and and orbital errors– GS network may not be able to observe these errors
- Airborne receiver may supplement GS monitoring by performing checks for local ionospheric and/or tropospheric variations
  - Limited by the effects of local multipath, noise, and user antenna bias
- Current single frequency (L1) GBAS is capable of achieving time-to-alert, accuracy, and integrity bounds with high availability for mid-latitude areas
- Dual frequency (L1/L5) GBAS is under development to enable high-availability operation in low-latitude areas

SBAS Mitigation of Threats

- Ground receiver network monitors and corrects errors that originate on the satellites and in the ionosphere
  - Satellite clock and ephemeris errors separately corrected
  - A grid of ionospheric of corrections is provided
  - Confidence bounds sent for each satellite and each grid point
  - Monitoring accuracy limited by the effects multipath, noise, and reference station antenna bias
  - Confidence bounds mainly limited by ionospheric disturbances
- Airborne receiver must limit the effects of local multipath, noise, and user antenna bias
- Capable of covering continental regions and simultaneously thousands of aircraft approach procedures in mid-latitudes
- High-availability extension to lower-latitudes will require dual-frequency airborne receivers to obviate iono delay estimation

Conclusions

- The Global Positioning System (GPS), and all other core constellations, require augmentation in order to meet the strict requirements for the guidance of aircraft
- GPS L1 signals widely in use for aircraft navigation
- The ionosphere is one of the most challenging error sources
  - Disturbances are difficult to predict and dramatically increase the magnitude of the ranging errors
  - Require extensive data sets to examine full range of possible behavior
  - Methods exist to achieve safe vertical guidance of aircraft
- Dual-frequency multi-constellation receivers will improve GBAS & SBAS performance & availability in the future