

# Ionospheric Effects on GNSS Augmentation Systems

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African Capacity Building Workshop on Space Weather Effects on GNSS



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## 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]

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## 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

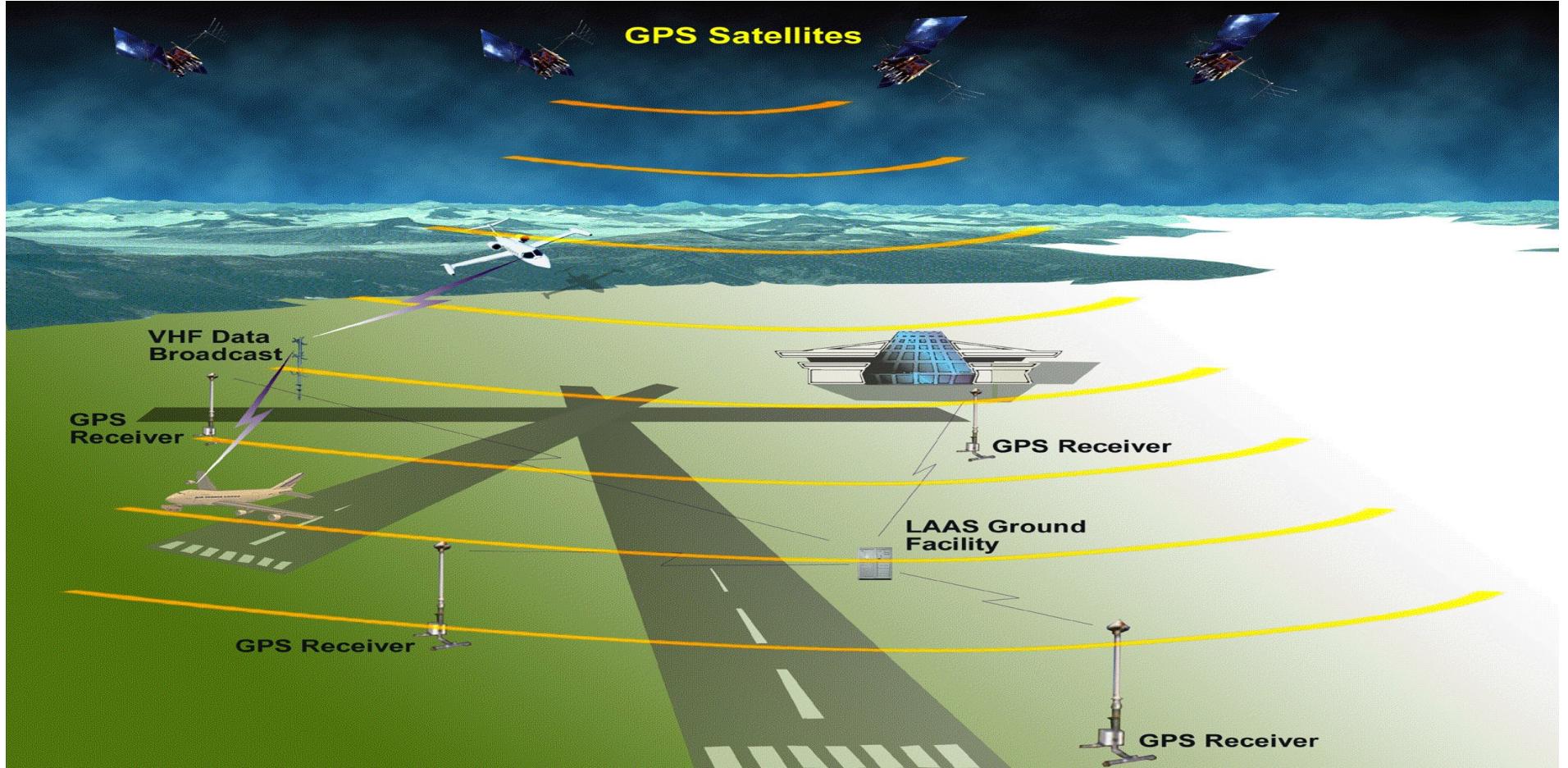


## 200' Decision Height (DH) Requirements

- **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



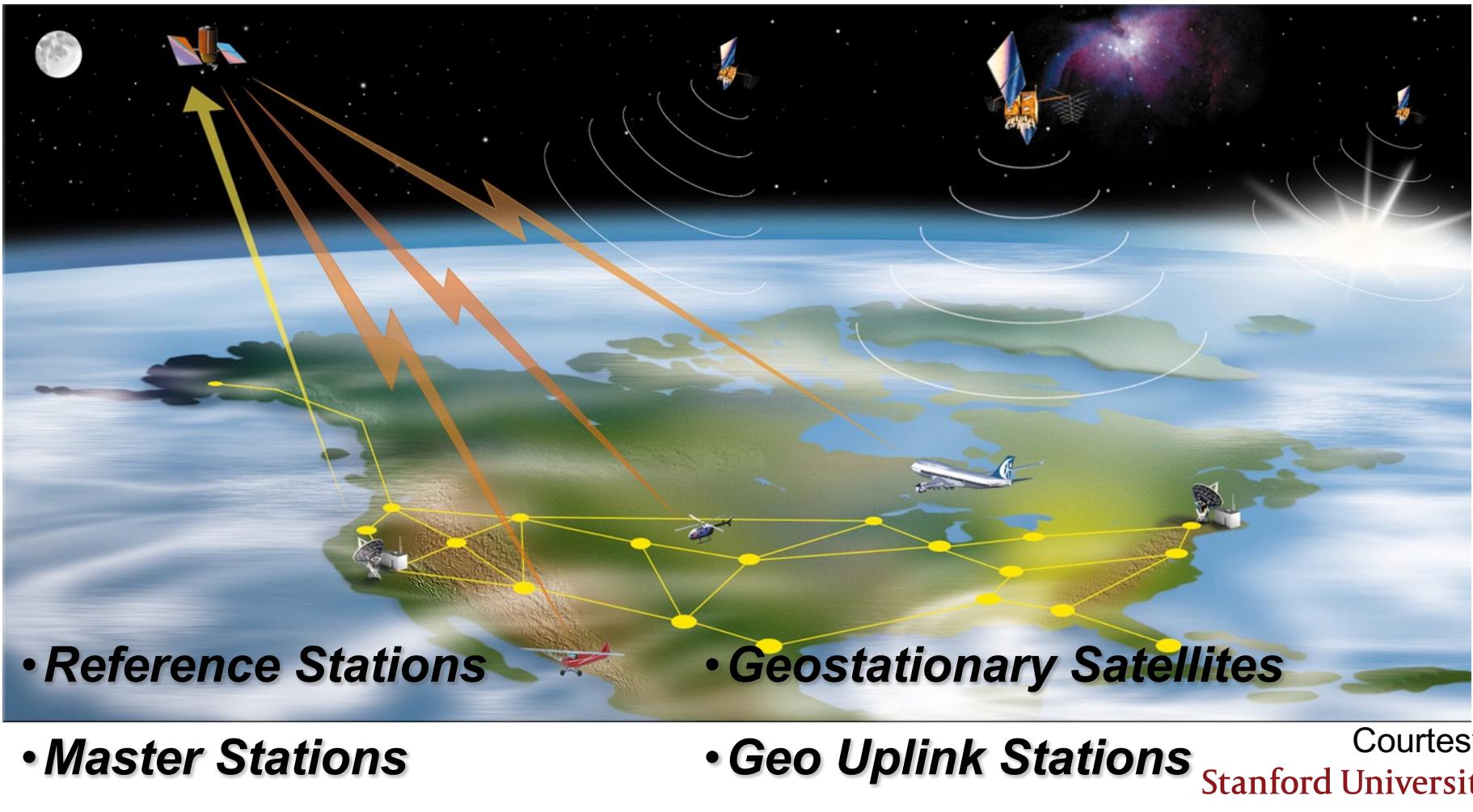
# Ground Based Augmentation System (GBAS)



Courtesy: FAA

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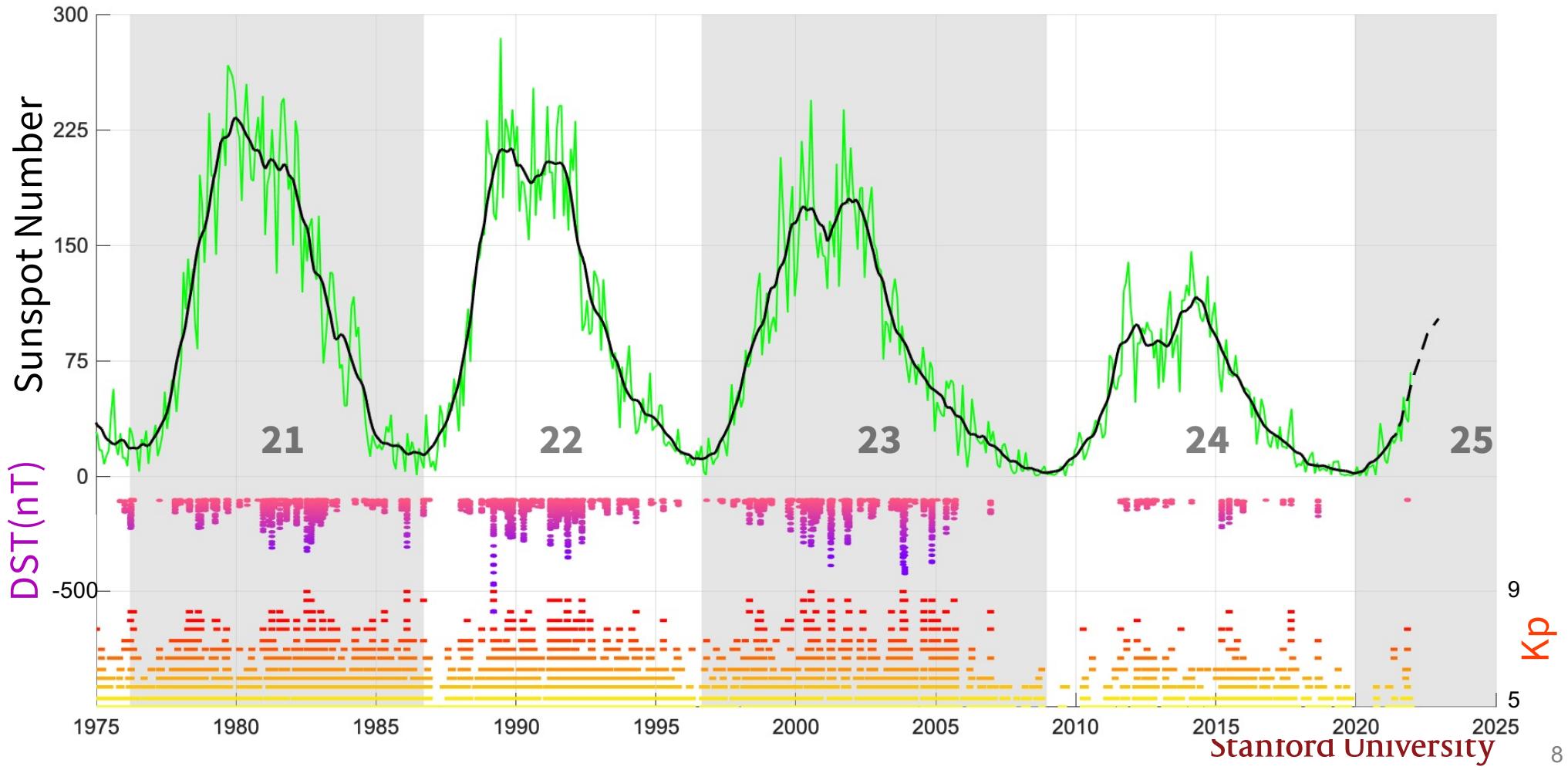
# Satellite Based Augmentation System (SBAS)



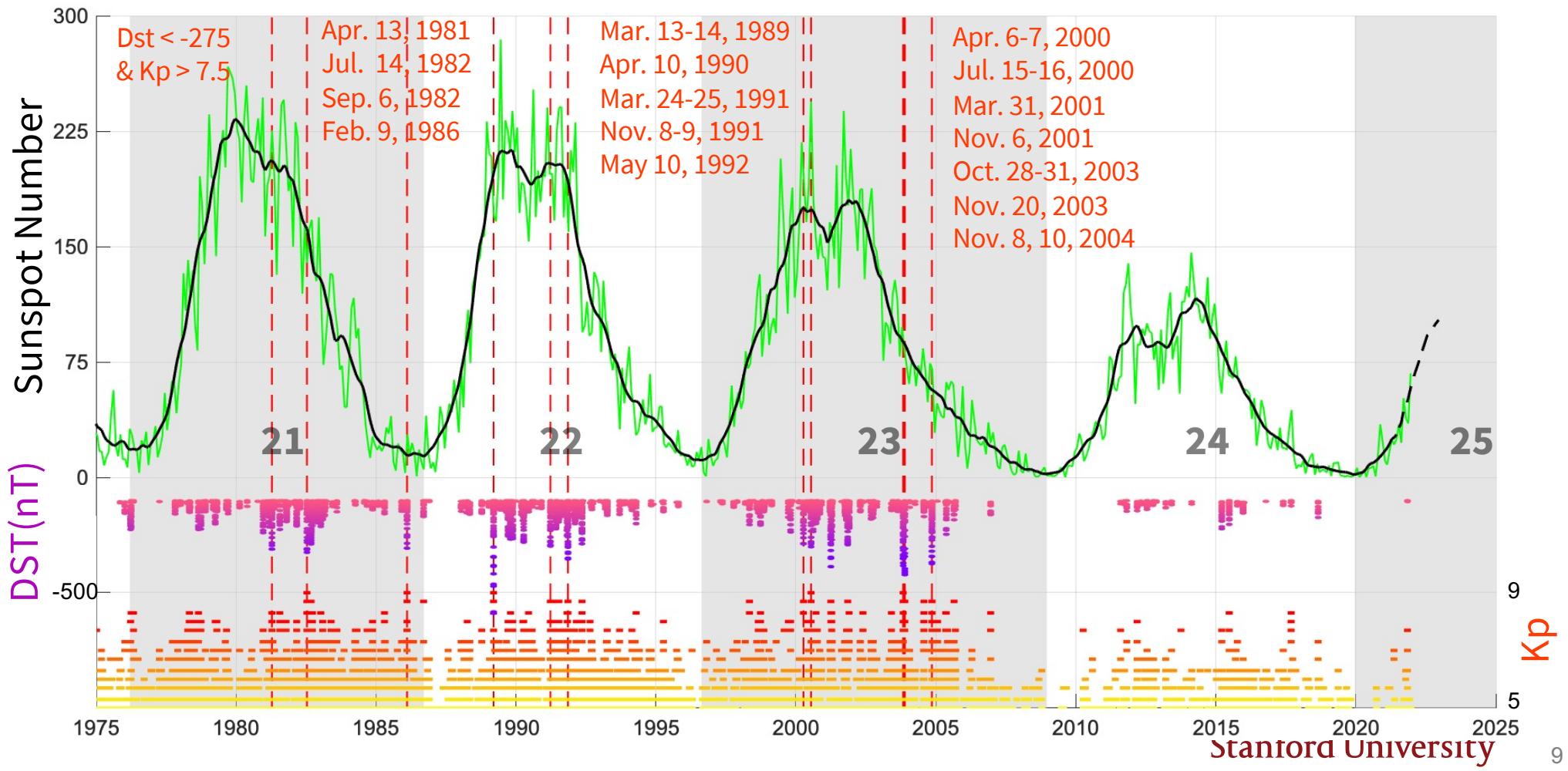
# Ionospheric Related Threats to Augmentation Systems

- 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 the system
  - › 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

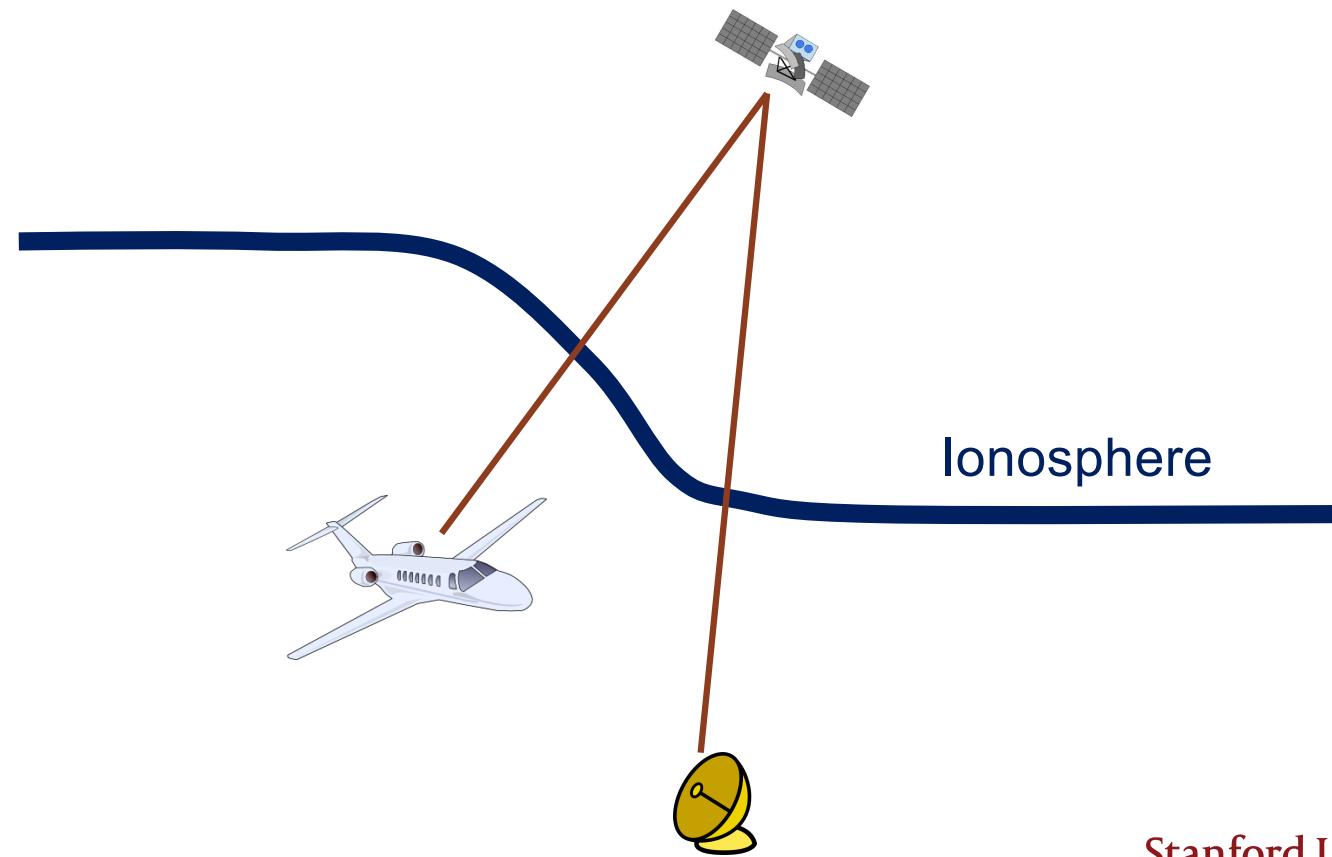
# 11 Year Solar Cycle



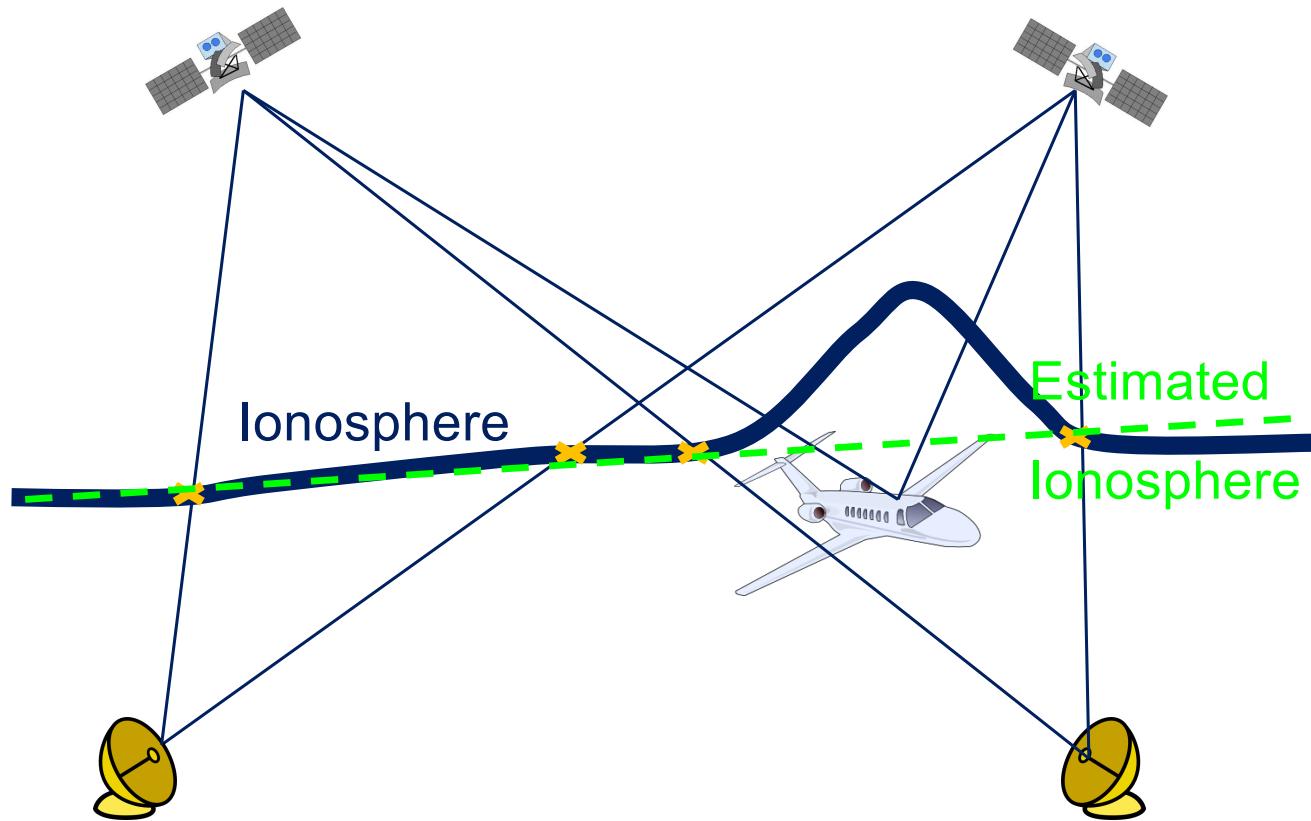
# Extreme Ionospheric Storms



# GBAS: Gradient Threat

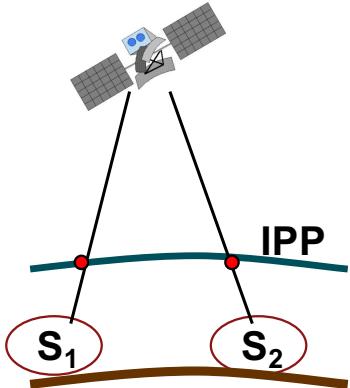


# SBAS: Undersampled Threat



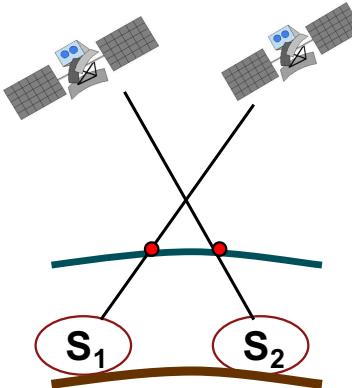
# Estimation of Ionospheric Gradients

Station Pair  
Method



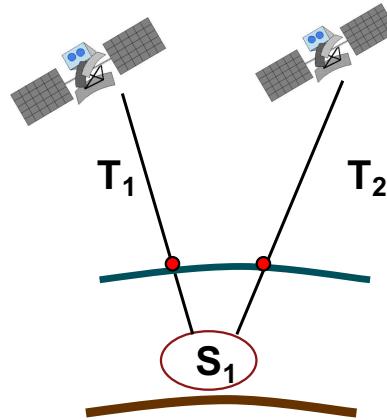
- Long baselines
- Free from satellite IFB calibration error

Mixed Pair  
Method



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

Time Step  
Method

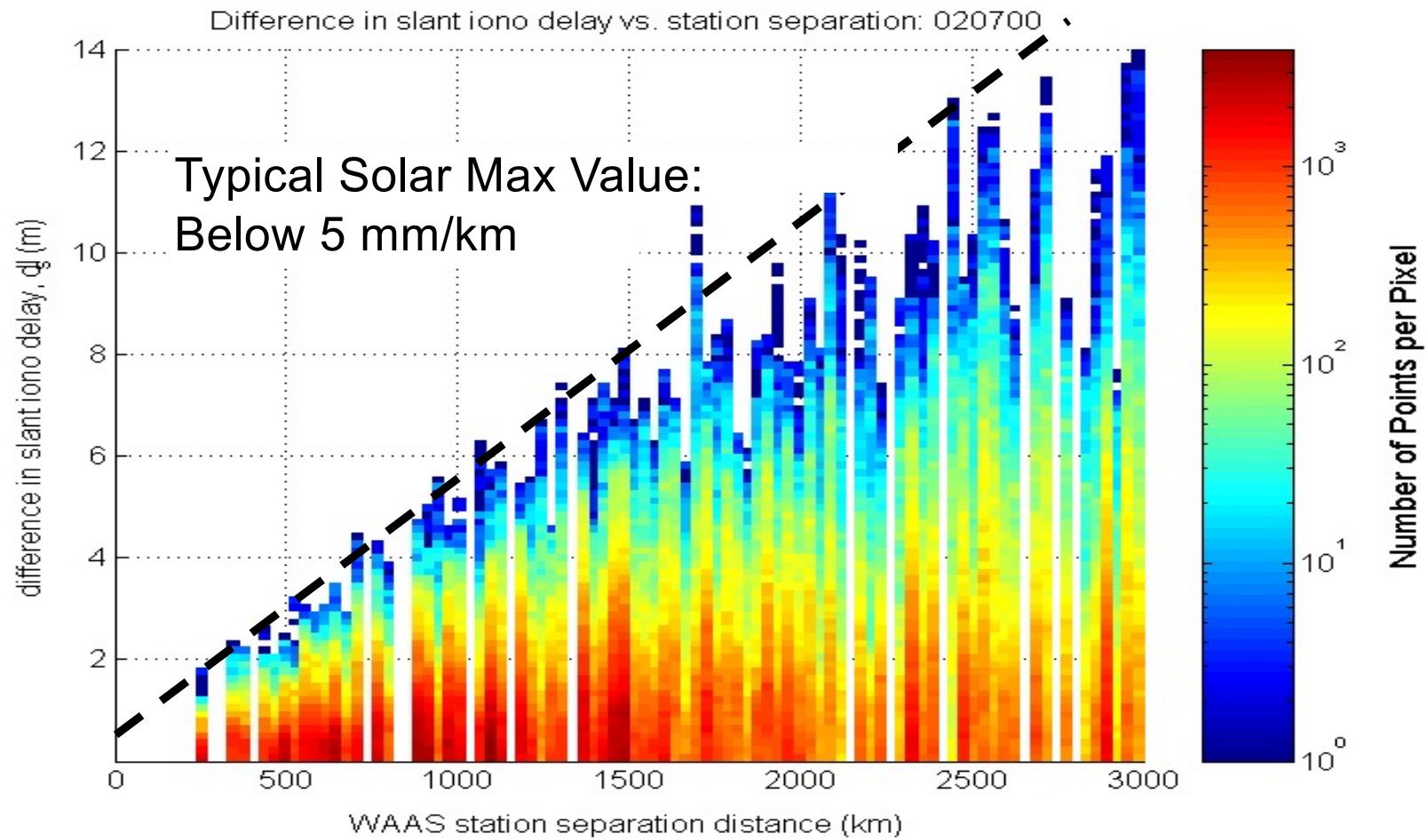


- Short baselines
- Free from IFB calibration error
- Corrupted by iono. temporal gradients

Slide  
Courtesy  
Jiyun Lee

Slide  
Courtesy  
Seebany  
Datta-Barua

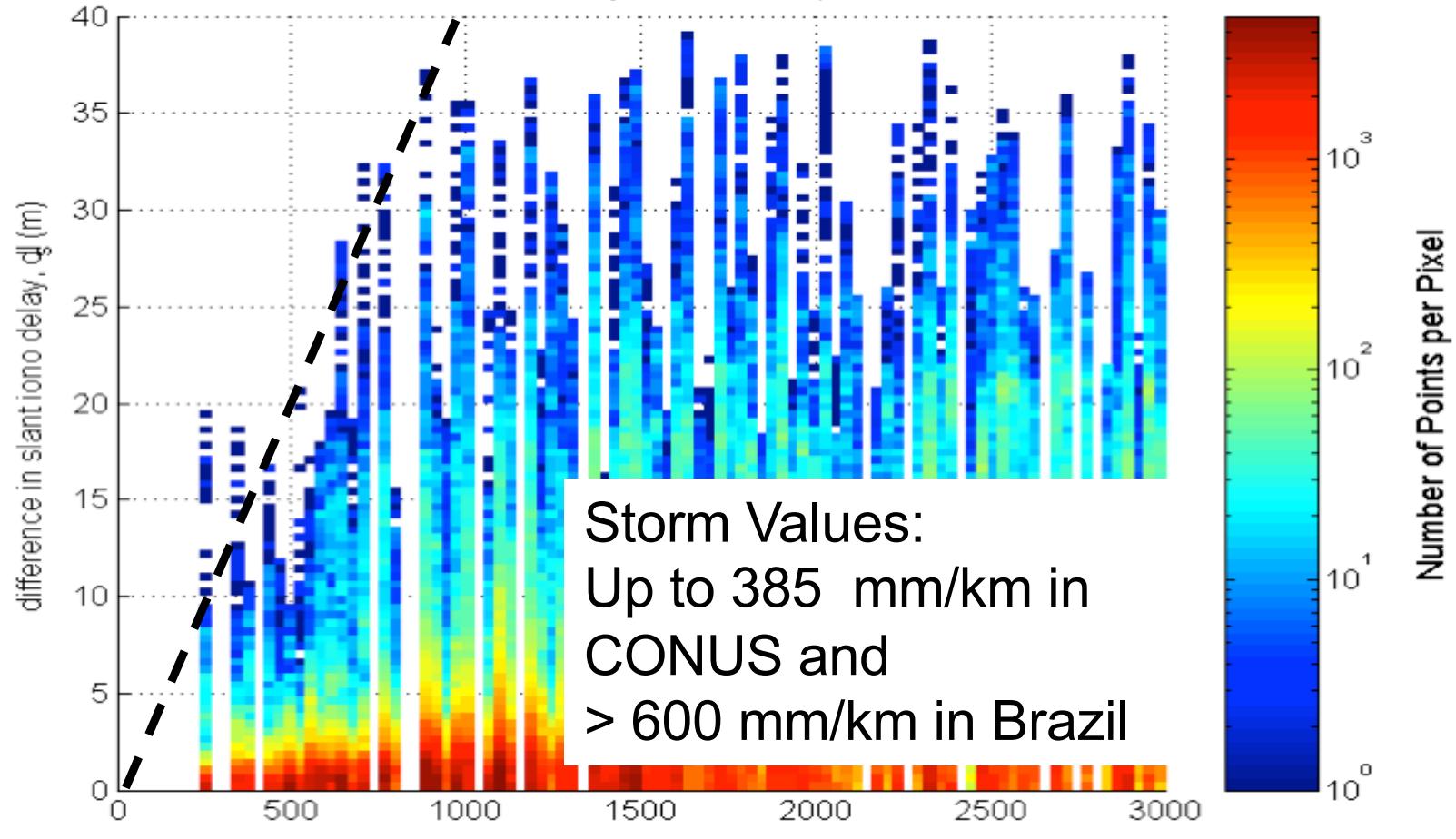
# Nominal Day Spatial Gradients Between WAAS Stations



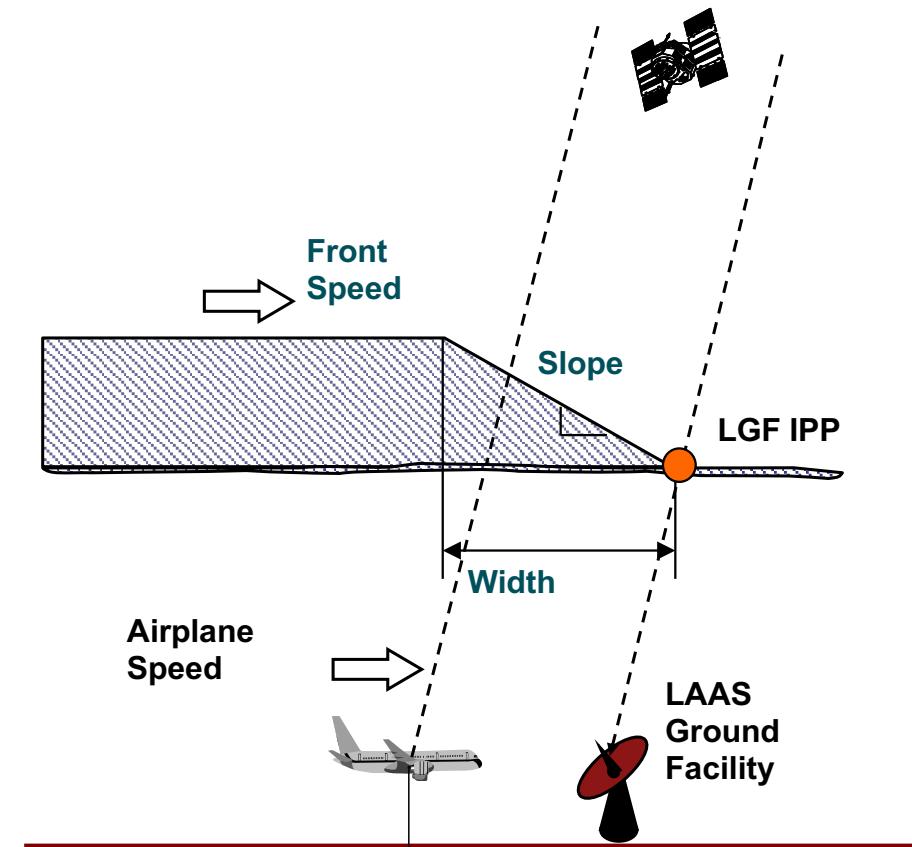
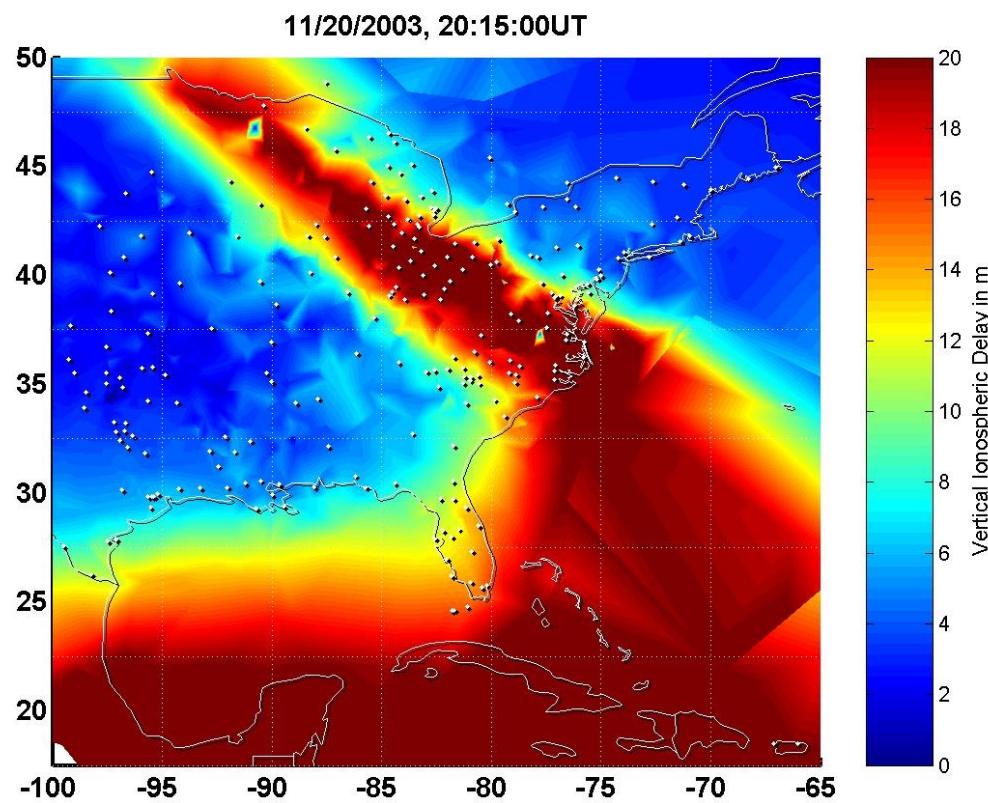
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# Spatial Gradients During a Disturbed Day

Difference in slant iono delay vs. station separation: 060400

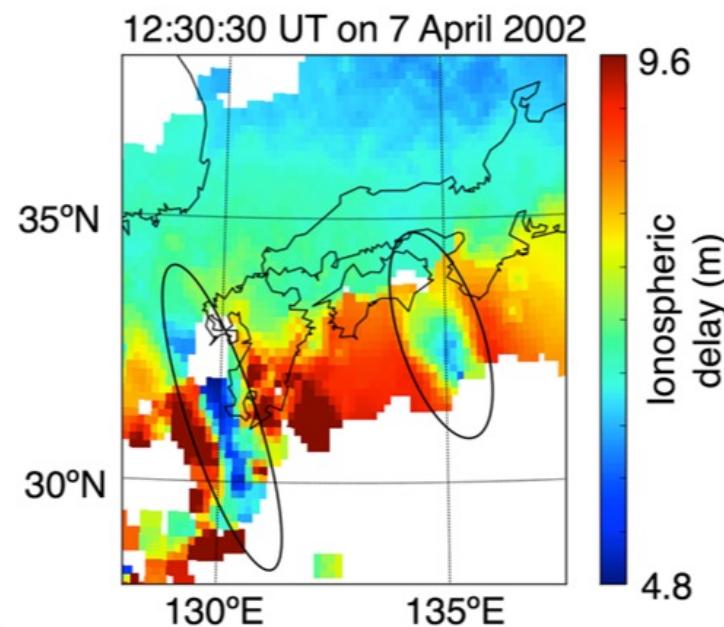
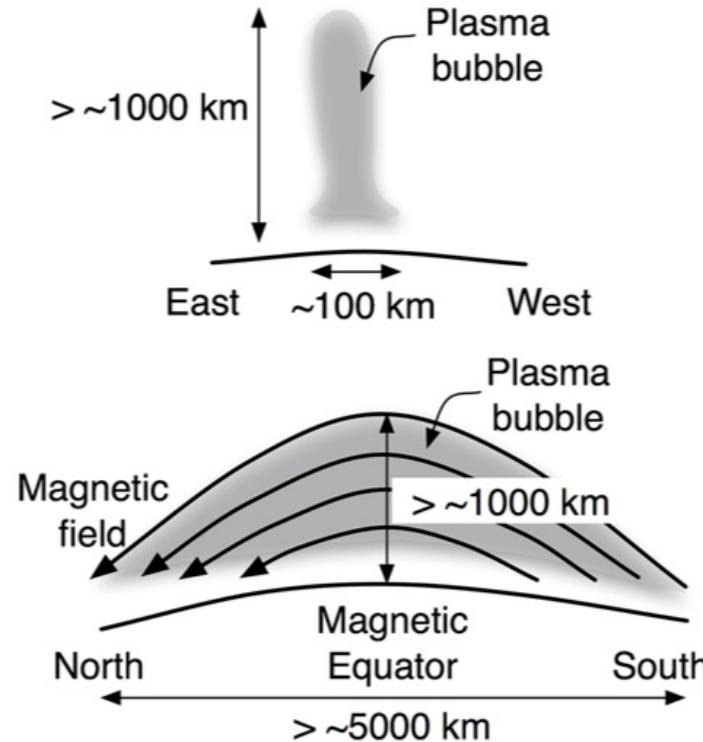


# GBAS Threat Model



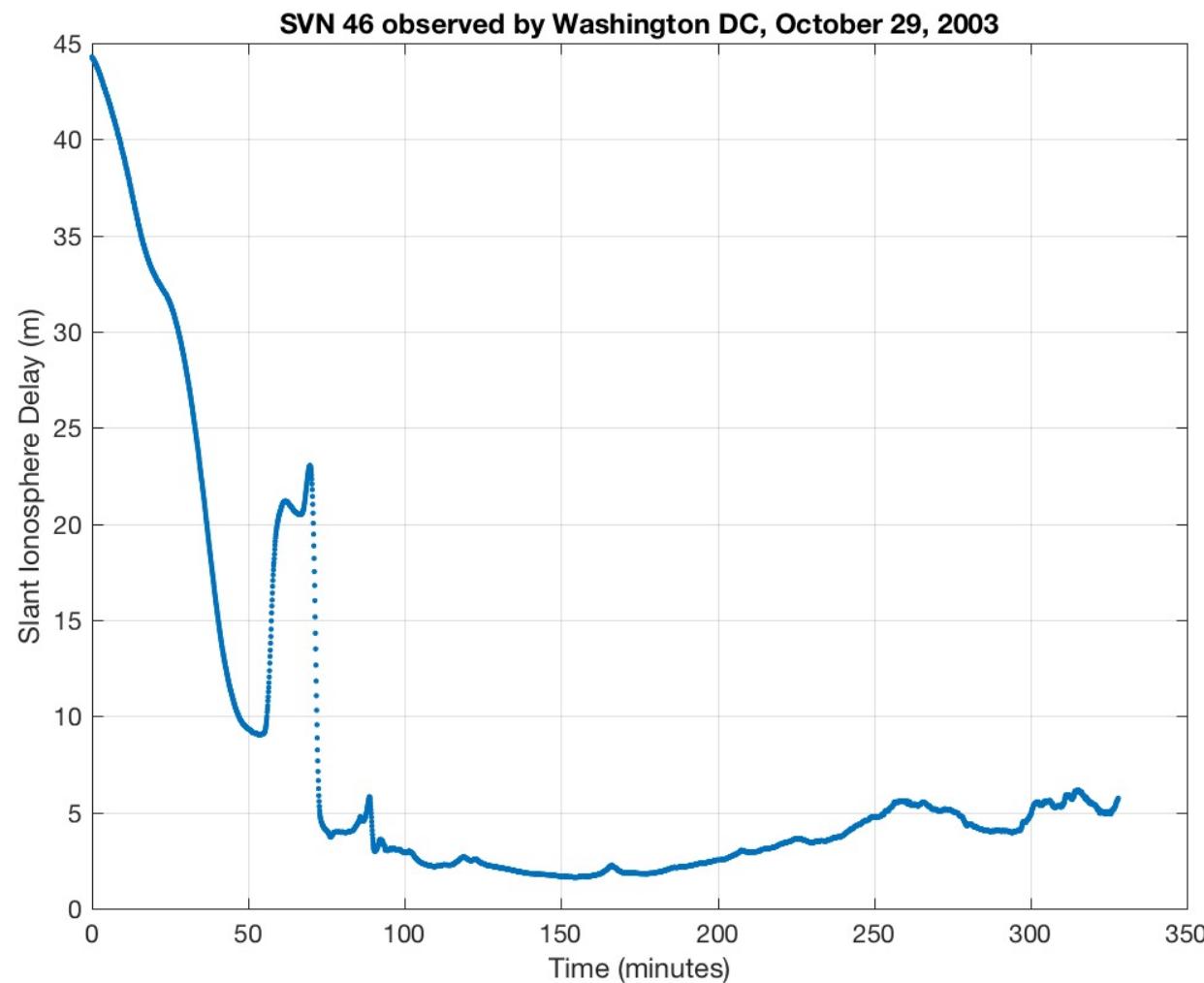
# Characteristics of Plasma Bubble

- 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].



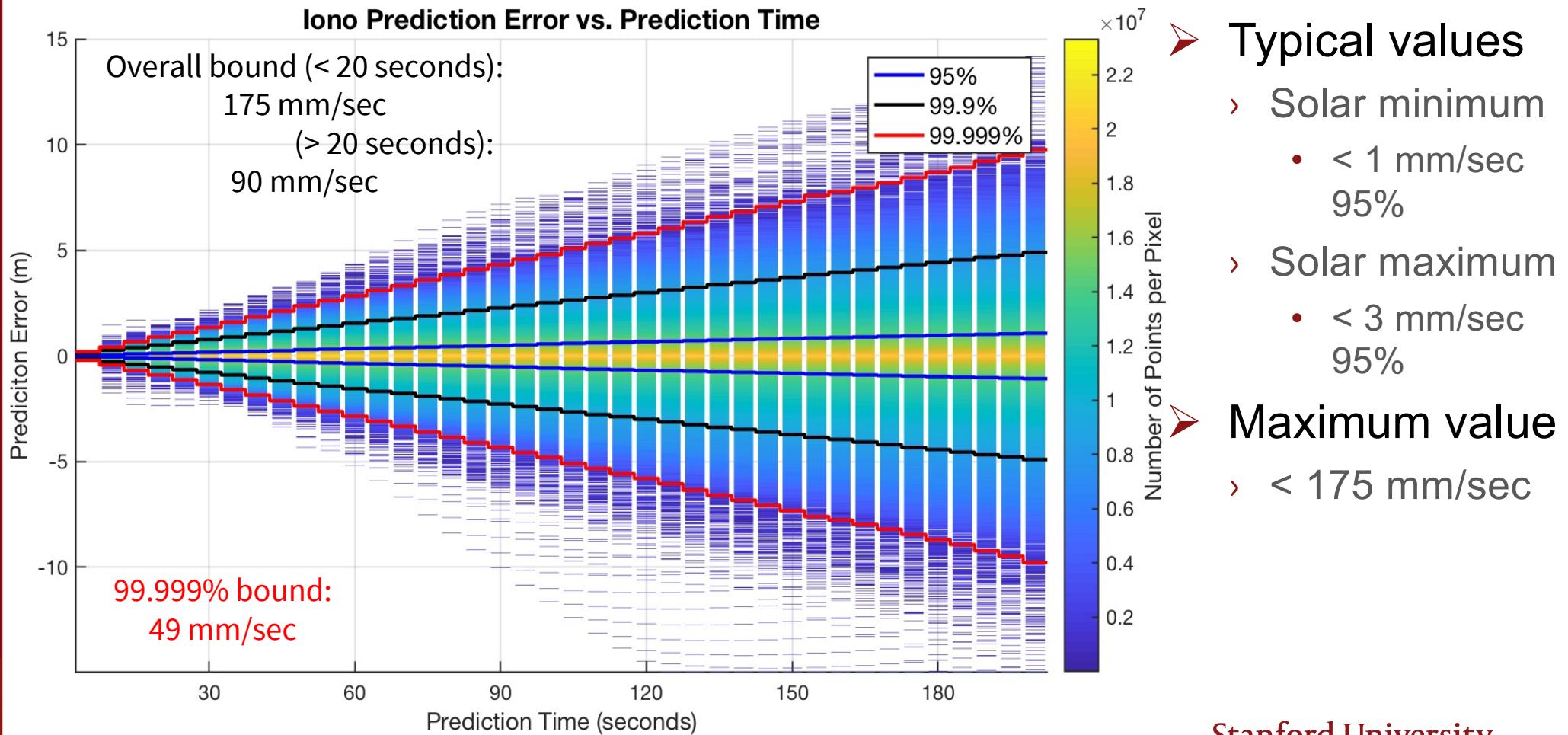
(Saito et al., 2009)

# Worst Track

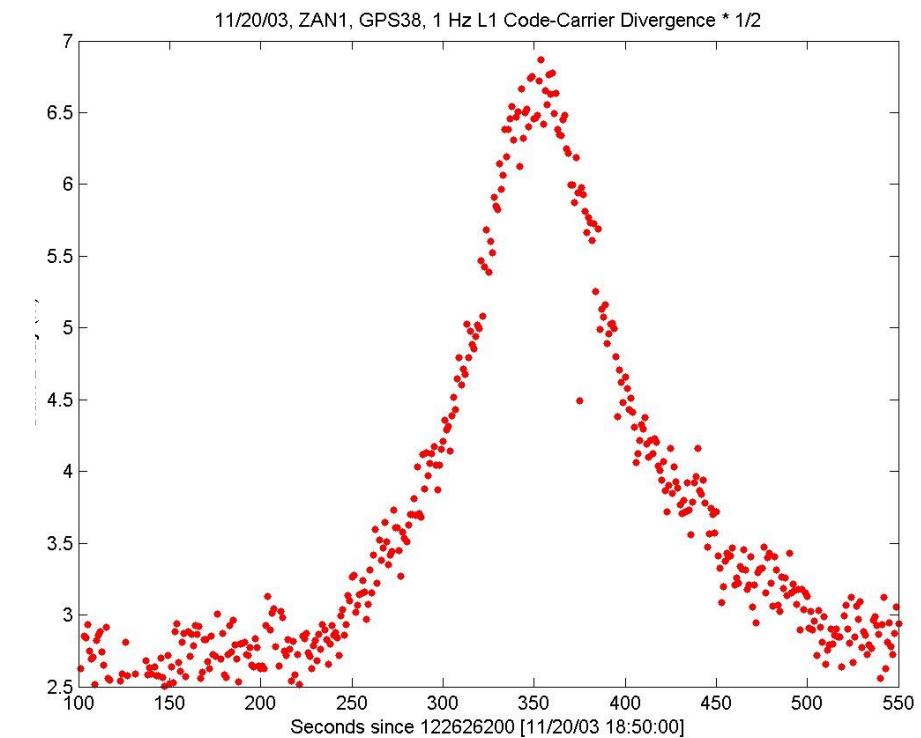
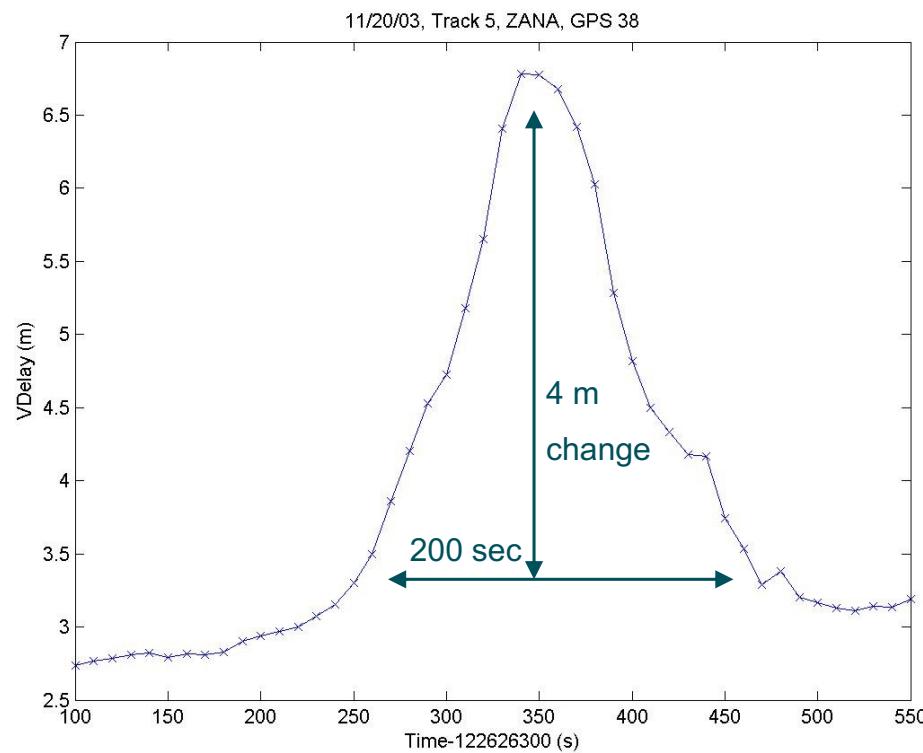


- October 29, 2003
  - › During a severe ionospheric storm
- Observed from Washington DC to PRN 11

# Error Growth



# Disturbance in Polar Region

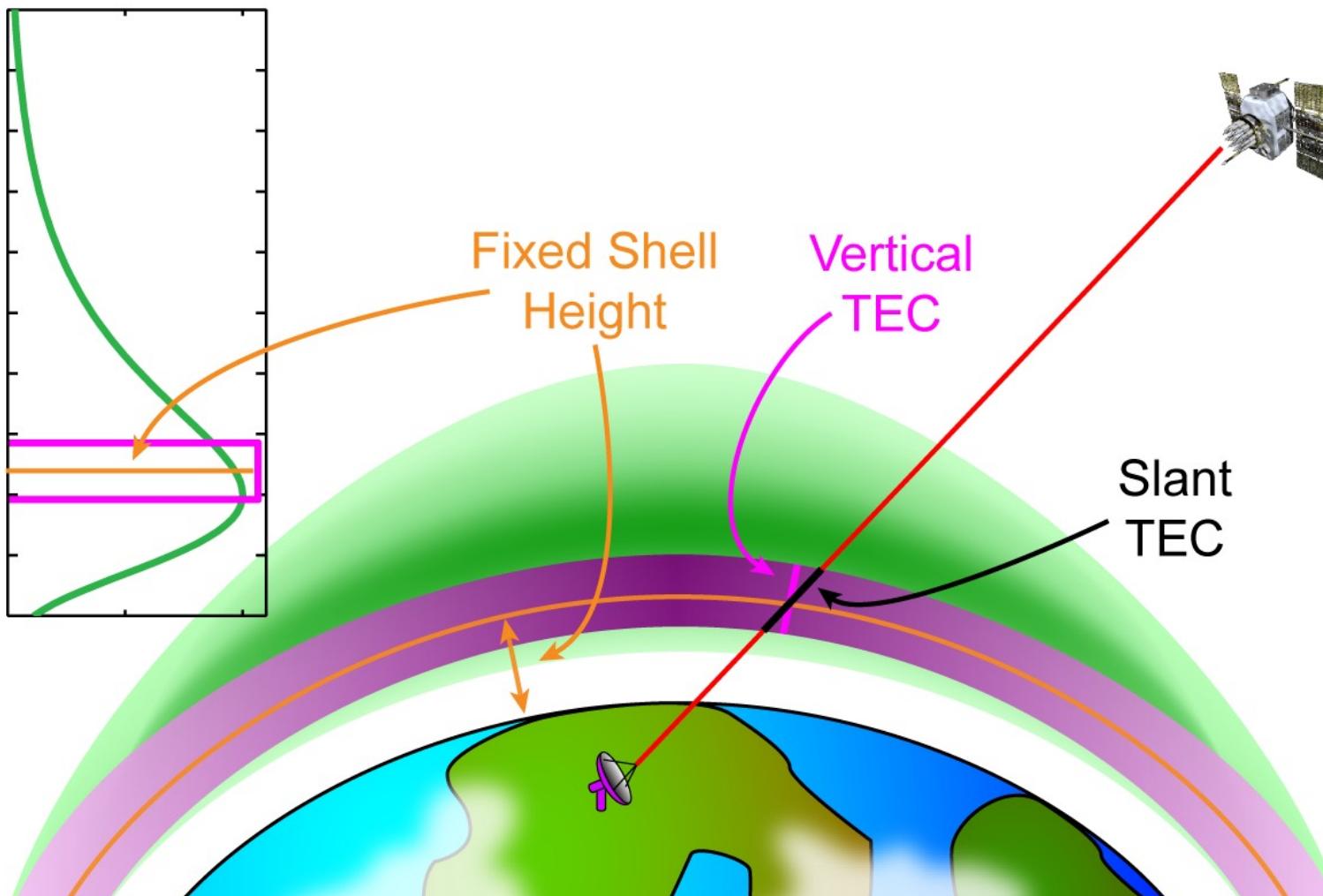


## Ionospheric Delay Threats Summary

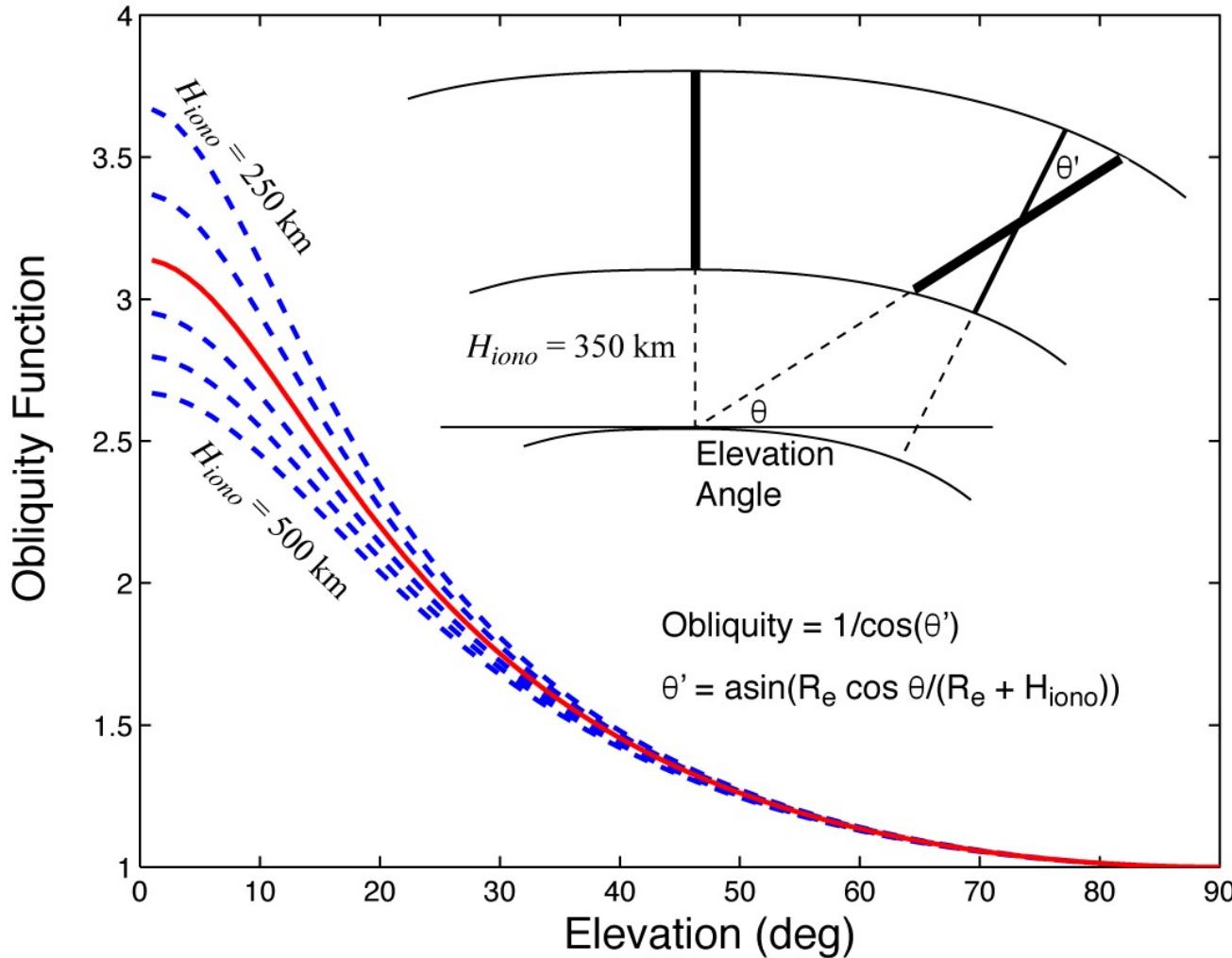
- Spatial gradients nominally below 4 mm/km
  - › Extreme values up to ~400 mm/km in disturbed mid-latitude conditions
  - › Extreme values greater than 500 mm/km observed in equatorial regions
- Temporal gradients nominally below 1 mm/sec
  - › Temporal gradients up to 175 mm/sec in disturbed mid-latitude conditions
- Localized variations observed after storm events
  - › ~10 m vertical delay difference over ~ 200 km
  - › Otherwise surrounded by smooth ionosphere



## Thin Shell Model



# Obliquity Factor



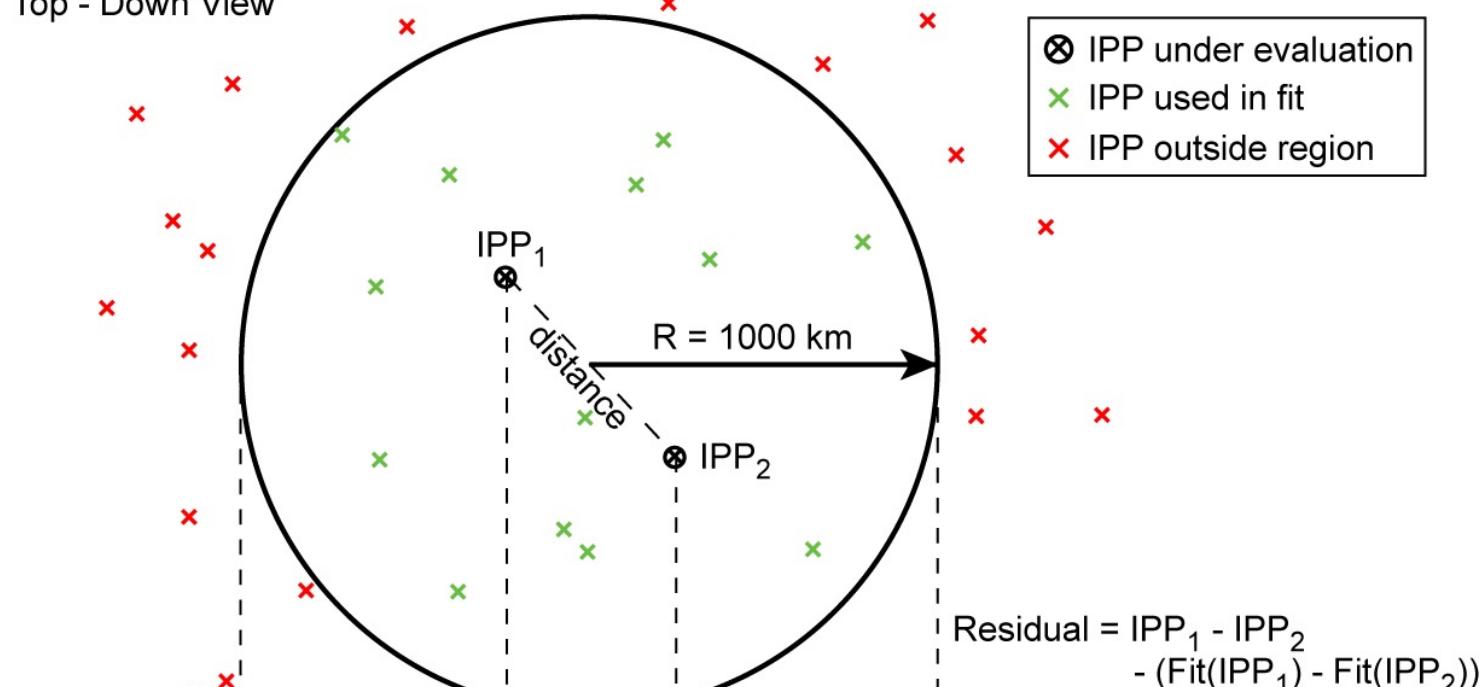
# Spatial Decorrelation Estimation

- 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

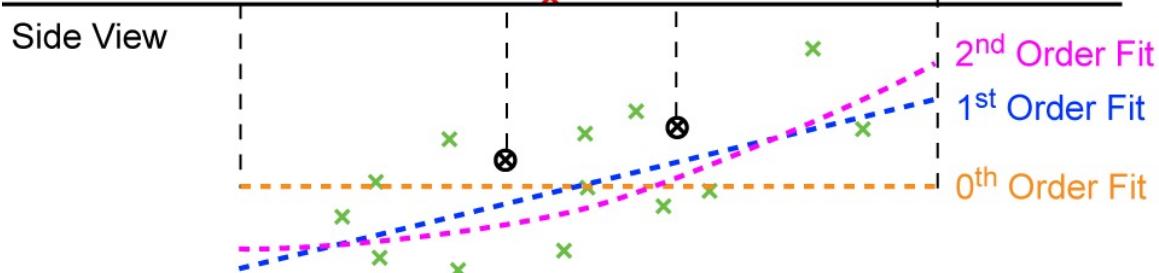


# Spatial Correlation Estimation Process

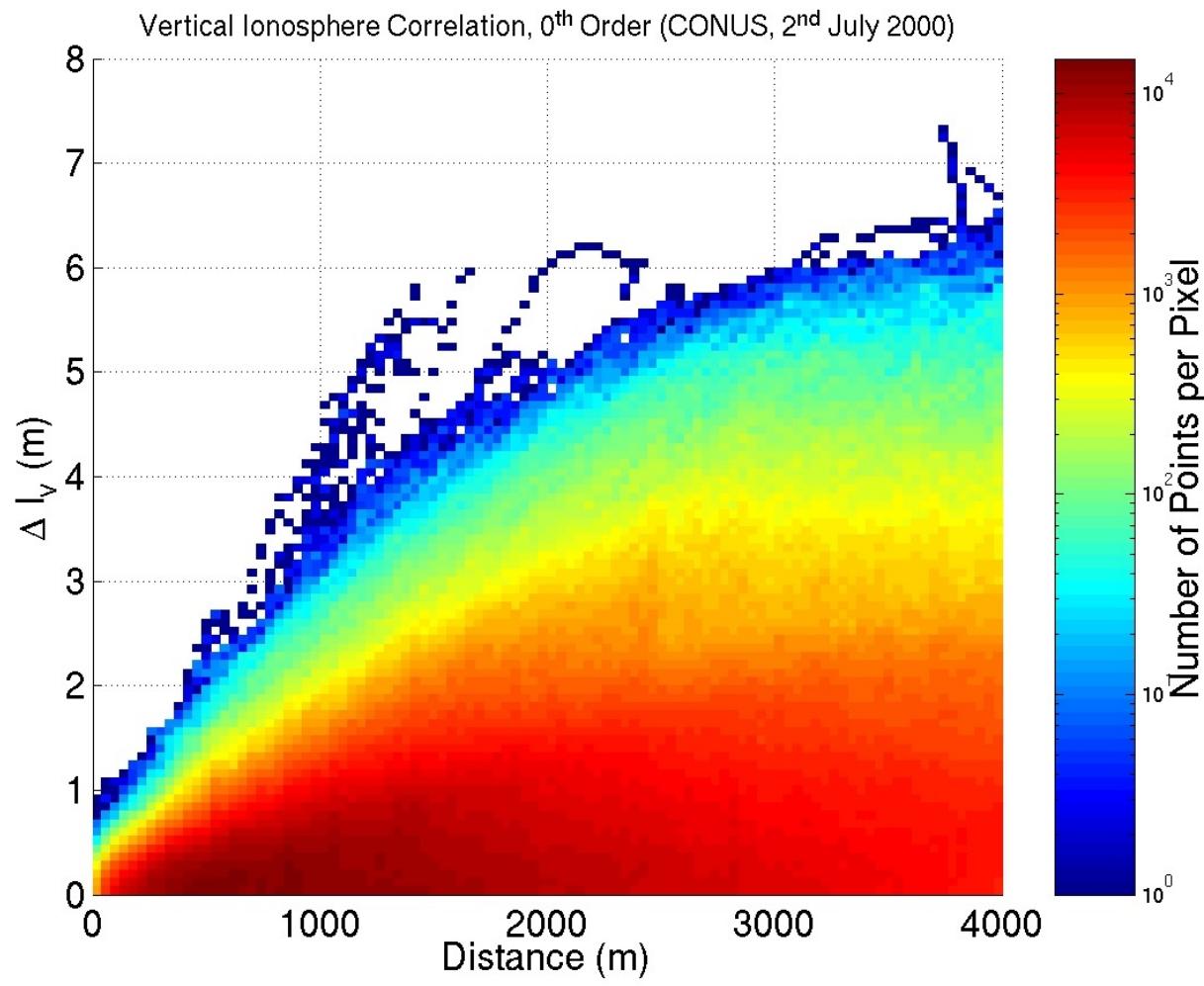
Top - Down View



Side View



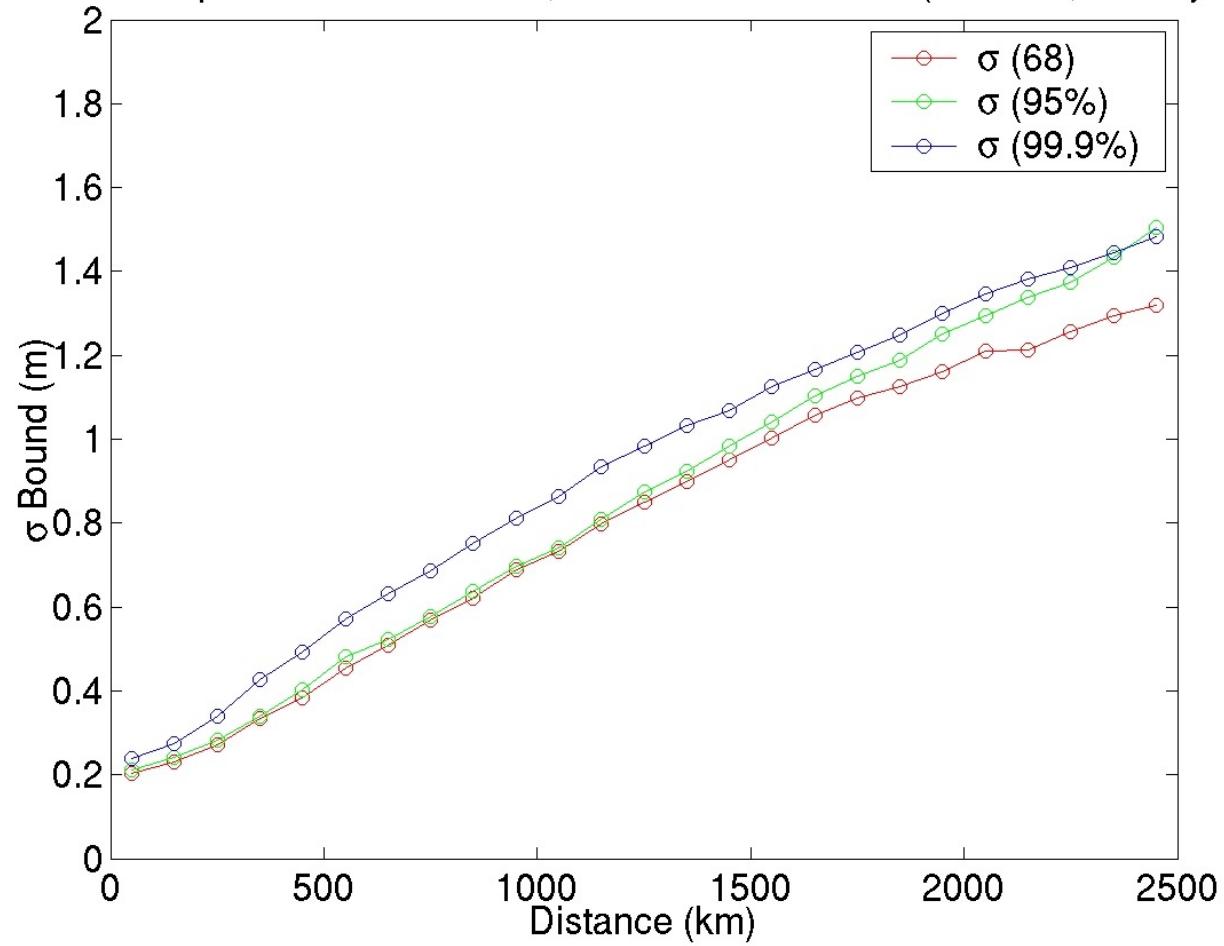
# Ionospheric Decorrelation (0<sup>th</sup> Order)



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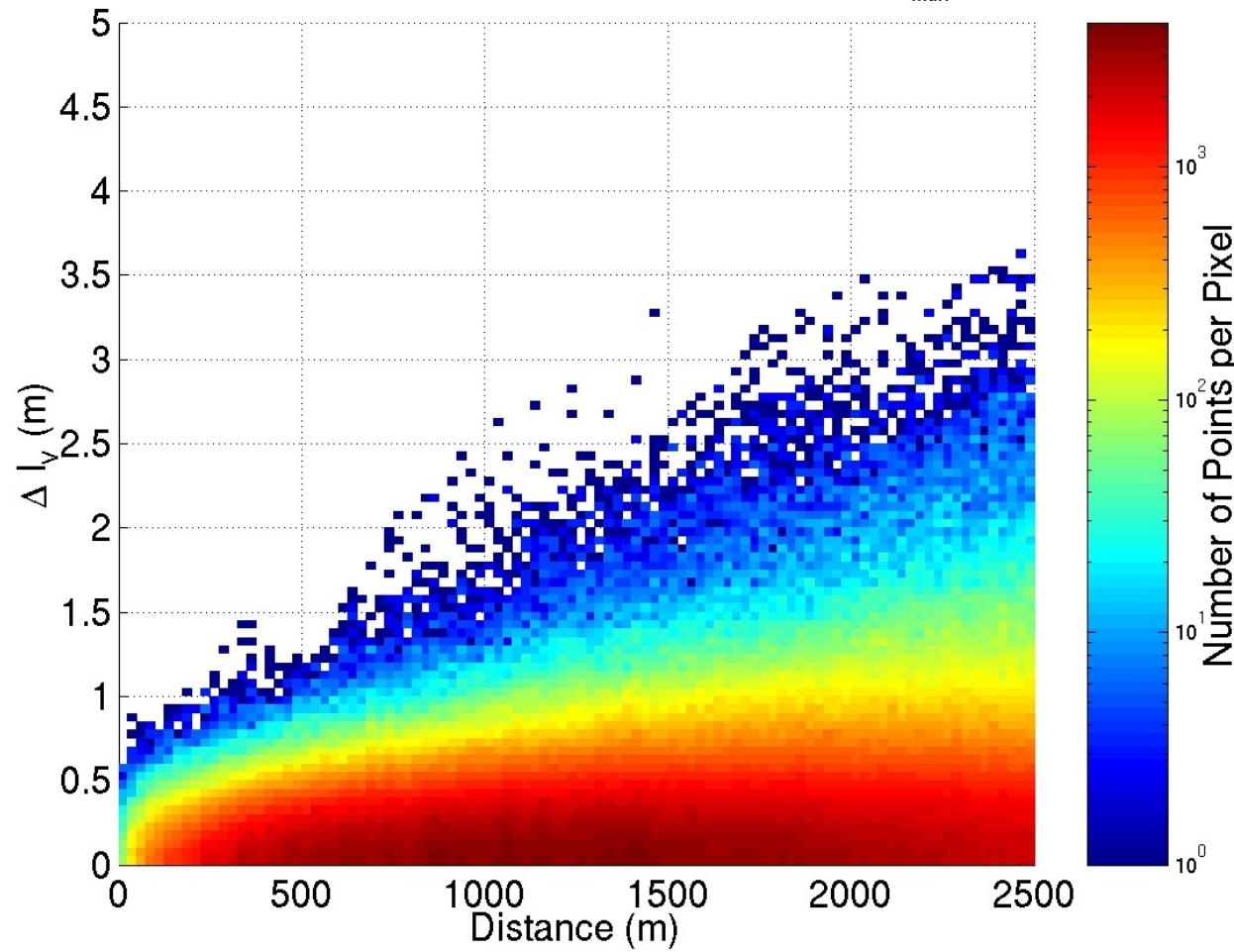
# Ionospheric Decorrelation Function (0<sup>th</sup> Order)

Vertical Ionosphere Containment  $\sigma$ , 0<sup>th</sup> Order Correlation (CONUS, 2<sup>nd</sup> July 2000)



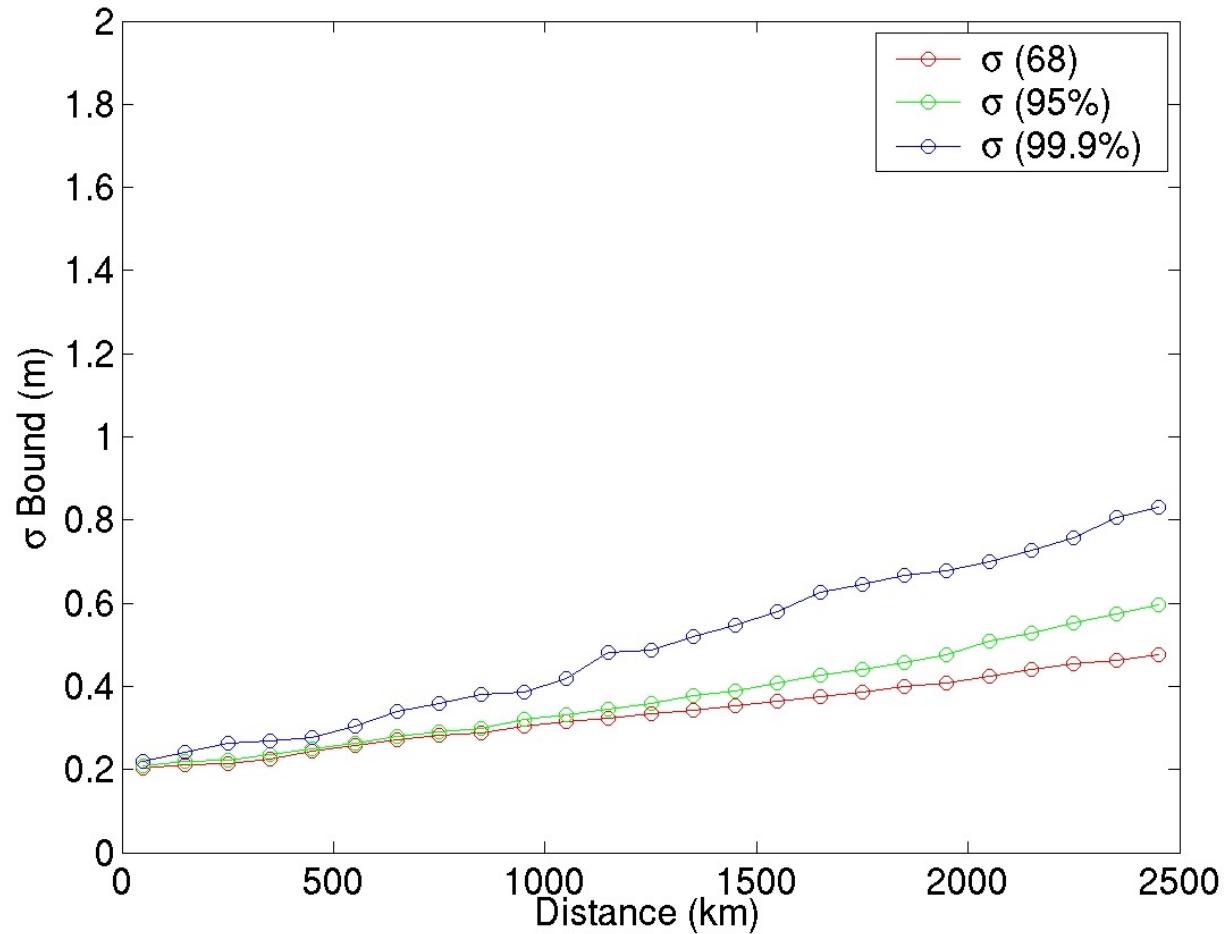
# Ionospheric Decorrelation About a Planar Fit (1<sup>st</sup> Order)

Vertical Ionosphere Correlation, 1<sup>st</sup> Order (CONUS, 2<sup>nd</sup> July 2000,  $R_{\max} = 1500\text{km}$ )



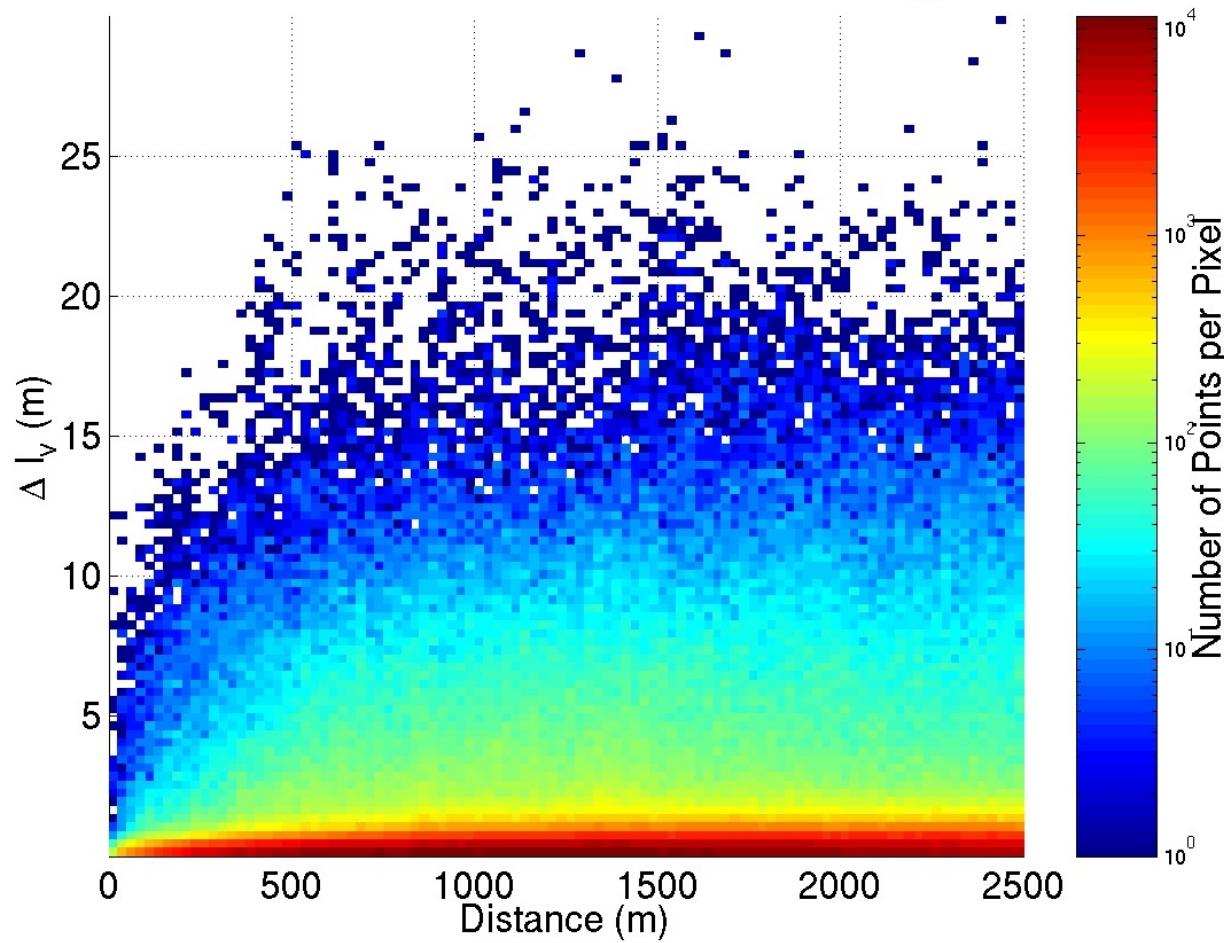
# Ionospheric Decorrelation Function (1<sup>st</sup> Order)

Vertical Ionosphere Containment  $\sigma$ , 1<sup>st</sup> Order Correlation (CONUS, 2<sup>nd</sup> July 2000)



# Disturbed Ionosphere

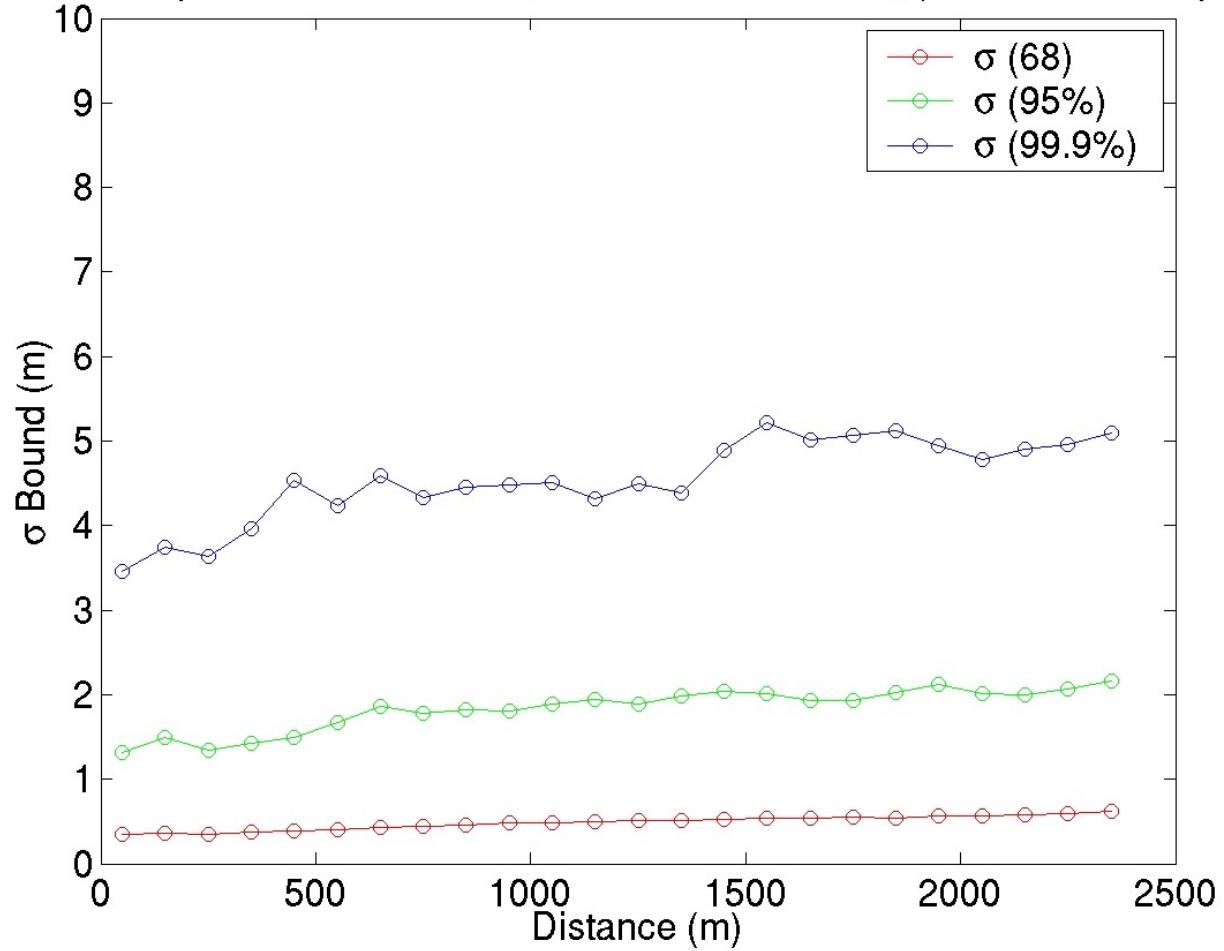
Vertical Ionosphere Correlation, 1<sup>st</sup> Order (CONUS, 15<sup>th</sup> July 2000,  $R_{\max} = 1500\text{km}$ )



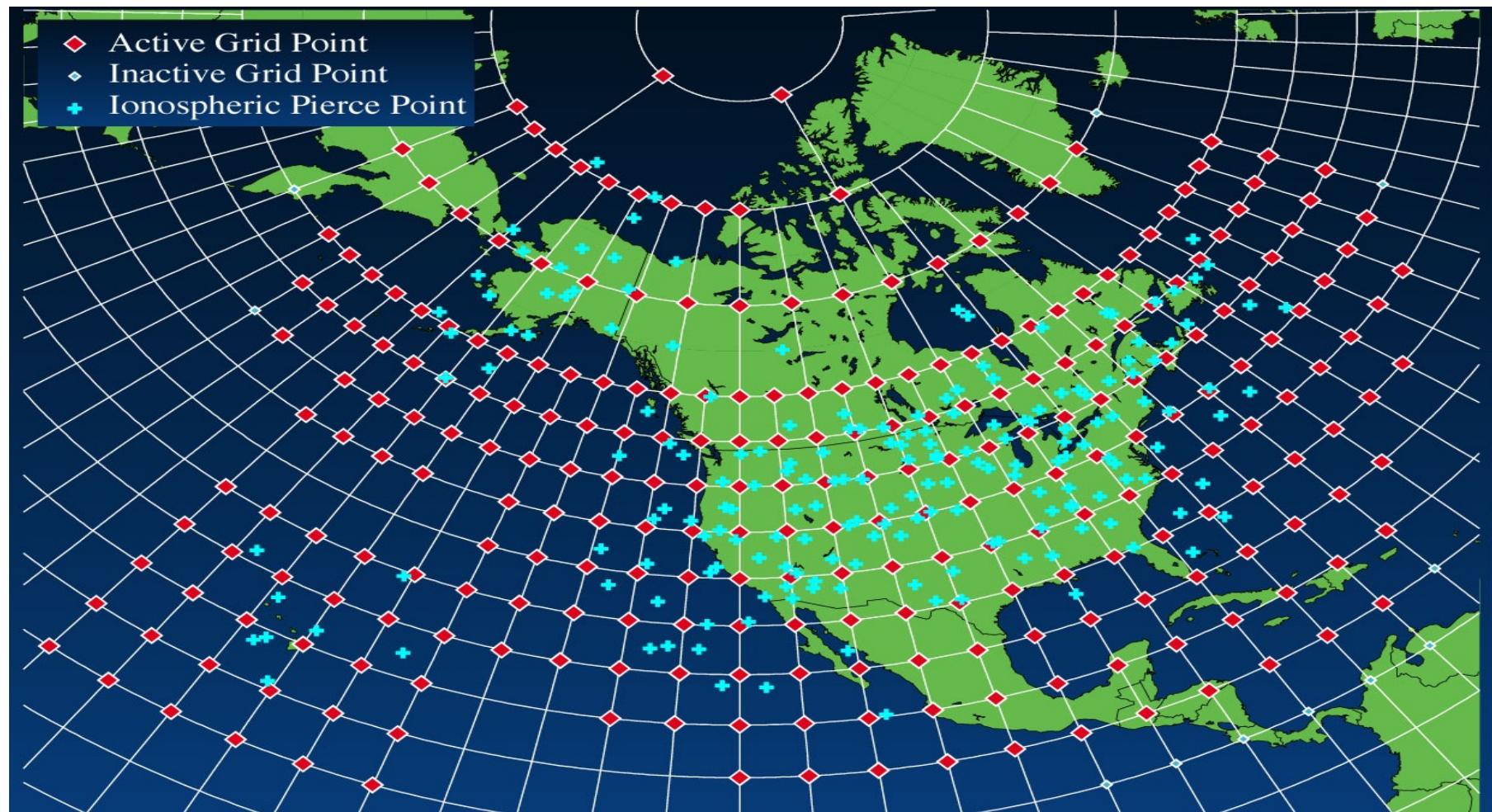
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Vertical Ionosphere Containment  $\sigma$ , 1<sup>st</sup> Order Correlation, (CONUS 15<sup>th</sup> July 2000)

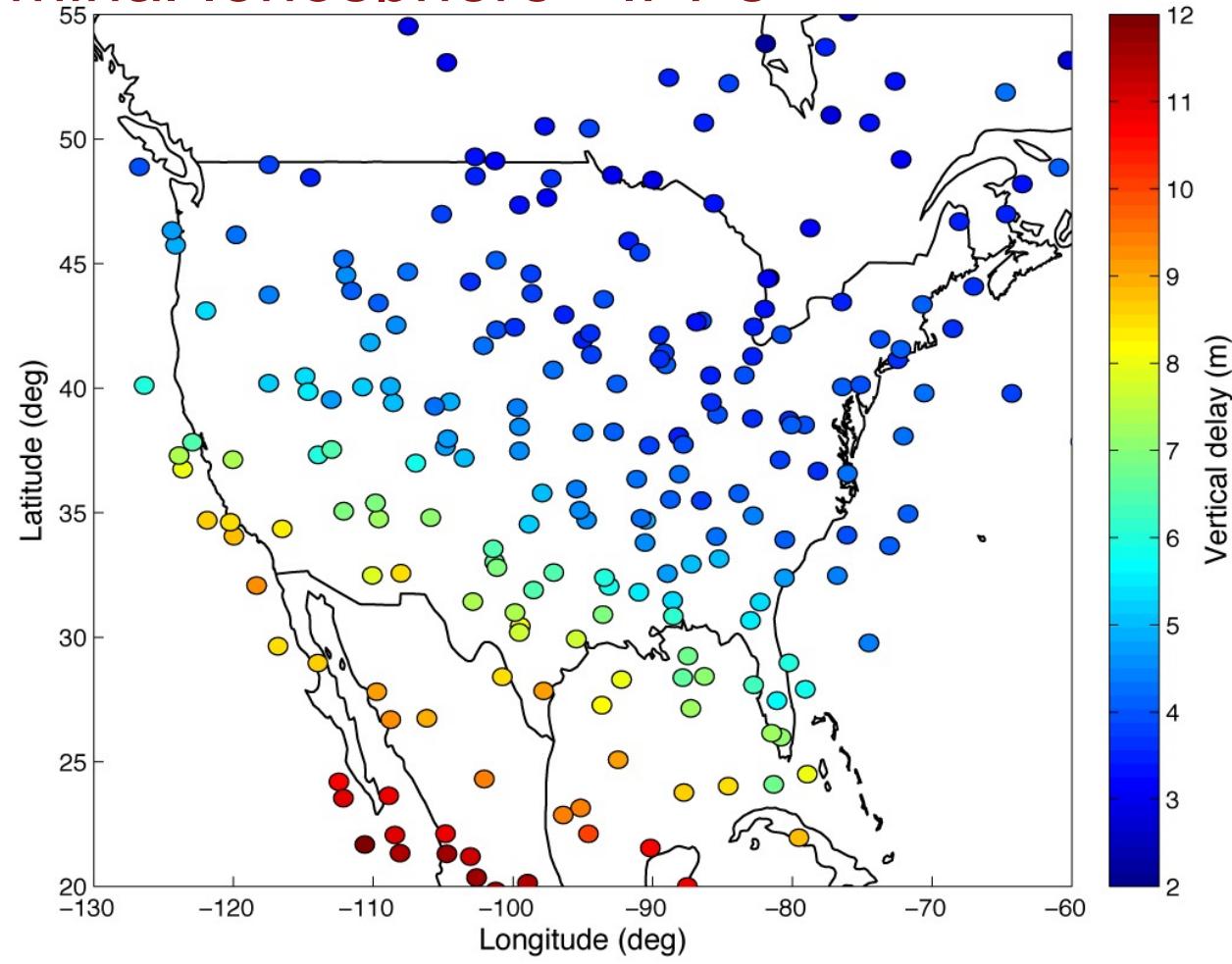


## SBAS Ionospheric Grid

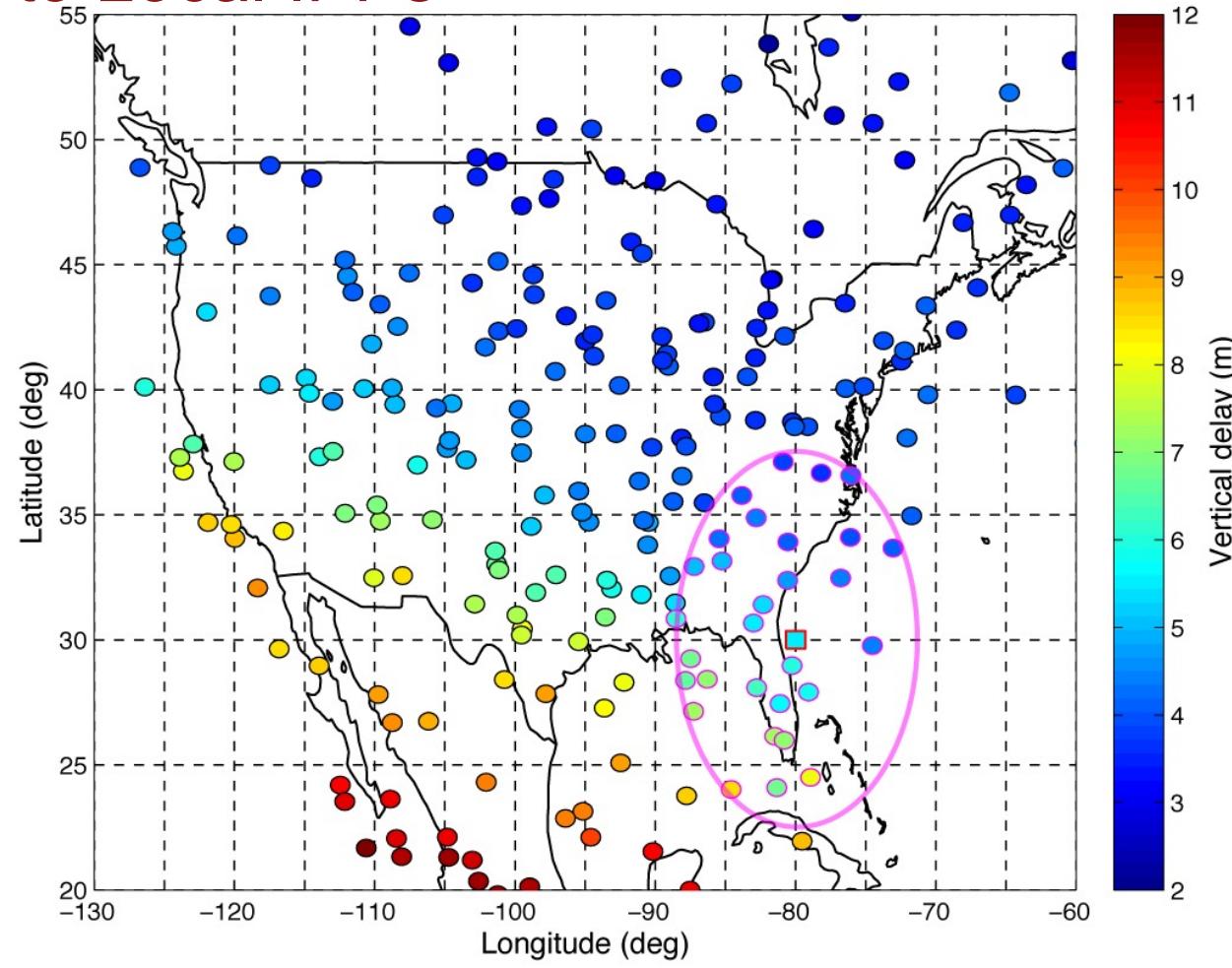


SBAS Ionospheric Grid

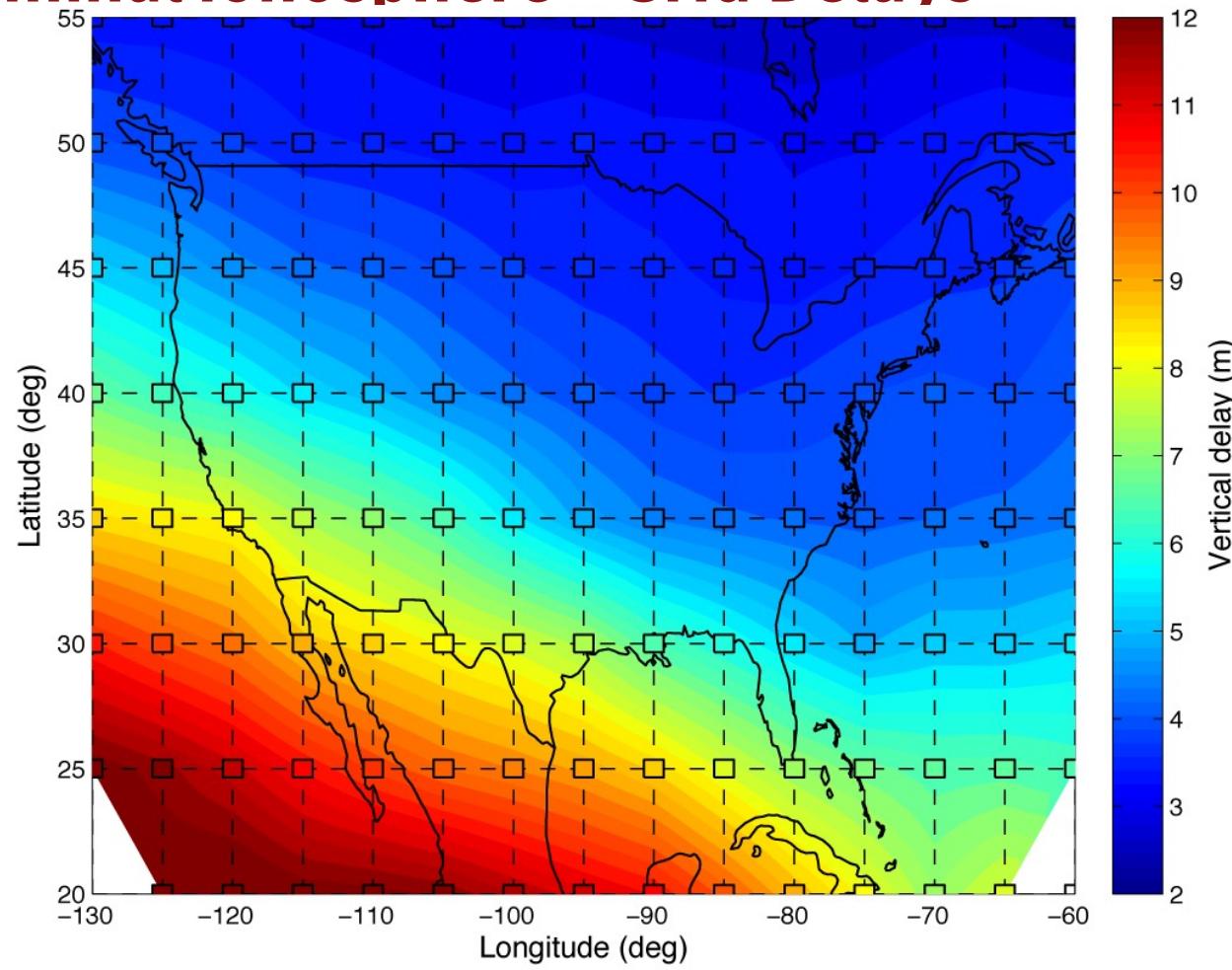
## Nominal Ionosphere - IPPs



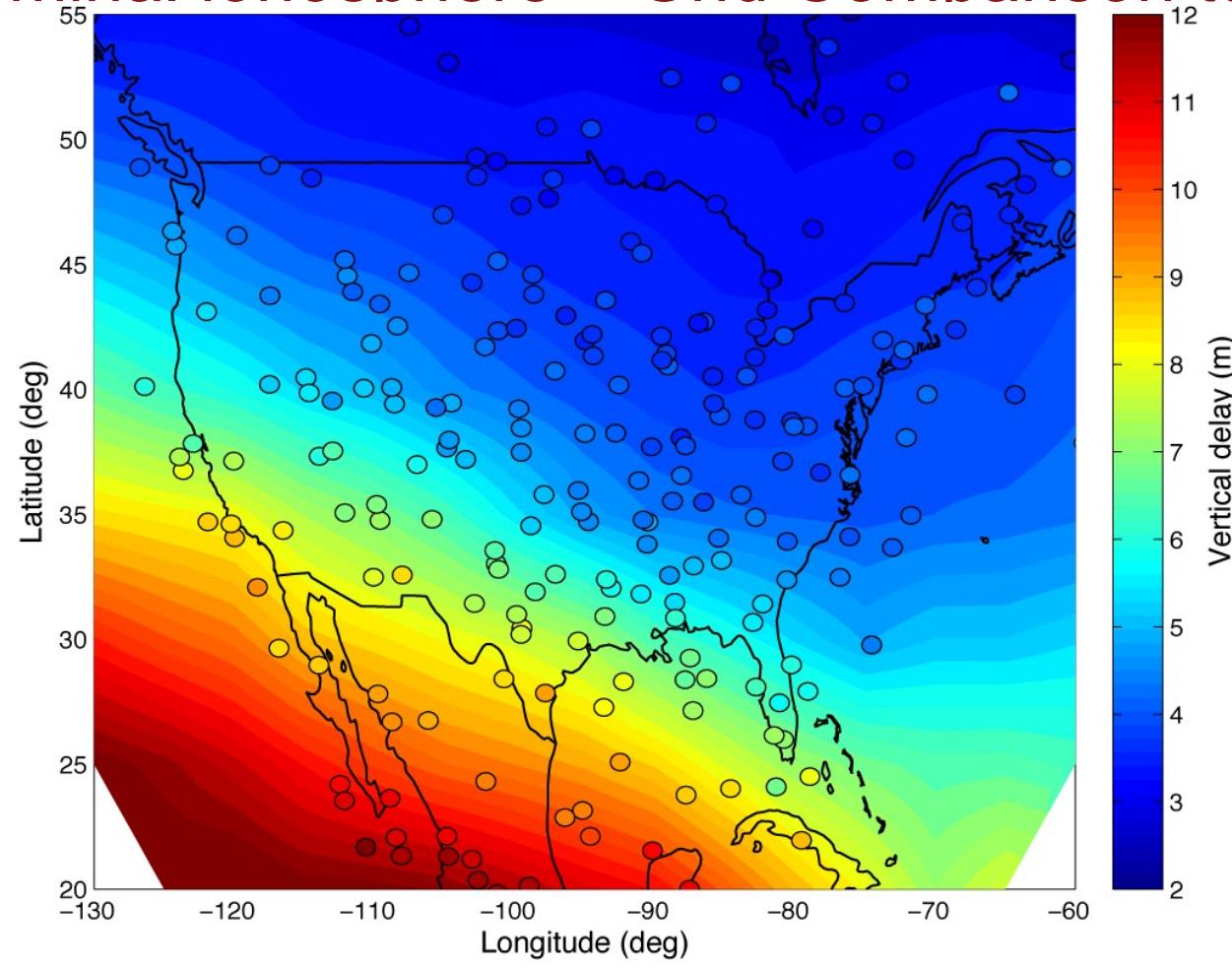
## Fit to Local IPPs



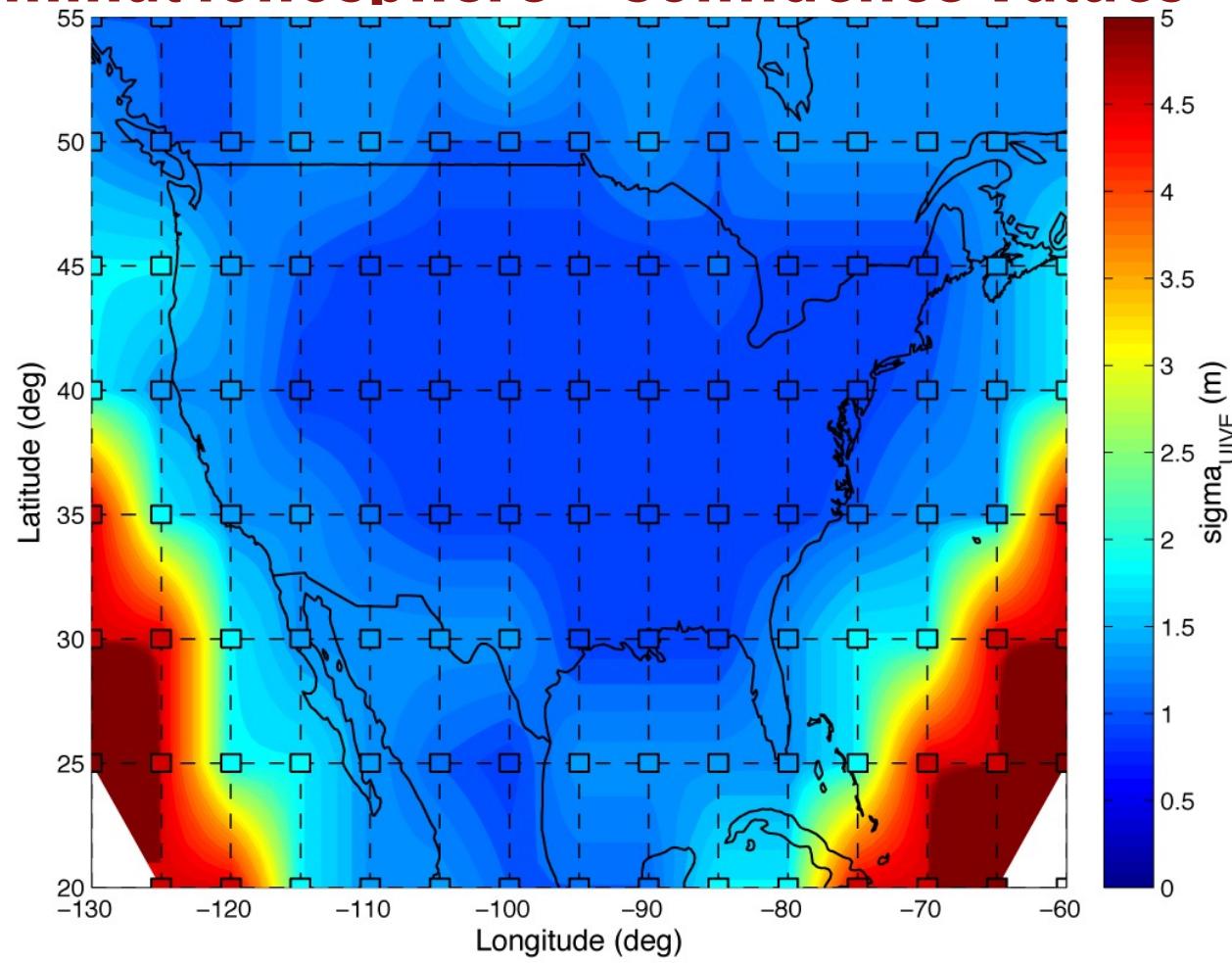
## Nominal ionosphere – Grid Delays



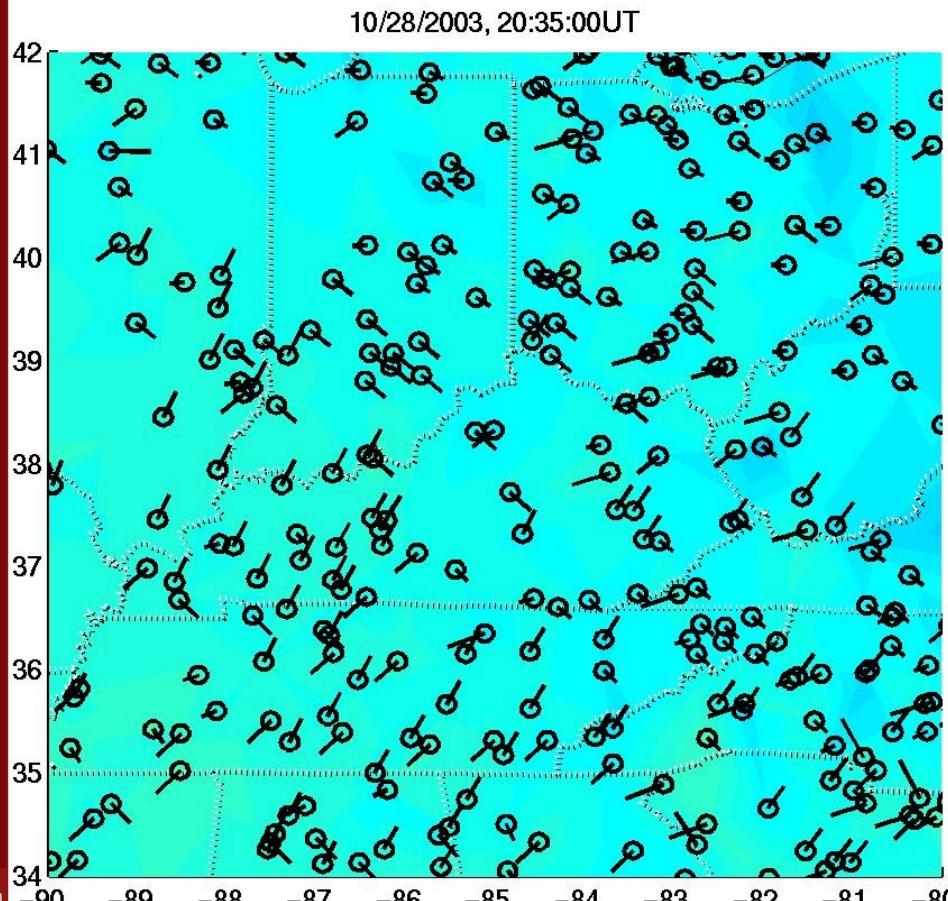
## Nominal ionosphere – Grid Comparison to IPPs



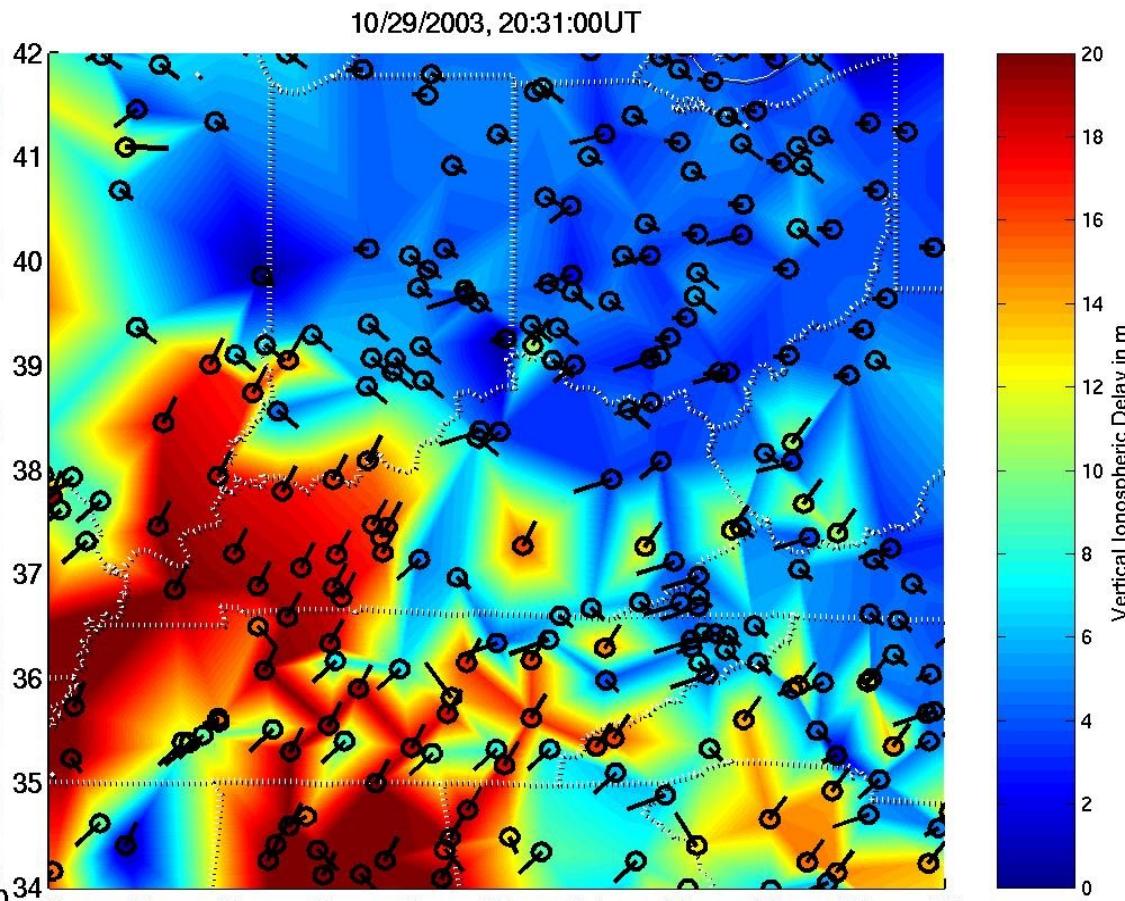
## Nominal ionosphere – Confidence Values



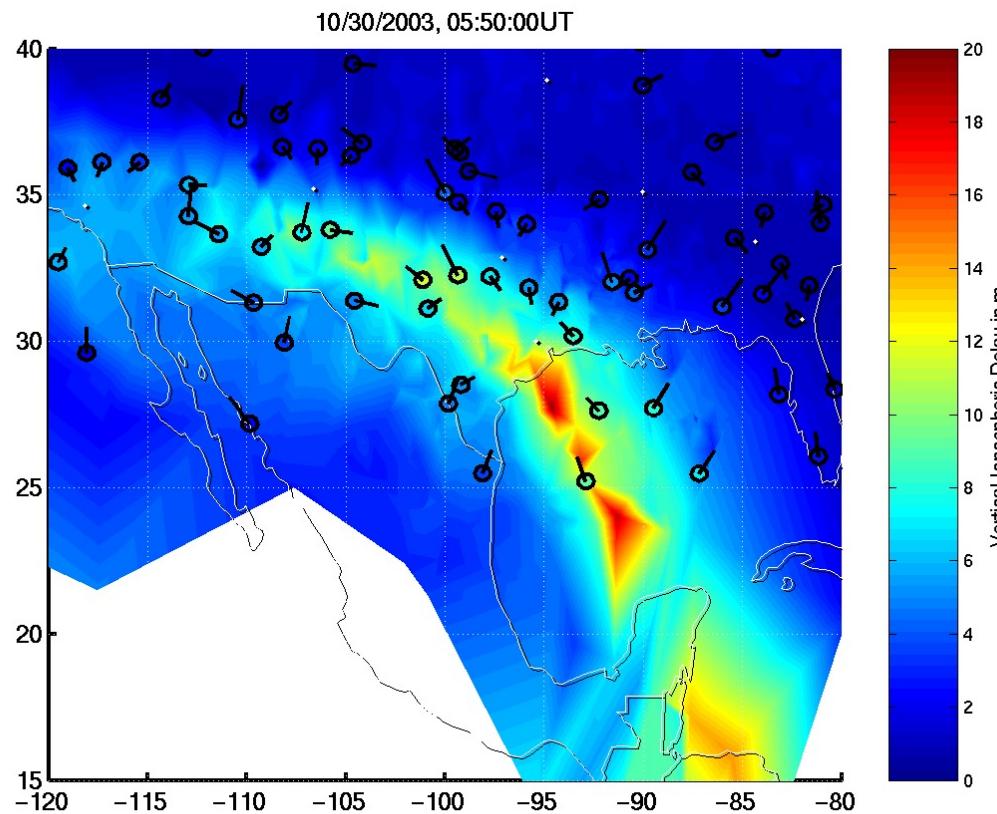
## Limits of the Thin Shell Model



## Disturbed Day



# Undersampled Ionospheric Threat Condition

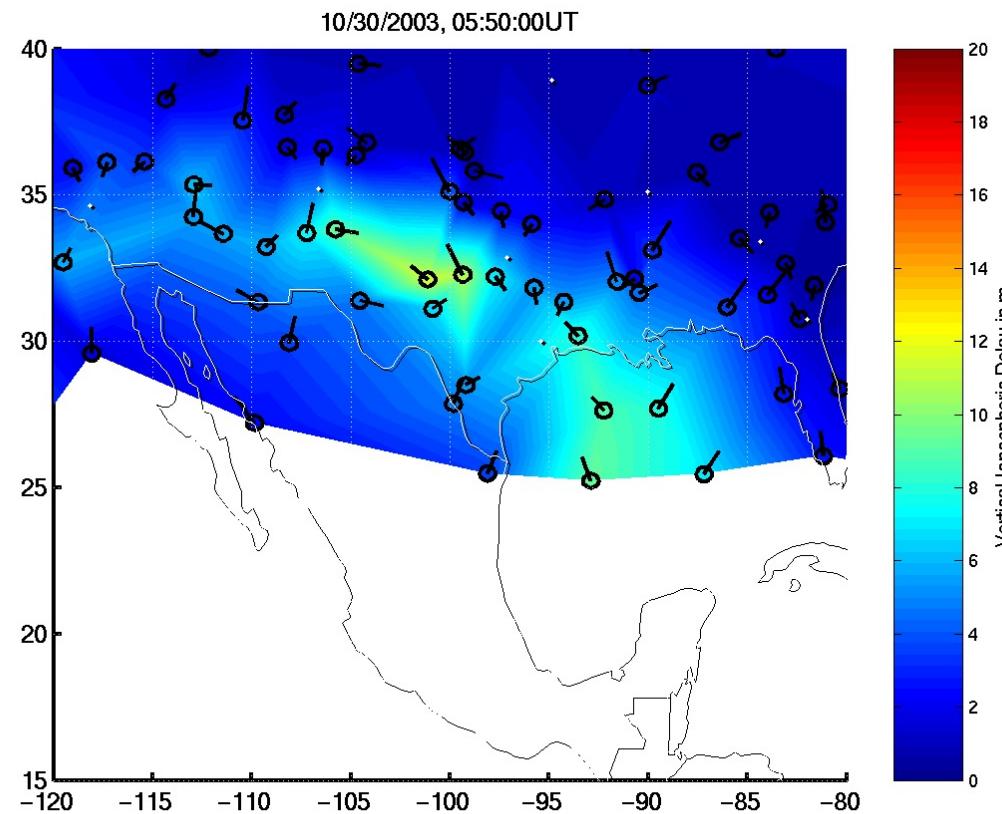


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# WAAS Measurements



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# GIVE Elements

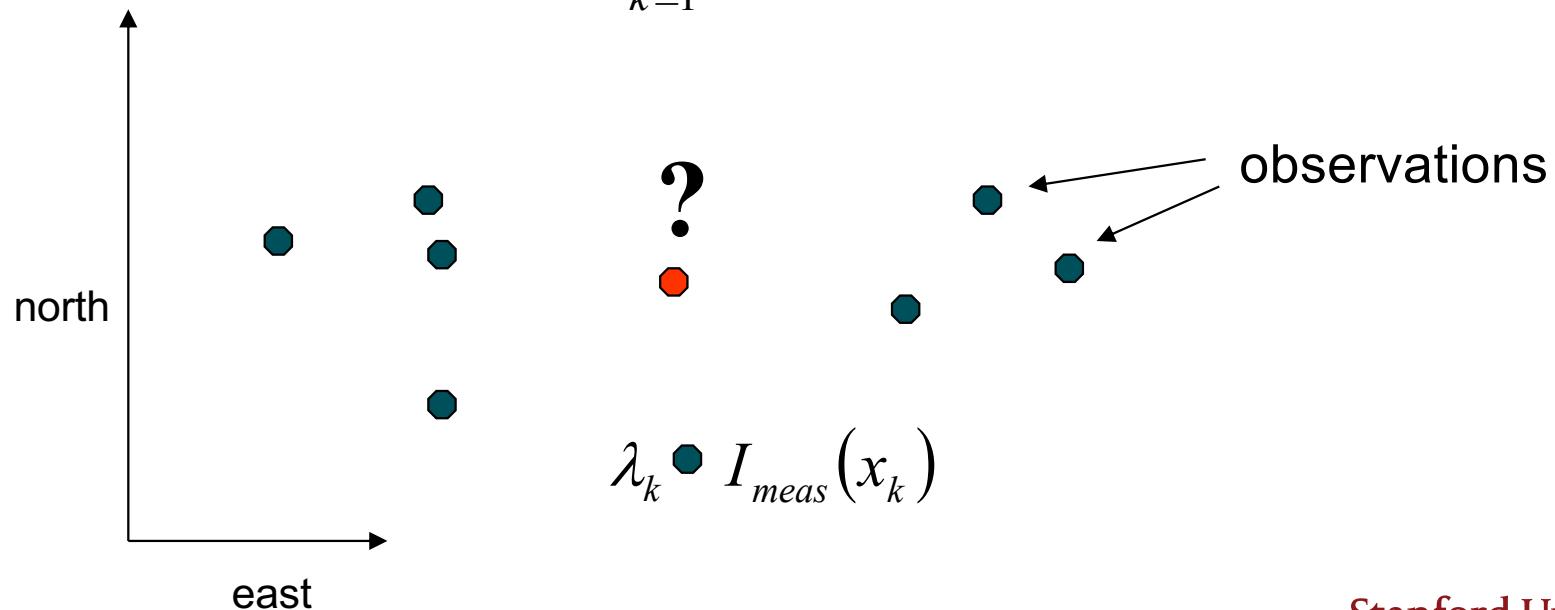
- Formal error term
  - › Measurement noise
  - › Ionospheric modeling error
    - Accounts for sampled ionosphere and disturbance state
  - › Antenna bias contribution
- Undersampled threat term
  - › Spatial & temporal threats
- Floor term
- Storm detector
  - › Local at the IGP
  - › Moderate storm 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:

$$I_{\text{meas}}(x_k) = a_0 + a_1 x_{\text{east},k} + a_2 x_{\text{north},k} + r(x_k) + n(x_k)$$

trend

Vertical Ionospheric Delay

Measurement noise

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

$$G^T \lambda = \begin{bmatrix} 1 \\ x_{\text{east}} \\ x_{\text{north}} \end{bmatrix}$$

$$G = \begin{bmatrix} 1 & x_{\text{east},1} & x_{\text{north},1} \\ \vdots & \vdots & \vdots \\ 1 & x_{\text{east},n} & x_{\text{north},n} \end{bmatrix}$$

# Confidence Computation

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

Formal error due to ionospheric uncertainty

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

Undersampled threat term

Measure of ionospheric state

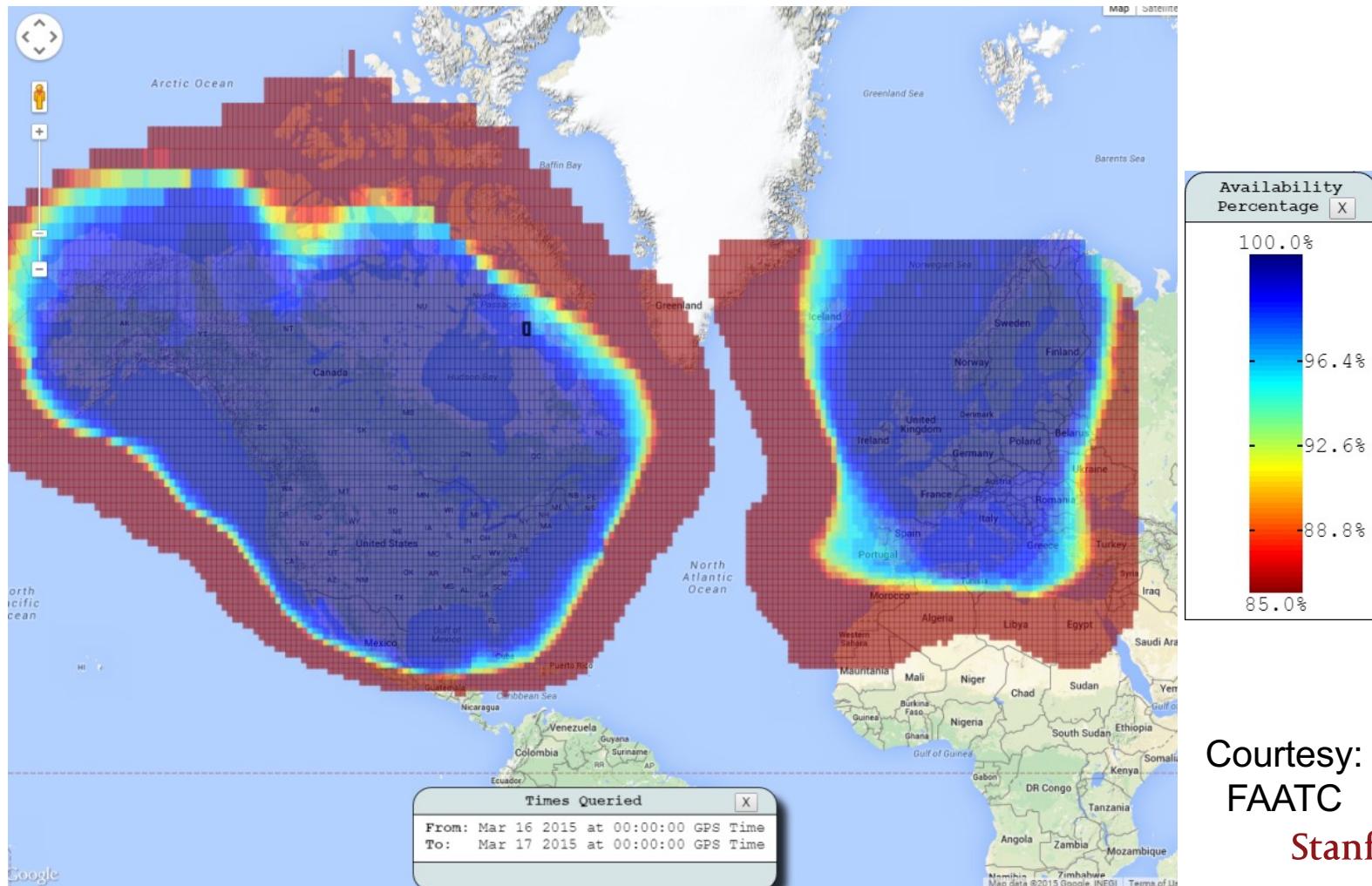
$$R_{irreg}^2 = \frac{R_{noise} \chi^2}{\chi_{lowerbound}^2}$$

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.

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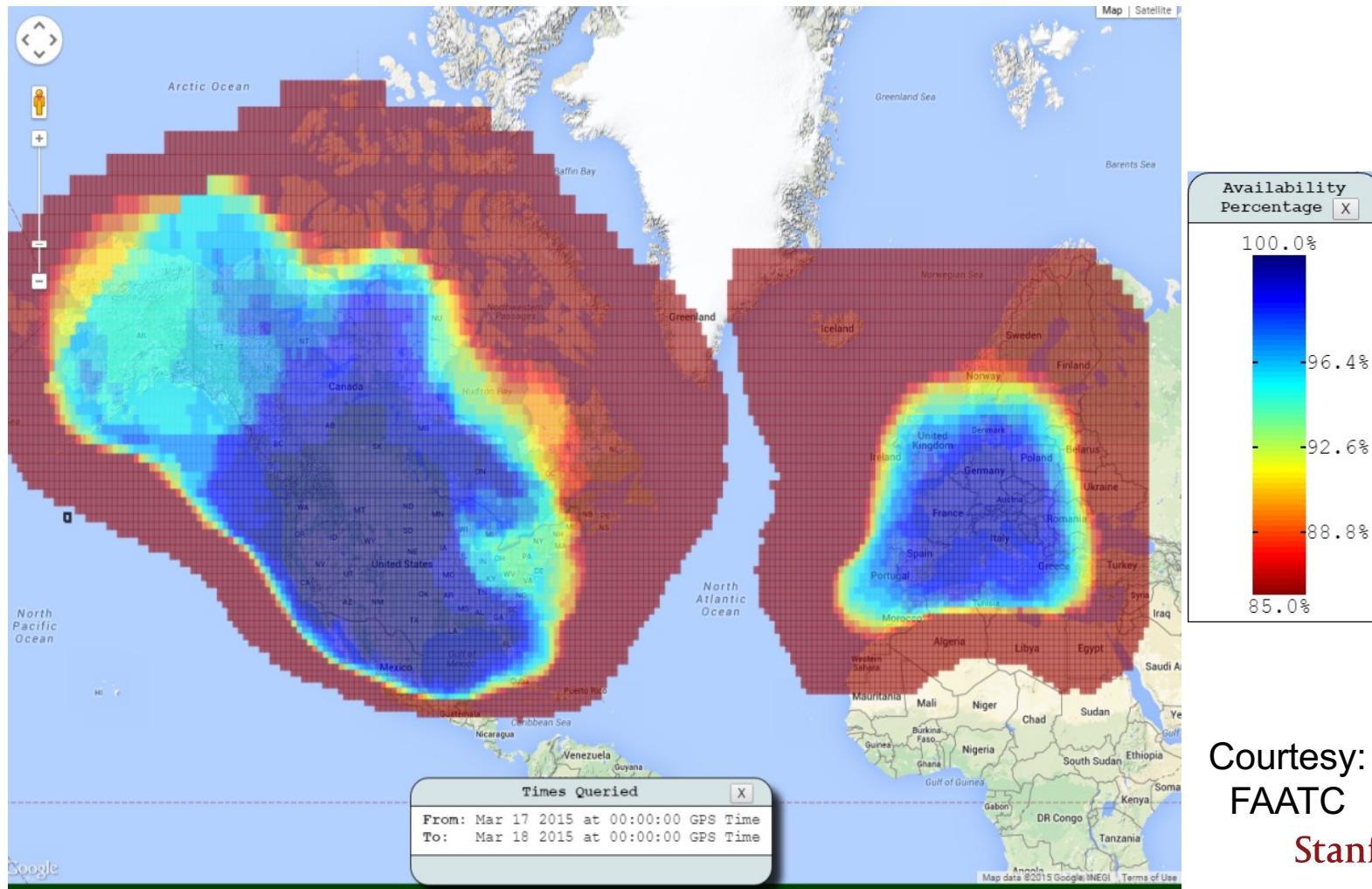
# March 16, 2015



Courtesy:  
FAATC

Stanford University

# March 17, 2015



Courtesy:  
FAATC

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## GBAS Mitigation of Threats

- Ground receivers monitor 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 reference station antenna bias
  - › Confidence bounds limited by ionosphere gradients and orbital errors
- Airborne receiver must limit the effects of local multipath, noise, and user antenna bias
  - › May supplement monitoring by performing checks for local ionospheric and/or tropospheric variations
- Capable of achieving the smallest time-to-alert, the best accuracy, and the smallest integrity bounds



## SBAS Mitigation of Threats

- Ground receivers monitor and correct errors that originate on the satellites and in the ionosphere
  - › Satellite clock and ephemeris errors separately corrected
  - › A grid of ionospheric 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 thousands of aircraft approach procedures



## 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

