The Abdus Salam International Centre for Theoretical Physics

2458-13

Workshop on GNSS Data Application to Low Latitude Ionospheric Research

6 - 17 May 2013

Satellite Navigation for Guidance of Aircraft (Part 2)

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Satellite Navigation for Guidance of Aircraft

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Outline

- **Ionospheric Modeling**
- Ionospheric Threats
- Next Generation Satellite Navigation
- Future Signals
- Conclusions

How Are Measurements Correlated Over Distance?

- Translate Our Measurements of the Ionosphere Into User Corrections
- How Does the Ionosphere Behave Spatially?
  - *What is the underlying structure?*
  - *What does one measurement tell us about the nearby ionosphere?*
  - *How should we combine multiple samples?*
  - *What confidence can we have in our prediction?*
- We Need to Determine the Ionospheric Decorrelation Function

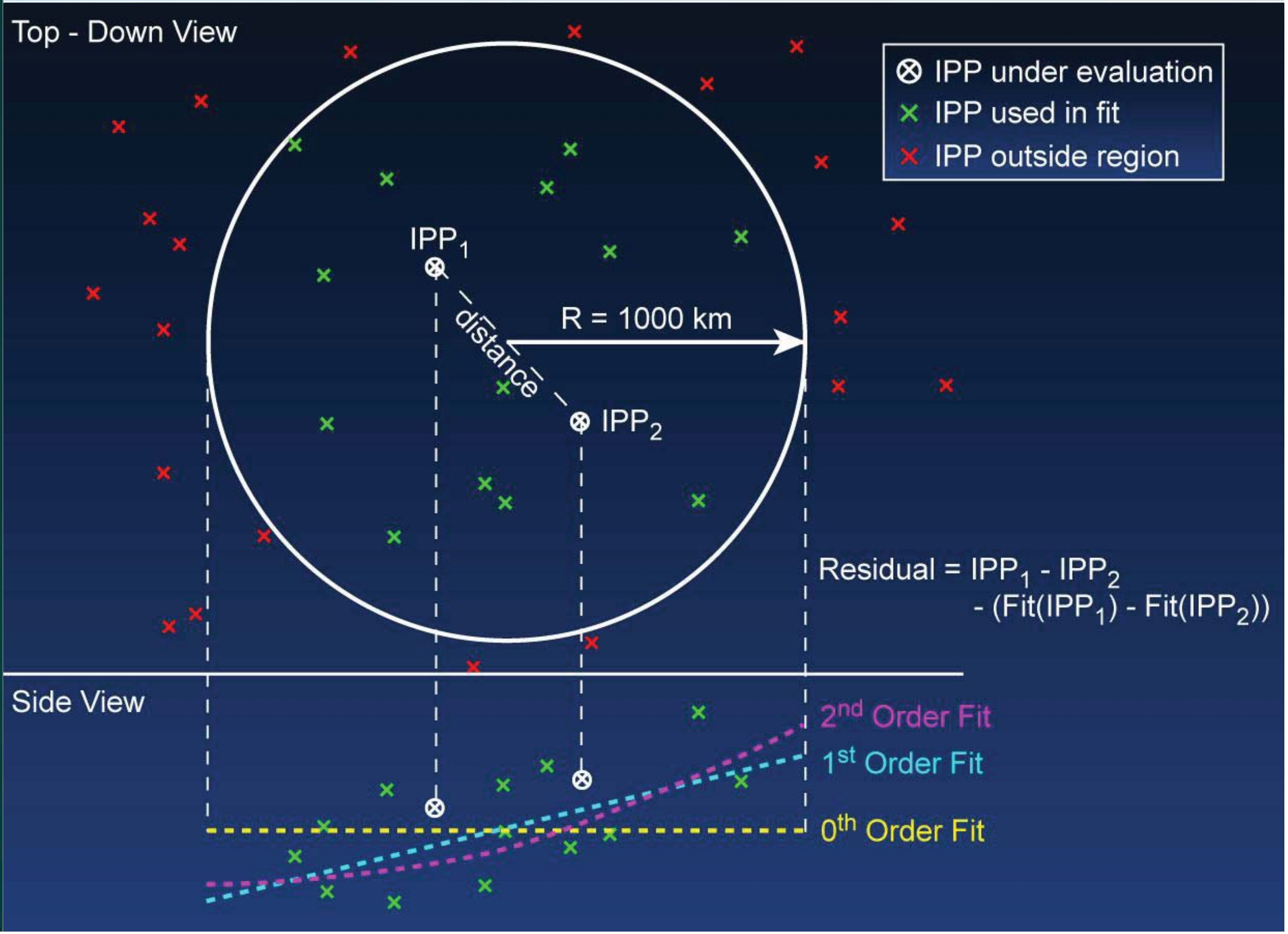
"Supertruth" Data

- Raw Data Collected From Each WRS
  - *3 independent receivers per WRS*
- Postprocessed to Create "Supertruth"
  - *Carrier tracks "leveled" to reduce multipath*
  - *Interfrequency biases estimated and removed for satellites and receivers*
  - *Comparisons made between co-located receivers (voting to remove artifacts)*
- Multipath and Bias Residuals are ~50 cm
- Without Voting, Receiver Artifacts Cloud Results and Make It Impossible to See Tails of the Distribution

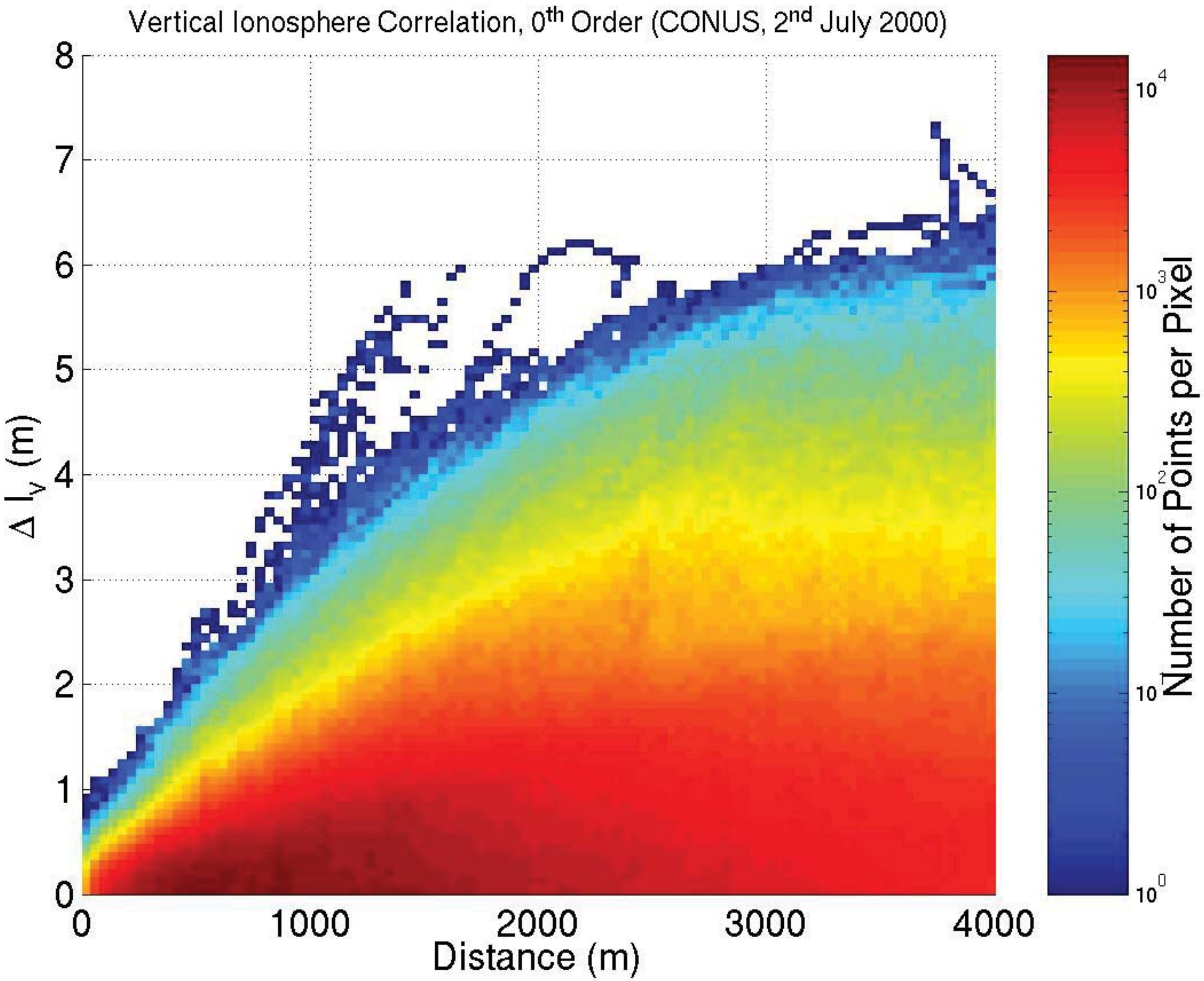
Decorrelation Estimation

- Every Supertruth 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

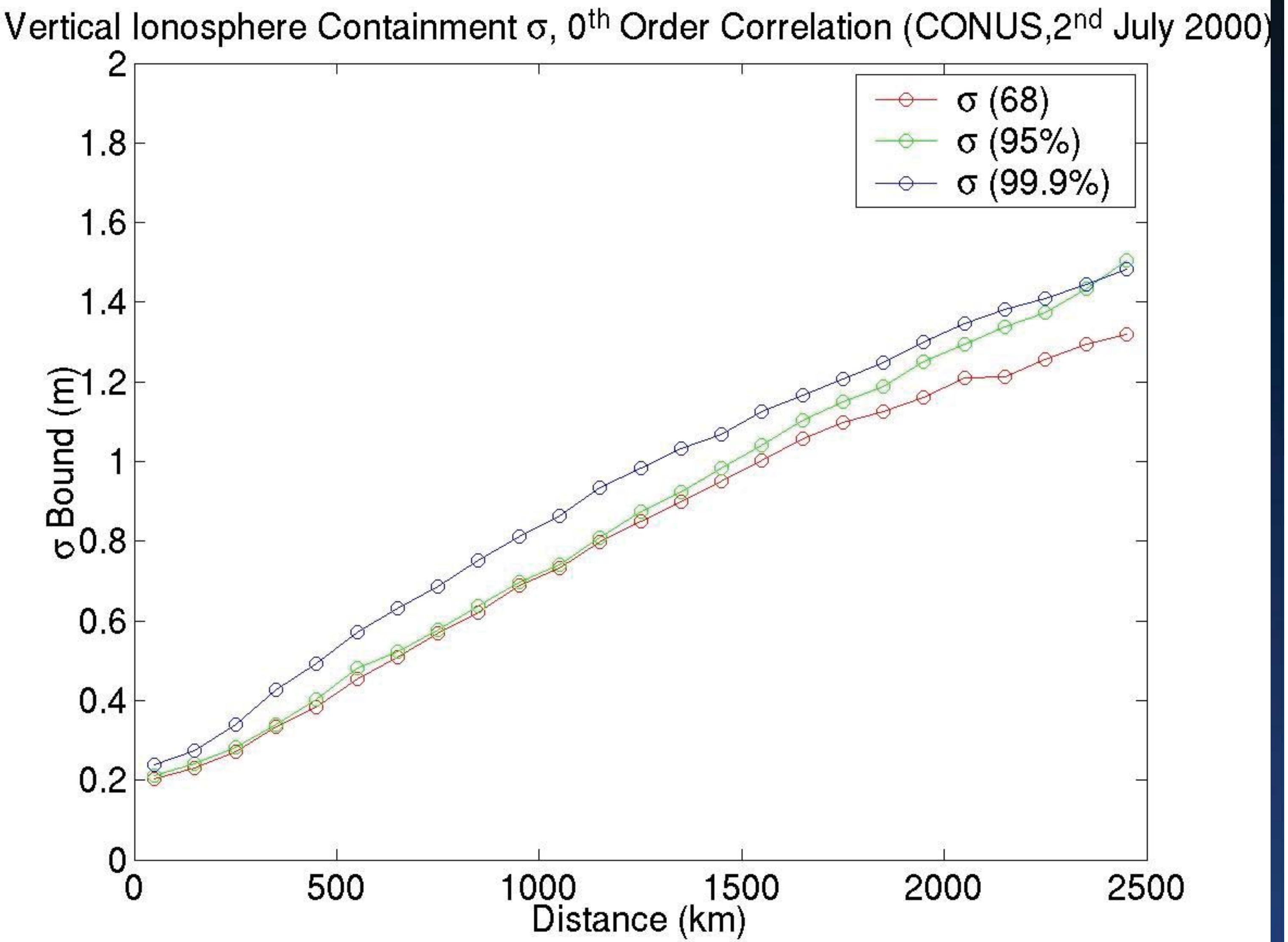
Correlation Estimation Process



Ionospheric Decorrelation (0th Order)



Ionospheric Decorrelation Function (0^{th} Order)

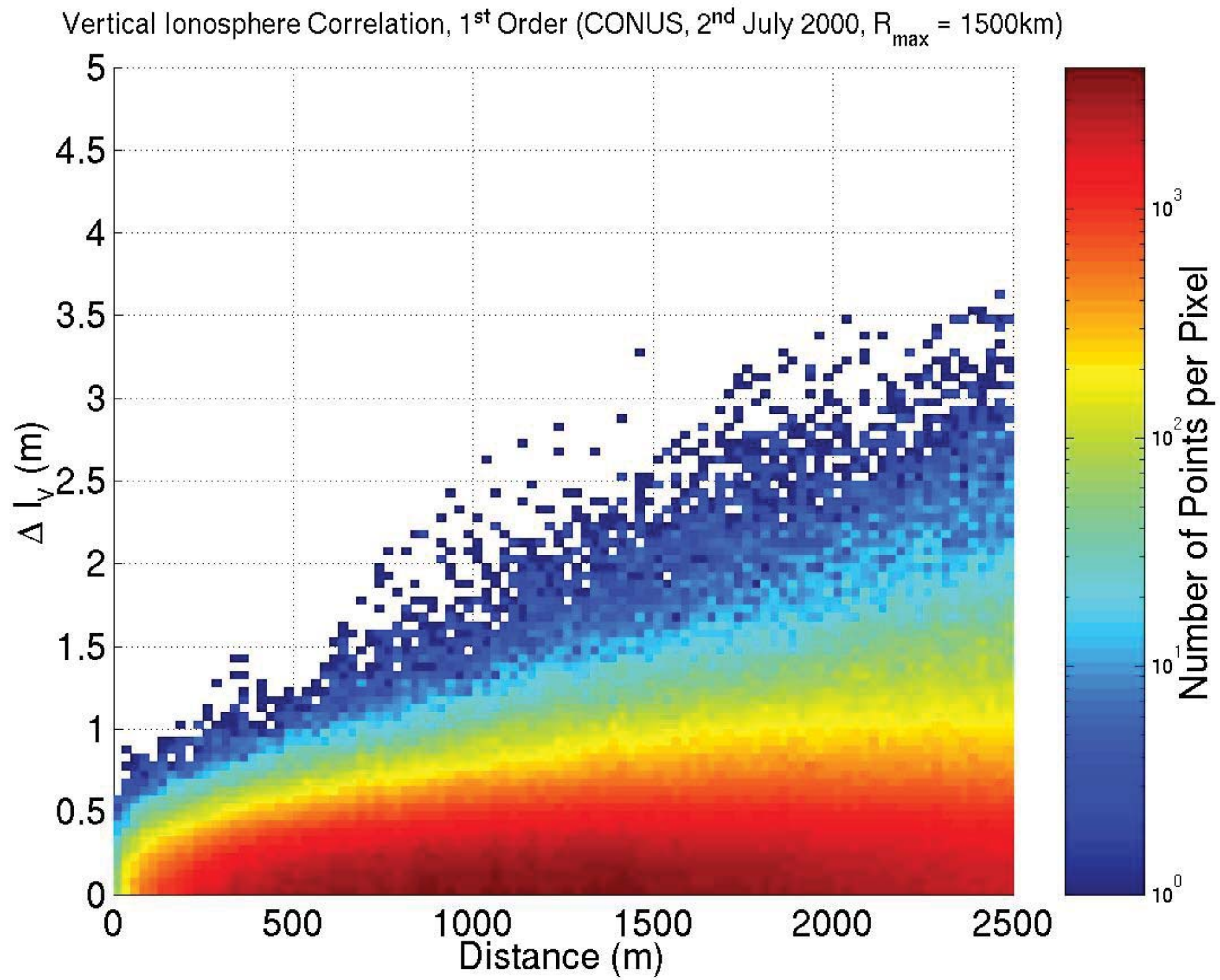


Preliminary Decorrelation Findings

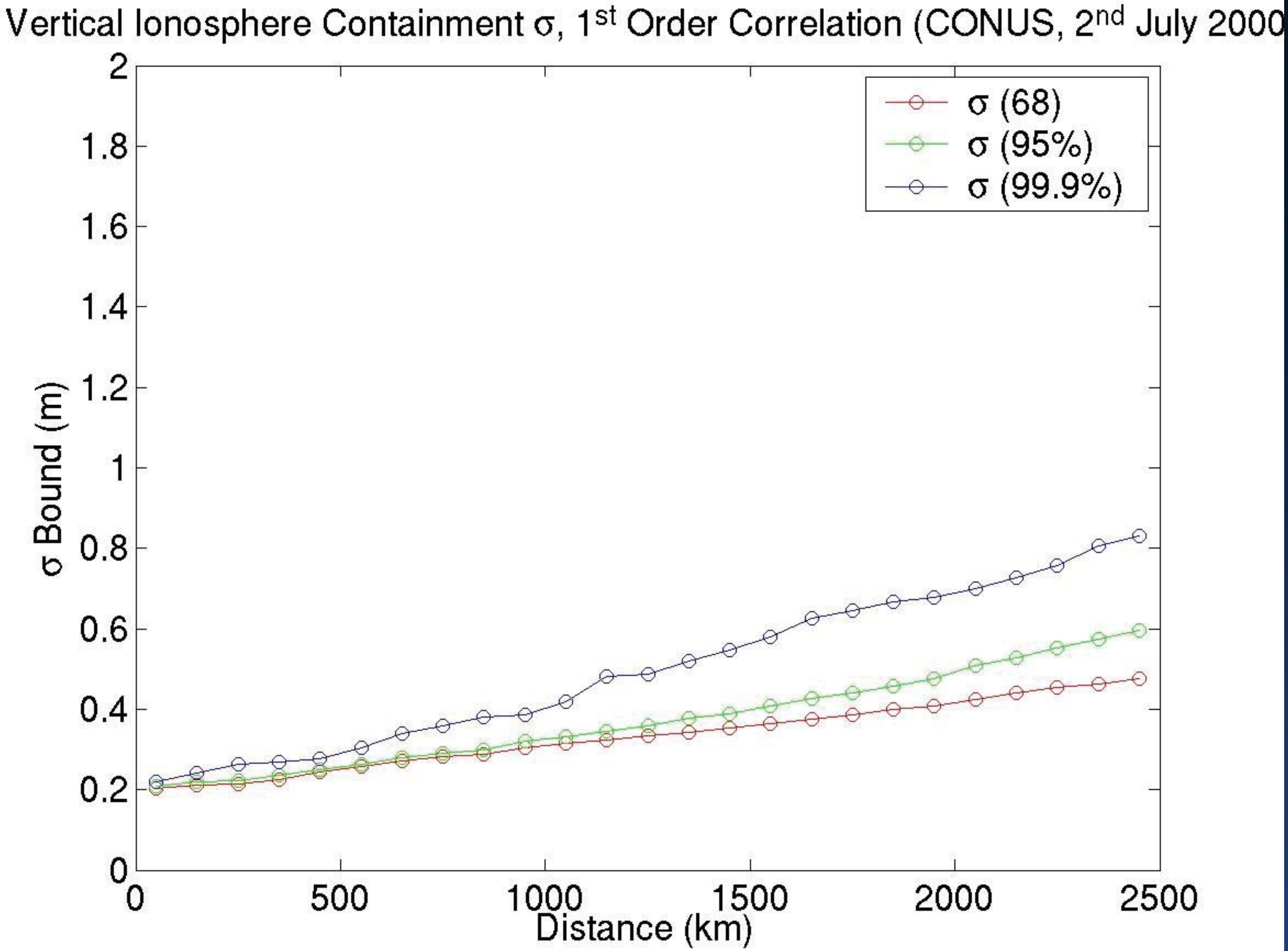
- Nominal Ionosphere is Relatively Smooth
  - *Nearby IPPs Well Correlated*
- Confidence About a Single Measurement Can Be Described As:

  $\sigma^2 = \sigma_m^2 + (0.3\ m + d * 0.5\ m/1000km)^2$
- There Appears to Be a Deterministic Component
- Next Try Removing a Planar Fit

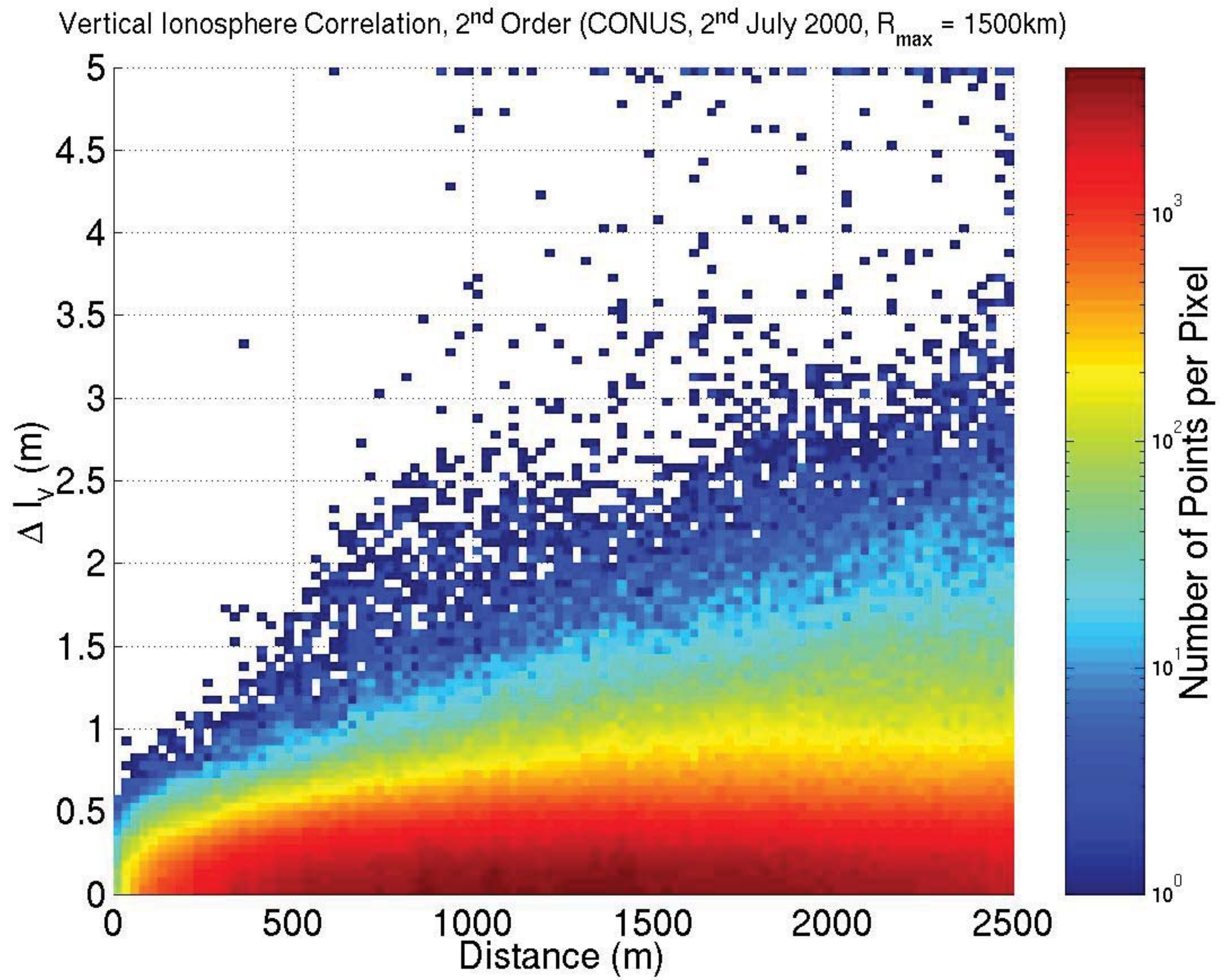
Ionospheric Decorrelation About a Planar Fit (1^{st} Order)



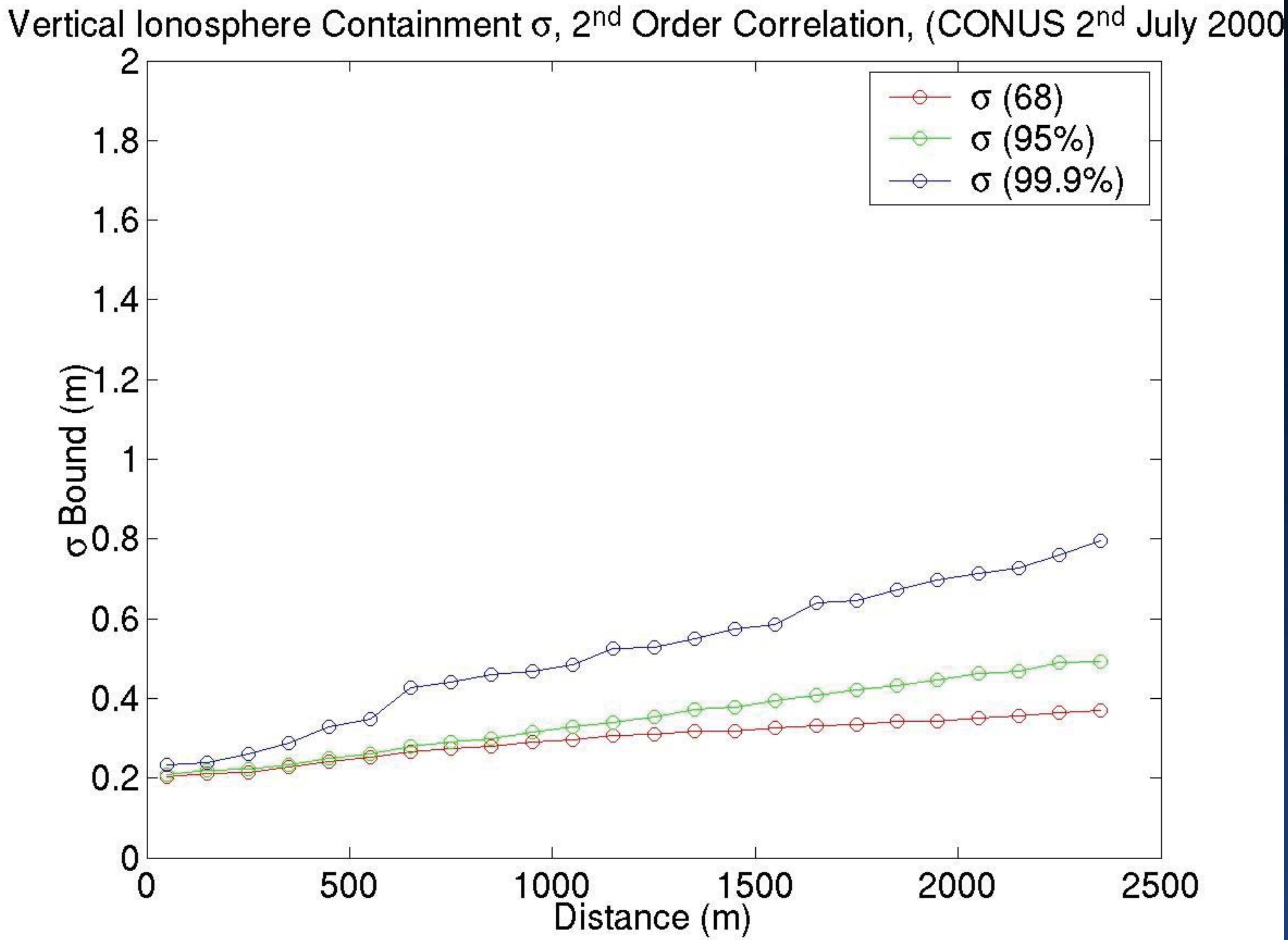
Ionospheric Decorrelation Function (1^{st} Order)



Ionospheric Decorrelation About a Quadratic Fit



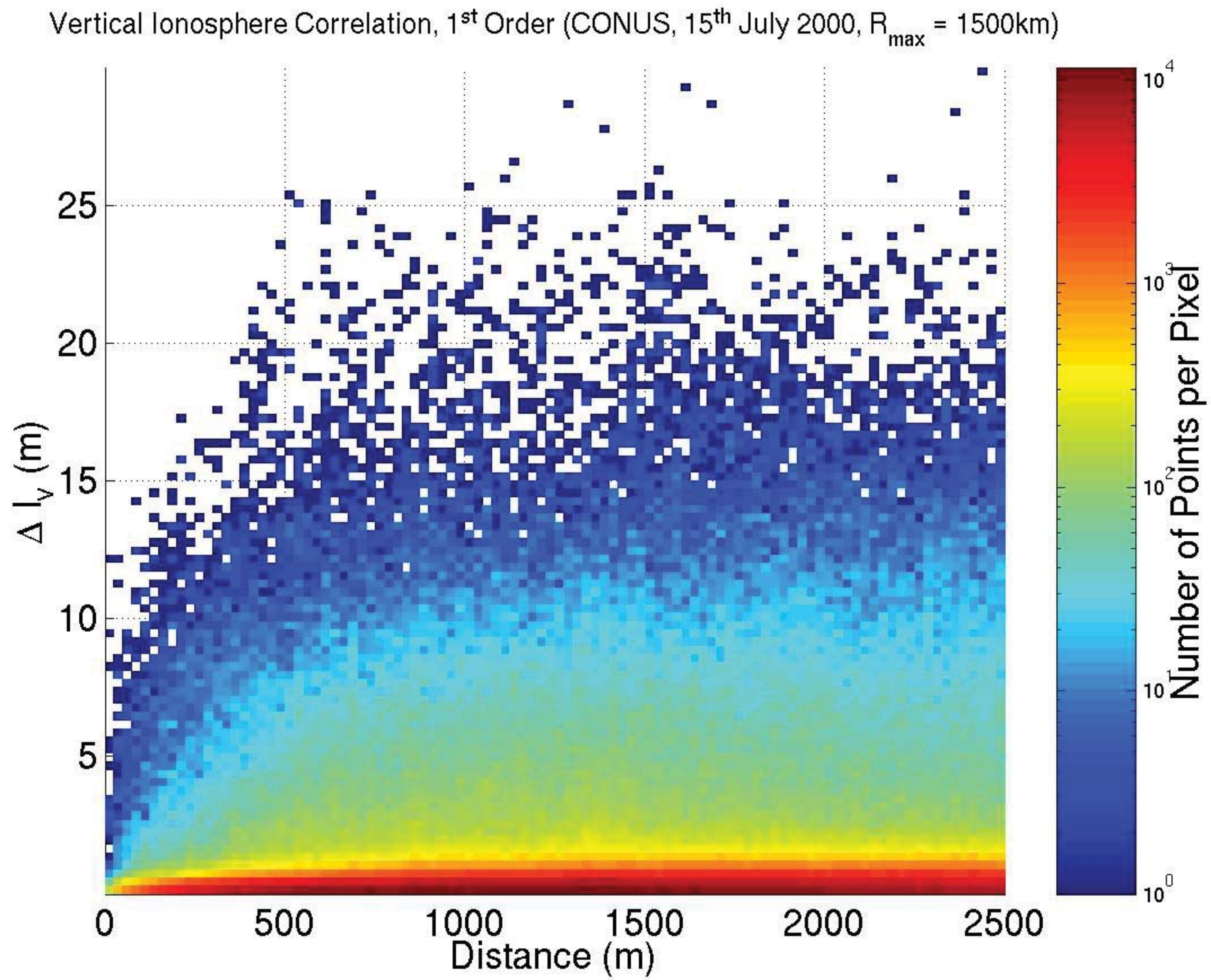
Ionospheric Decorrelation Function (2nd Order)



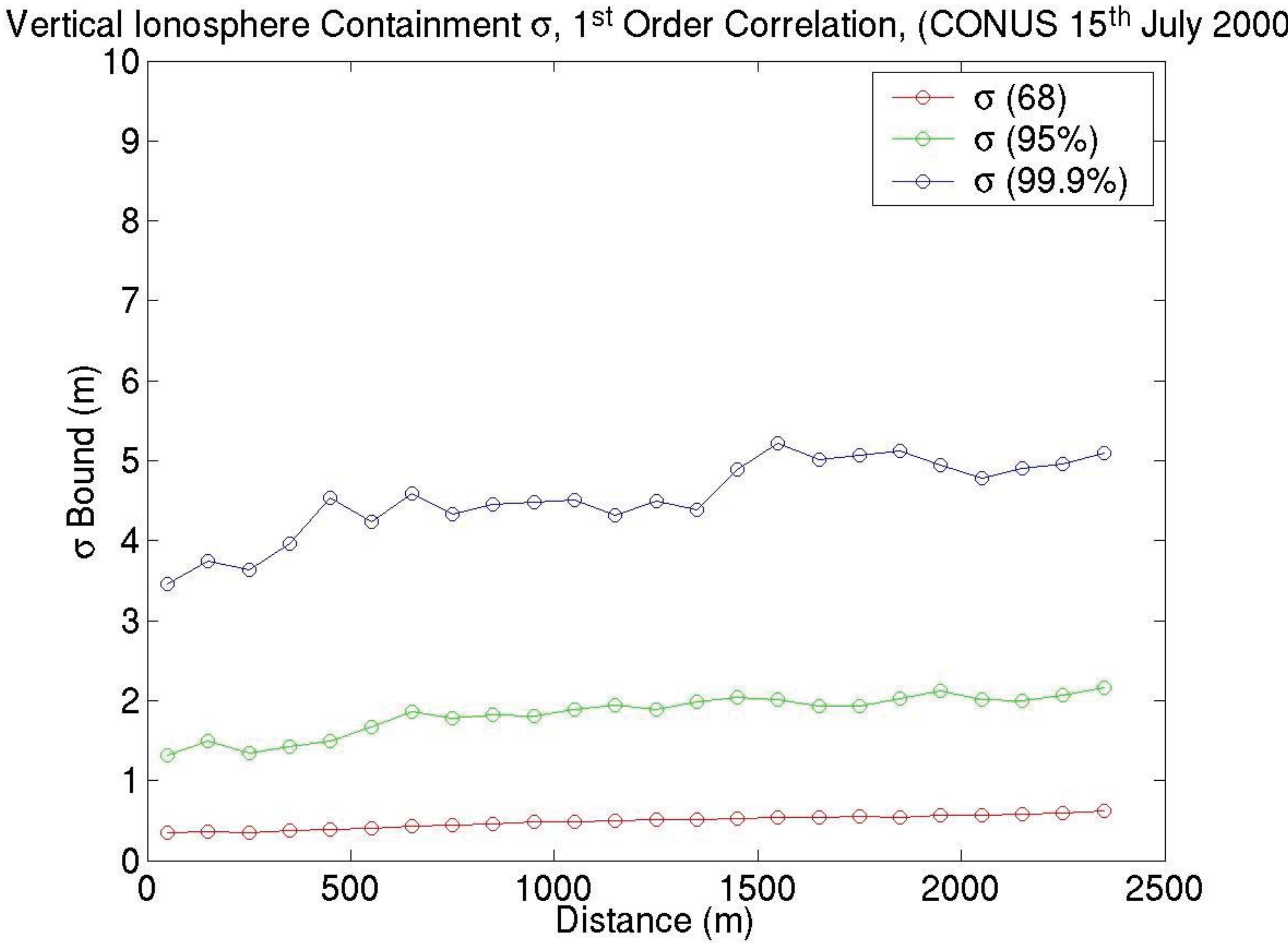
Initial Decorrelation Summary

- Planar Fit Appears to Remove Nearly All Deterministic Elements
- No Decorrelation Variation With Elevation Angle or vs Day/Night
  - *Decorrelation appears to result from residual error in supertruth data*
- 35 cm Valid for Mid-Latitude Nominal Decorrelation (R < ~1000 km)
- Decorrelation at Lower Latitudes Is Likely Different (larger, more orders?)

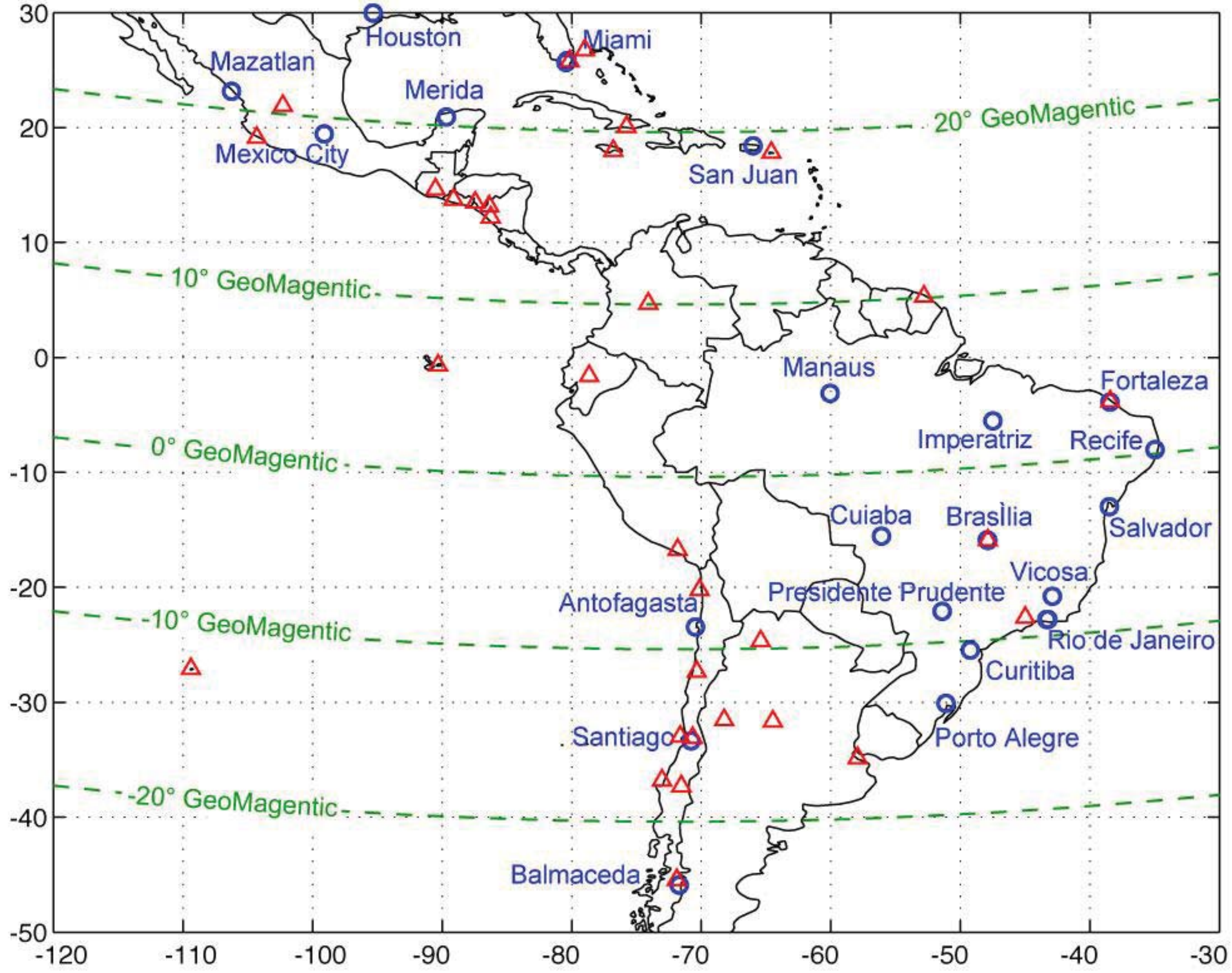
Disturbed Ionosphere



Disturbed Ionosphere



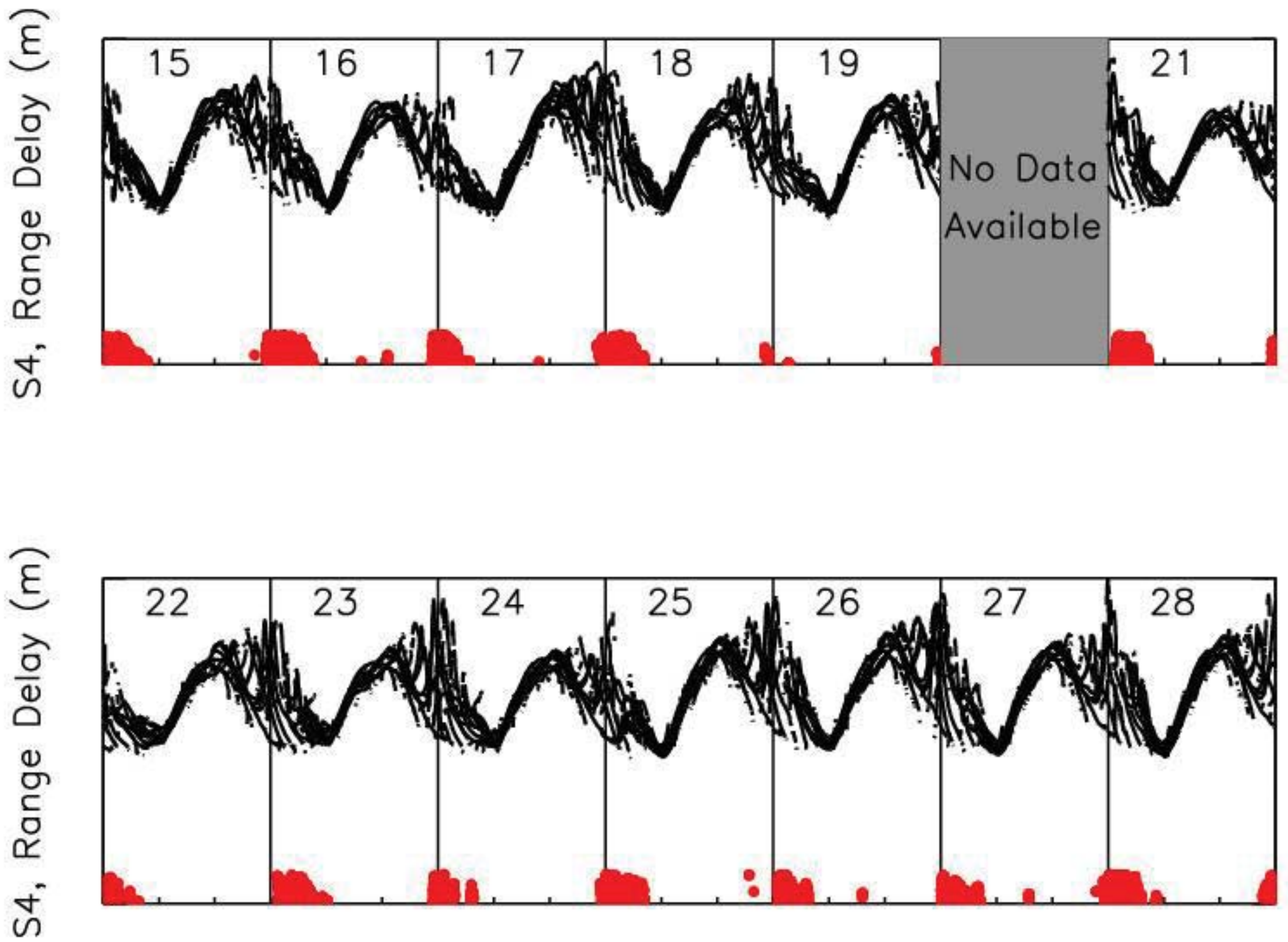
Map of South American Stations



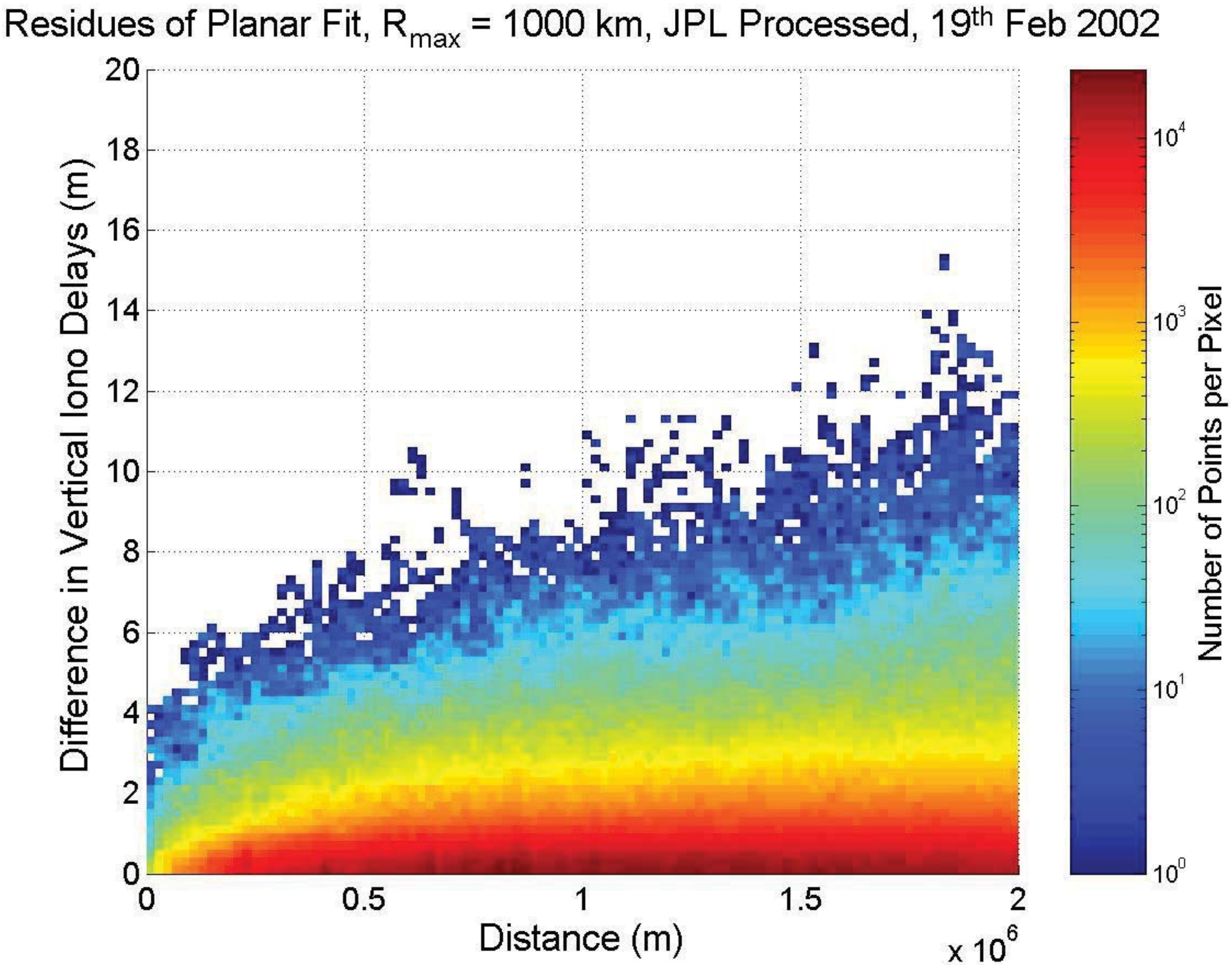
Determination of Quiet Days

- First wish to identify “undisturbed” days to use as basis for “nominal” model
  - *Want a day free of depletions and scintillation*

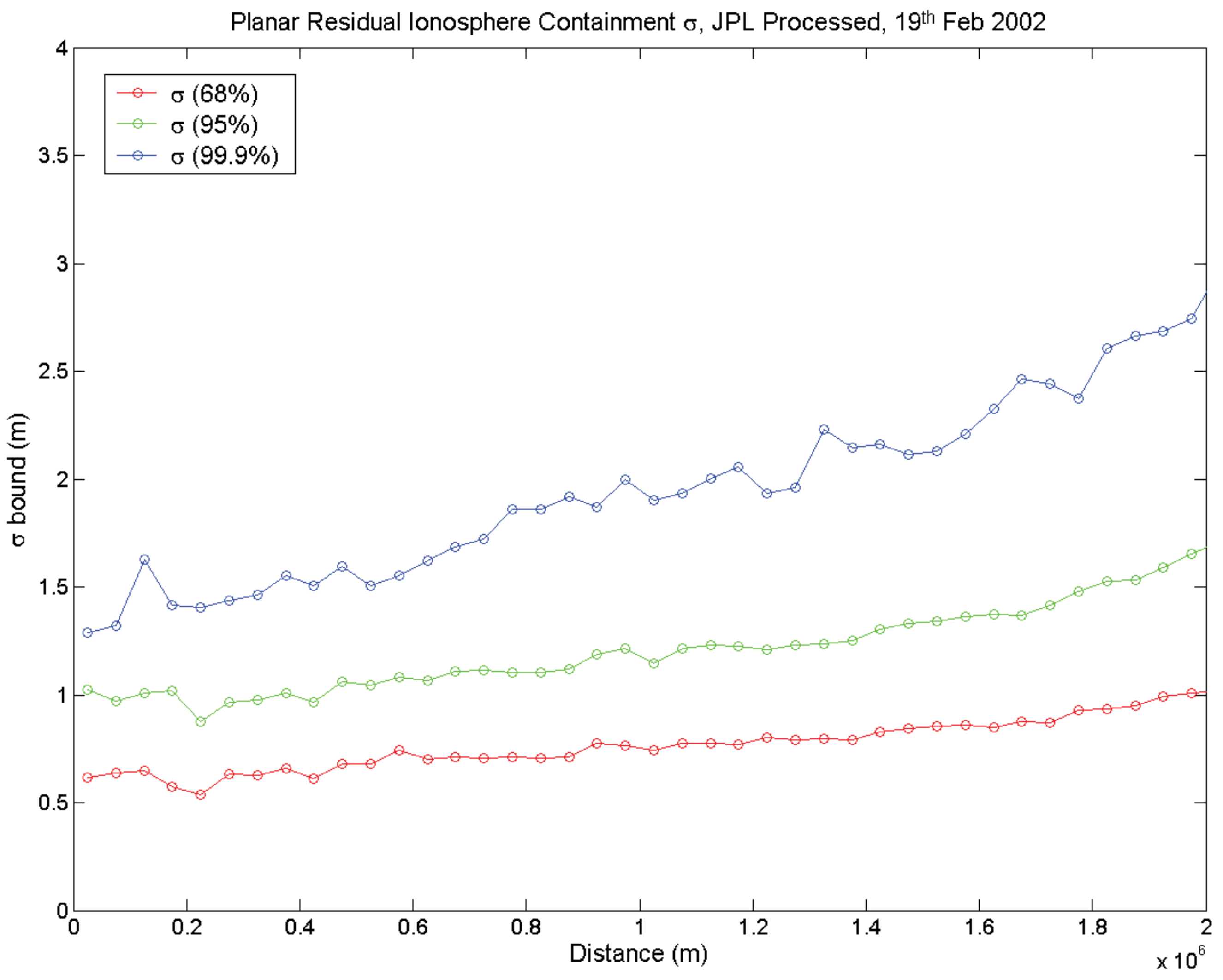
Daily Observations of TEC and S4



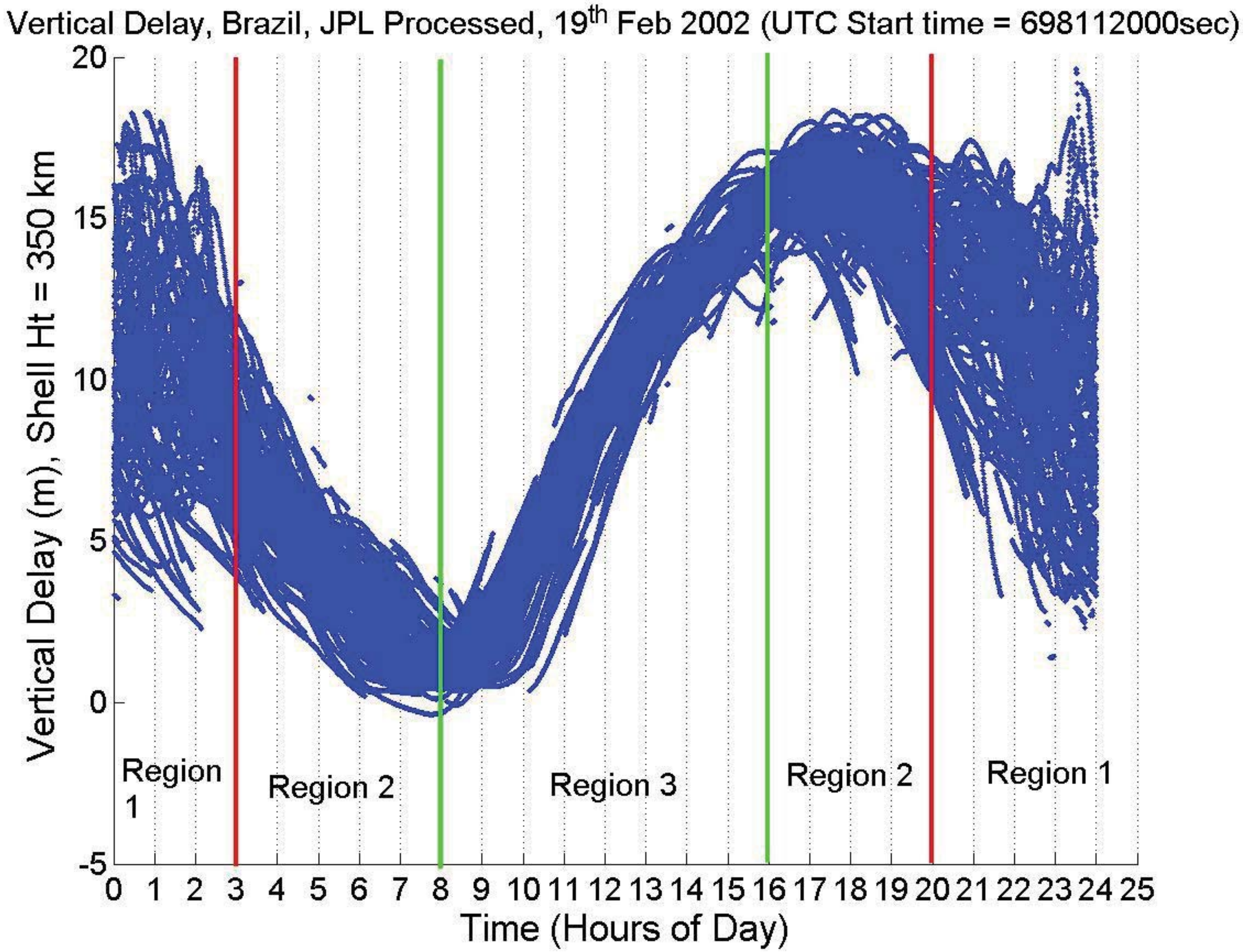
Two-D Histogram 1st Order



Sigma Estimate 1st Order



Vertical TEC



Presented at ICTP
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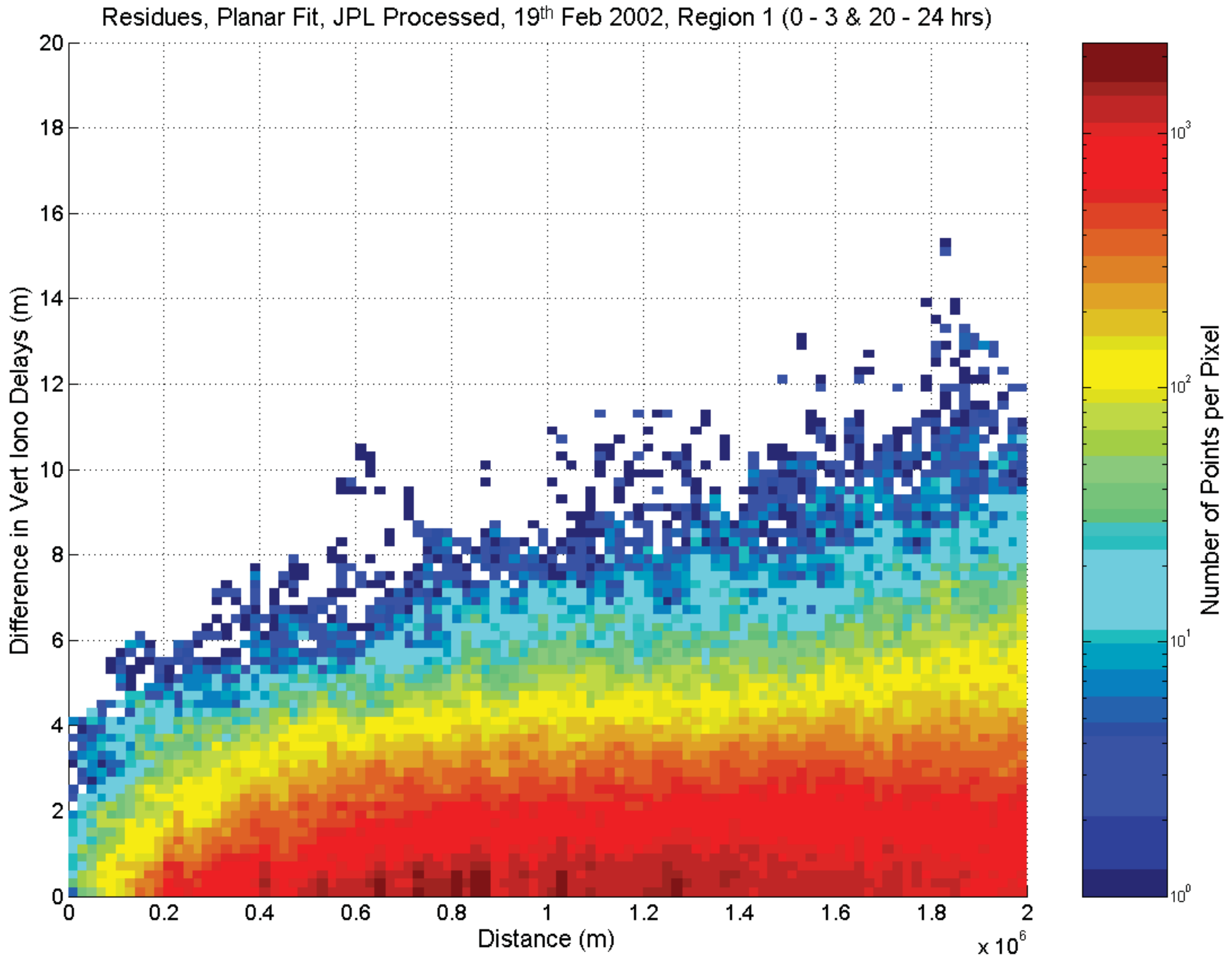
Two-D Histogram 1st Order (Region 1)



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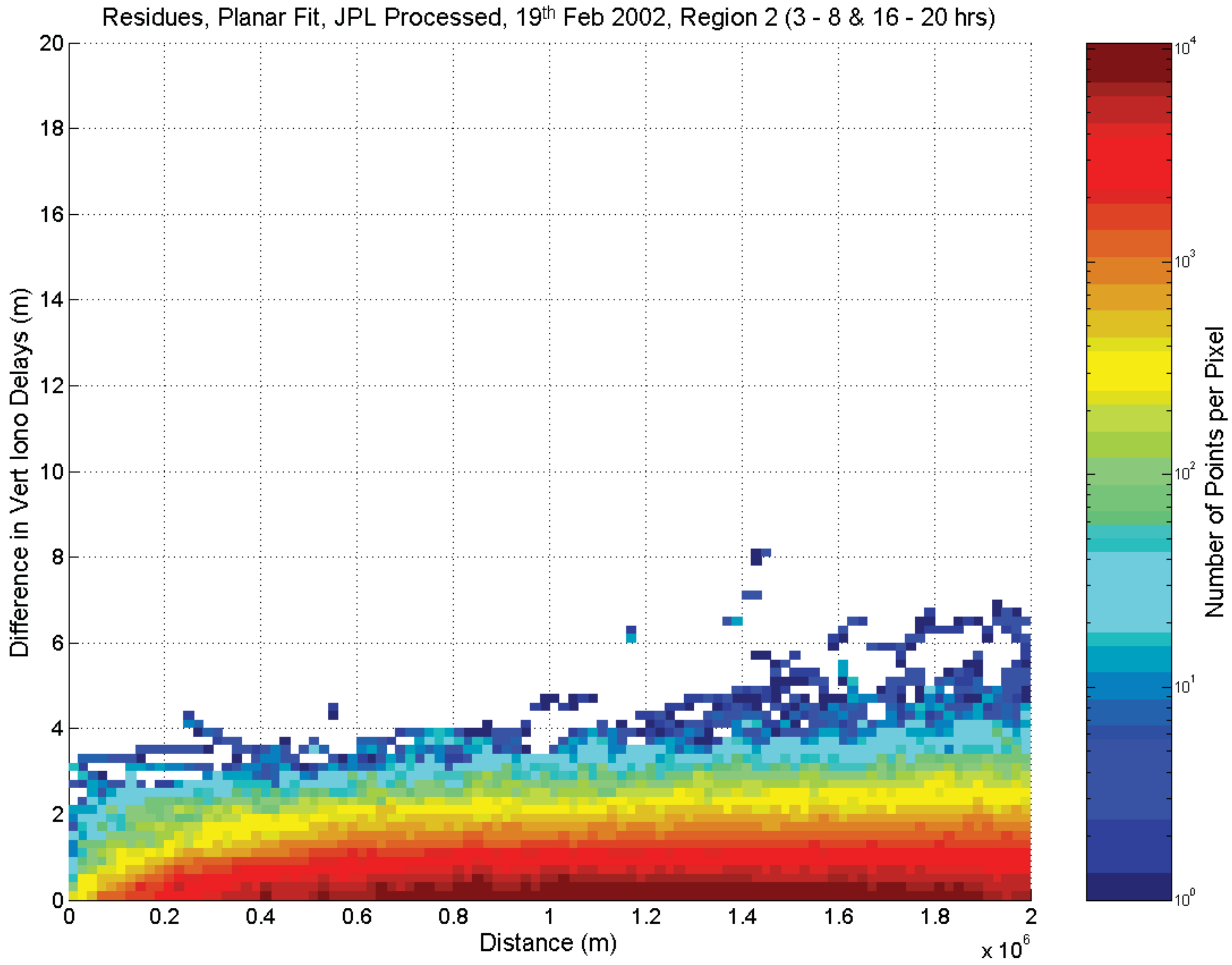
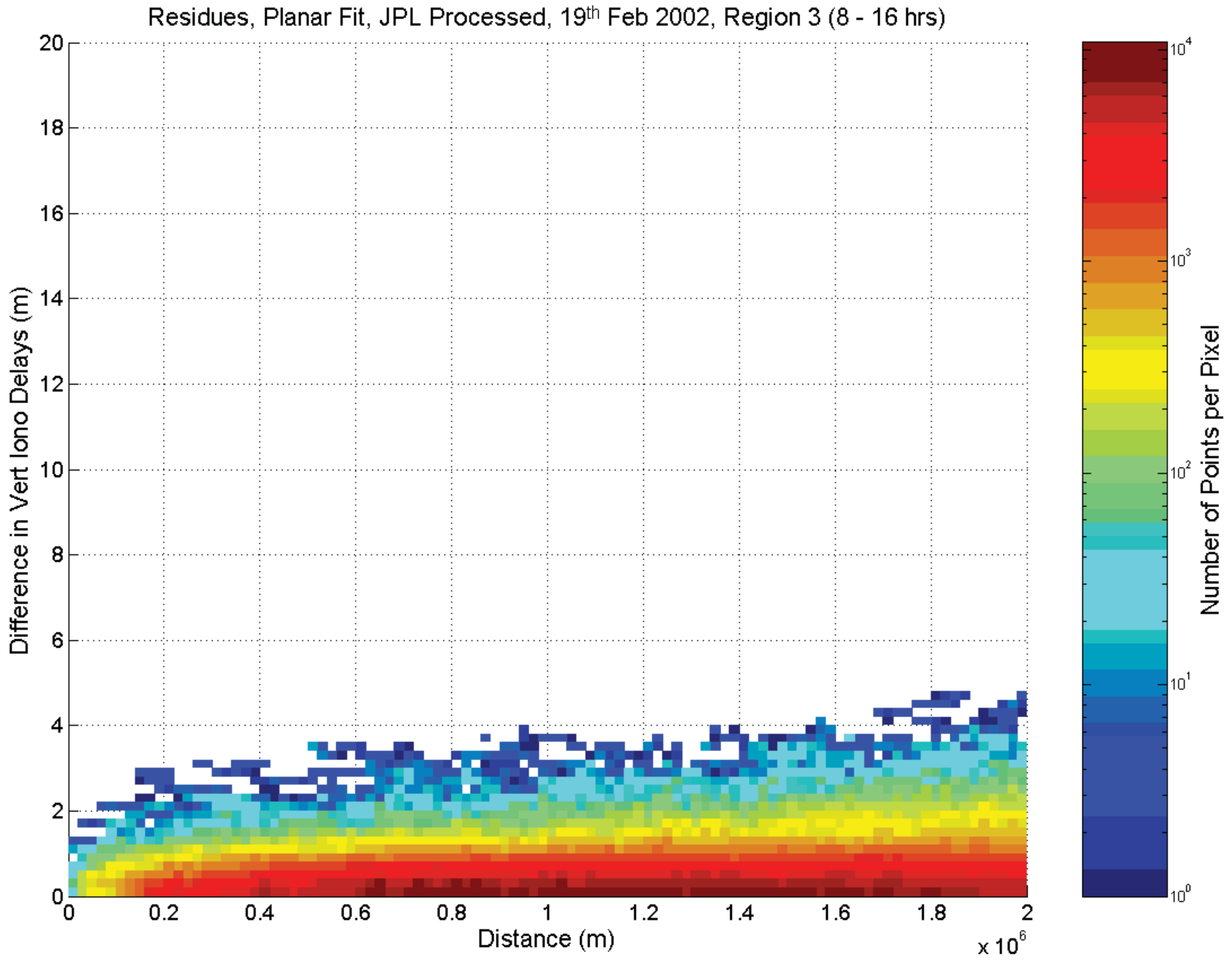
Two-D Histogram 1st Order (Region 2)



Two-D Histogram 1st Order (Region 3)



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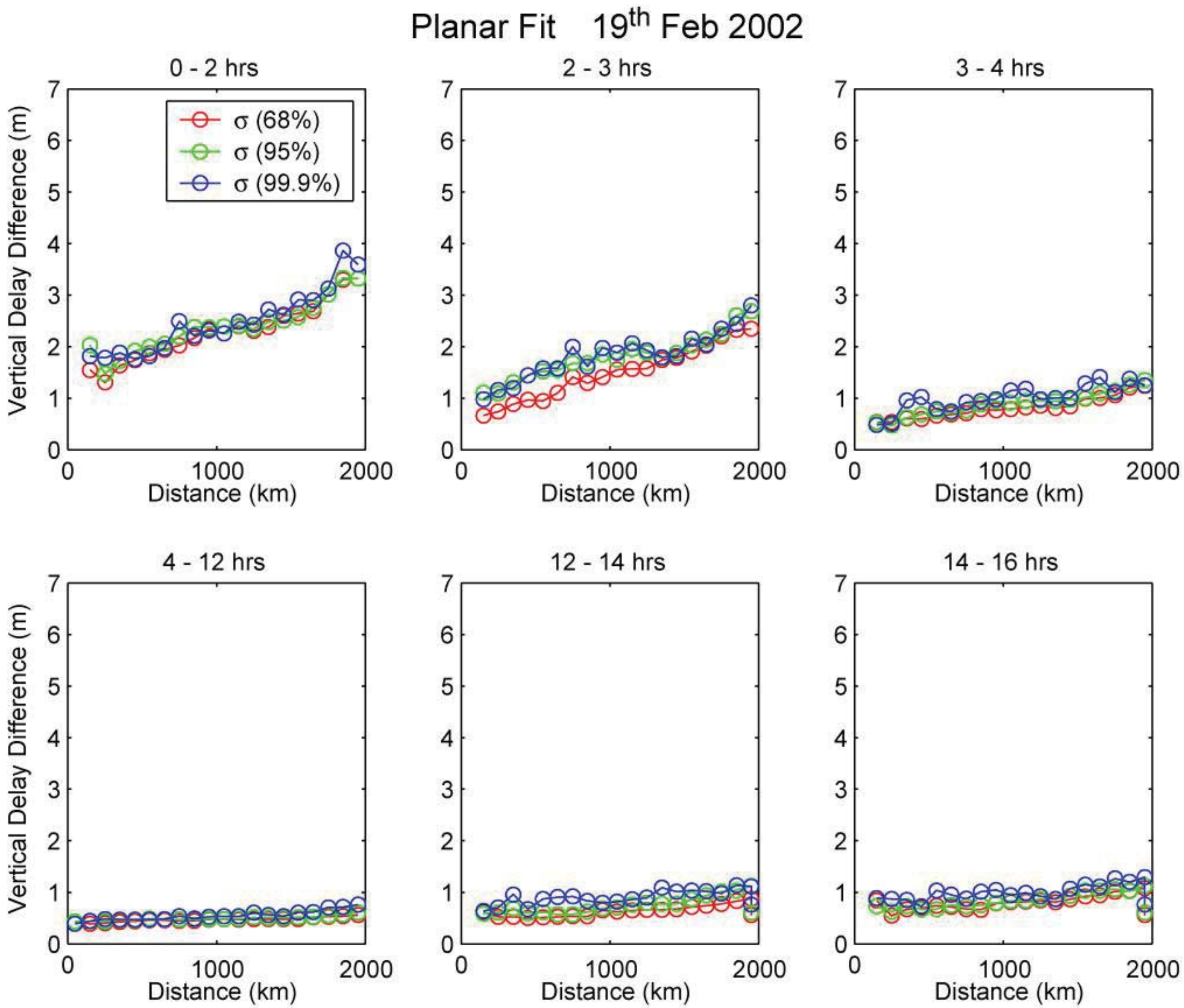
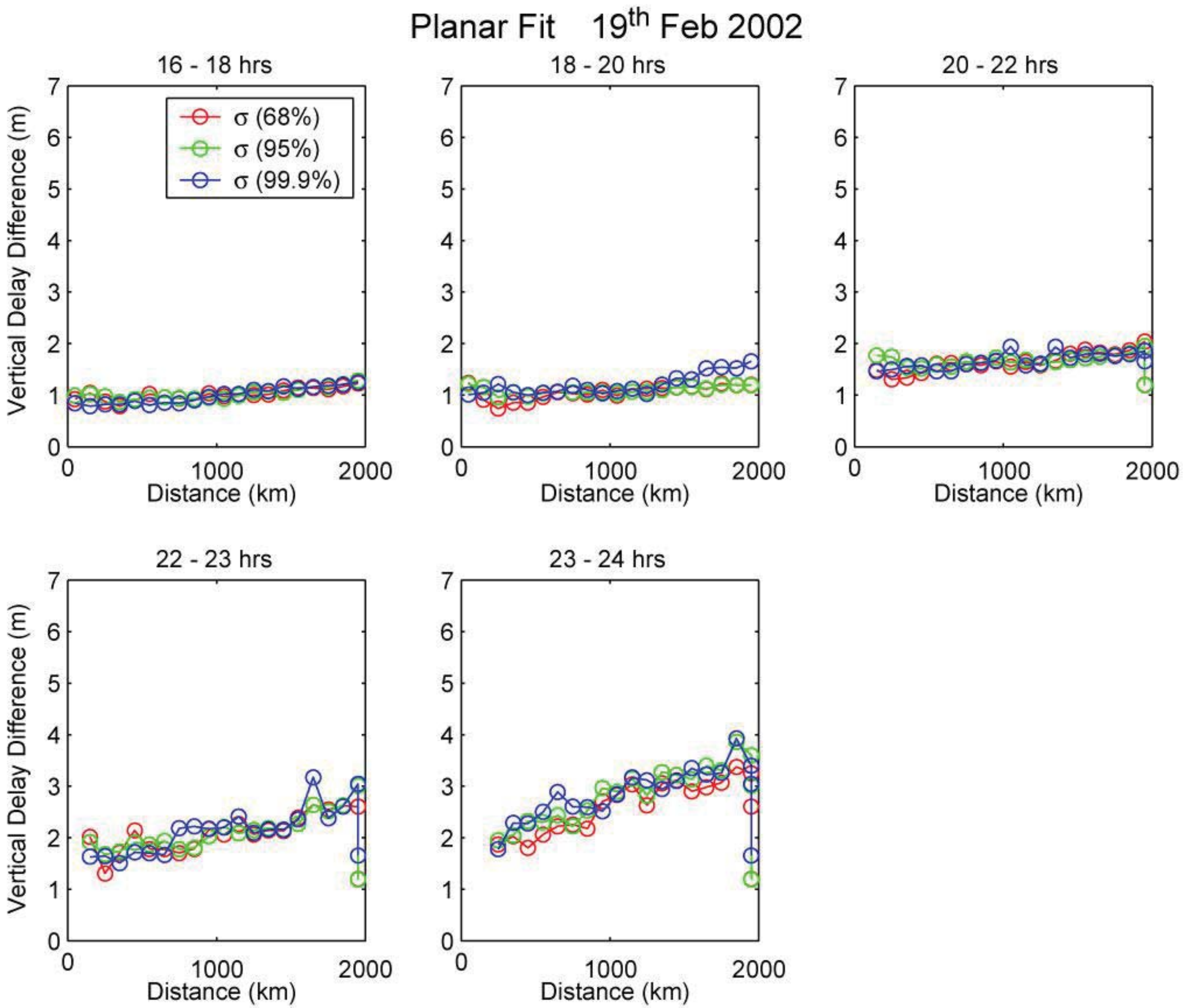
Sigma Estimate 1st Order (Sliced by Time)



Sigma Estimate 1st Order (Sliced by Time)



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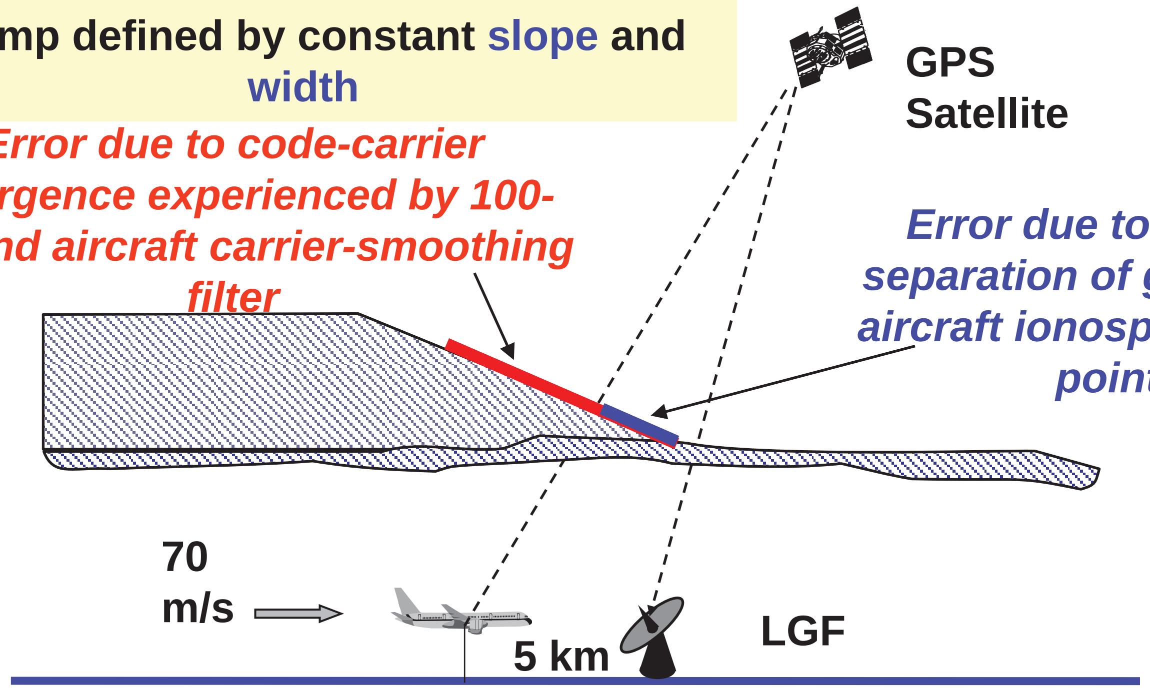
Correlation Observations

- Clear temporal dependencies in the variogram (σ_{decorr} term)
  - *Evening into nighttime is worst*
  - *Daytime more easily modeled*
- Clear spatial trends in the data
  - *1st and 2nd order model the trend about equally well, both better than 0th order*
- Random Component significantly larger than mid-latitude
  - *Gaussian over short times*

Contributors to Differential Ionosphere Error

Simplified Ionosphere Wave Front Model:
a ramp defined by constant slope and width



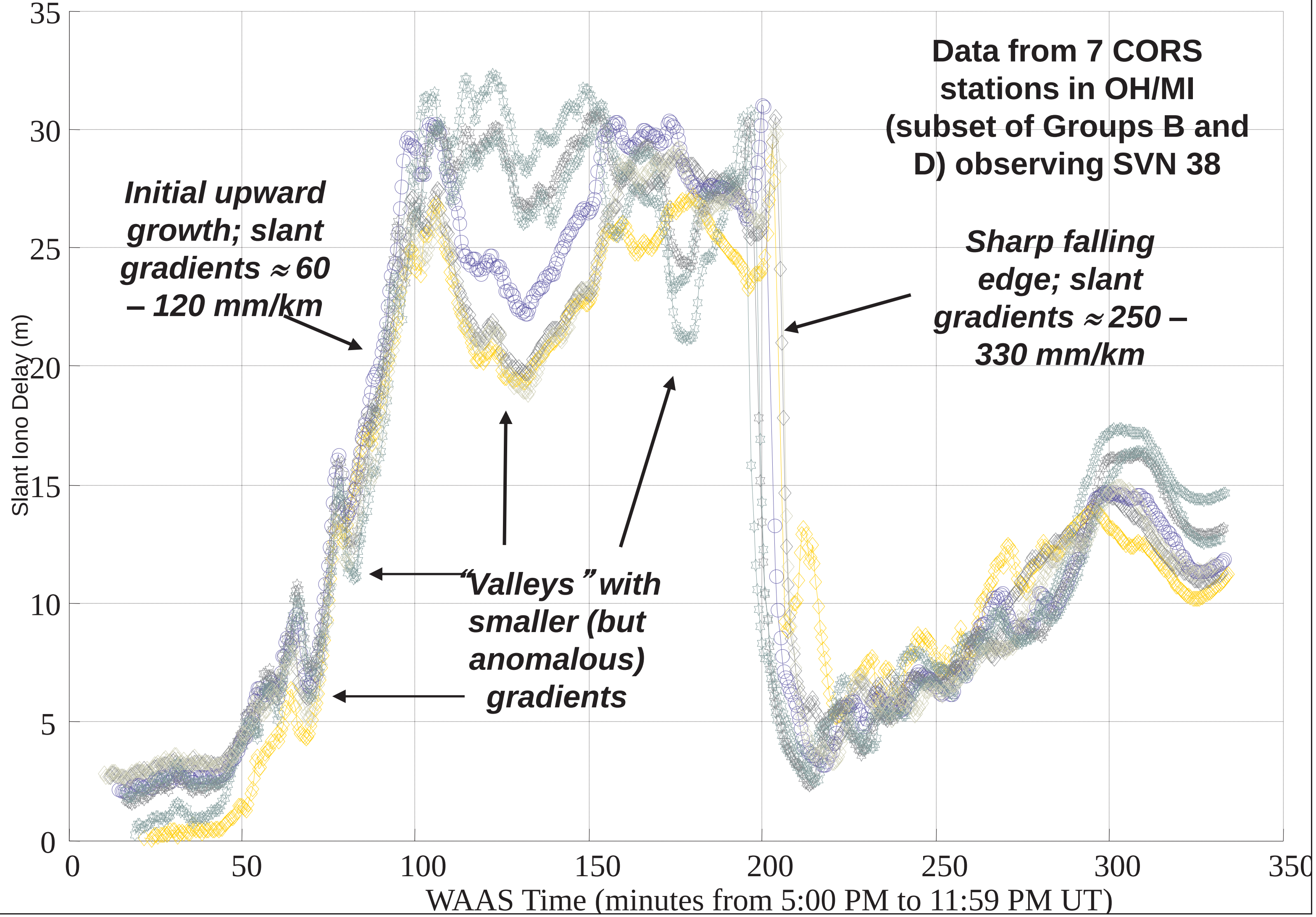
Diff. Iono Range Error = gradient slope × min{ (x + 2 τ v_{air}), gradient width}

For 5 km ground-to-air separation at CAT I DH: x = 5 km; τ = 100 sec; v_{air} = 70 m/s

=> *"virtual baseline" at DH* = x + 2 τ v_{air} = 5 + 14 = 19

Courtesy:
Sam Pullen

Ionosphere Delay Gradients 20 Nov. 2003

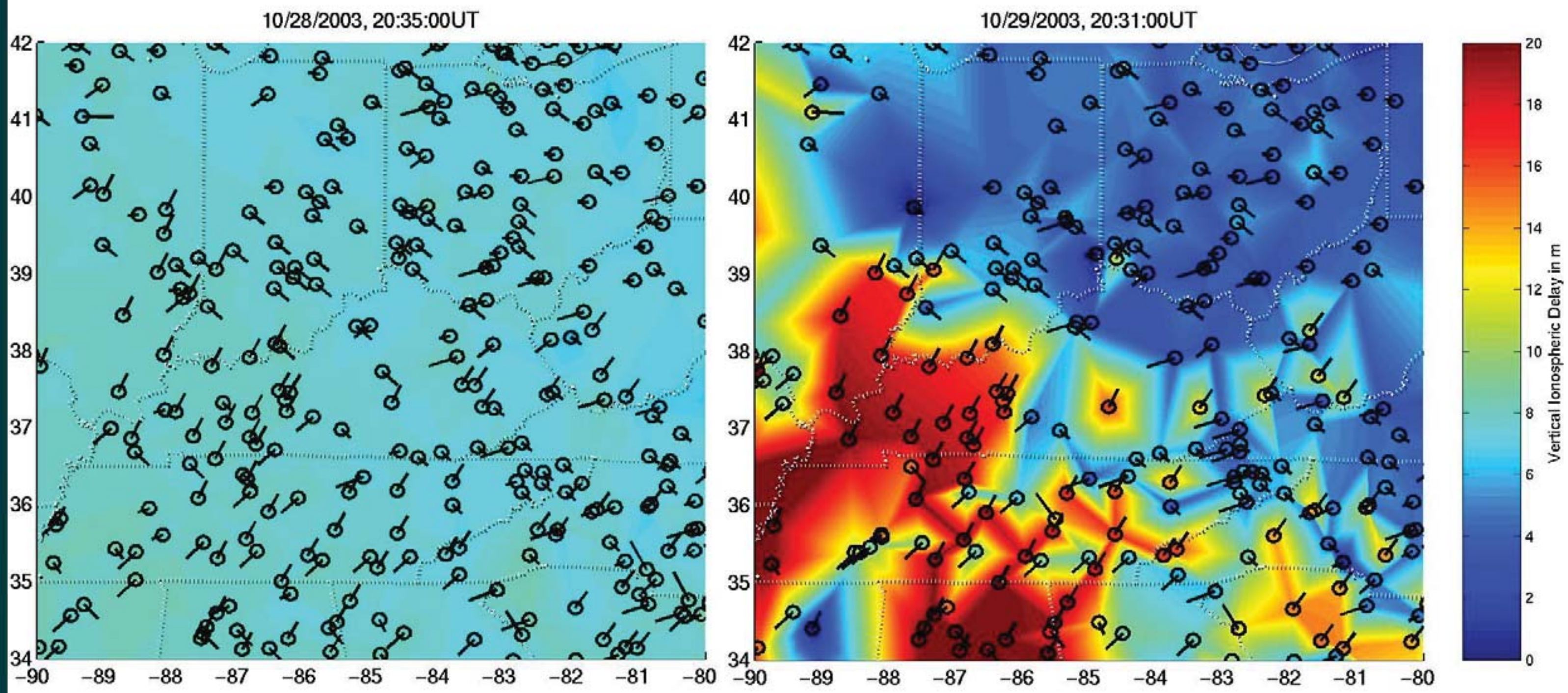


Courtesy:
Sam Pullen

SBAS Ionospheric Threats

- WAAS Was Commissioned on 10 July 2003
  - *Availability > 99% for first 3 months*
- October 29-31 Two Large Disturbances Each Cause the Storm Detectors to Trip for Hours
  - *Protection factor set to ~15 m 1-sigma*
- November 20-21 Another Large Disturbance Limits Vertical Guidance for Several Hours

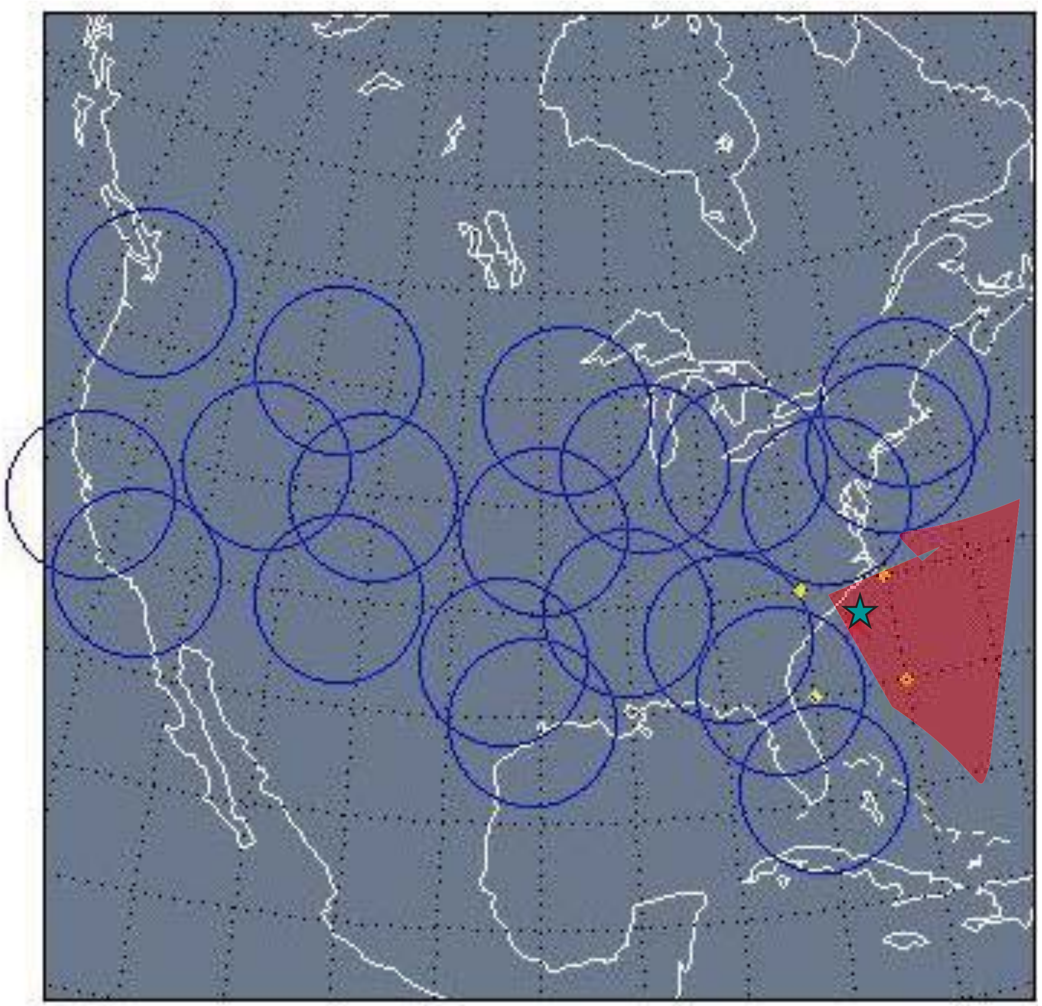
Failure of Thin Shell Model



Quiet Day

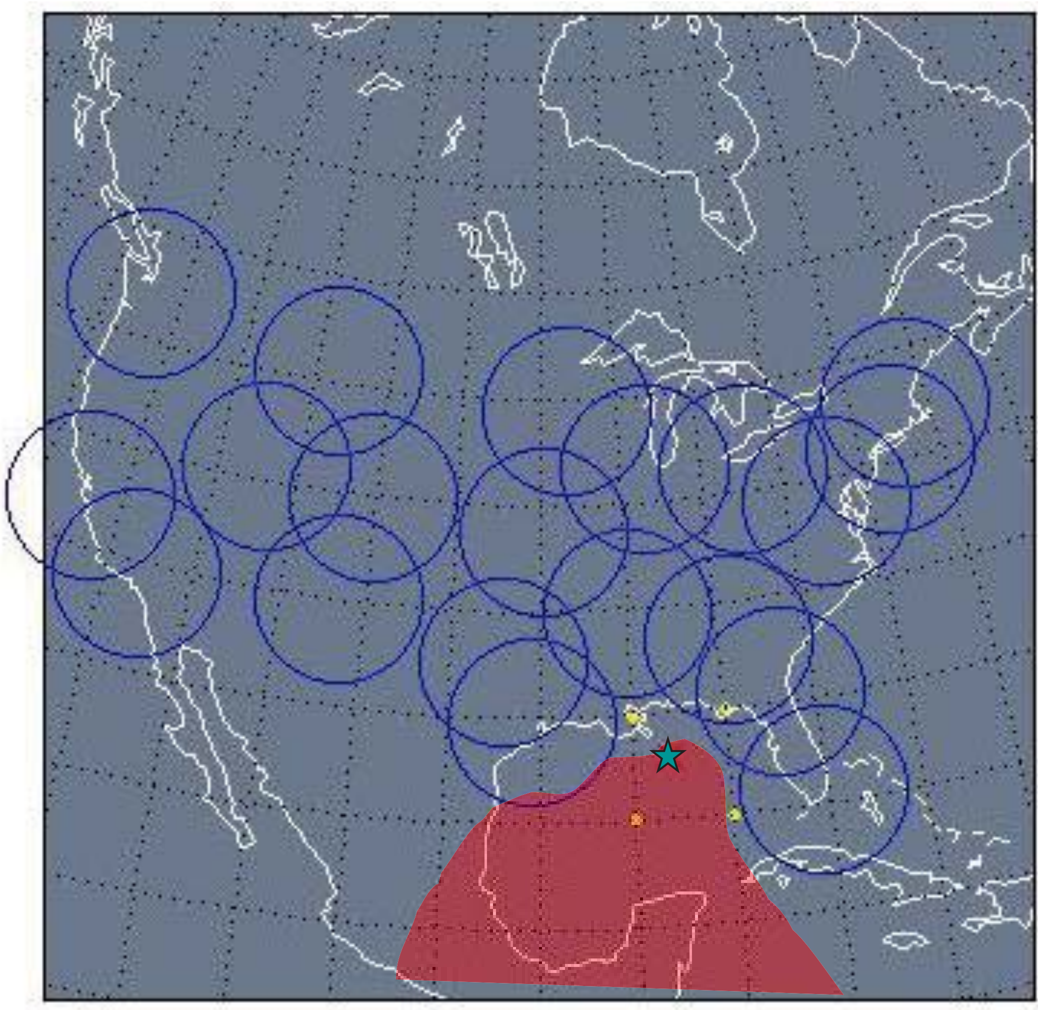
Disturbed Day

Threats at the Edge of Coverage



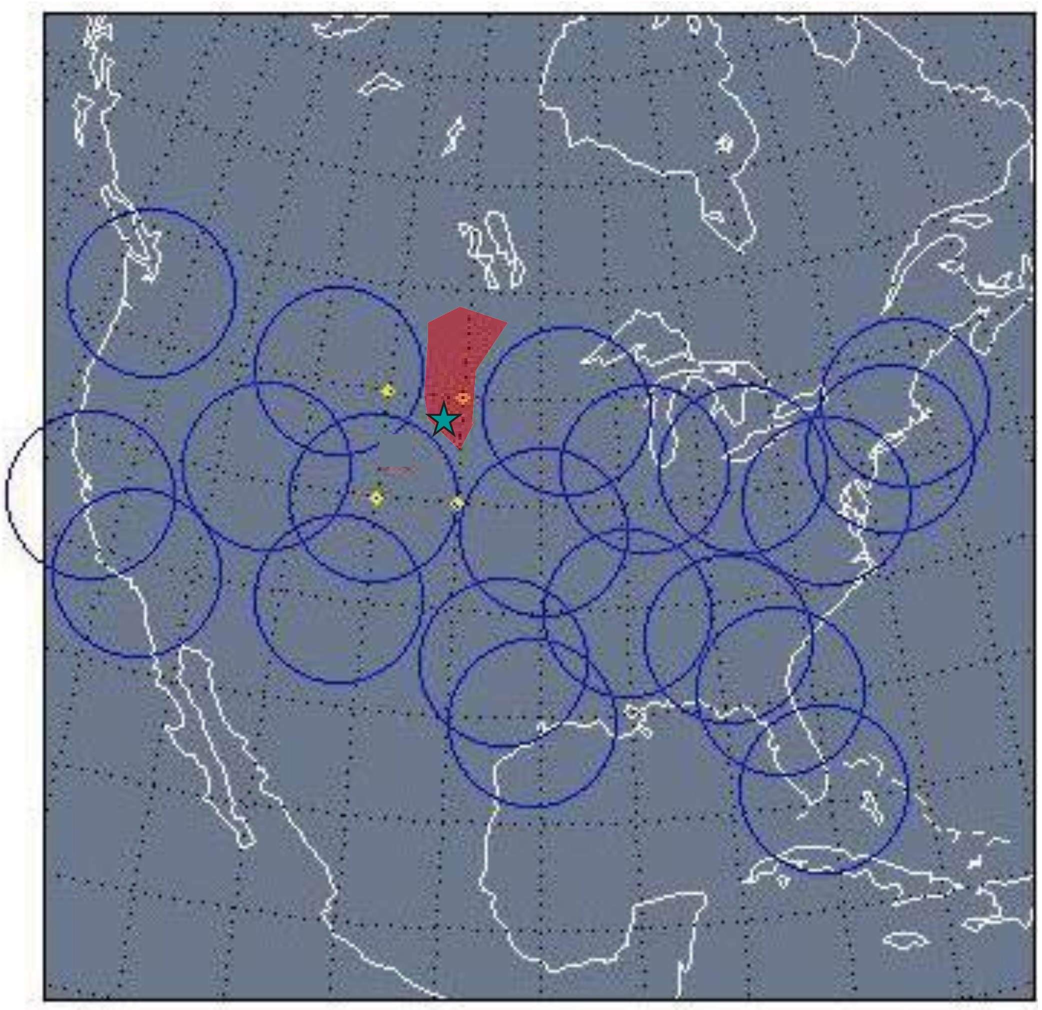
Courtesy:
Seebany
Datta-Barua

Edge of Coverage 2



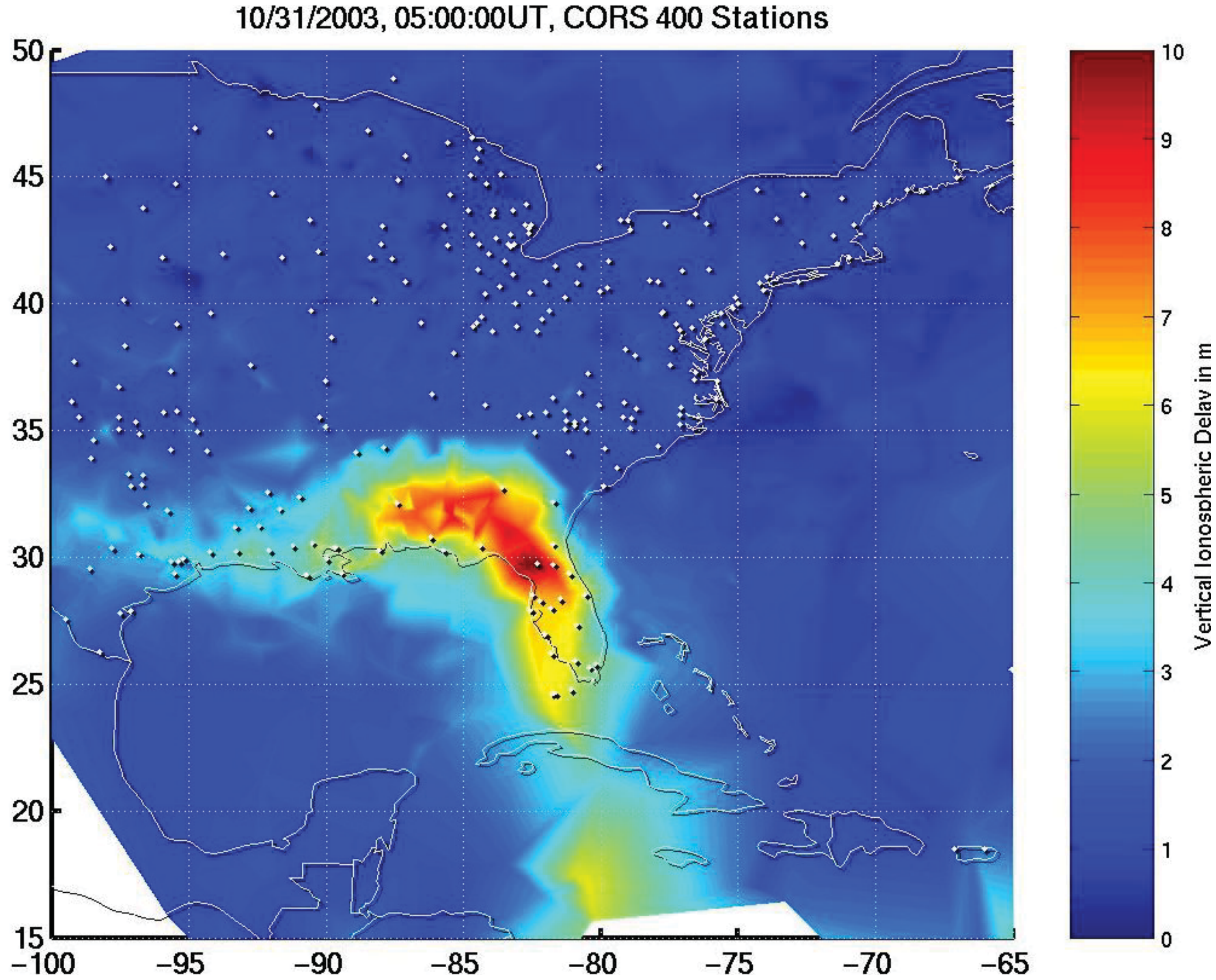
Courtesy:
Seebany
Datta-Barua

Undersampling Within CONUS



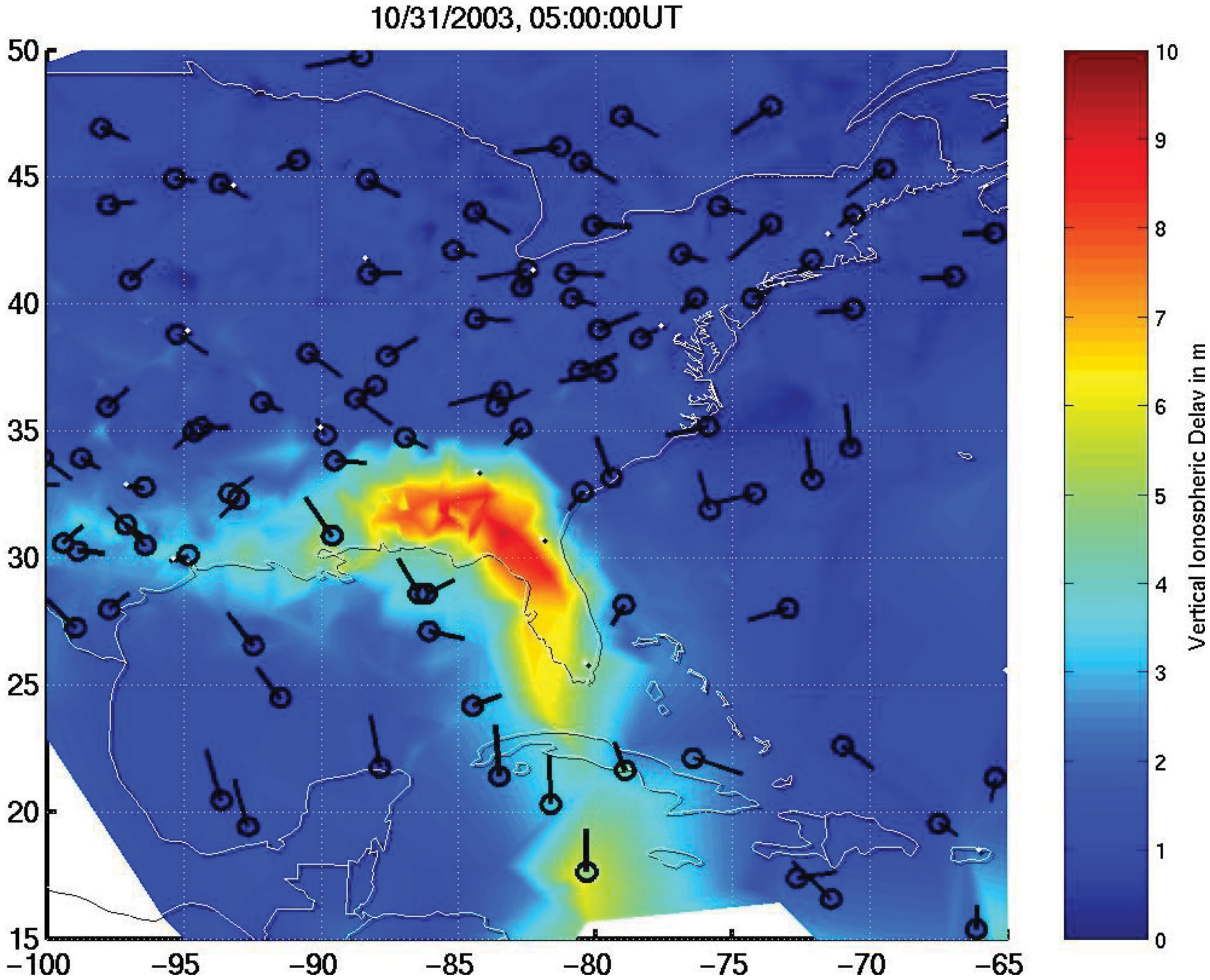
Courtesy:
Seebany
Datta-Barua

Small-scale Irregularity



Courtesy:
Seebany
Datta-Barua

Artificial Undersampled Scenario



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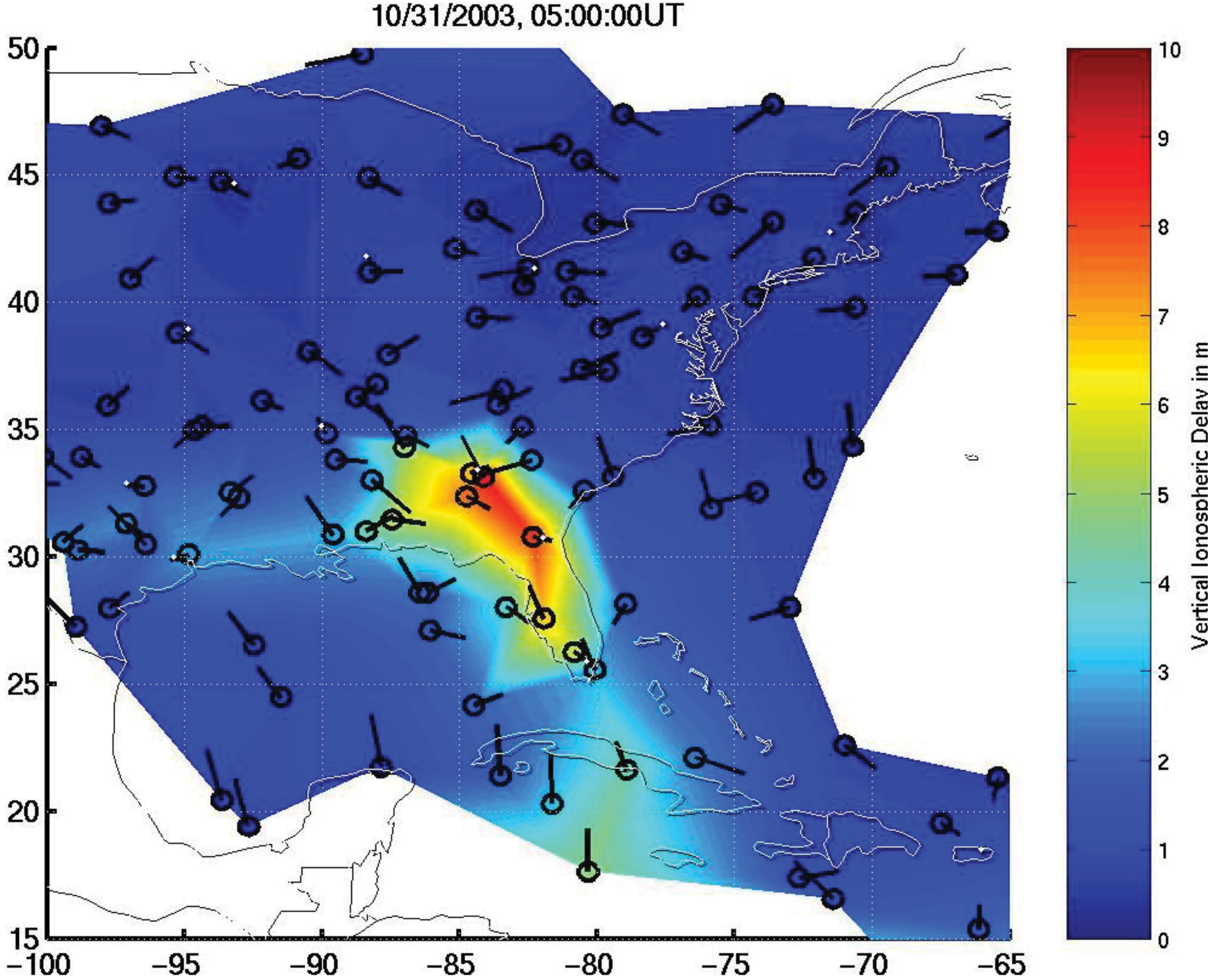
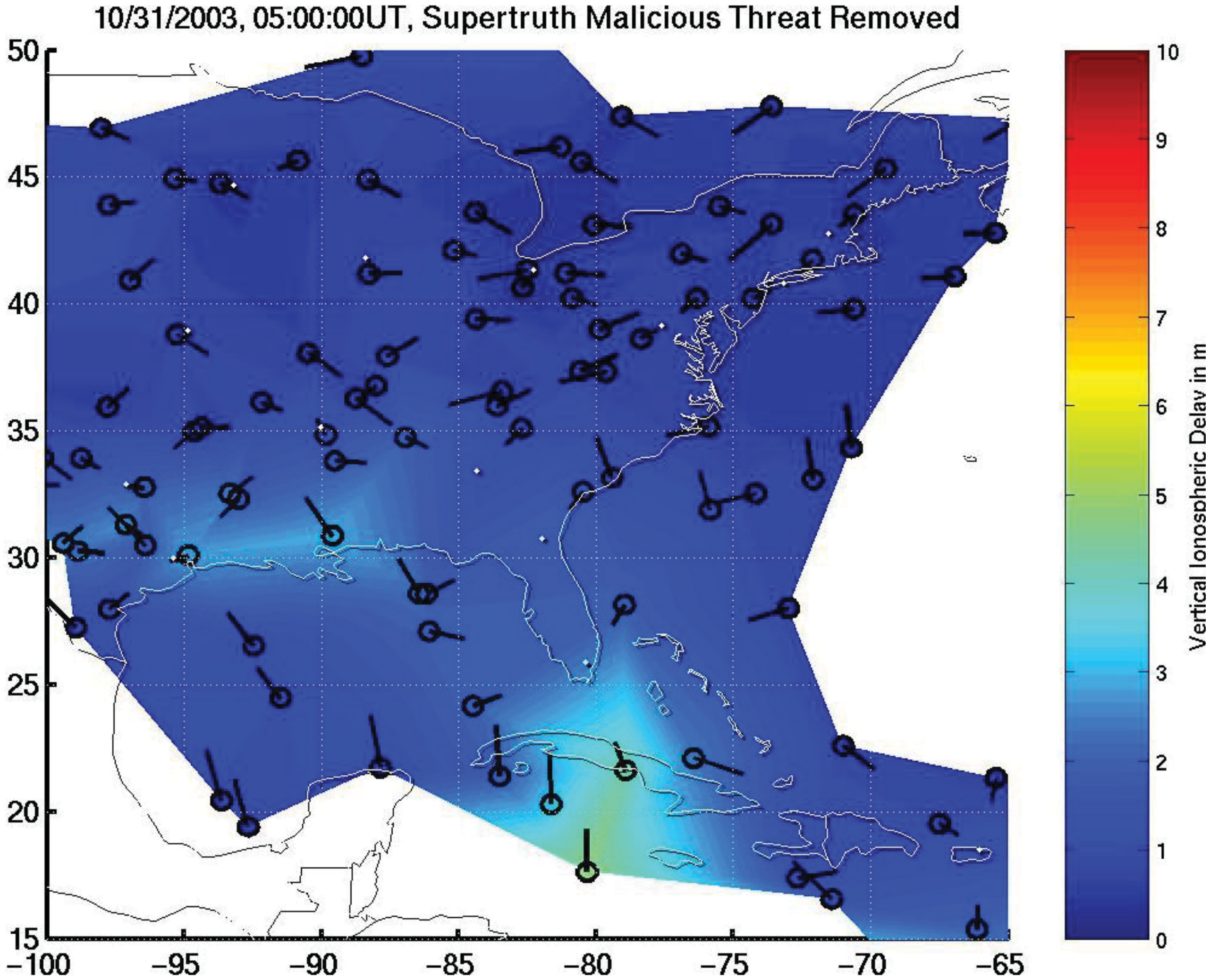
Seebany
Datta-Barua

WAAS Measurements



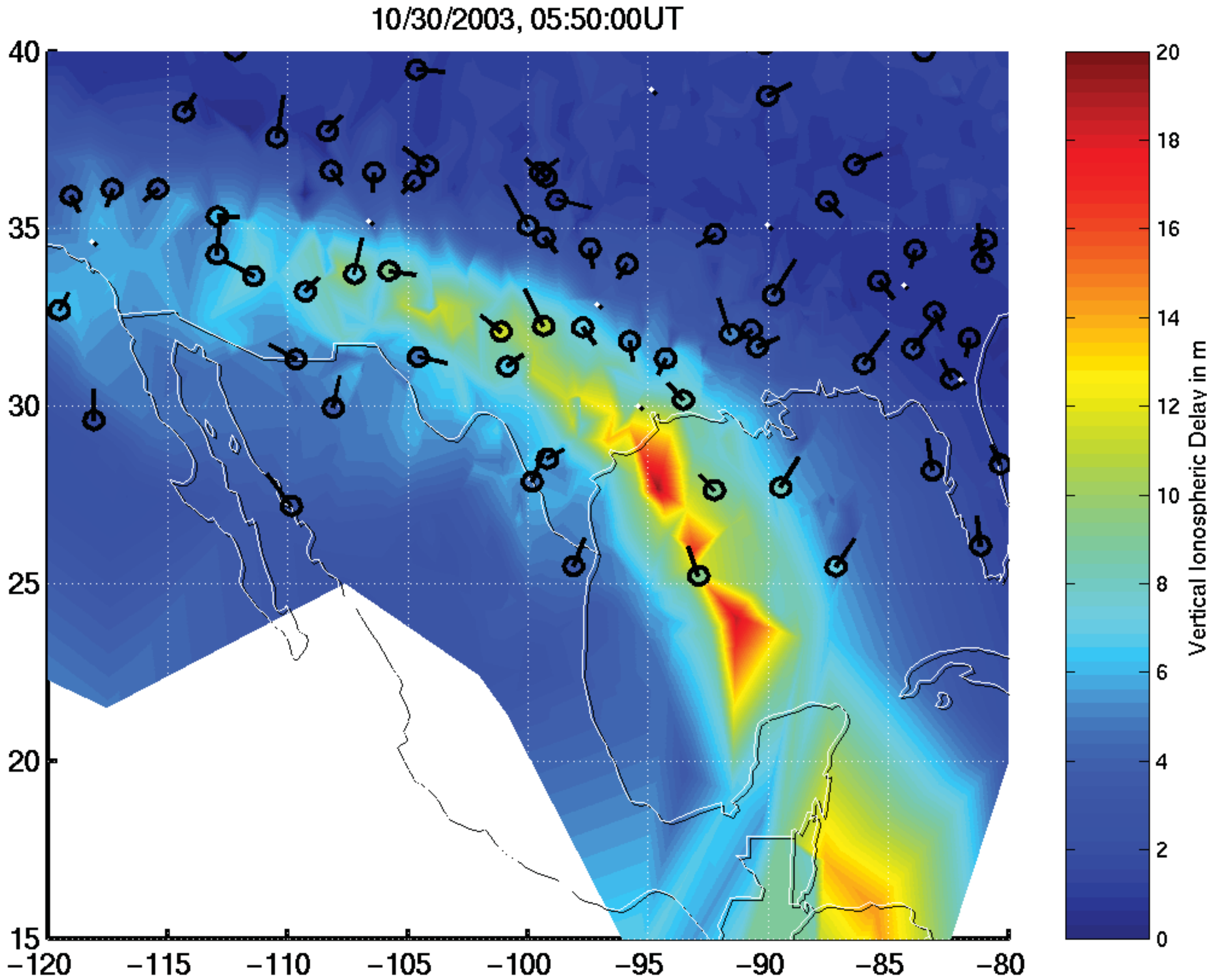
Courtesy:
Seebany
Datta-Barua

Artificial WAAS Undersampling Scenario



Courtesy:
Seebany
Datta-Barua

Real Undersampled Condition



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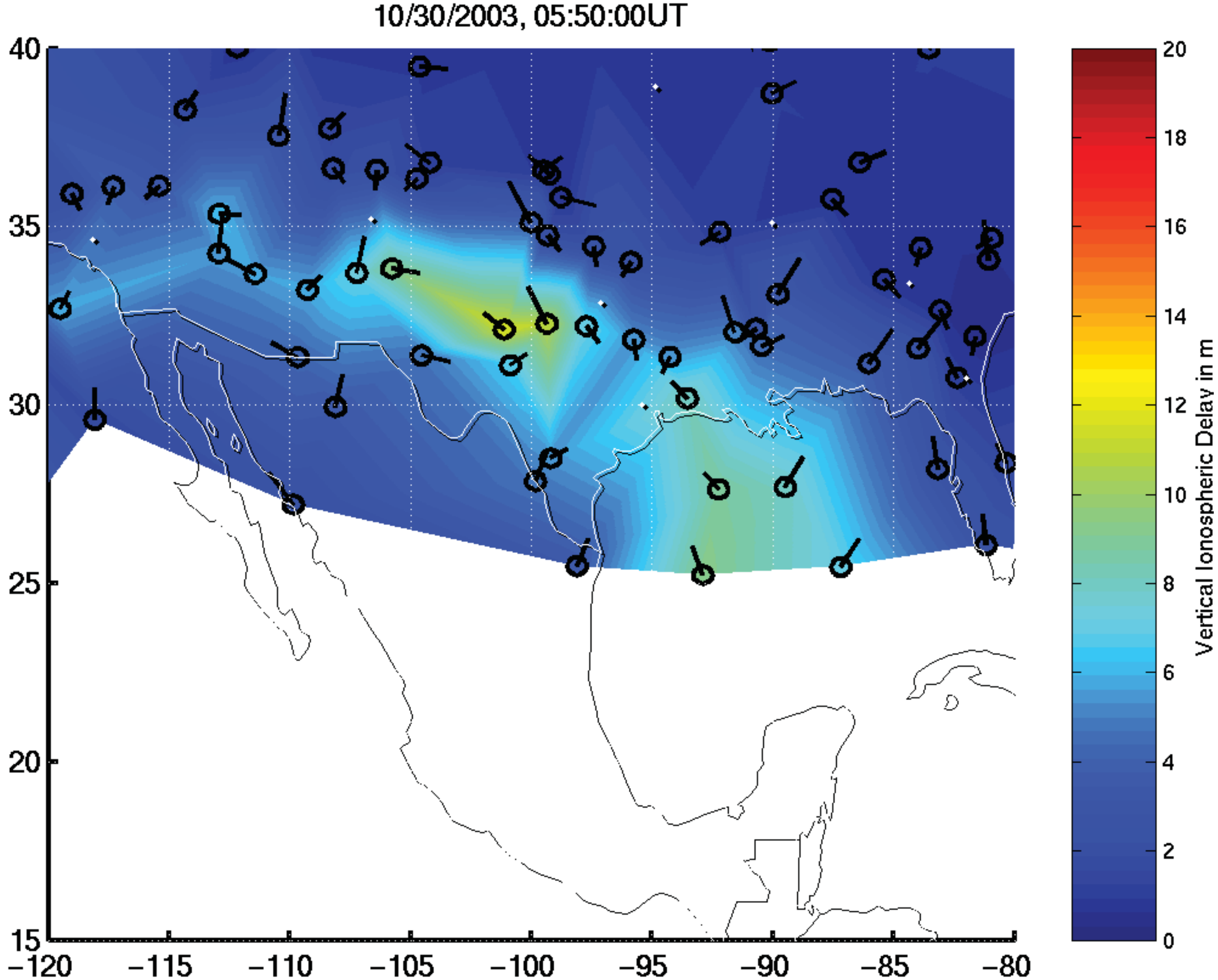
Seebany
Datta-Barua

WAAS Measurements



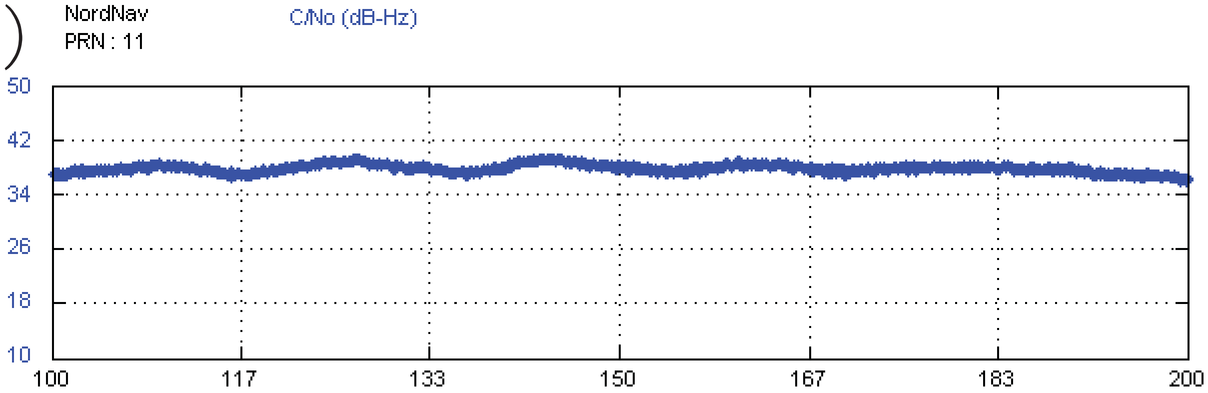
Courtesy:
Seebany
Datta-Barua

Scintillation and Deep Signal Fading

- Signal to noise ratio (C/No) of PRN 11 (Mar. 18, 2001)

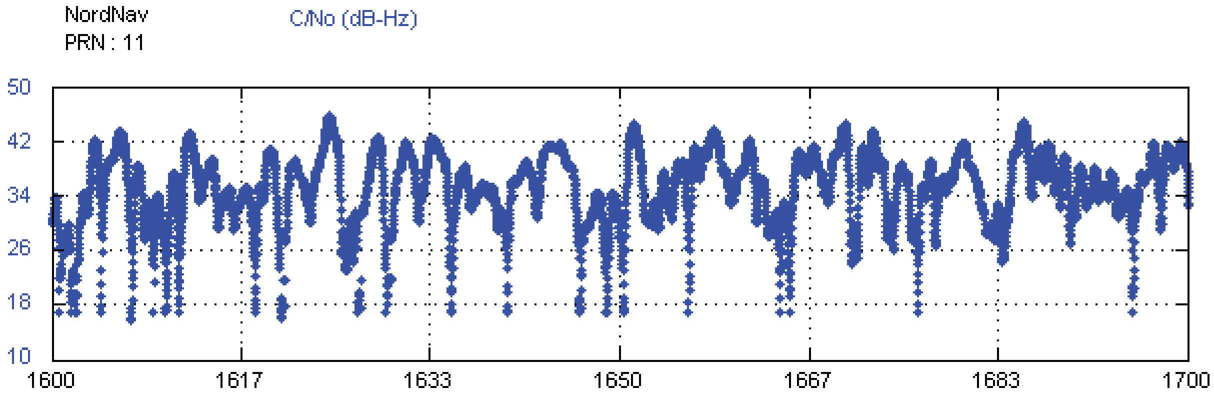
C/No

Nominal



Scintillation

(equatorial & solar max)

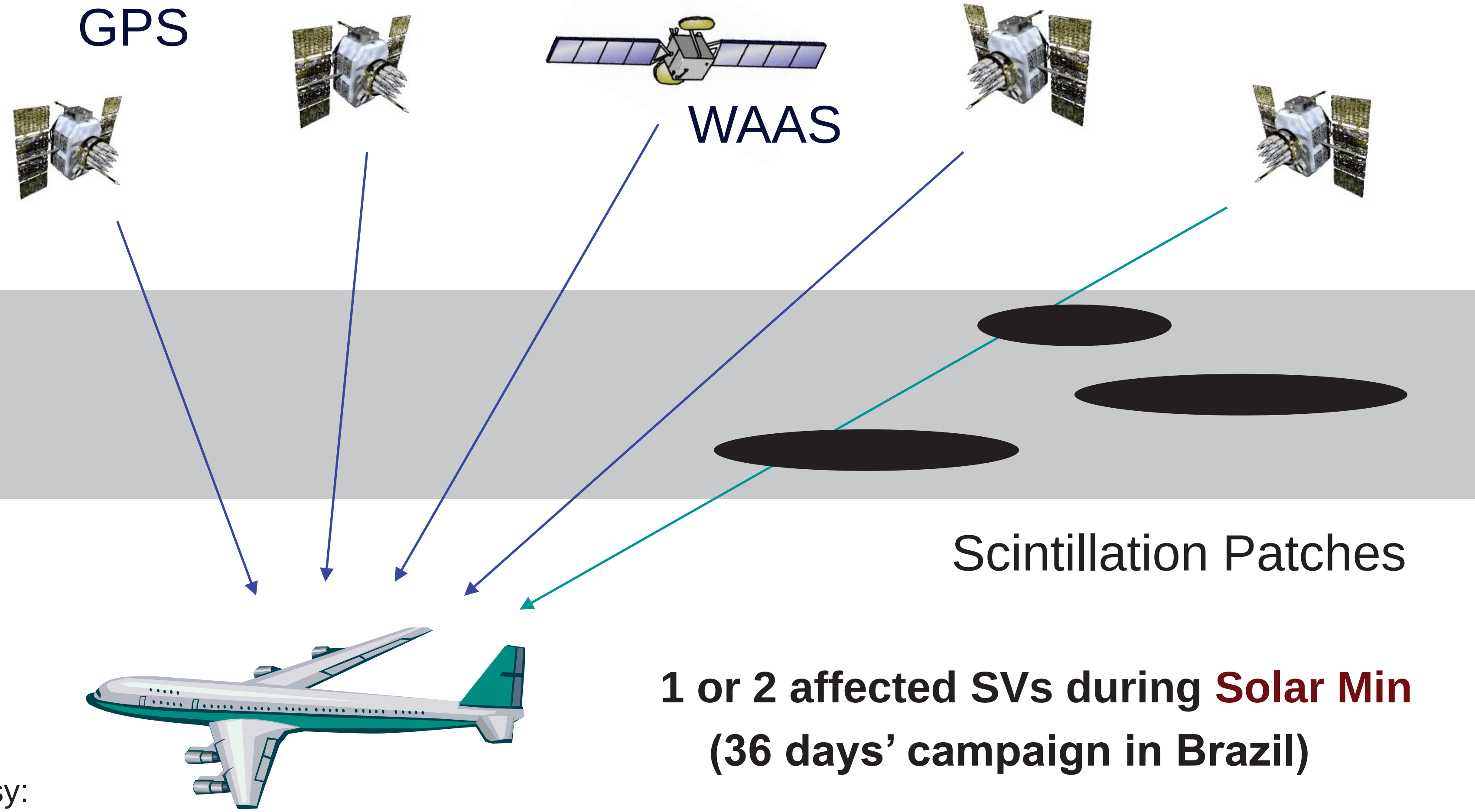


25 dB

Courtesy: Jiwon Seo

100 sec

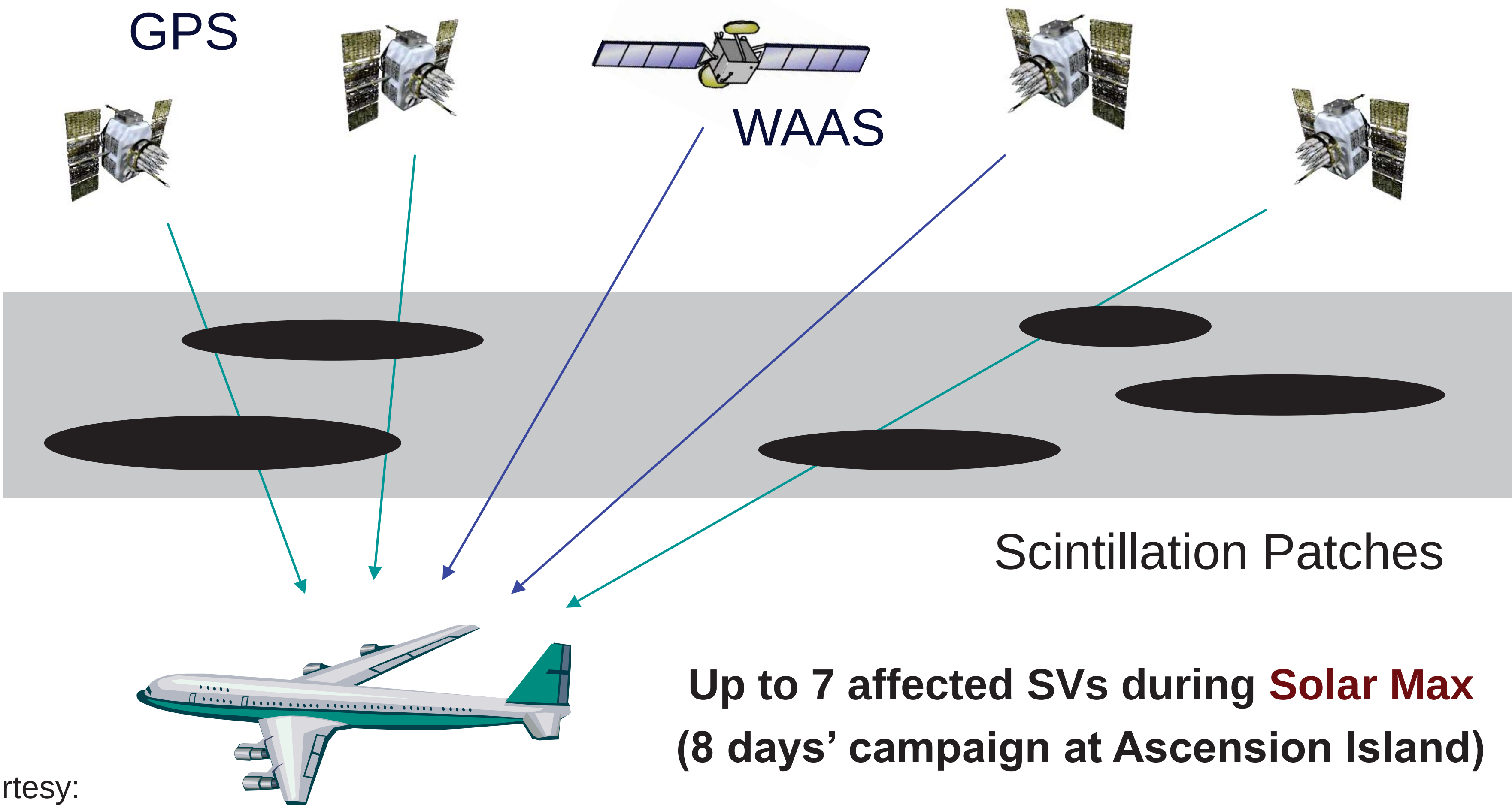
Scintillation and Navigation



1 or 2 affected SVs during Solar Min
(36 days' campaign in Brazil)

Courtesy:
Jiwon Seo

Scintillation and Navigation



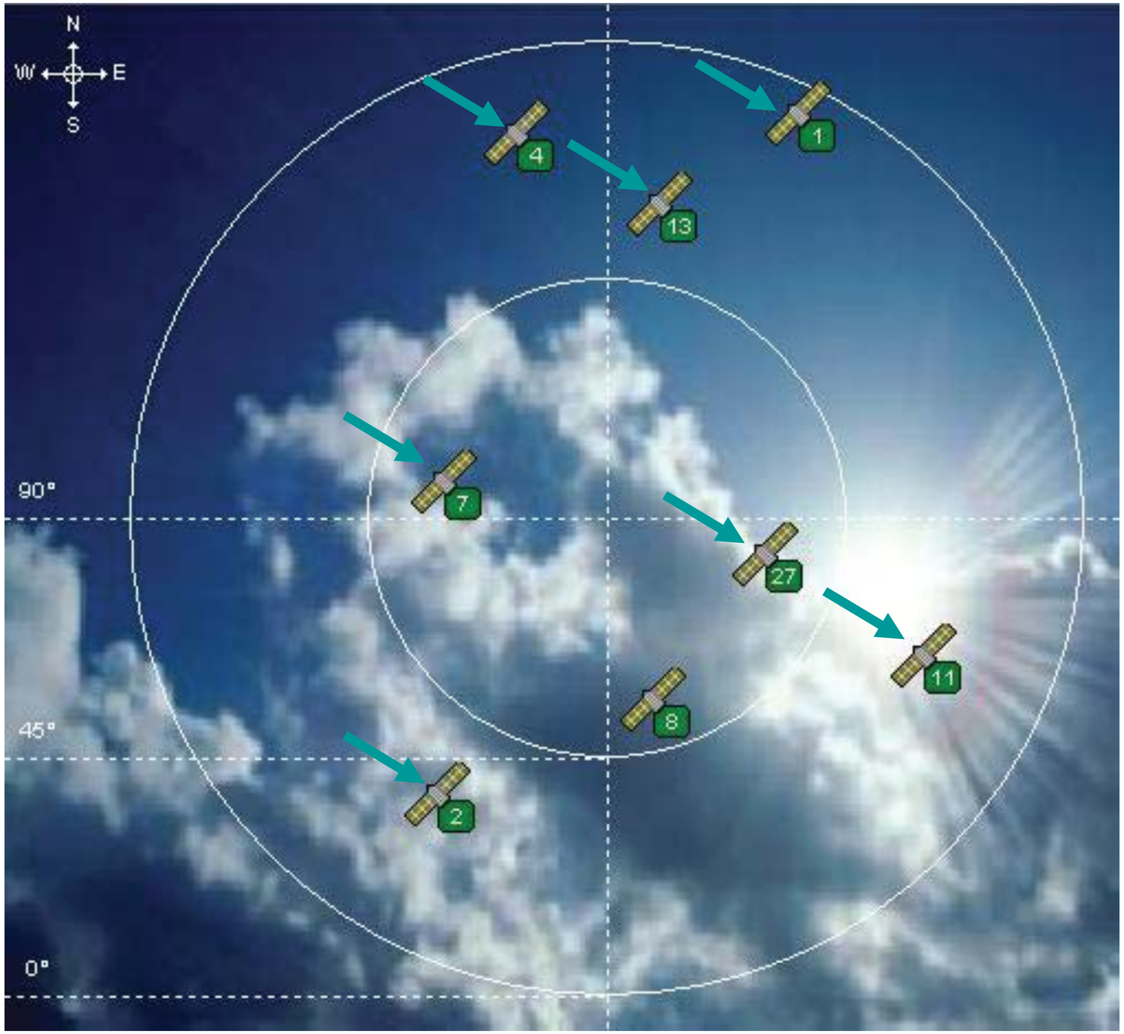
Up to 7 affected SVs during Solar Max
(8 days' campaign at Ascension Island)

Courtesy:
Jiwon Seo

Severe Scintillation Data

Solar Max

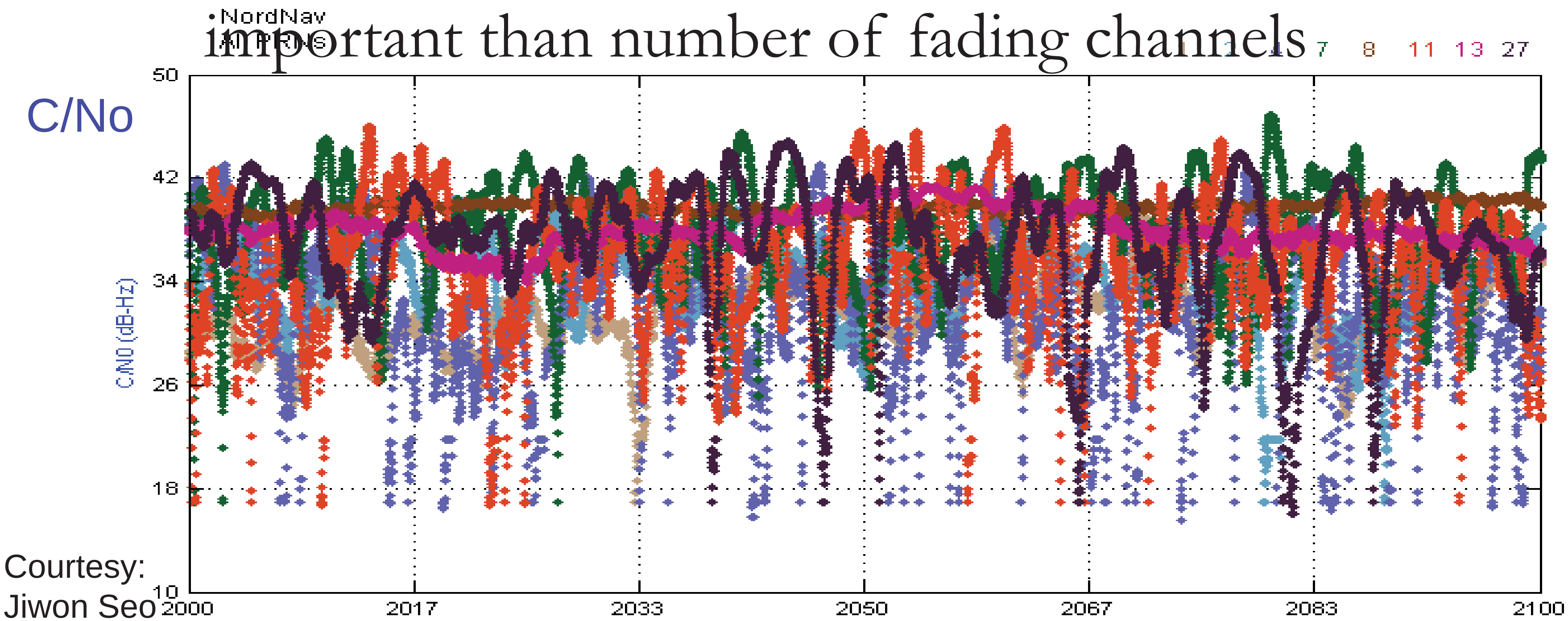
(worst 45 min in 8 days)



Courtesy:
Jiwon Seo

Severe Scintillation (example)

- 50 Hz C/No outputs of all 8 satellites on sky (100 sec out of 45 min data as an example)
- Number of simultaneous loss of satellites is more important than number of fading channels



Courtesy: Jiwon Seo

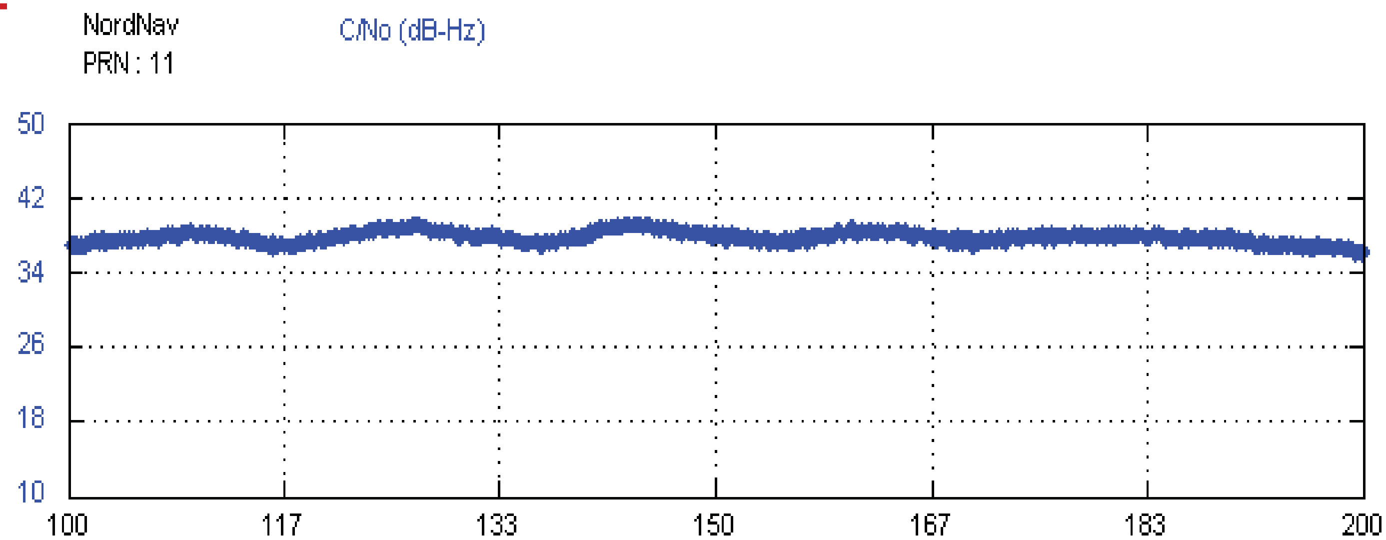
100 sec

Hatch Filter Model

50 dB-Hz

C/No

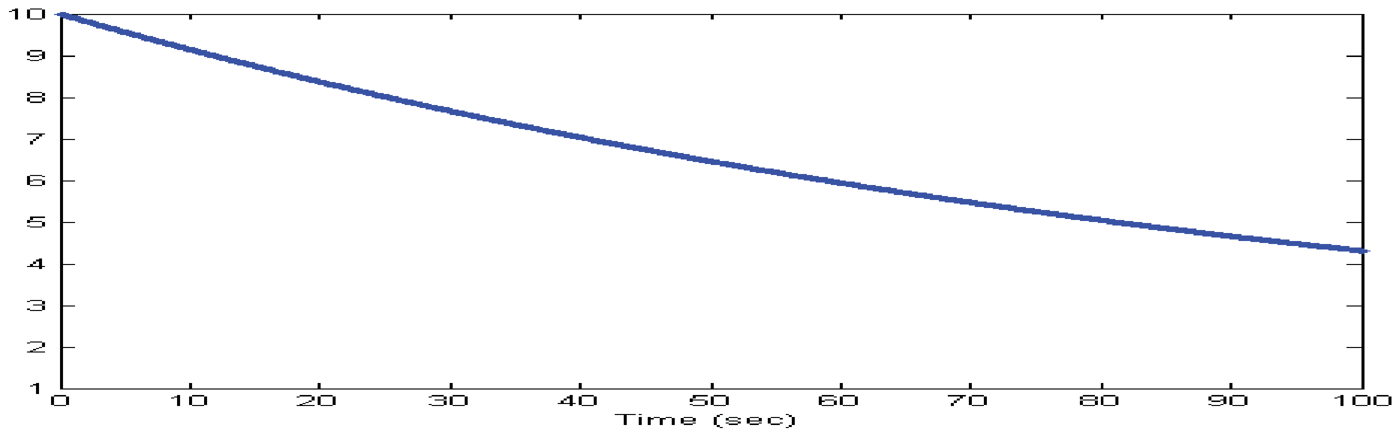
10 dB-Hz



10

Relative
Noise
Level

1



Courtesy:
Jiwon Seo

100 sec

Hatch Filter Model

50 dB-Hz

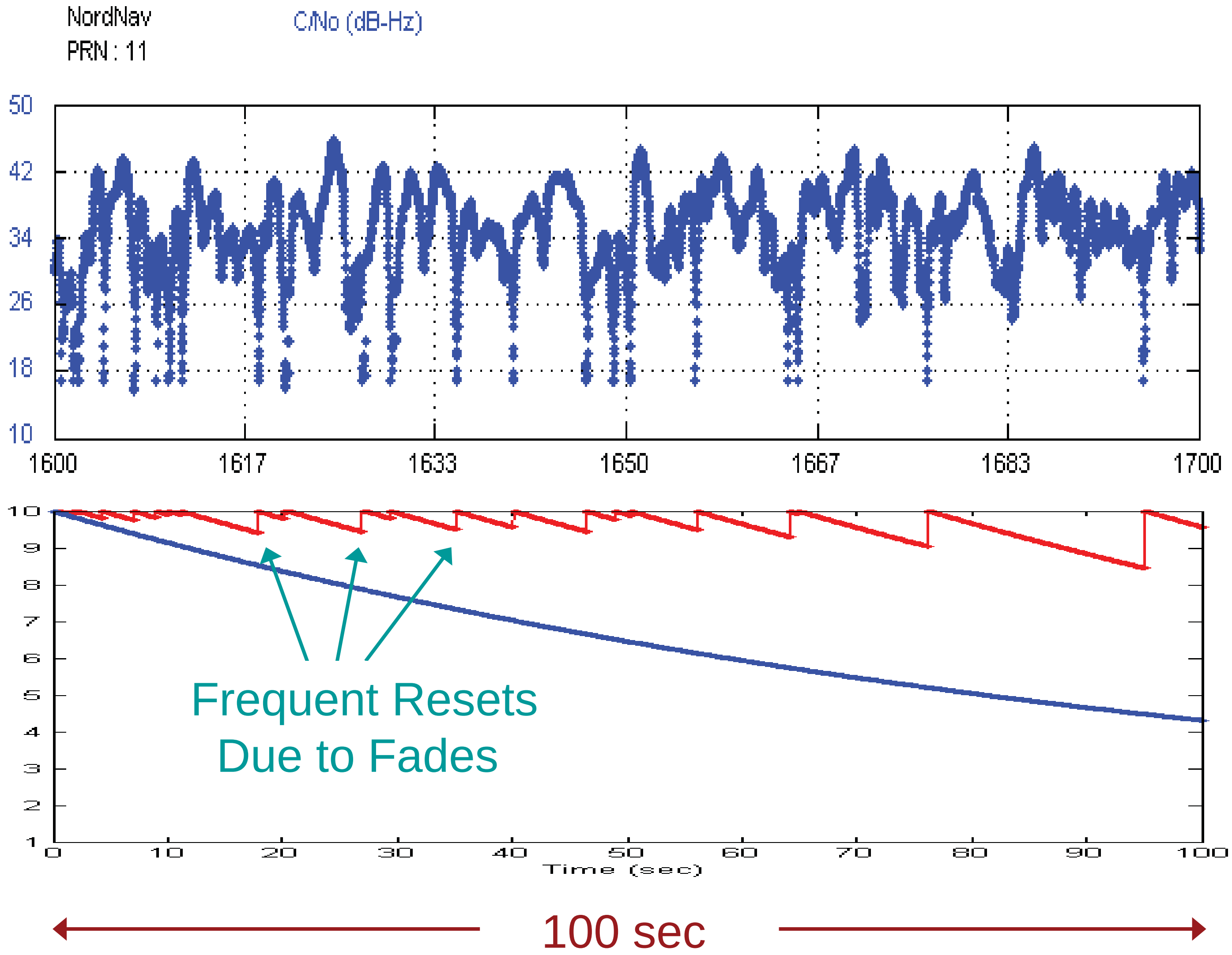
C/No

10 dB-Hz

10

Relative Noise Level

1



Courtesy:
Jiwon Seo

Regions with Scintillation

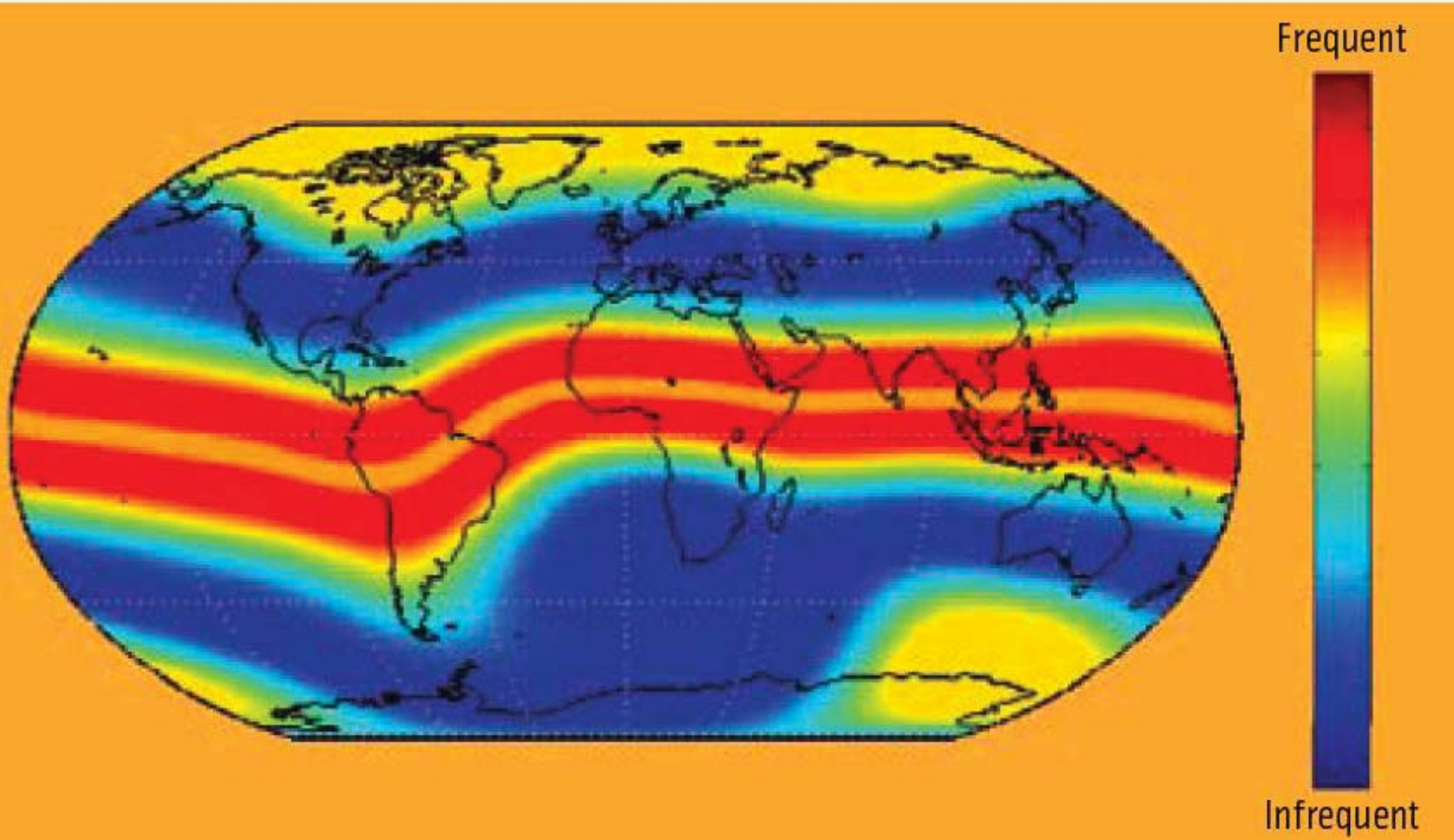


FIGURE 1 Scintillation map showing the frequency of disturbances at solar maximum. Scintillation is most intense and most frequent in two bands surrounding the magnetic equator, up to 100 days per year. At poleward latitudes, it is less frequent and it is least frequent at mid-latitude, a few to ten days per year.

Courtesy: Paul Kintner

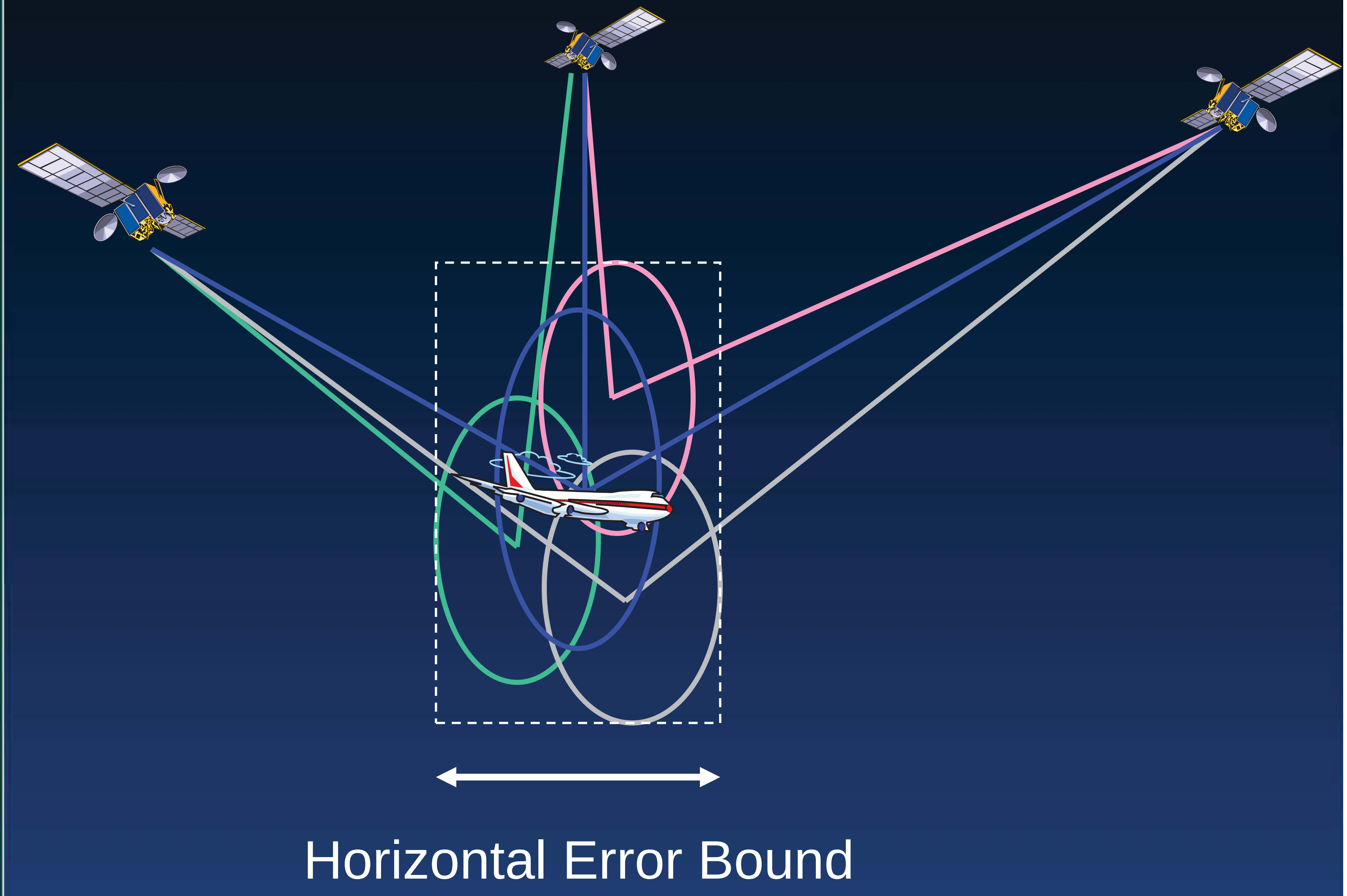
Outline

- Ionospheric Modeling
- Ionospheric Threats
- **Next Generation Satellite Navigation**
- Future Signals
- Conclusions

Looking Ahead

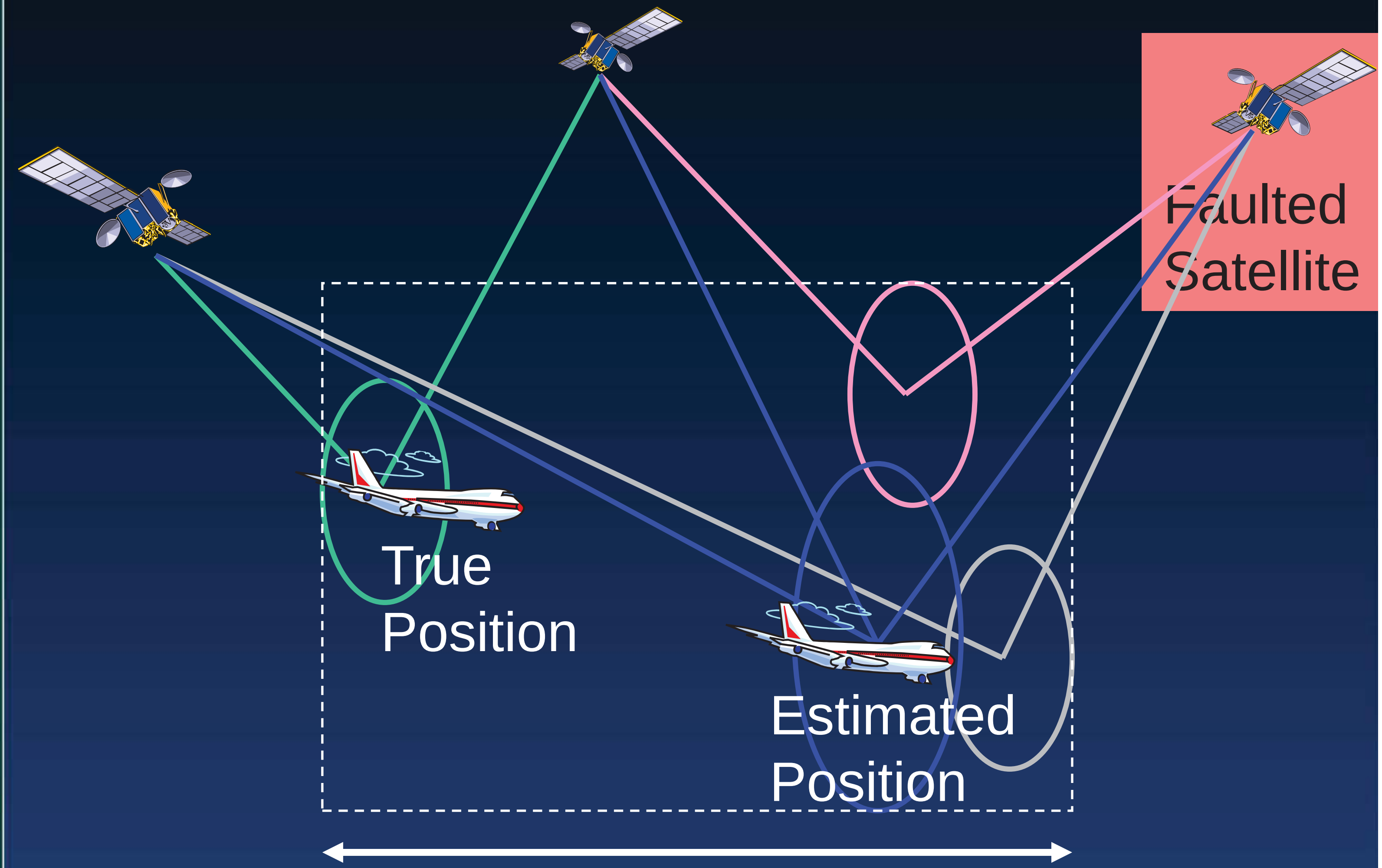
- Next generation of satellite navigation will exploit new signals and new systems
  - *GPS is being modernized*
  - *Other nations developing SatNav*
- It is time to plan ahead
  - *What new capabilities can we provide?*
  - *Are there more efficient ways to provide them?*

RAIM Protection



Courtesy:
Juan Blanch

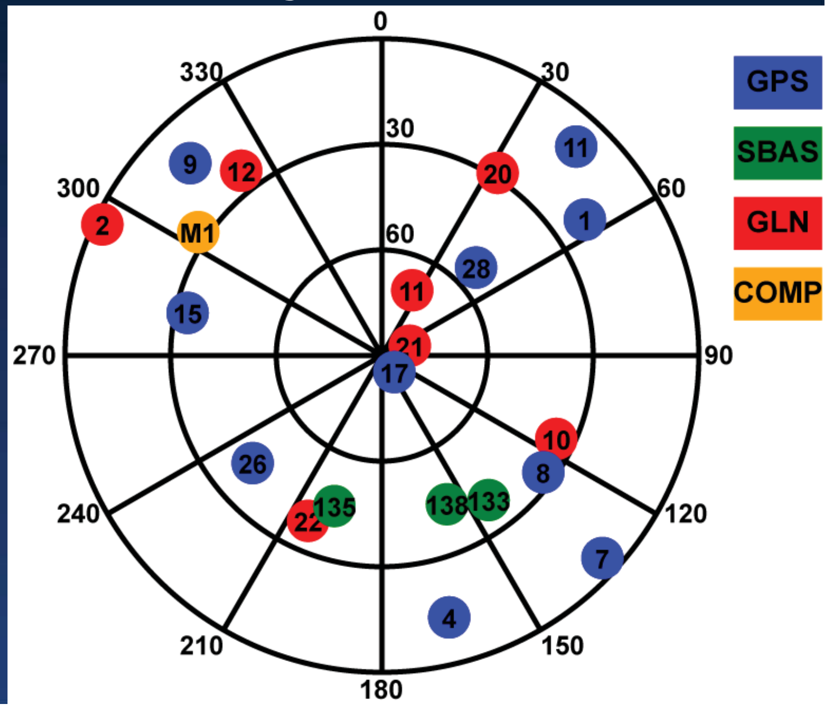
RAIM Protection



Courtesy:
Juan Blanch

New GNSS Constellations

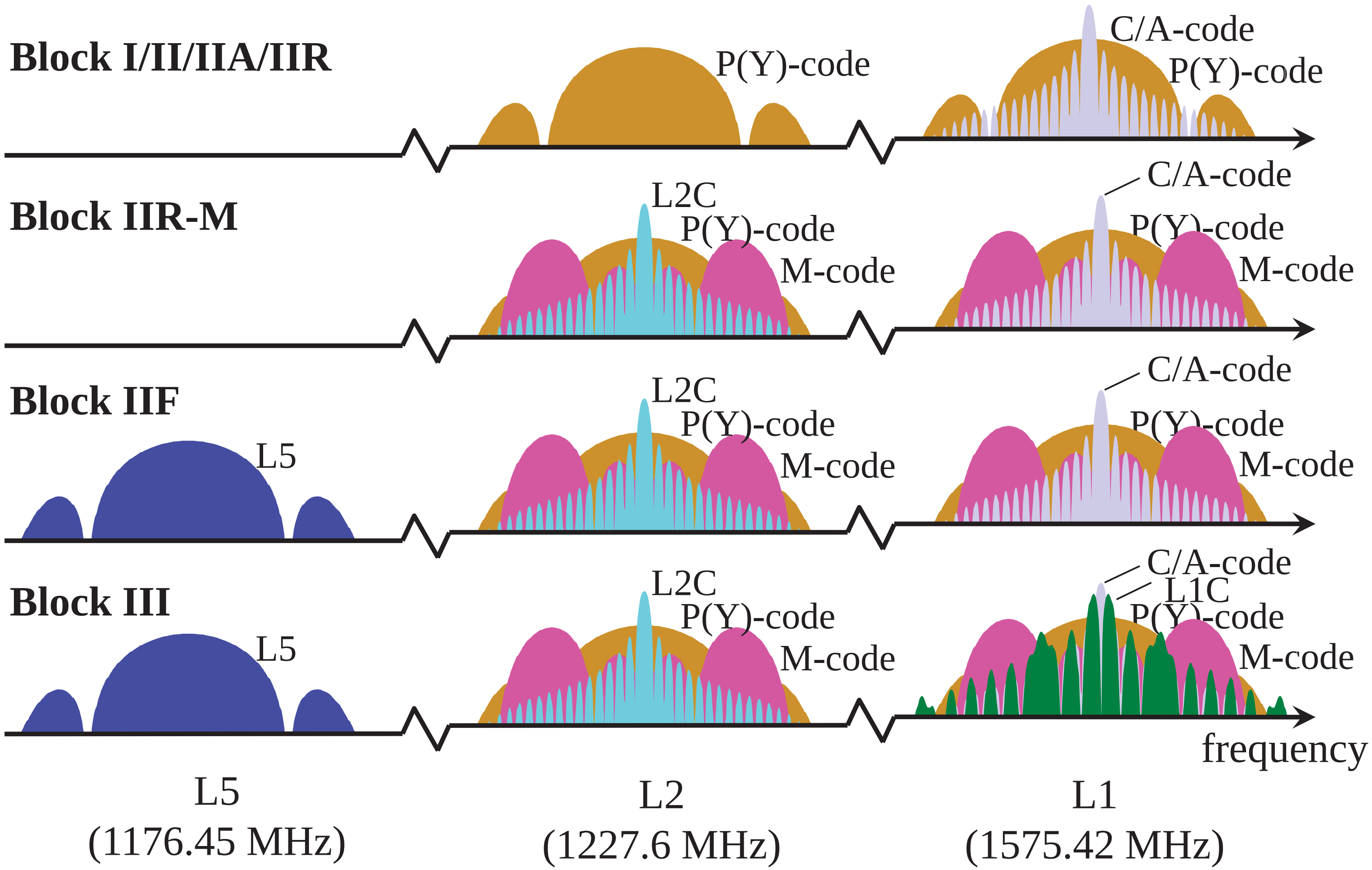
- A solution to constellation weakness
  - *Many more ranging sources*
  - *Fills in gaps*
  - *Provides extra redundancy*
  - *Averages down uncertainty*



Advanced RAIM (ARAIM)

- Dual Frequency - Multi-constellation
  - *Eliminates multiple SV iono threat*
  - *Strong geometries*
- Support for vertical guidance
  - *Requires a more stringent level of certification than RAIM for lateral*
  - *May require ground monitoring by approving agency*
- Potential for near global coverage
  - *Modest infrastructure requirements*

GPS Signals



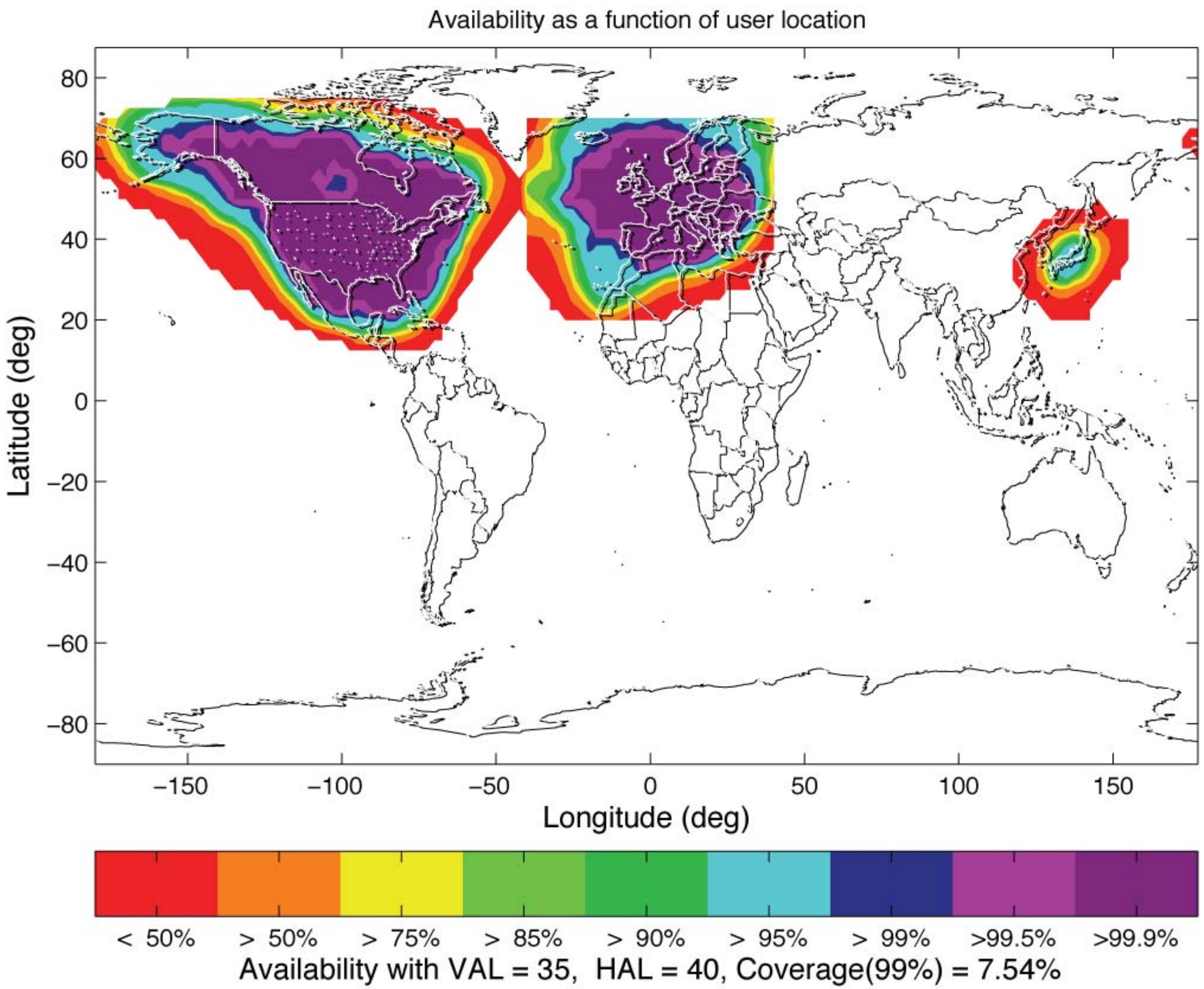
Block I/II/IIA/IIR
P(Y)-code
C/A-code
P(Y)-code
Block IIR-M
L2C
P(Y)-code
M-code
C/A-code
P(Y)-code
M-code
Block IIF
L5
L2C
P(Y)-code
M-code
C/A-code
P(Y)-code
M-code
Block III
L5
L2C
P(Y)-code
M-code
C/A-code
L1C
P(Y)-code
M-code
frequency
L5
(1176.45 MHz)
L2
(1227.6 MHz)
L1
(1575.42 MHz)

Current SBAS Coverage

WAAS

EGNOS

MSAS

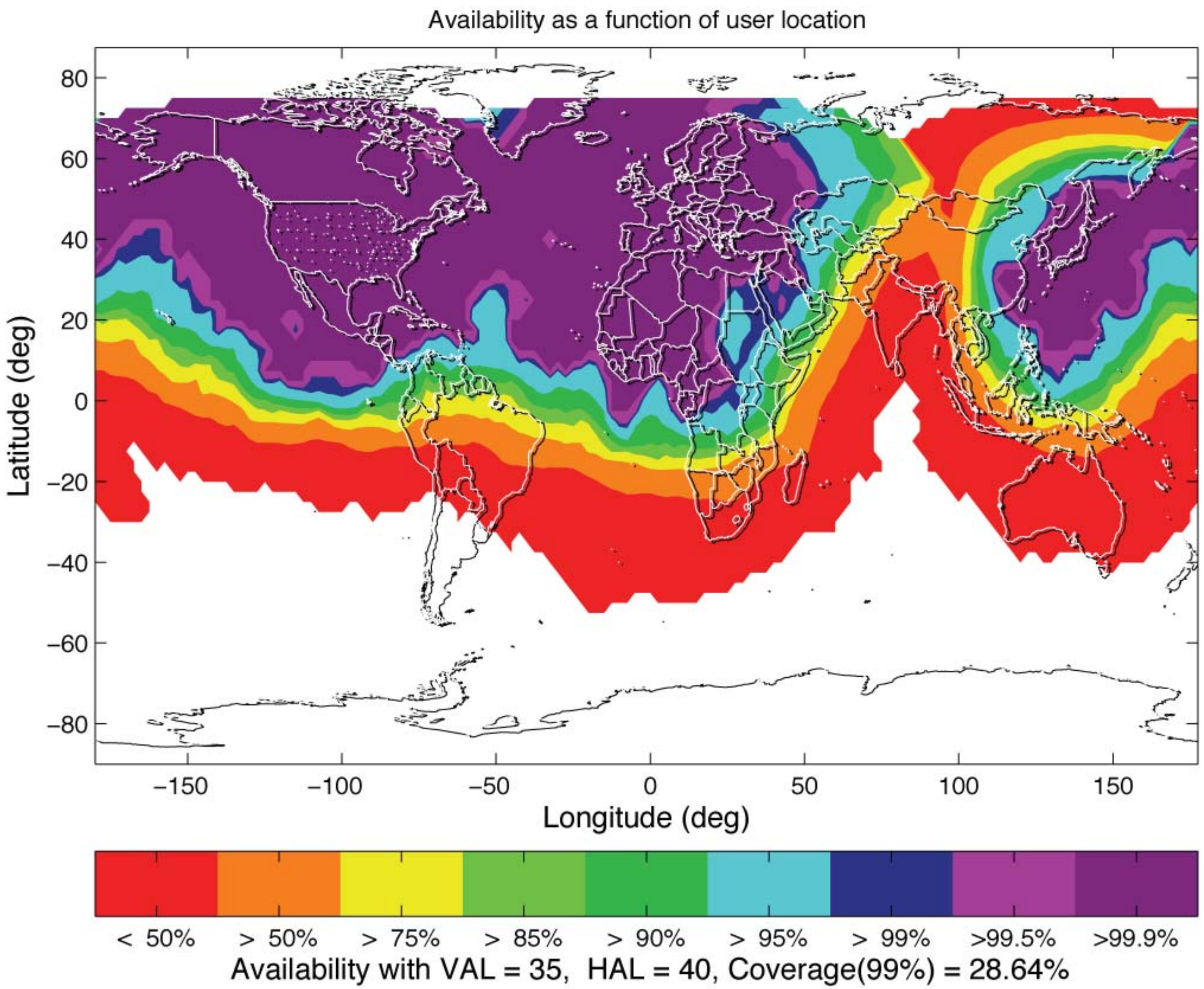


Dual Frequency Coverage (WAAS, EGNOS, MSAS)

WAAS

EGNOS

MSAS



Dual Frequency Coverage (with GAGAN + Russia)

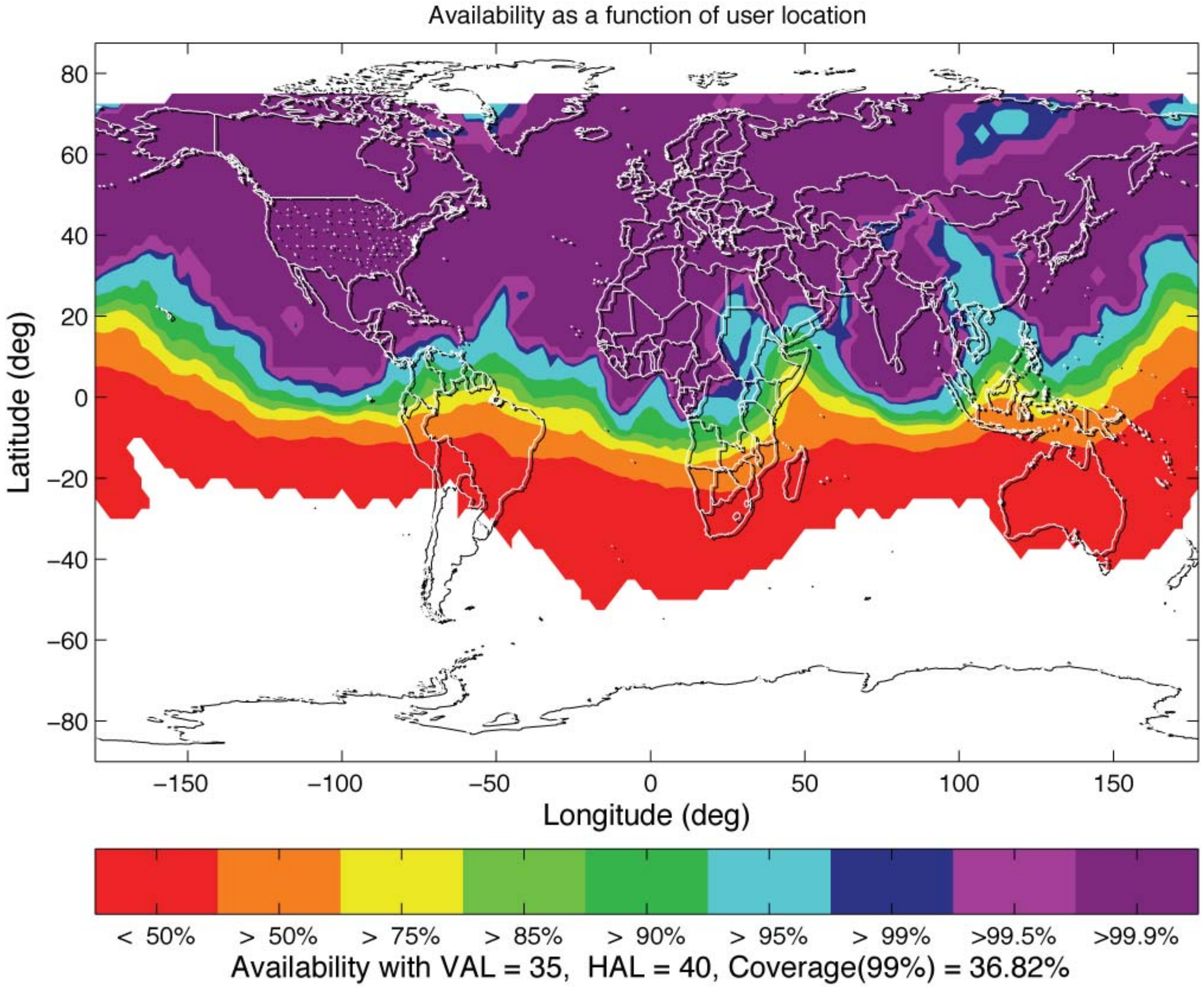
WAAS

EGNOS

MSAS

GAGAN

SDCM



Dual Frequency + Second Constellation (Galileo)

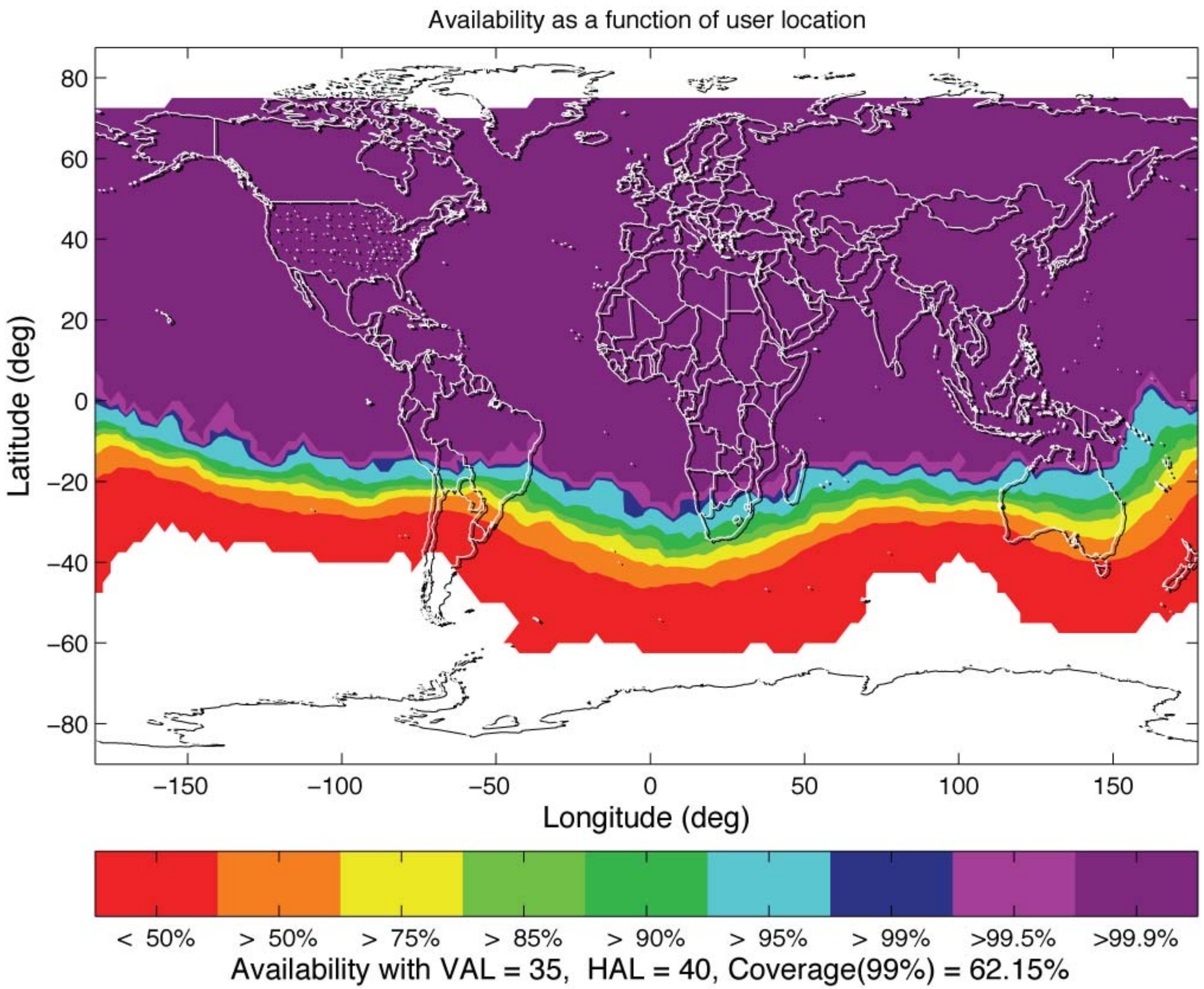
WAAS

EGNOS

MSAS

GAGAN

SDCM



Dual Frequency, Dual GNSS, Expanded Networks

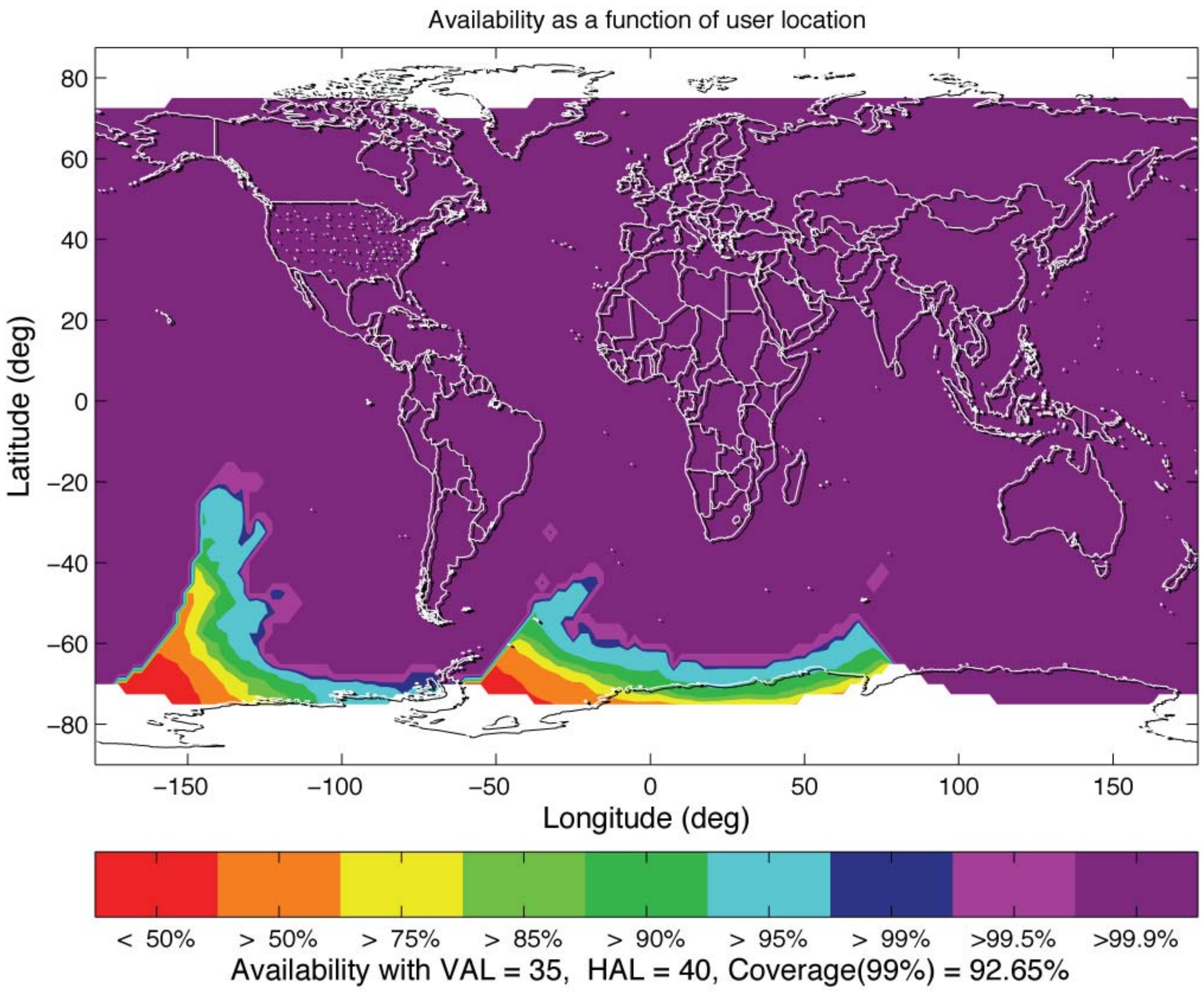
WAAS

EGNOS

MSAS

GAGAN

SDCM



Conclusions

- GNSS can be used to provide aircraft navigation for all levels of service
- Integrity is a key concern
  - *Important to understand what can go wrong and how to protect users*
- Observation and data collection are key to understanding behavior
  - *A long history of careful and consistent data monitoring are required*
  - *Practical experience leads to trust and acceptance*

Outline

- Ionospheric Modeling
- Ionospheric Threats
- **Other Integrity Threats**
- Integrity Methodology
- Next Generation Satellite Navigation
- Future Signals
- Conclusions

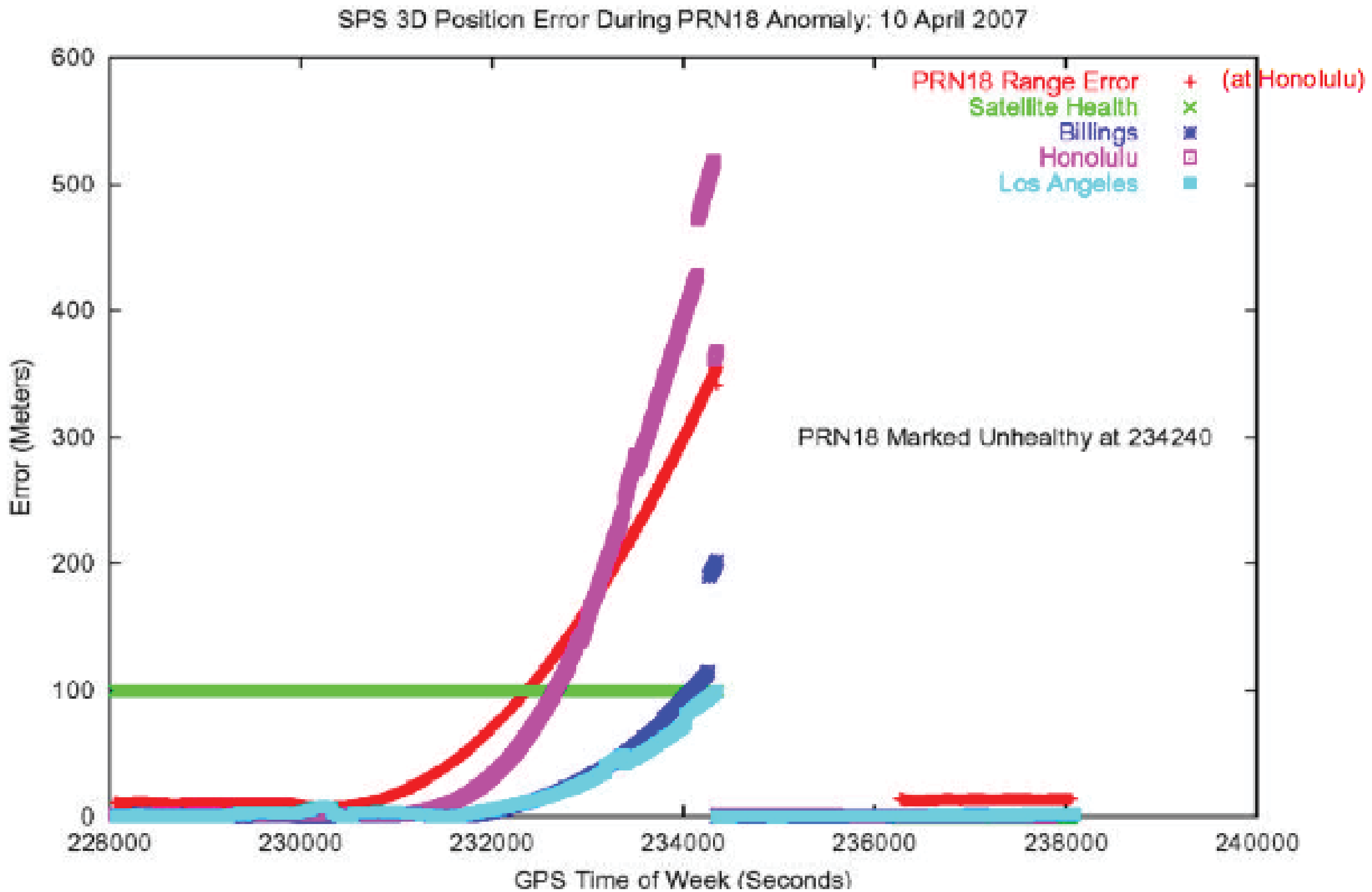
Integrity

- Monitor network or signal redundancy identifies observable threats
  - *Protection against satellite failures*
    - Ephemeris errors
    - Clock errors
    - Signal errors
  - *Protection against ionospheric errors*
- Design assumes worst credible values for all unobservable threats

Satellite Ephemeris Anomaly

Observed GPS SPS 3-D Position Errors on April 10, 2007

***Source*: FAATC GPS SPS PAN Report #58, 31 July 2007.**



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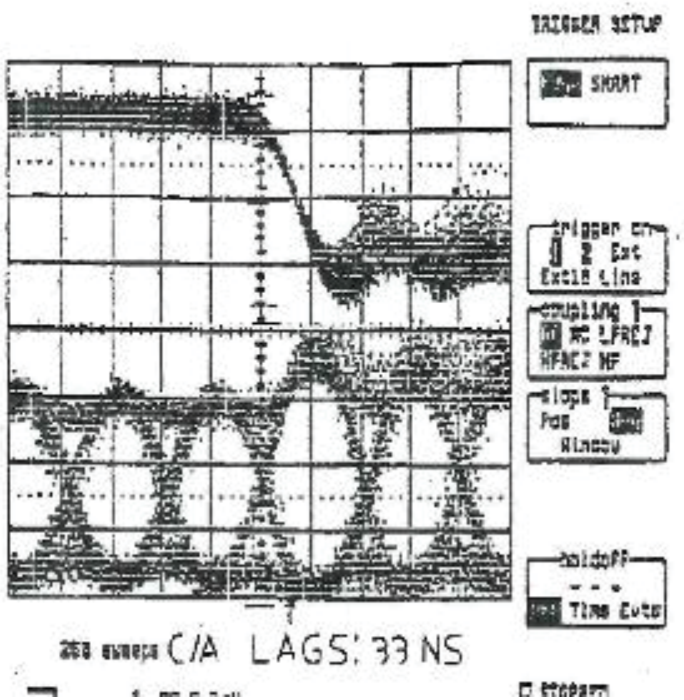
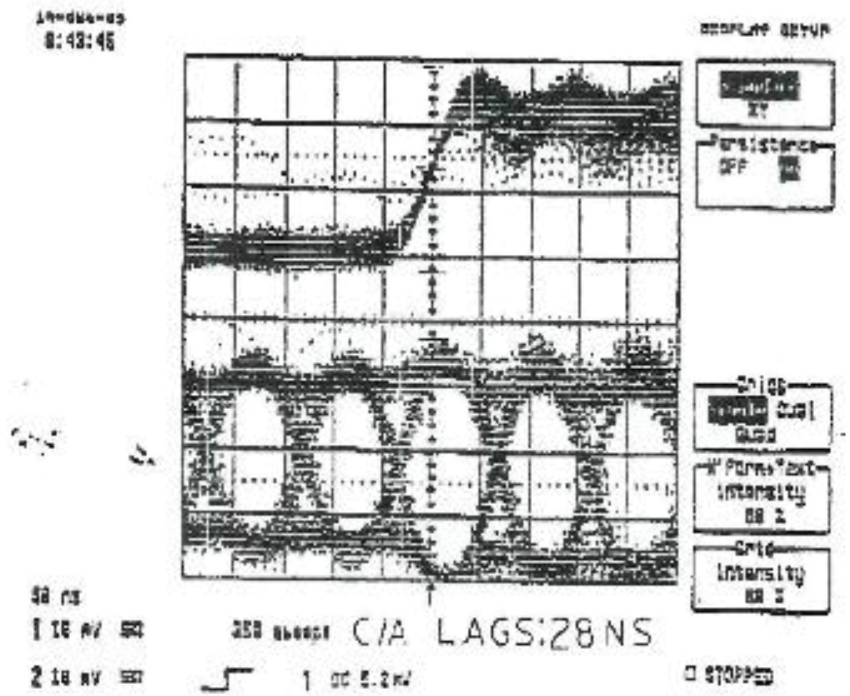
Satellite Signal Anomaly

L1 C/A Lags L1 P Code
Falling Edge or Leading Edge

Oct 13, 1993, 23:45



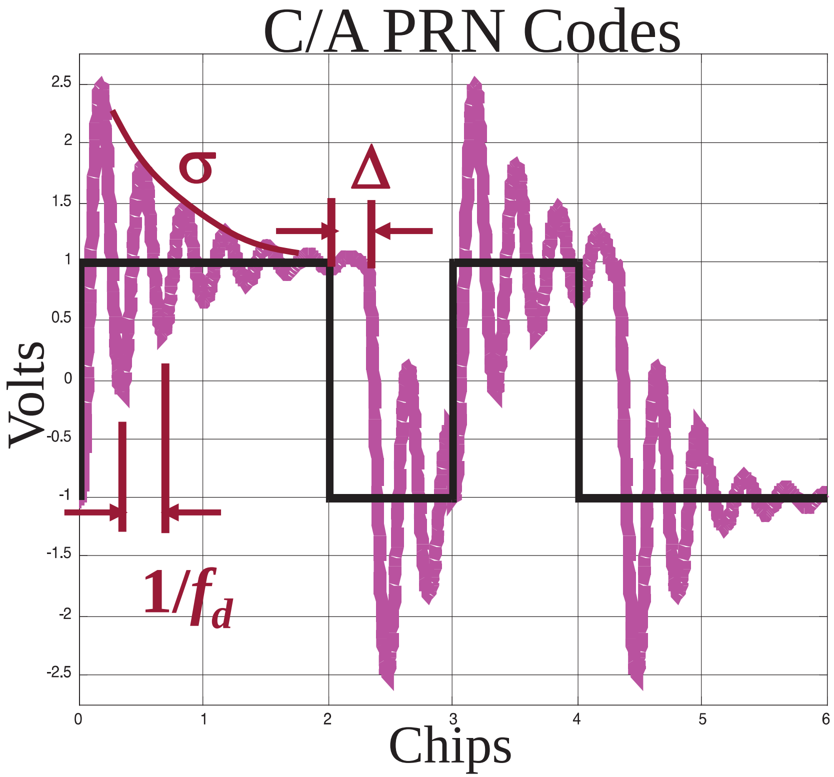
Oct 14, 1993, 08:43

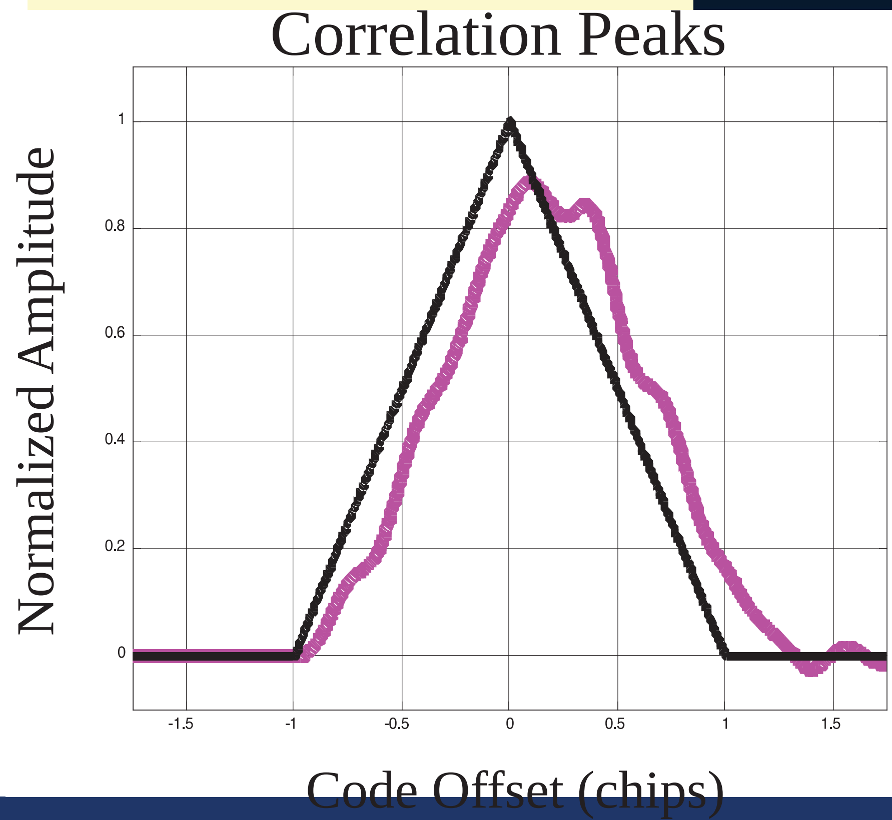


Courtesy:
Per Enge

"Evil Waveform" Failure Mode Example

Comparison of Ideal and "Evil Waveform" Signals for Threat Model C





<u>Note:</u>

Threat Model A: Digital Failure Mode (Lead/Lad Only: Δ)

Threat Model B: Analog Failure Mode ("Ringing" Only: f_dσ)

Outline

- Ionospheric Modeling
- Ionospheric Threats
- Other Integrity Threats
- **Integrity Methodology**
- Next Generation Satellite Navigation
- Future Signals
- Conclusions

Overall Integrity Approach

- Conventional Differential GPS Systems Rely on Lack of Disproof
  - *"I've been using it for N years and I've never had a problem"*
- 10^{-7} Integrity Requires Active Proof
- Analysis, Simulation, and Data Must Each Support Each Other
  - *None sufficient by themselves*
- Clear Documentation of Safety Rationale is Essential

Interpretation of “Probability of HMI < 10^{-7} Per Approach”

- Possible Interpretations
  - *Ensemble Average of All Approaches Over Space and Time*
  - *Ensemble Average of All Approaches Over Time for the Worst Location*
  - *Previous Plus No Discernable Pattern (Rare & No Correlation With User Behavior)*
  - *Worst Time and Location*

Probability of Integrity Failure

- Average Risk

$$\sum_{all\ conditions} P(fault \mid condition) \cdot P(condition)$$

- Specific Risk

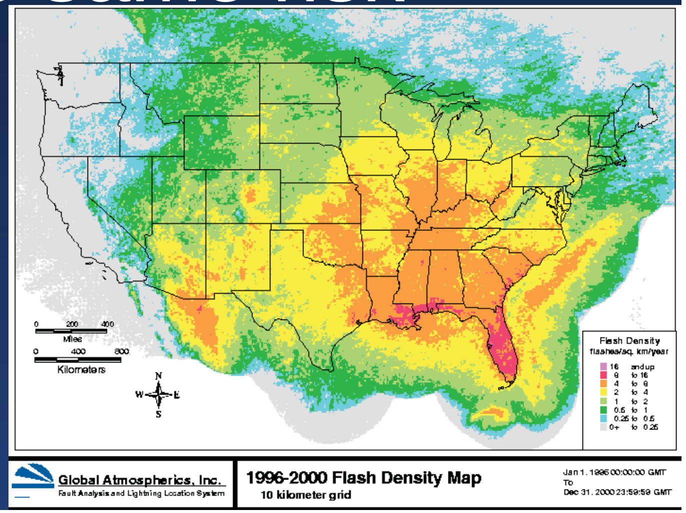
$$P(fault \mid condition)$$

Probability of Being Struck by Lightning

- From the Lightning Safety Institute
  - *USA population = 280,000,000*
  - *1000 lightning victims/year/average*
  - *Odds = 1 : 280,000 of being struck by lightning*
- Not everyone has the same risk

One person struck 7 times

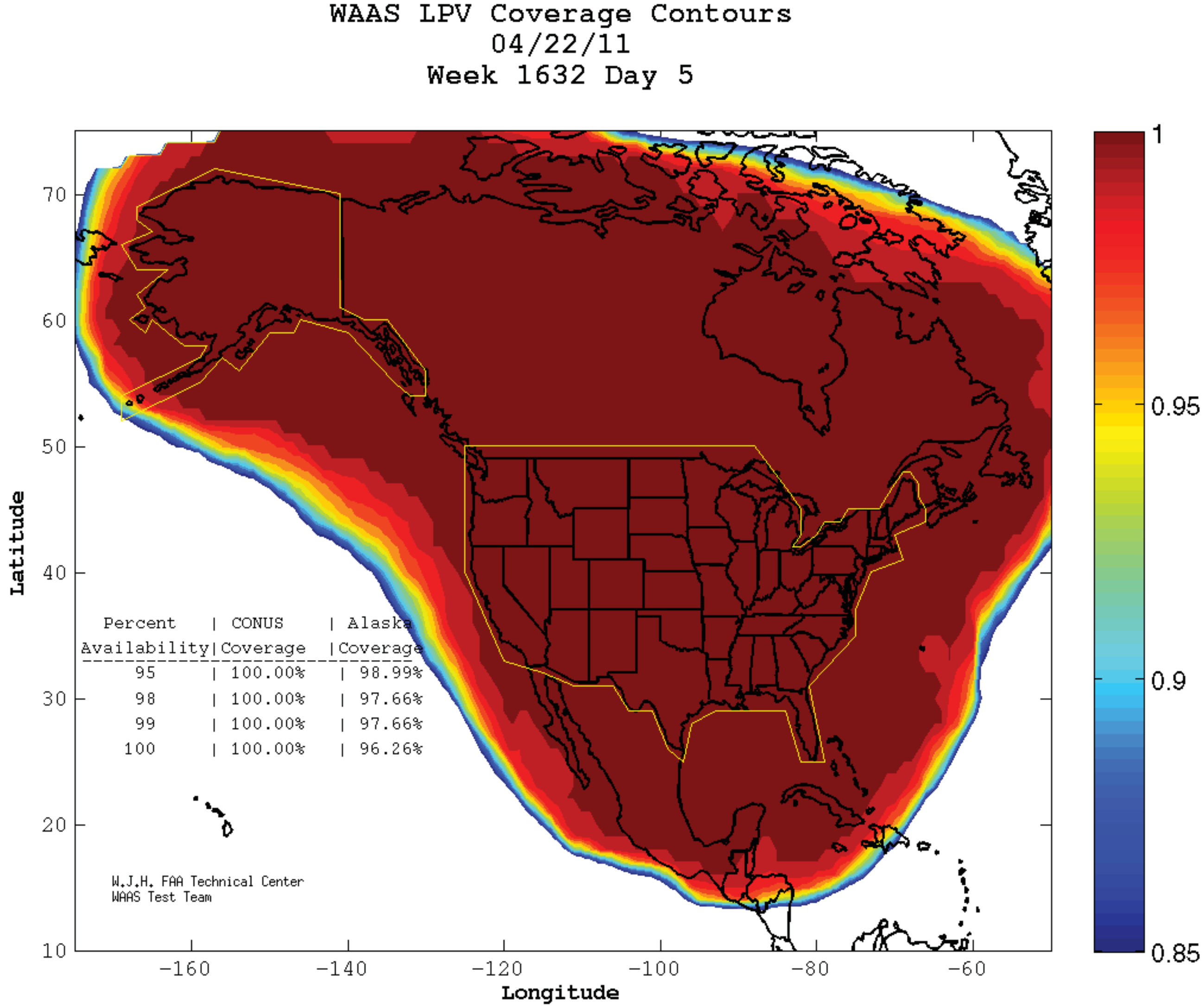
Naïve calculation:
< 1e-38 probability



WAAS Interpretation

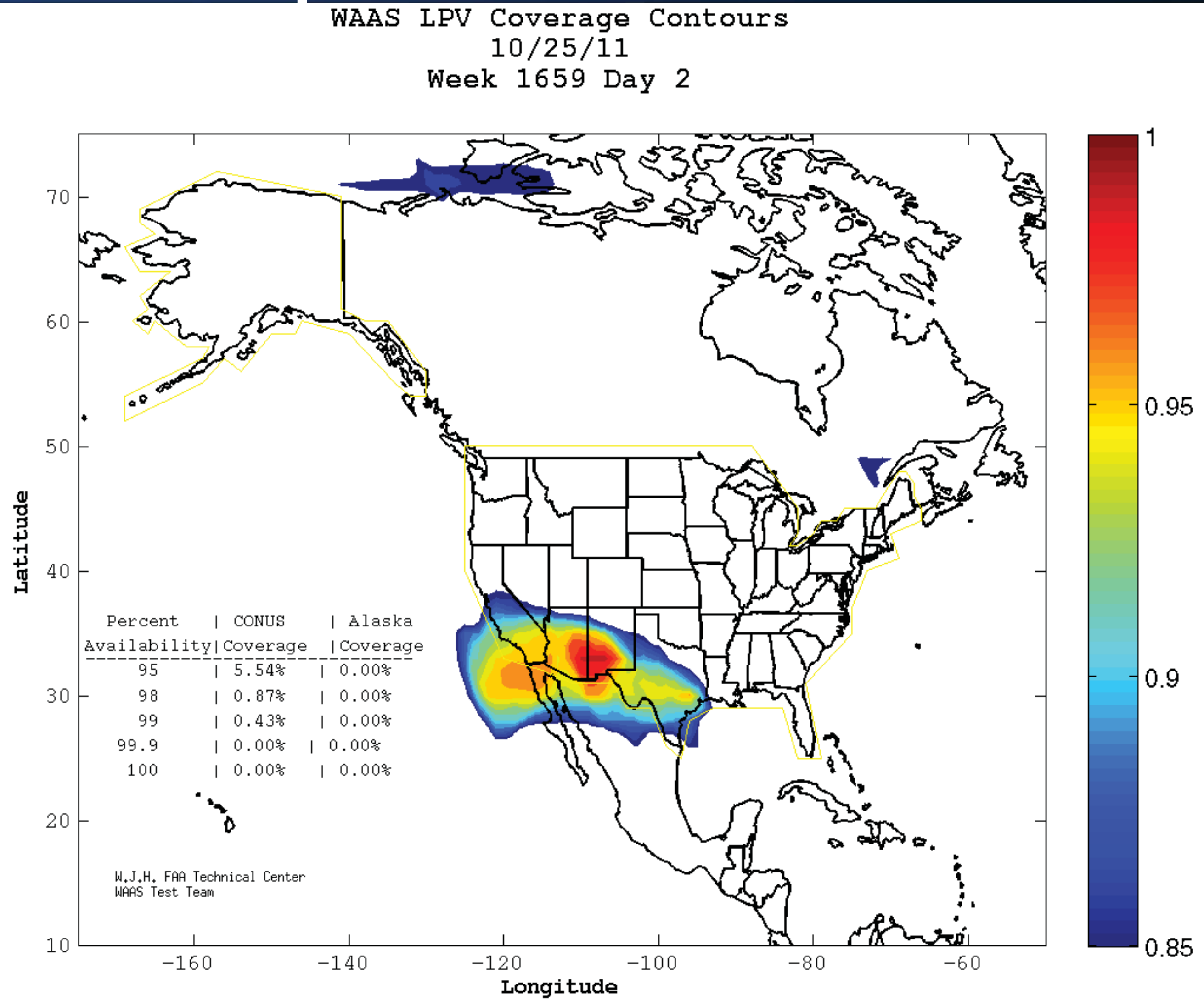
- Events handled case by case
- Events that are rare and random may take advantage of an *a priori*
- Deterministic events must be monitored or treated as worst-case
- Events that are observable must be detected (if risk > 10^{-7})
- Must account for worst-case undetected events

Nominal WAAS Vertical Guidance Performance



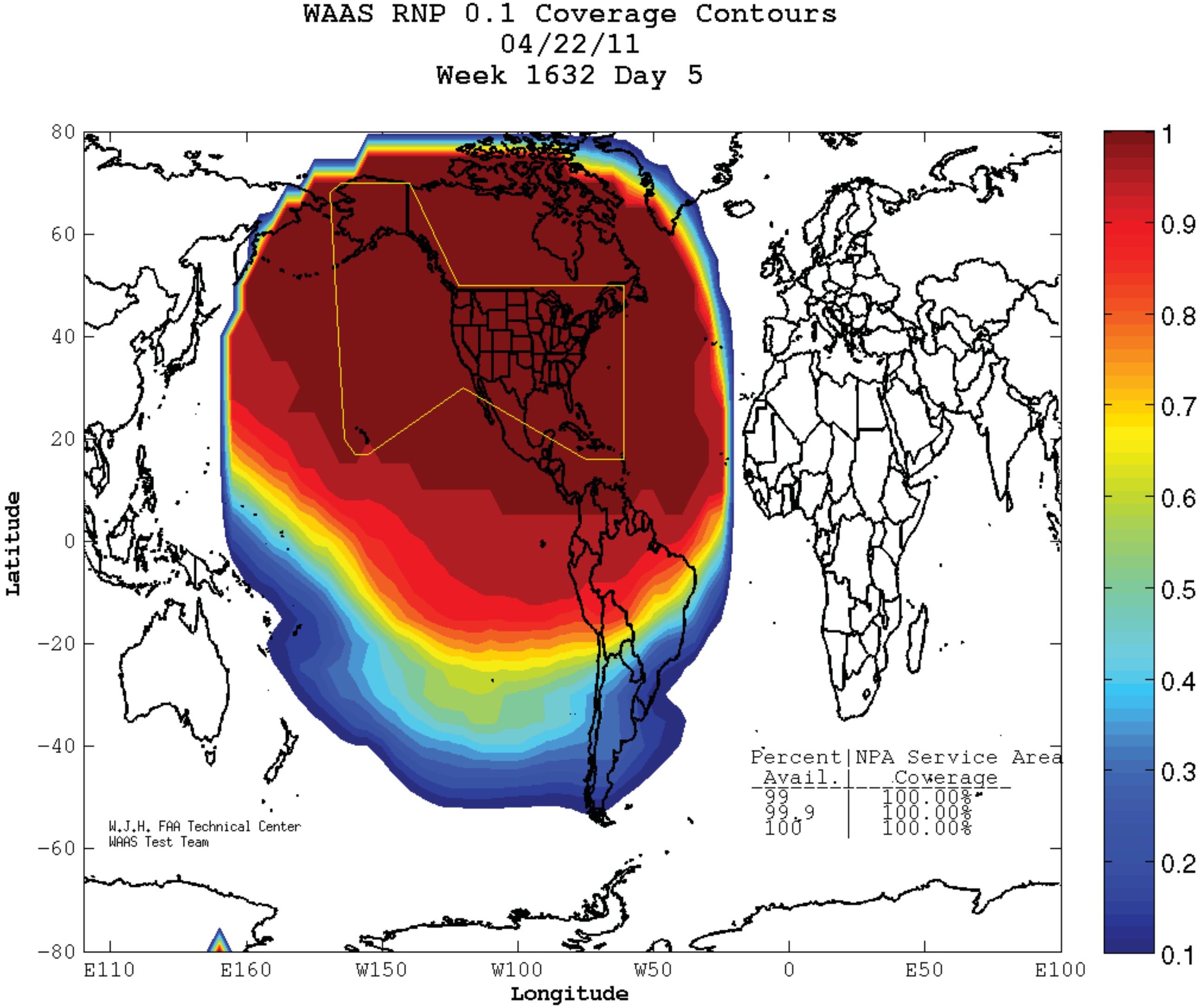
Courtesy: FAA

Vertical Guidance with Major Ionospheric Disturbance



Courtesy: FAA

Nominal WAAS Horizontal Guidance Performance



Courtesy: FAA

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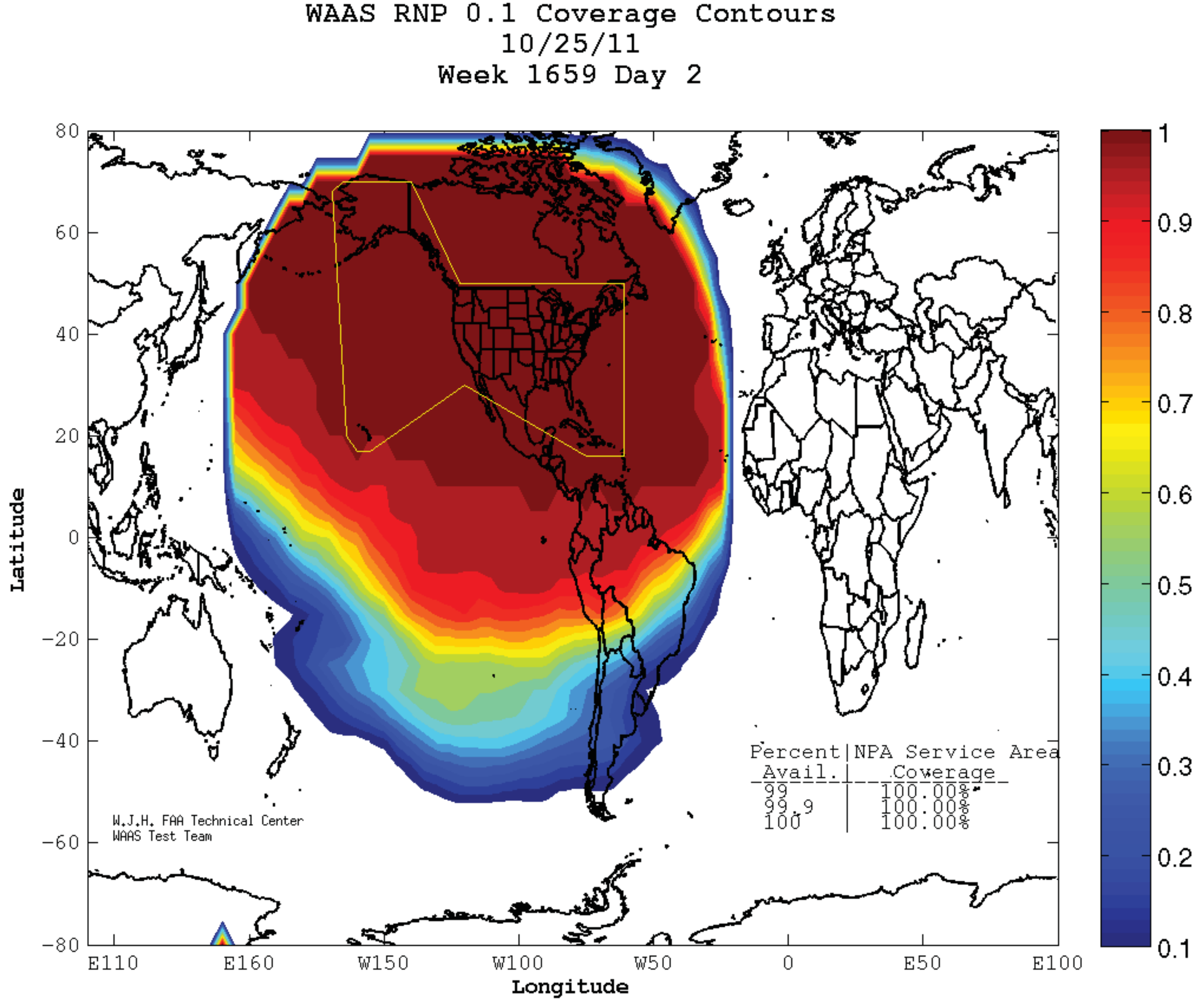
Horizontal Guidance in Major Ionospheric Disturbance



Courtesy: FAA

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