The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2025-25

Satellite Navigation Science and Technology for Africa

23 March - 9 April, 2009

Air Navigation Applications (SBAS, GBAS, RAIM)

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Satellite Navigation for Guidance of Aircraft

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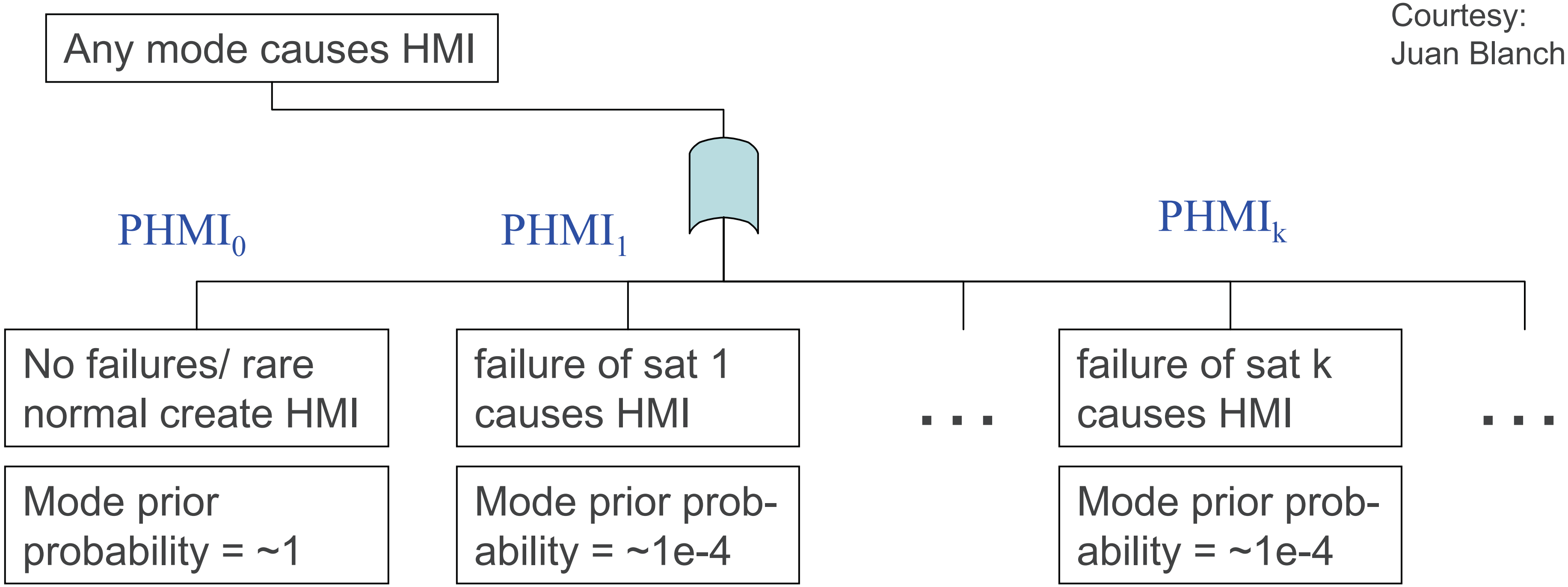
http://waas.stanford.edu

Outline

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

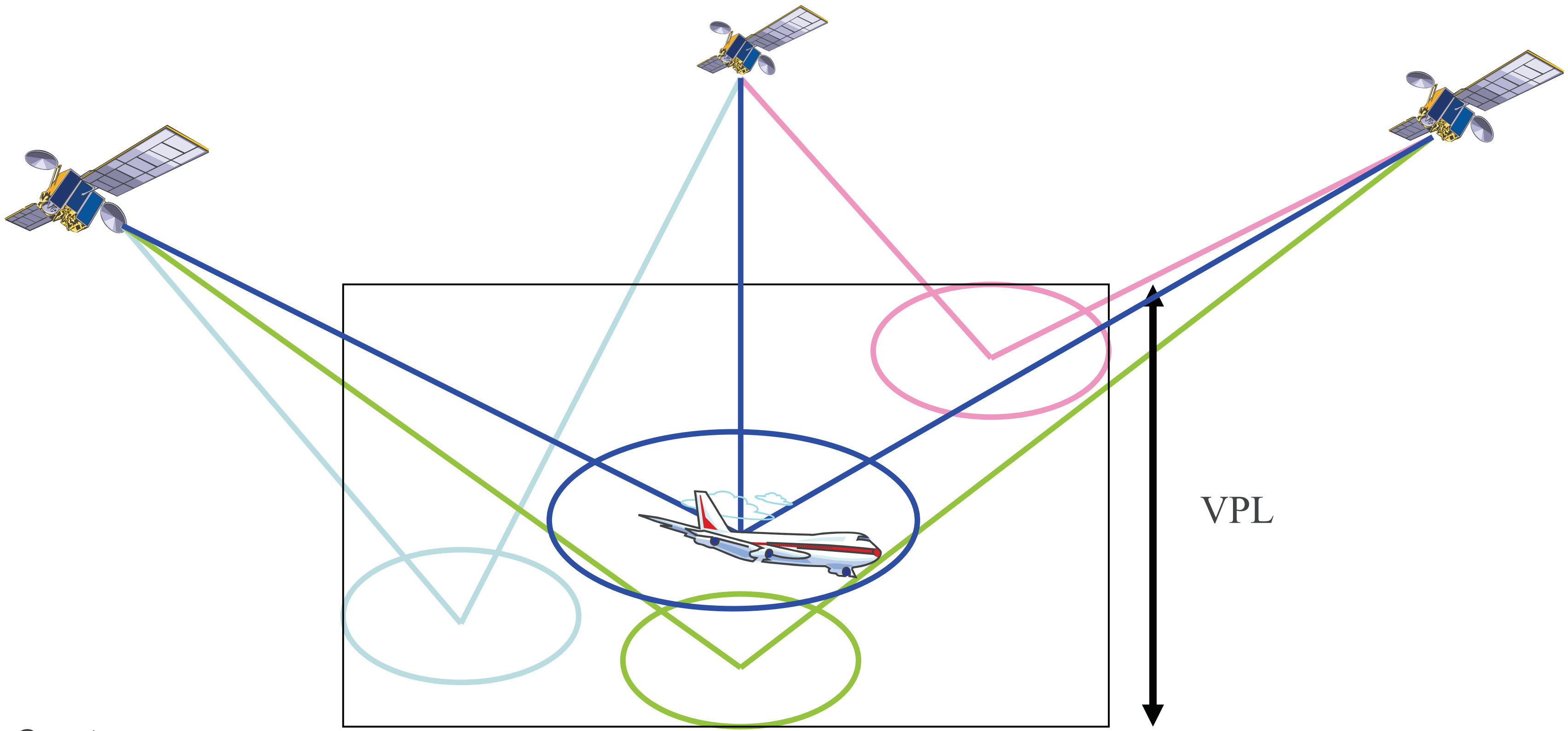
Fault Tree and Probability of Hazardously Misleading Information (PHMI)

Courtesy:
Juan Blanch



- For each branch, a monitor mitigates the probability of HMI given the failure
- In ARAIM, the monitors are formed by comparing subset solutions

ARAIM Protection Level



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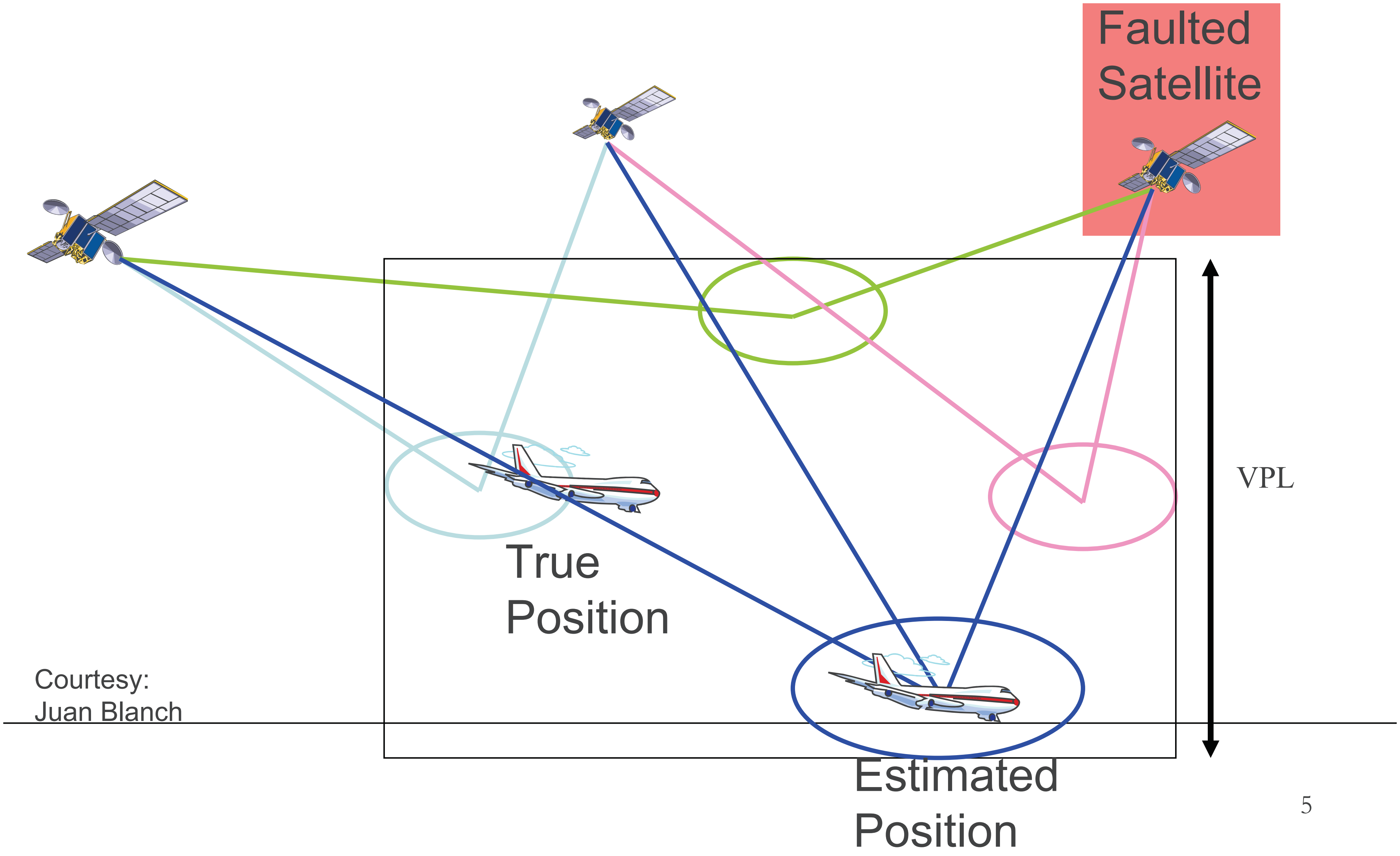
ARAIM Protection Level



Courtesy:
Juan Blanch

Outline

- RAIM
- **Ionospheric Modeling**
- Ionospheric Threats
- Other Integrity Threats
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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

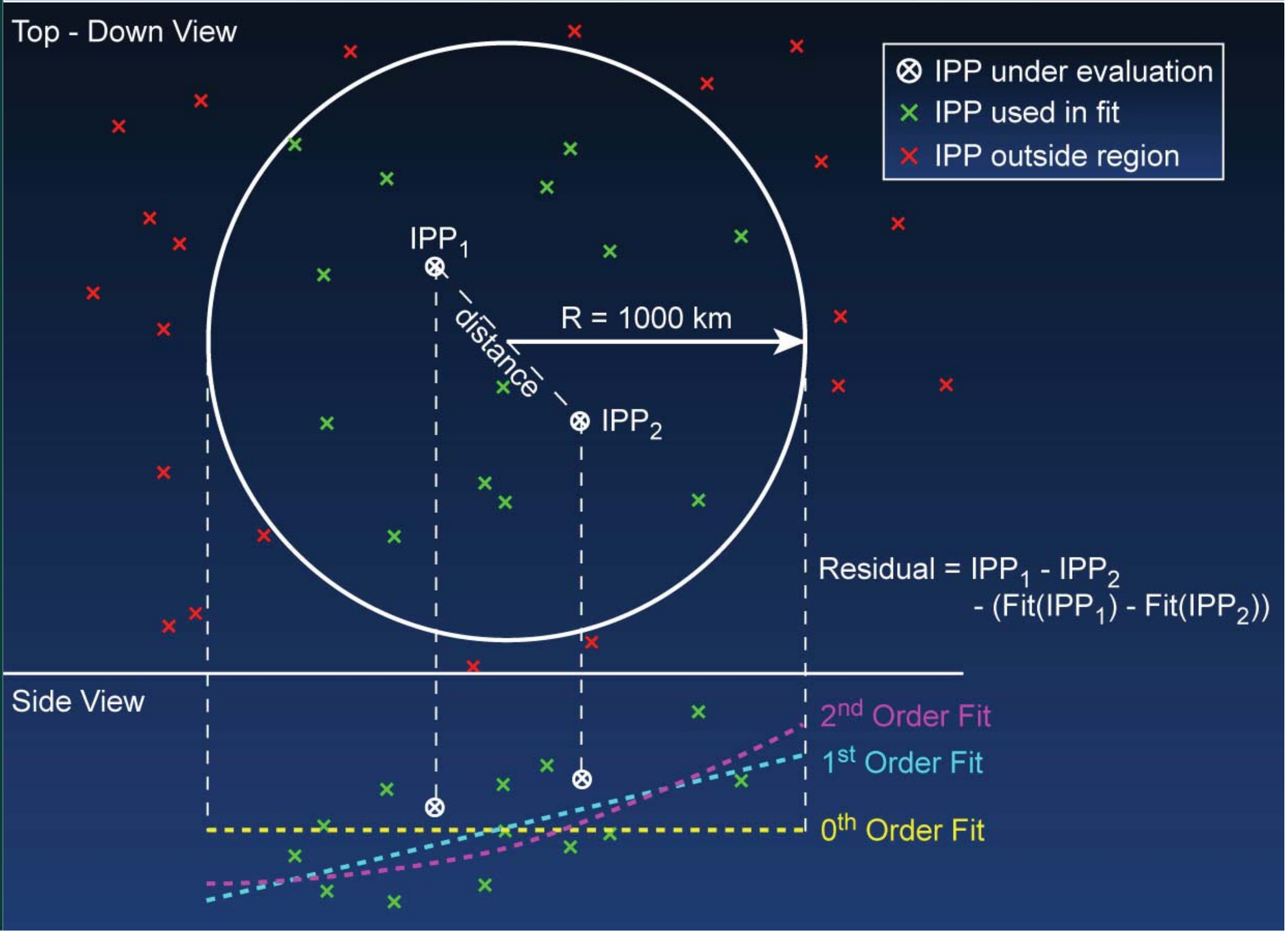
"Supertruth" Data

- 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



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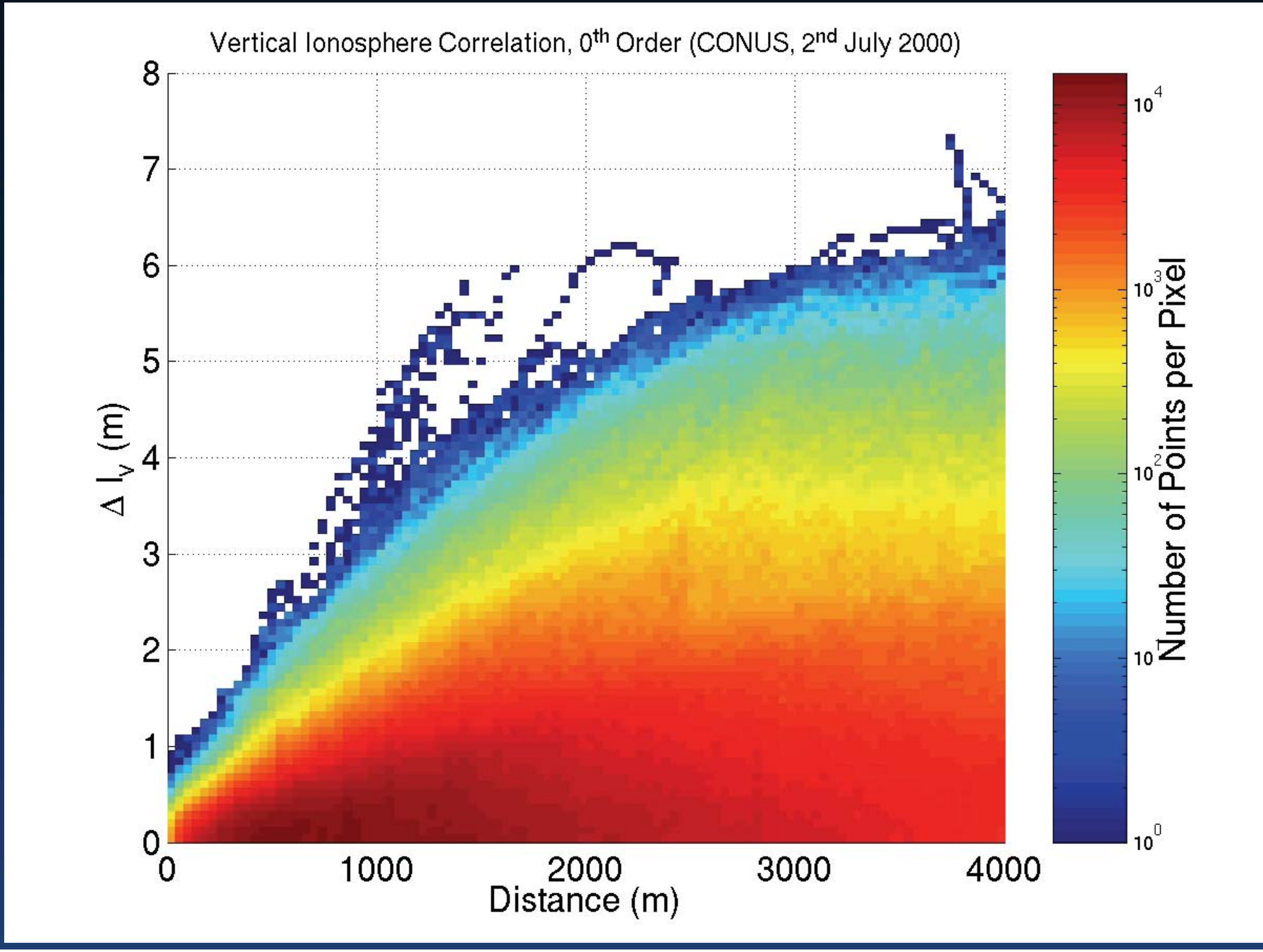
Ionospheric Decorrelation (0th Order)



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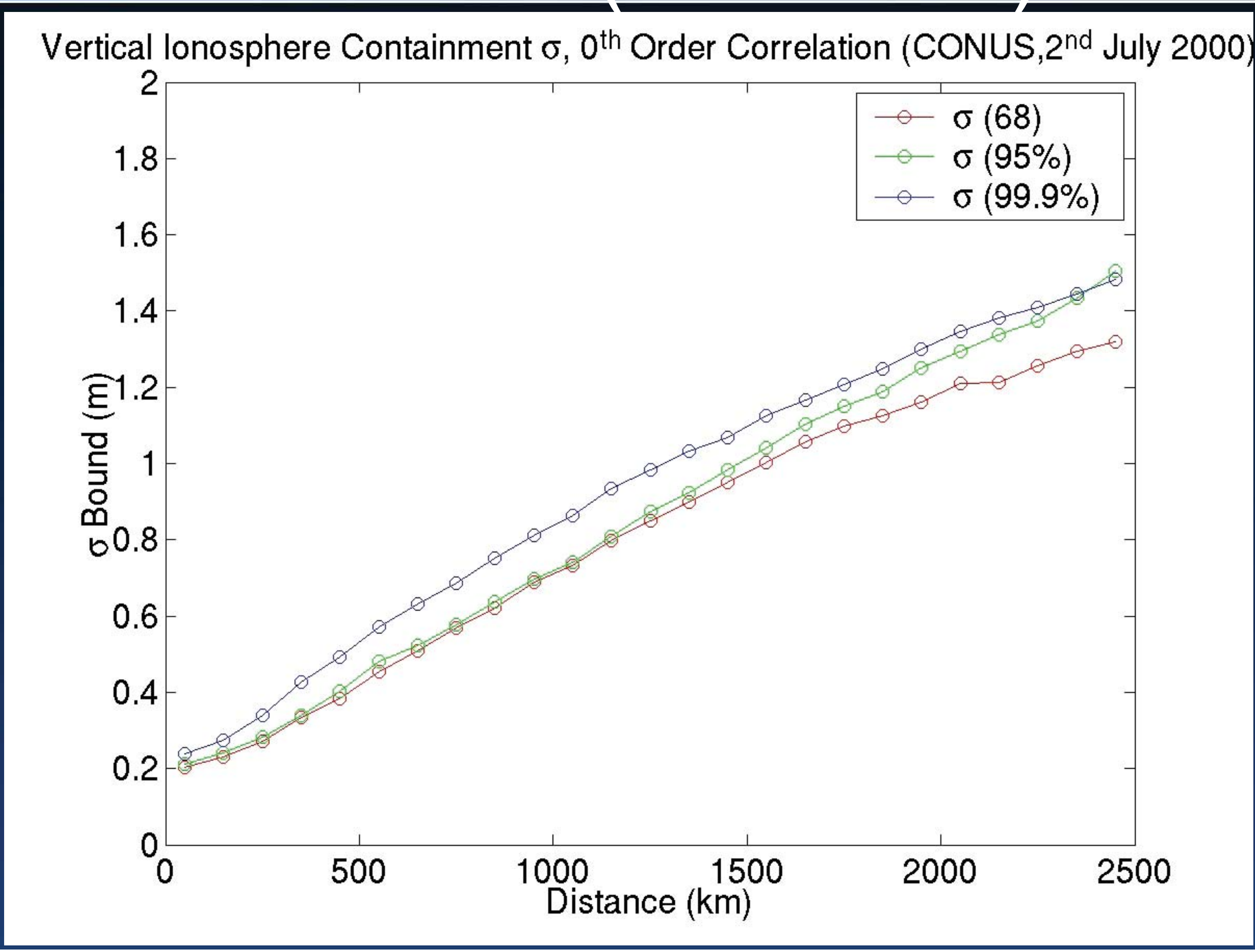
Ionospheric Decorrelation Function (0th Order)



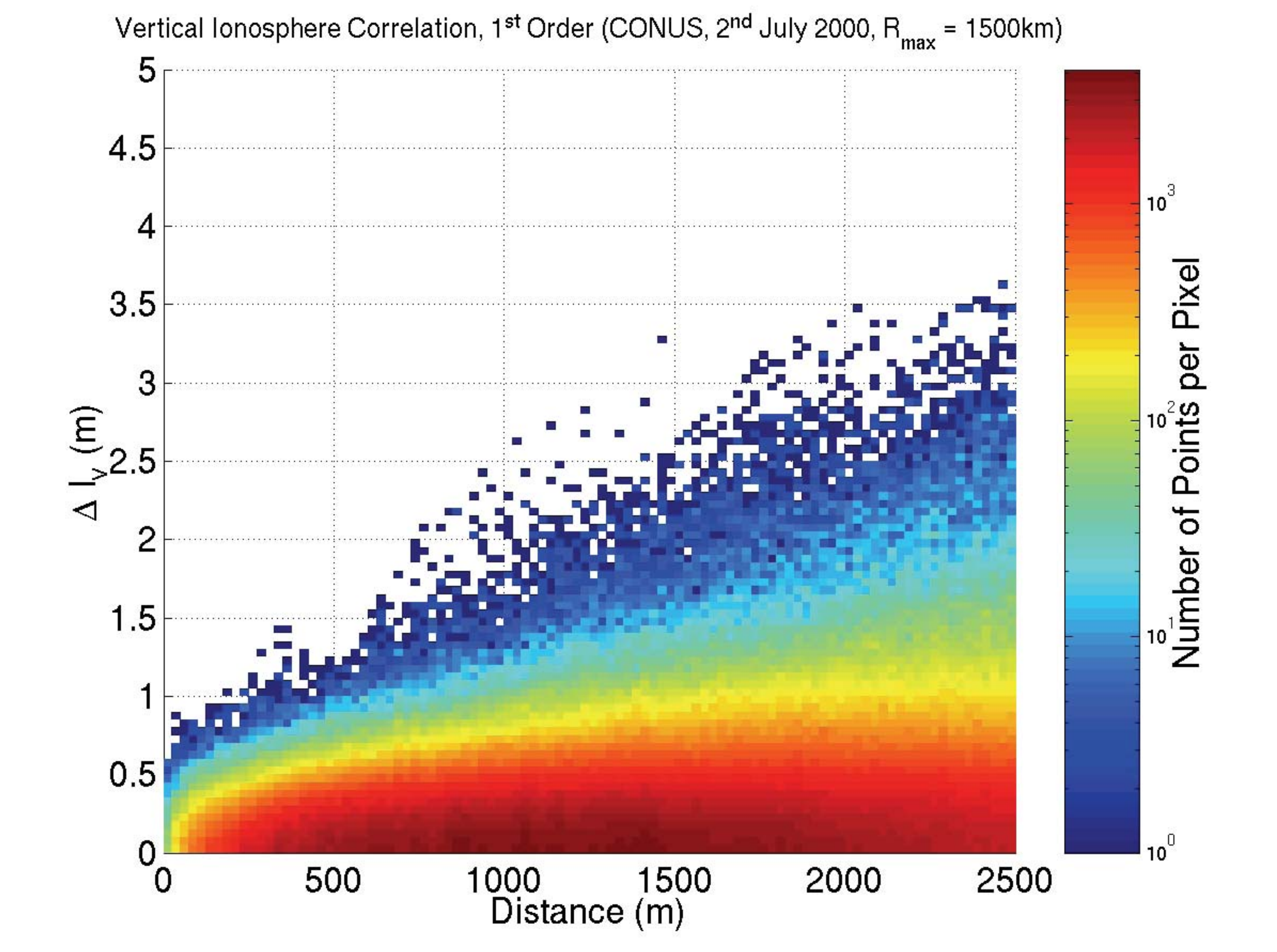
Preliminary Decorrelation Findings

- 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 (1st Order)



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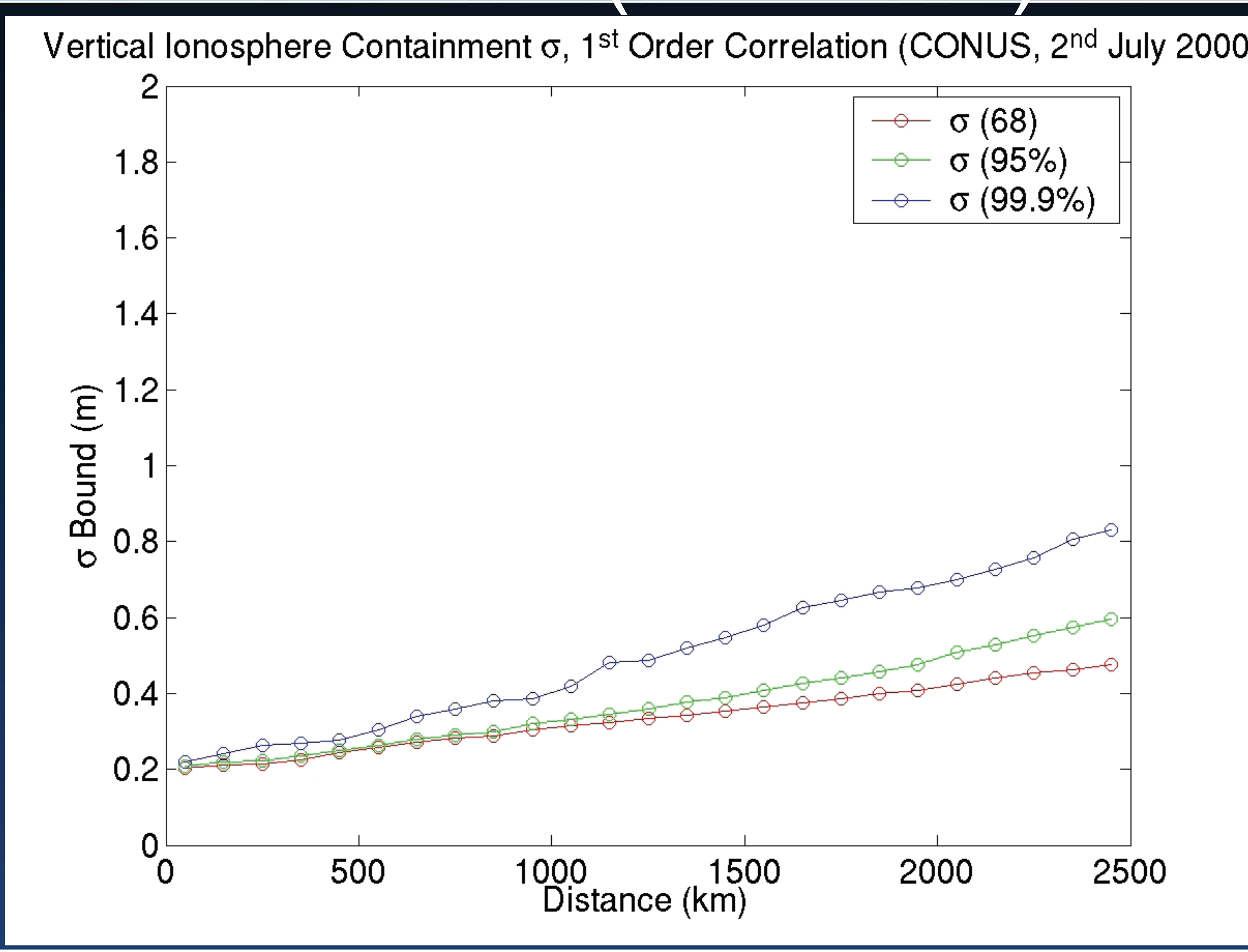
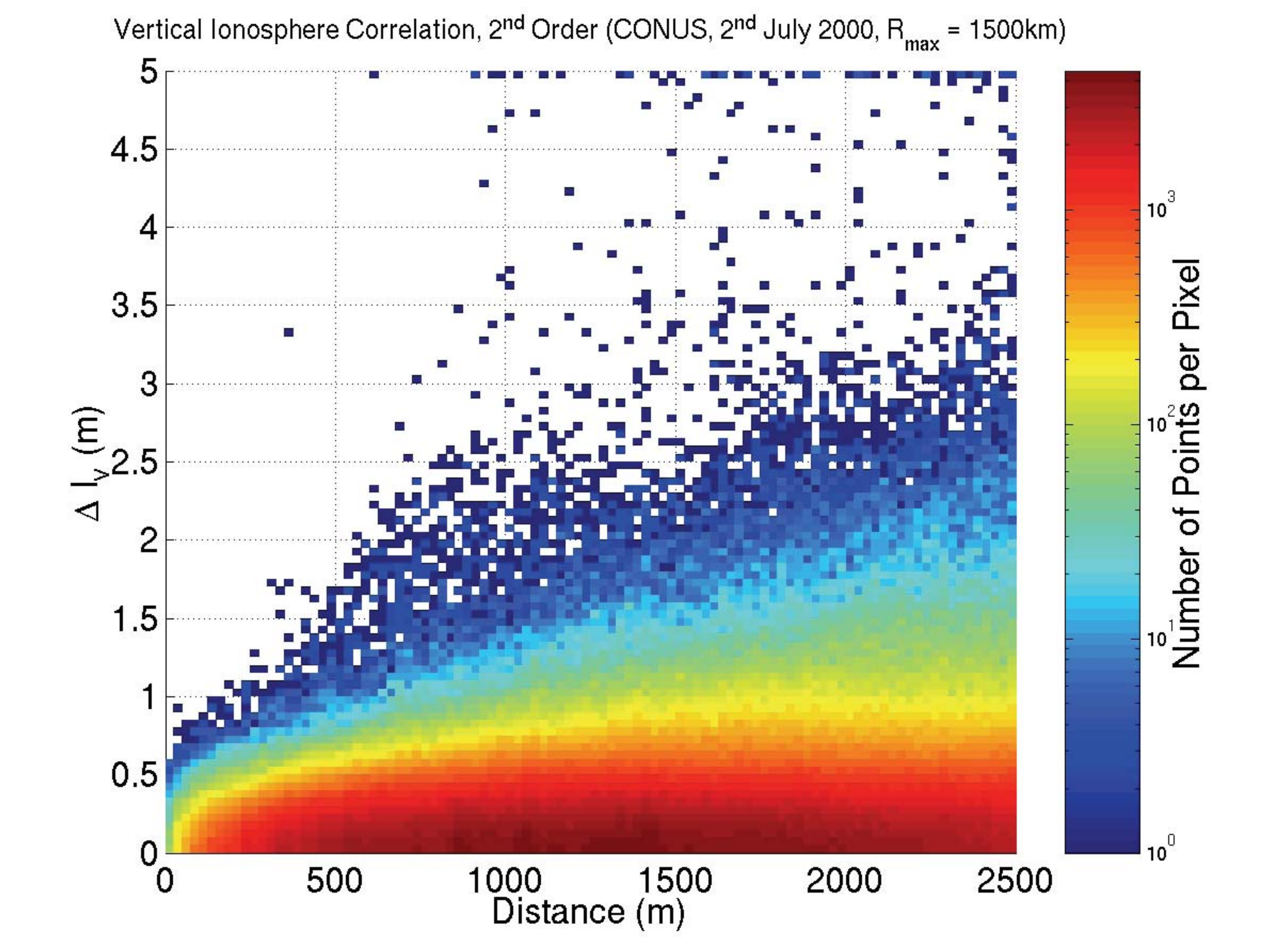
Ionospheric Decorrelation Function (1st Order)



Ionospheric Decorrelation About a Quadratic Fit



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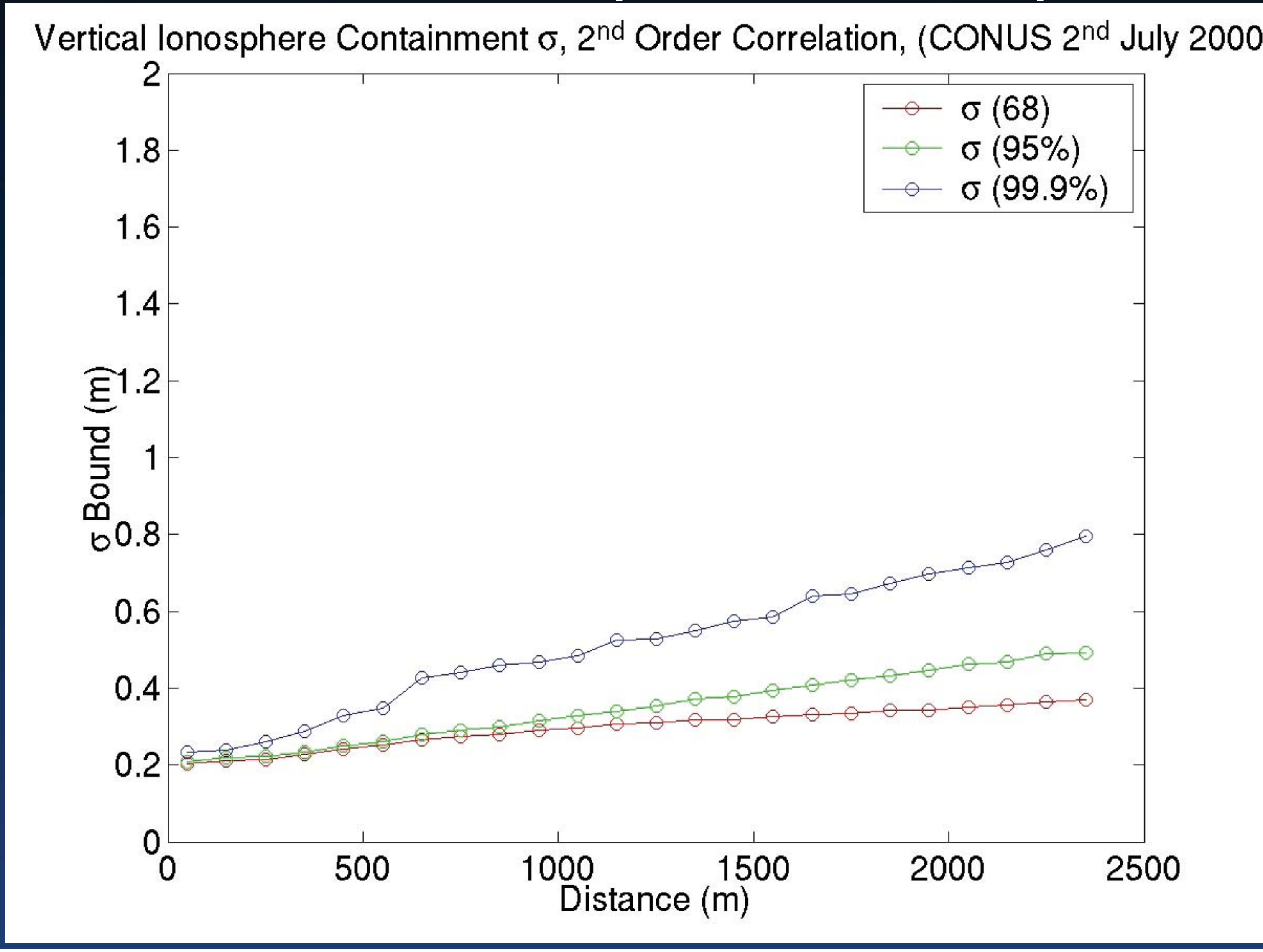
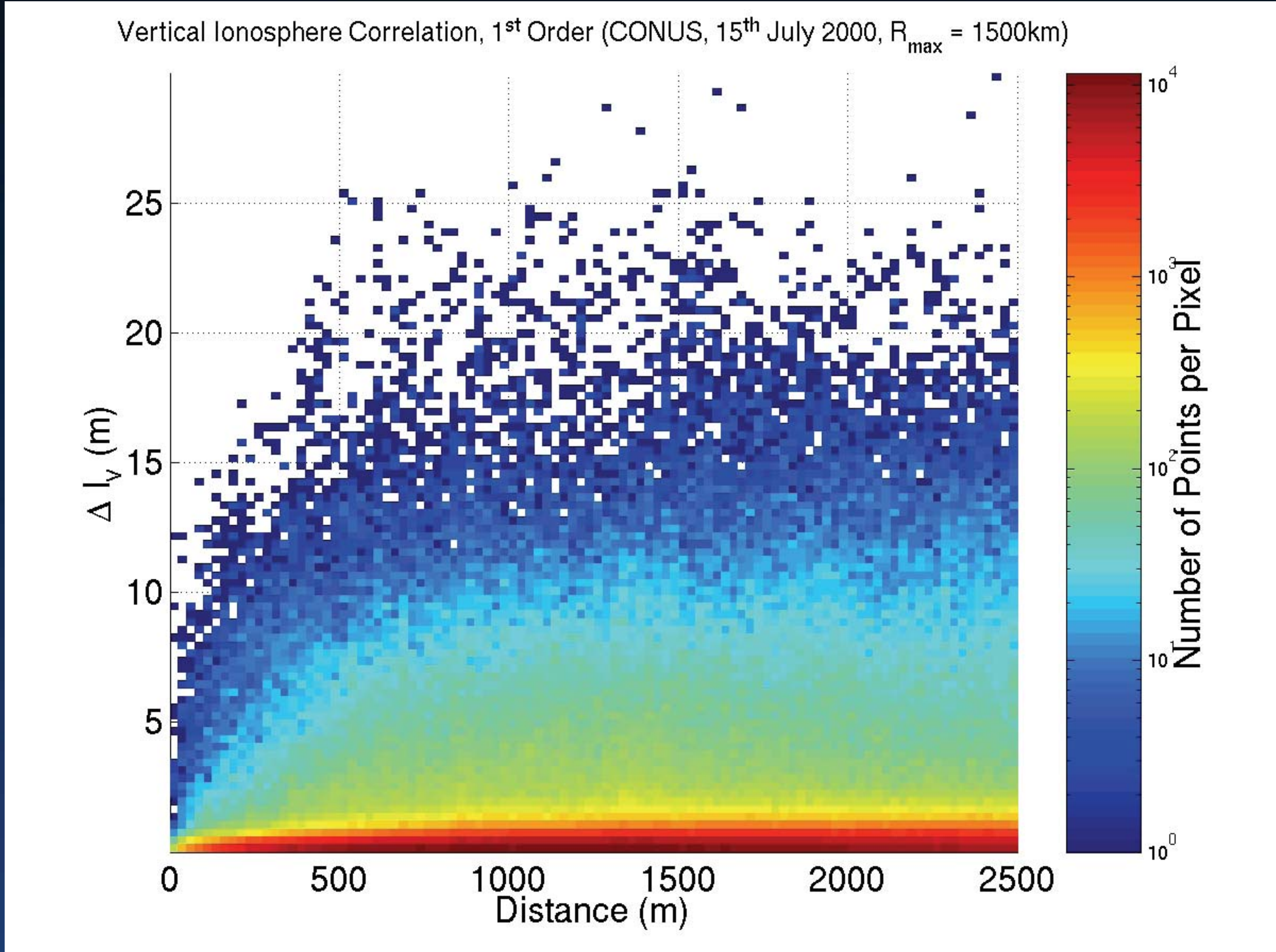
Ionospheric Decorrelation Function (2nd Order)



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



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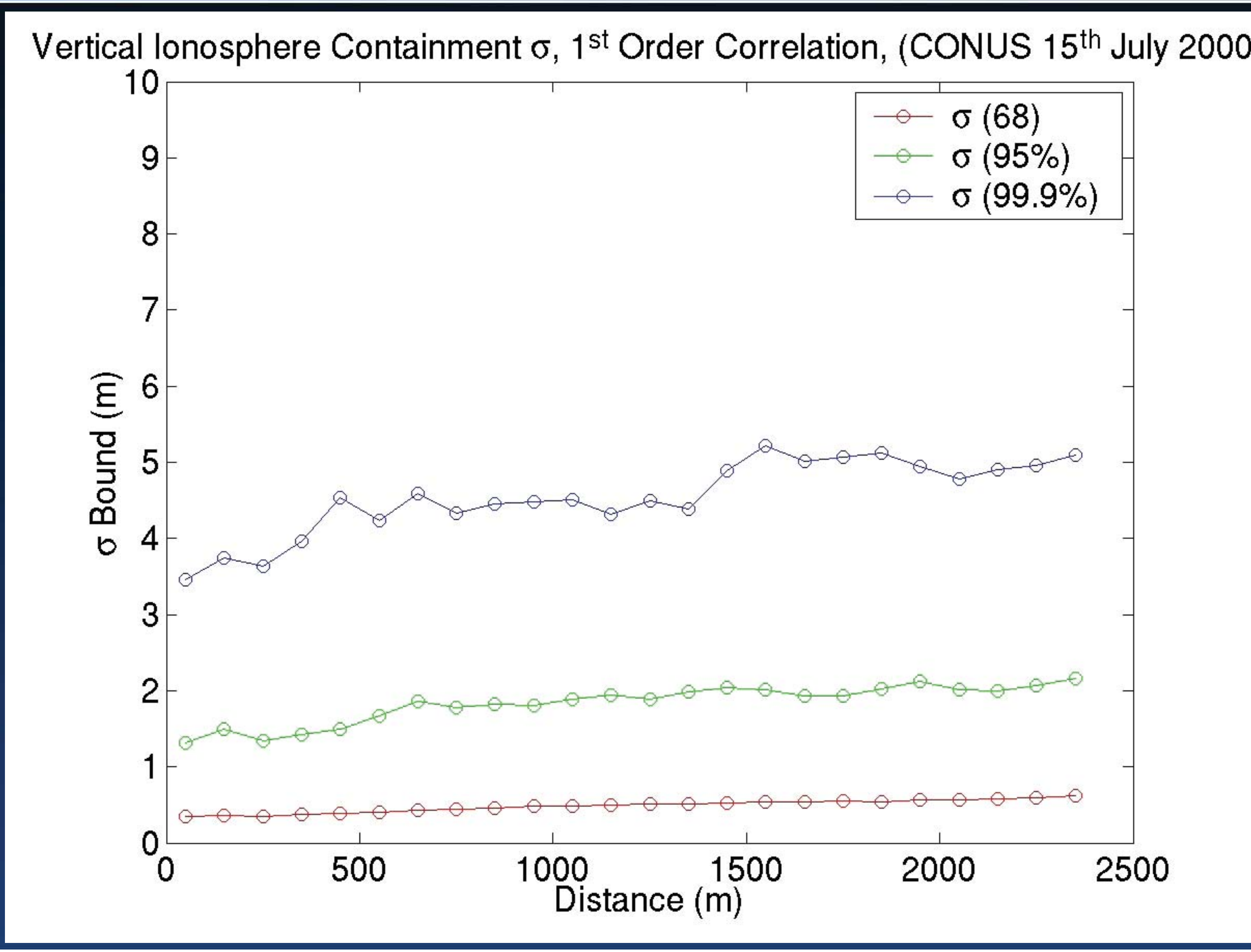
Disturbed Ionosphere



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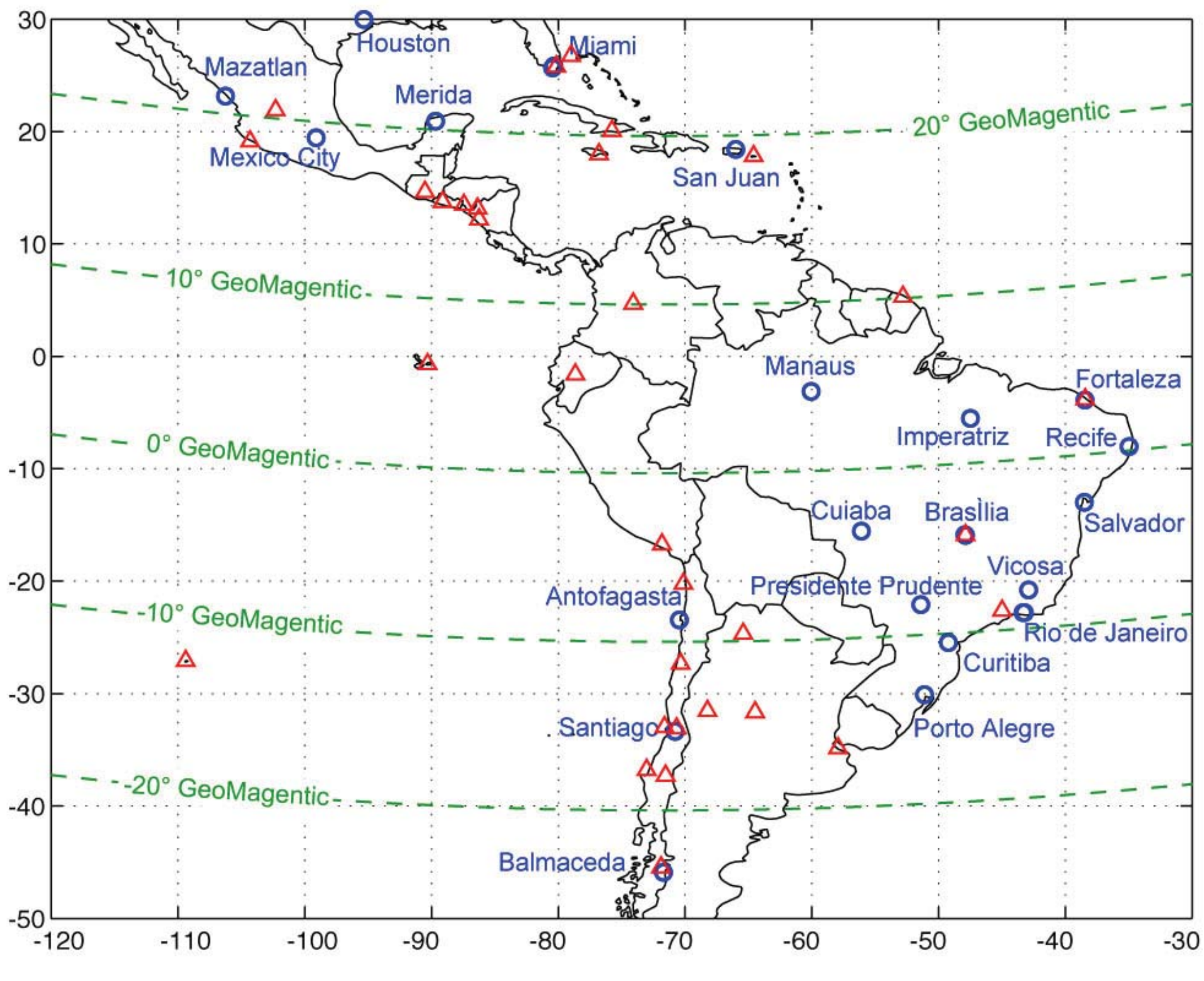
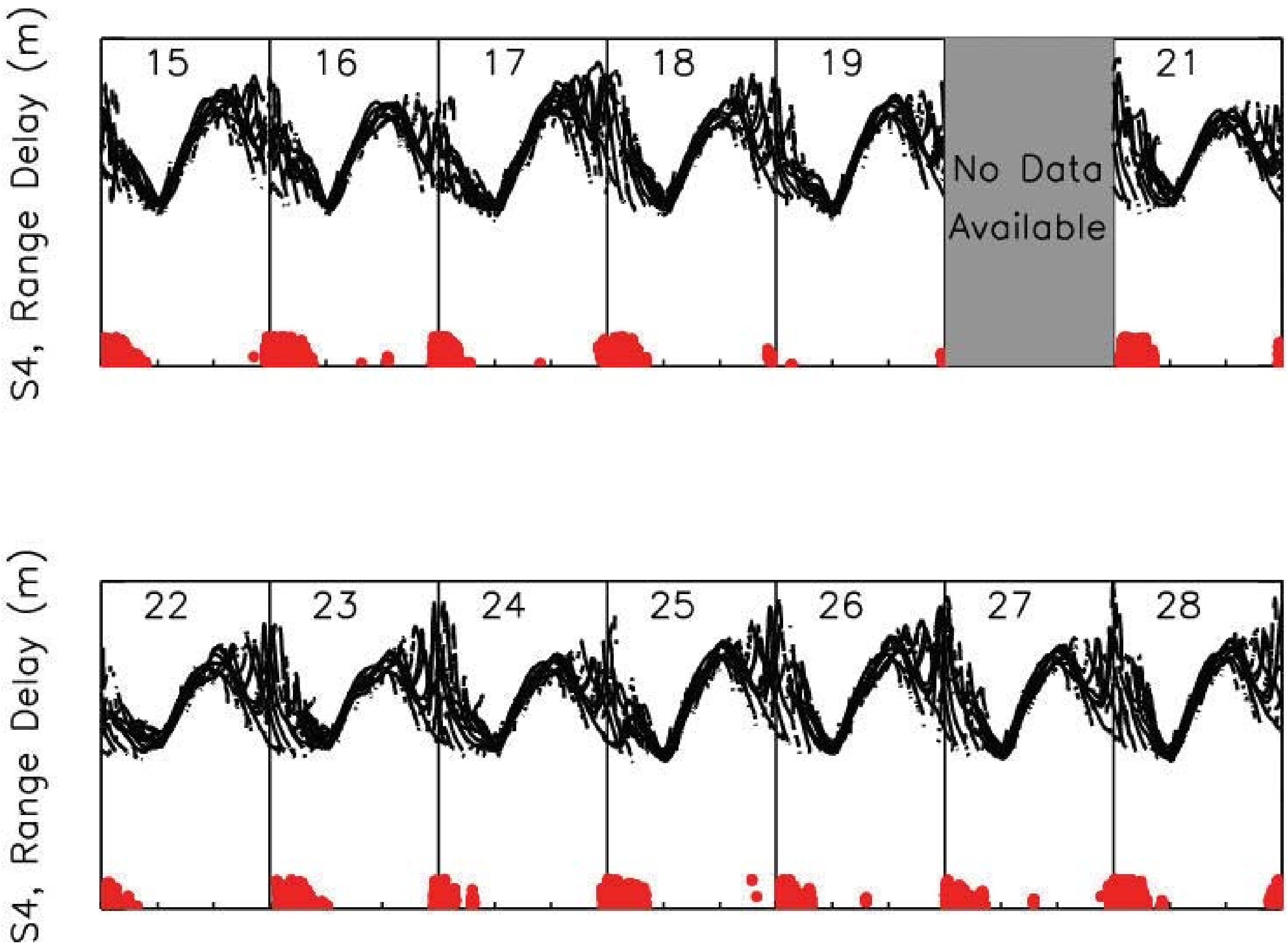
Map of South American Stations



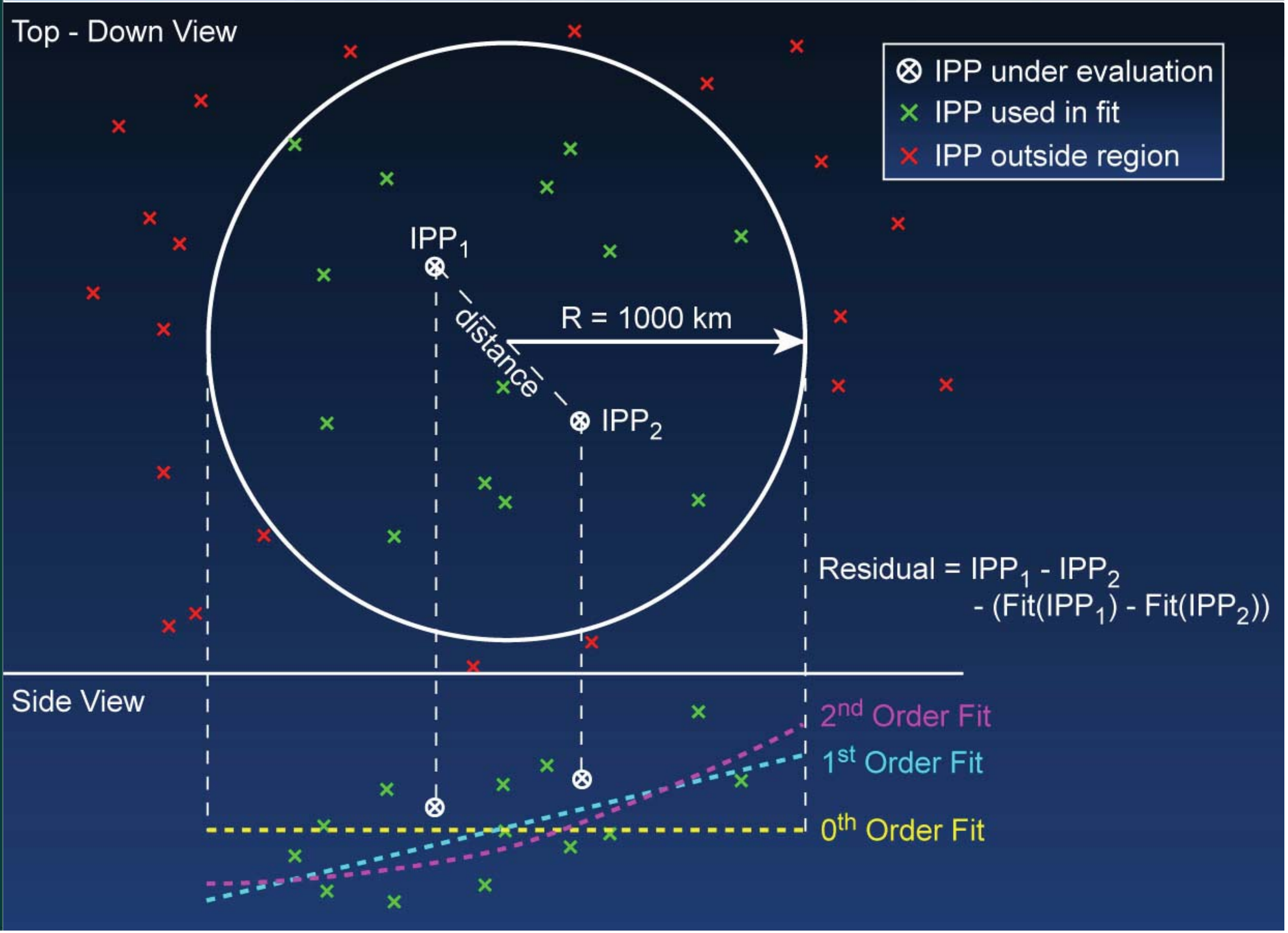
Determination of Quiet Days

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

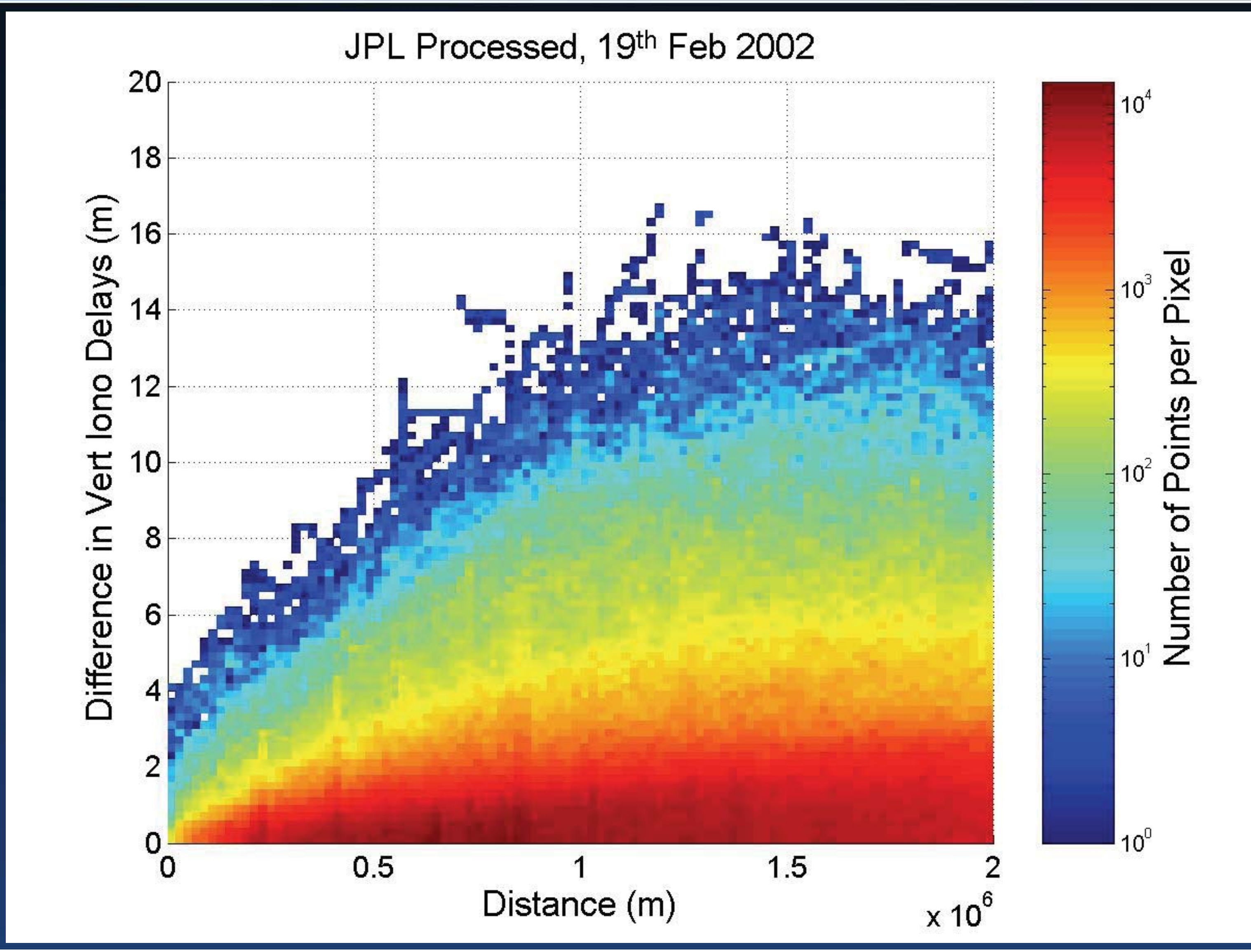
Daily Observations of TEC and S4



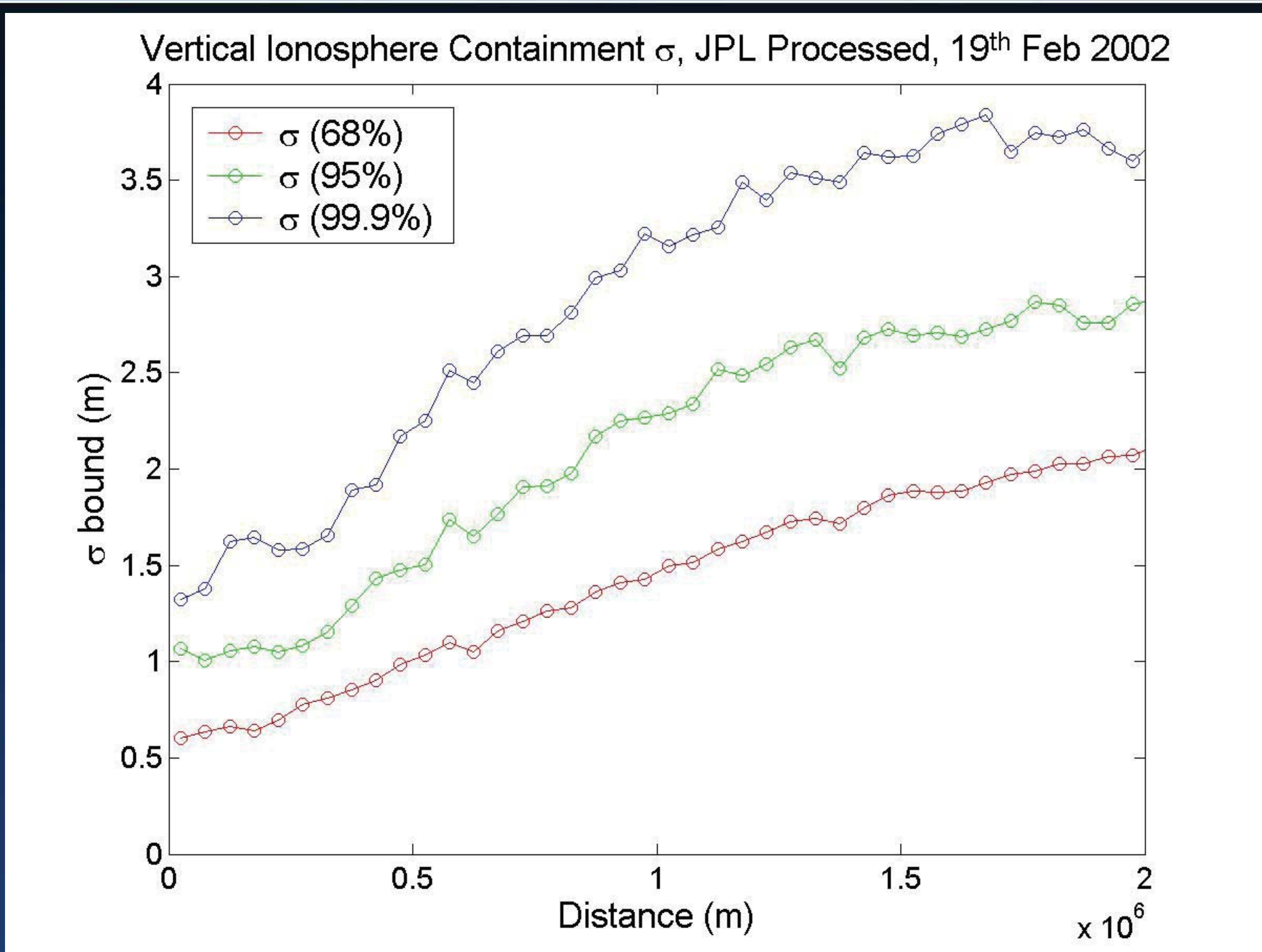
Correlation Estimation Process



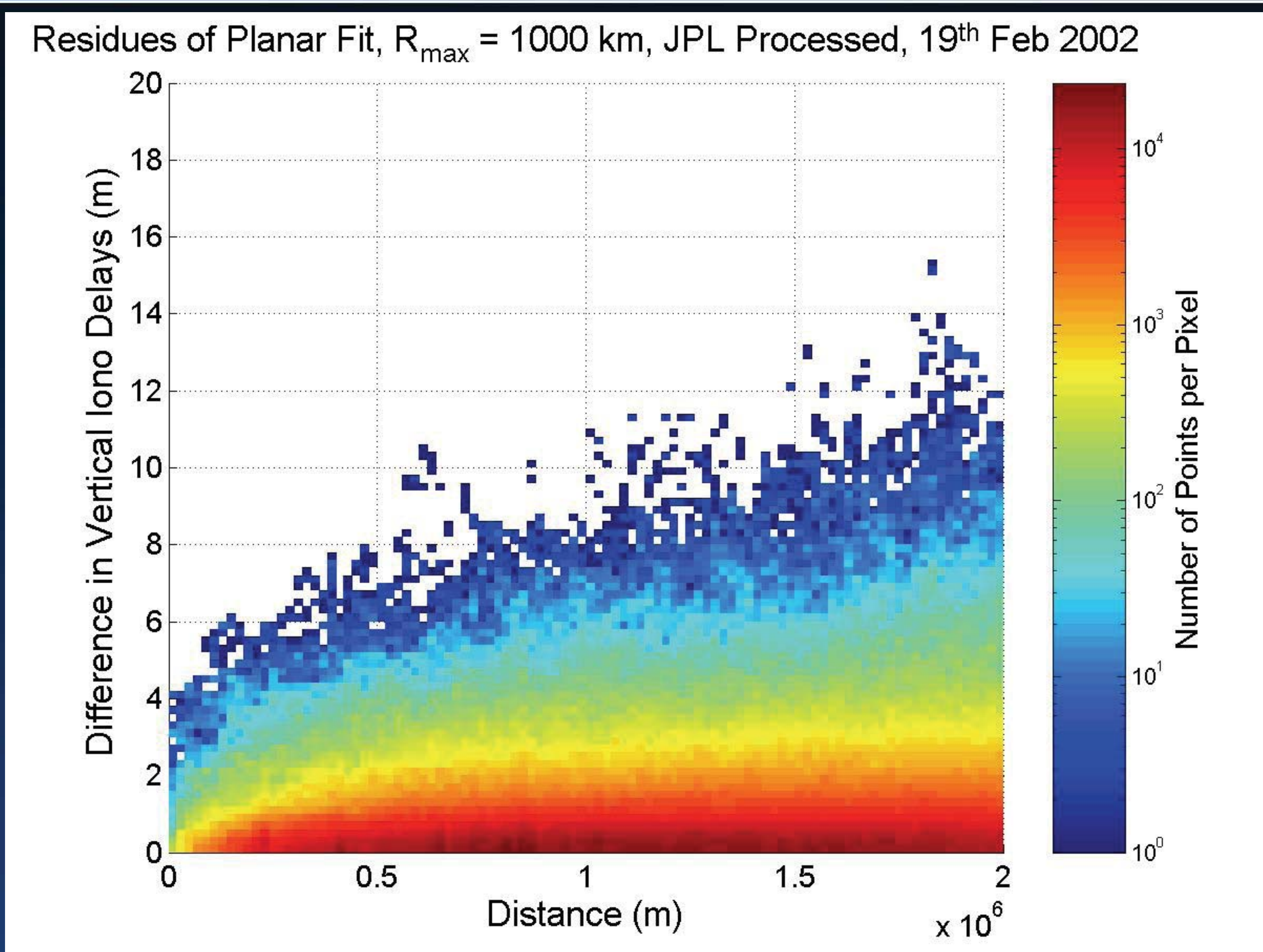
Two-D Histogram 0th Order



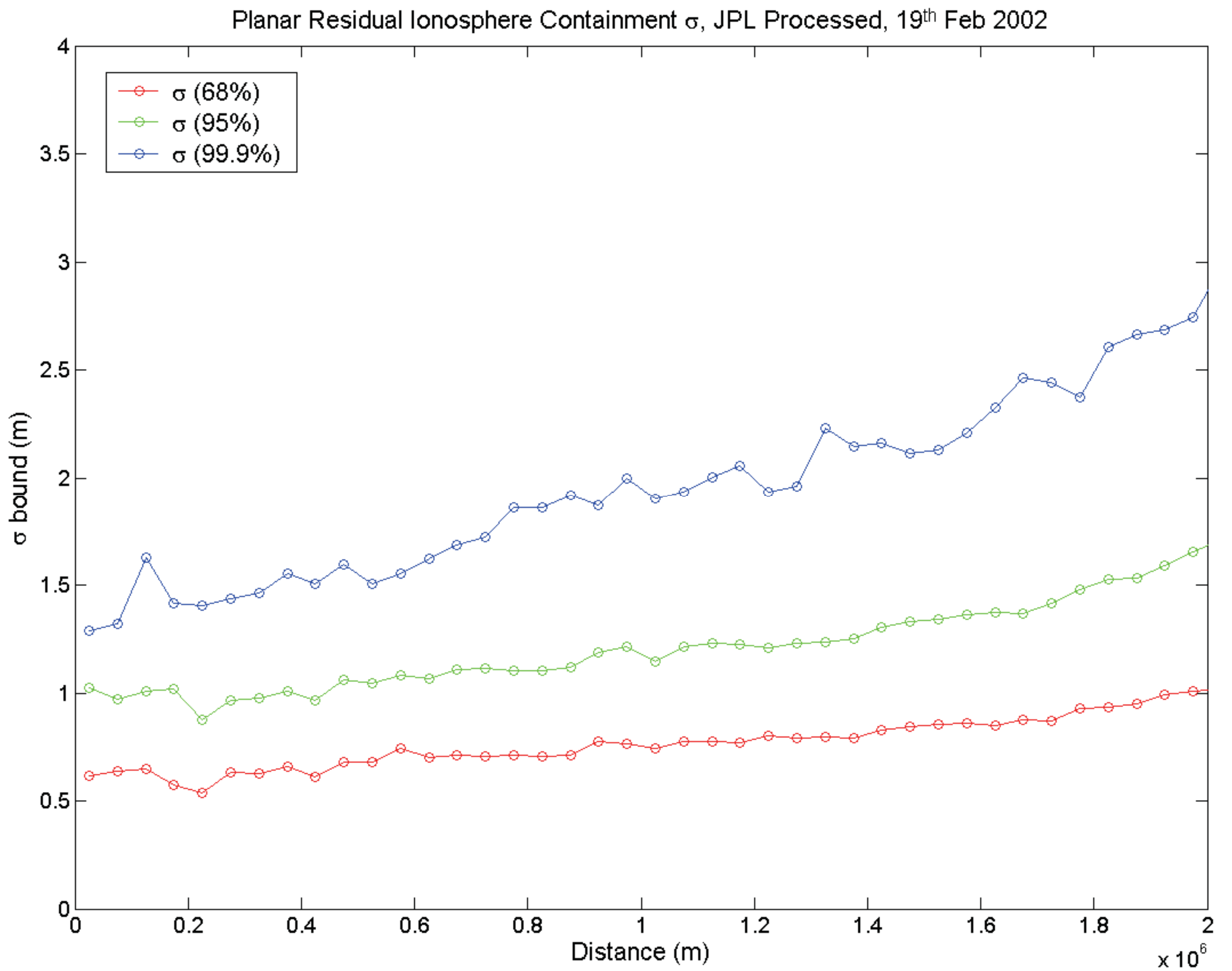
Sigma Estimate 0th Order



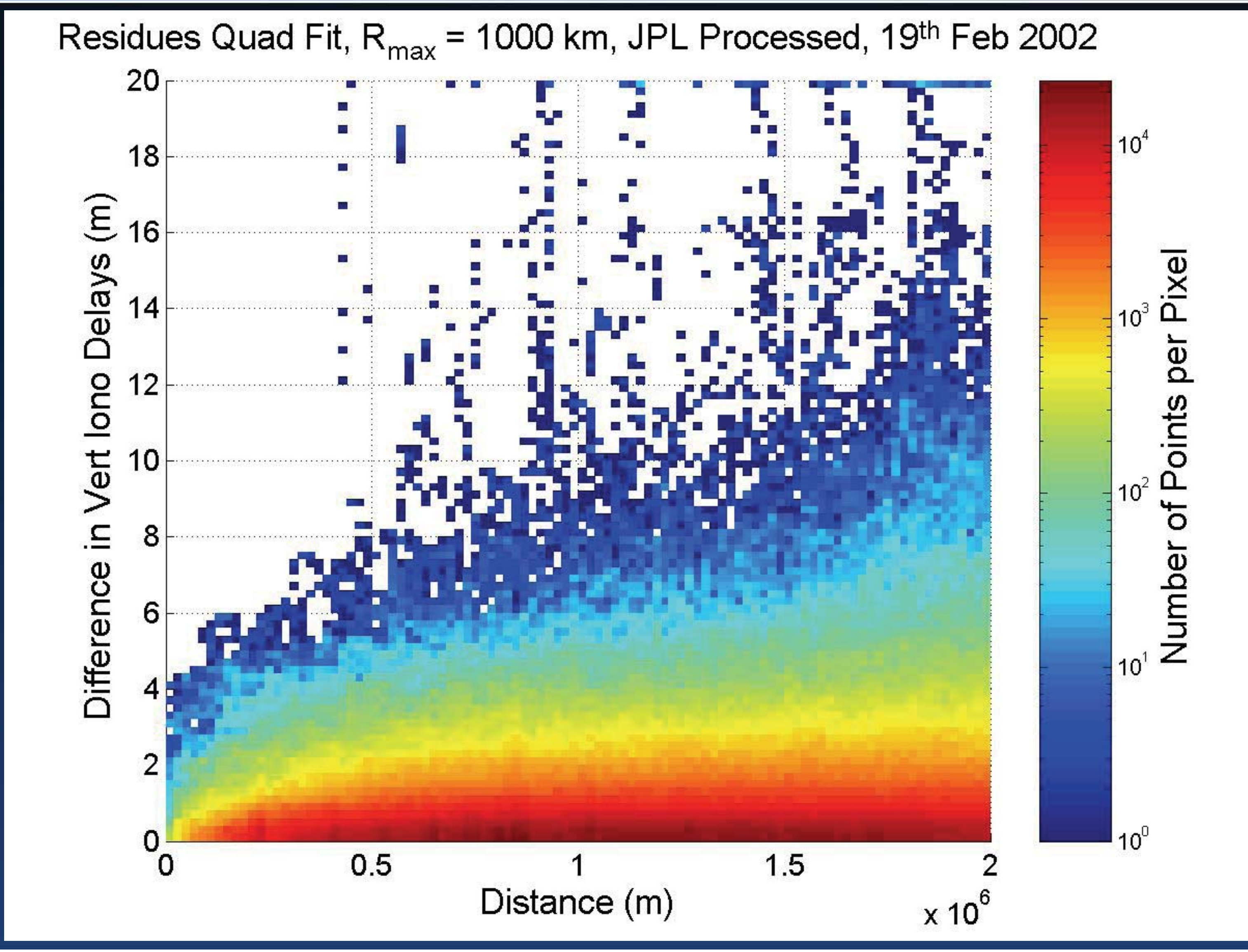
Two-D Histogram 1st Order



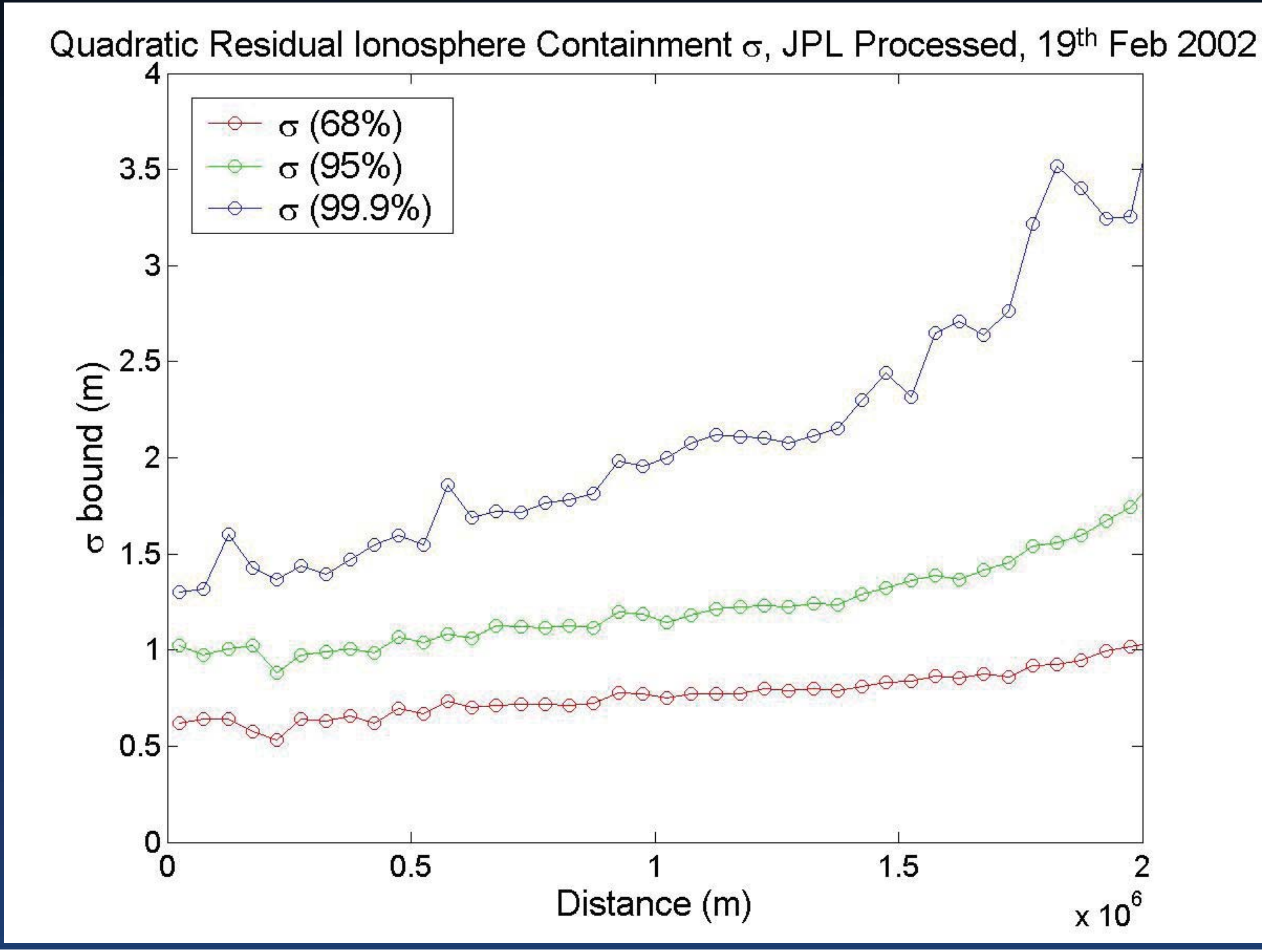
Sigma Estimate 1st Order



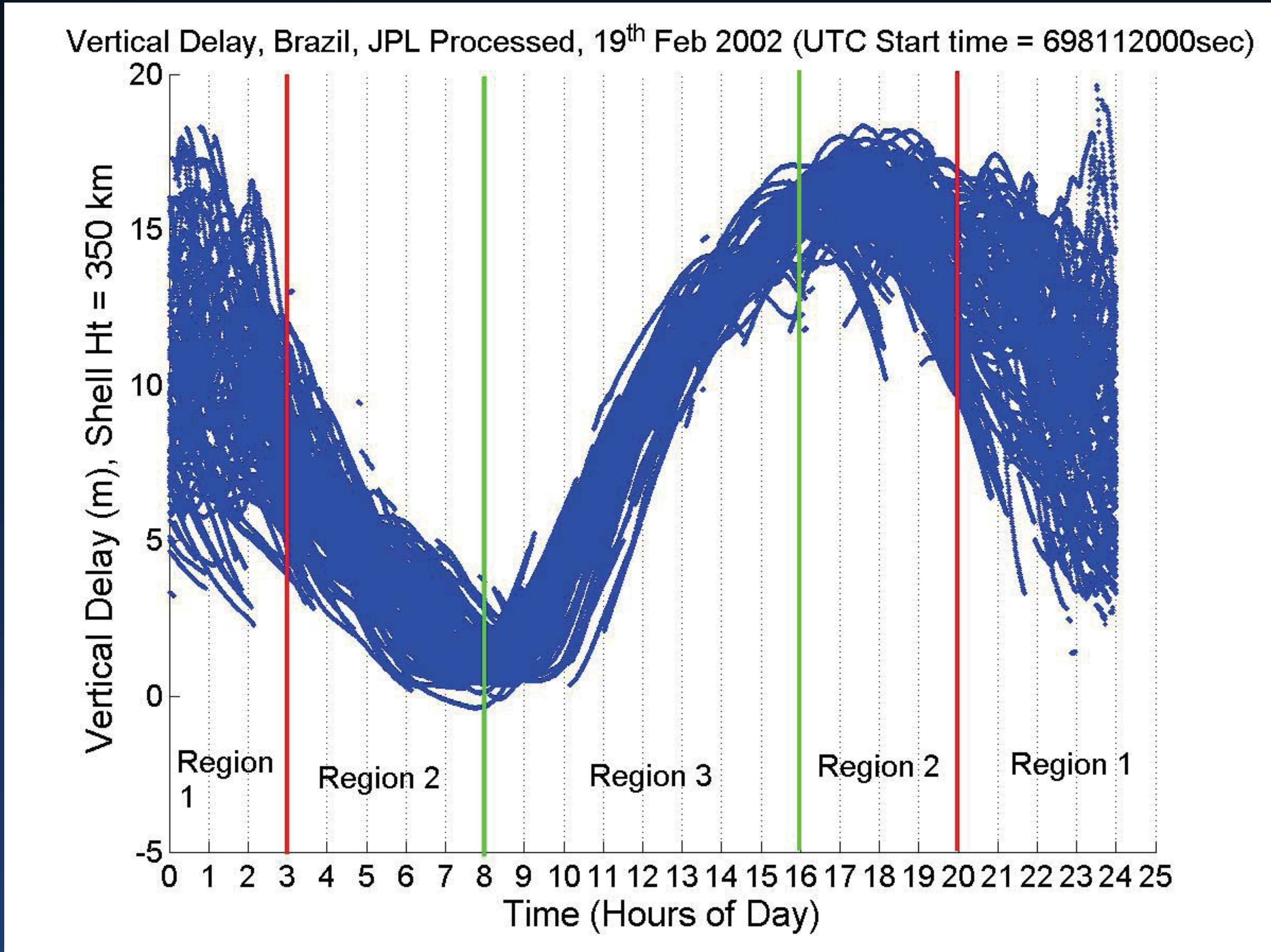
Two-D Histogram 2nd Order



Sigma Estimate 2nd Order



Vertical TEC



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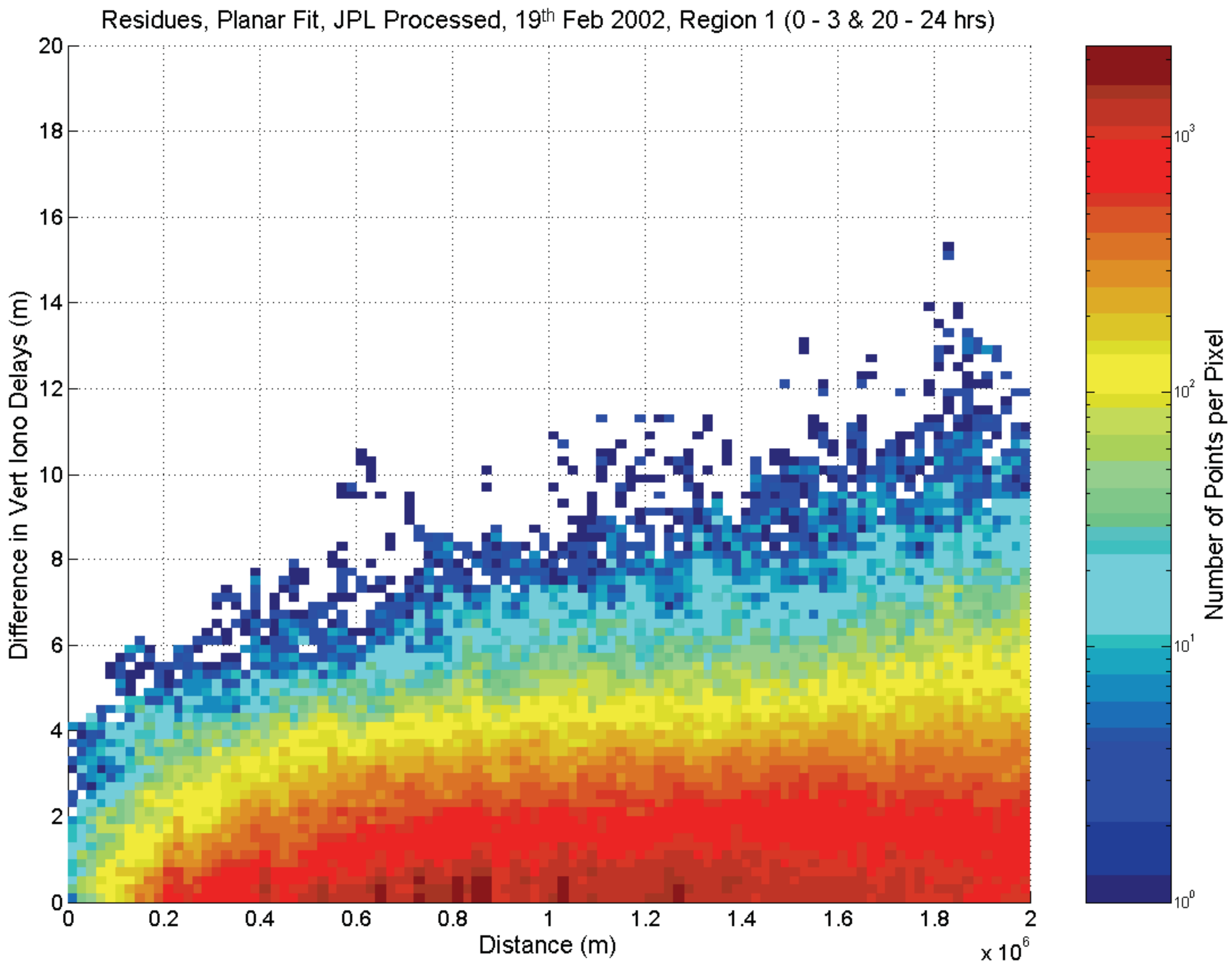
Two-D Histogram 1st Order (Region 1)



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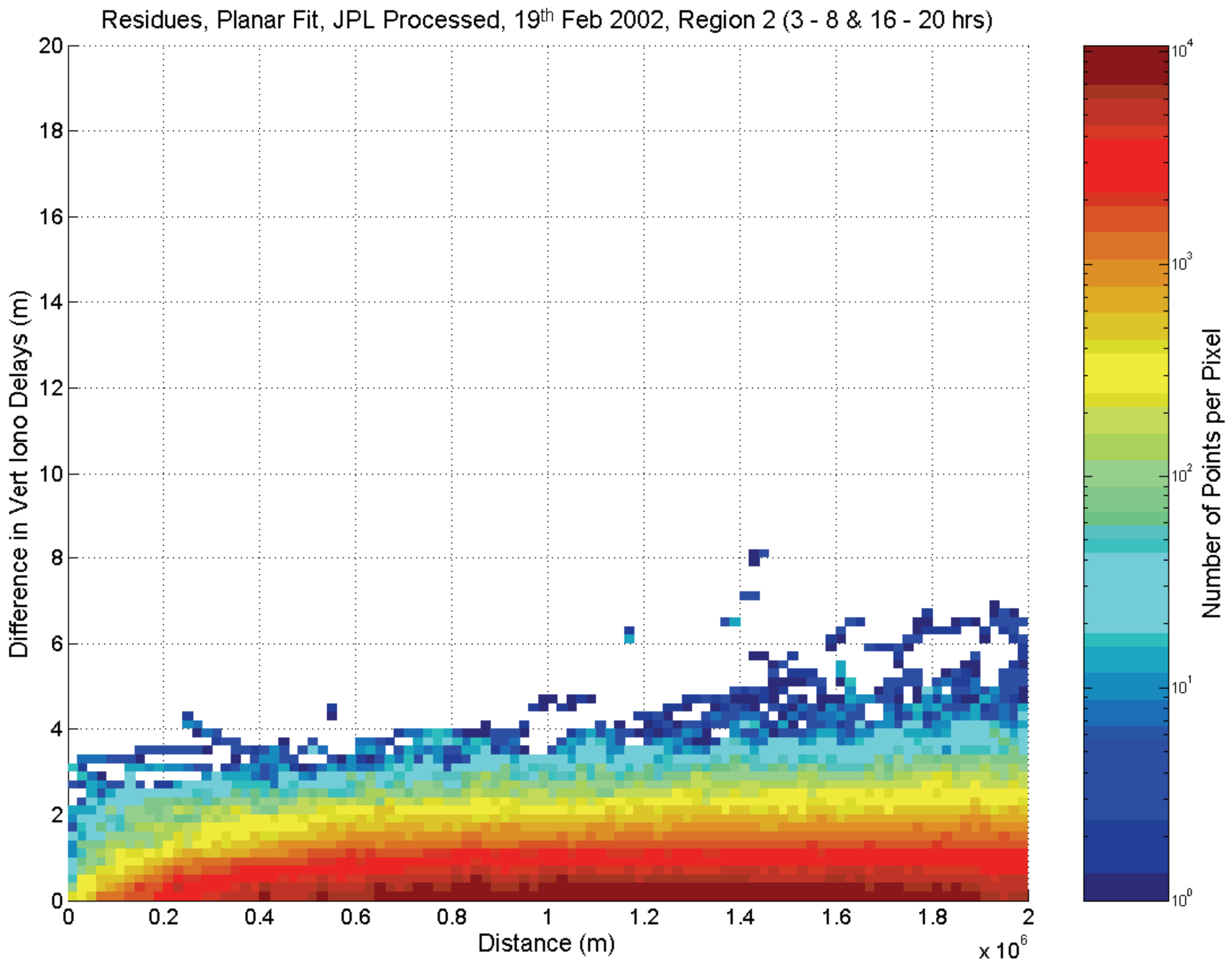
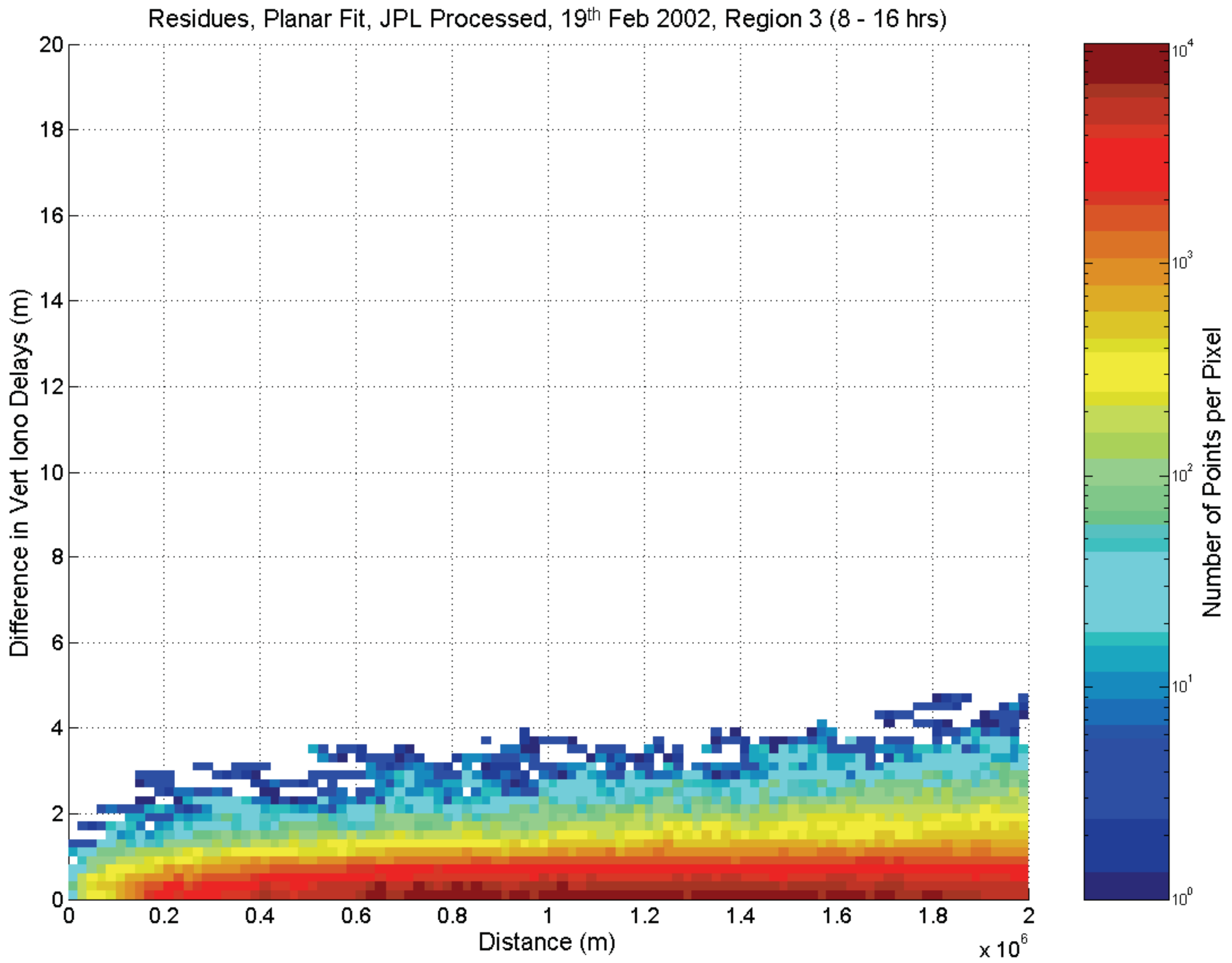
Two-D Histogram 1st Order (Region 2)



Two-D Histogram 1st Order (Region 3)



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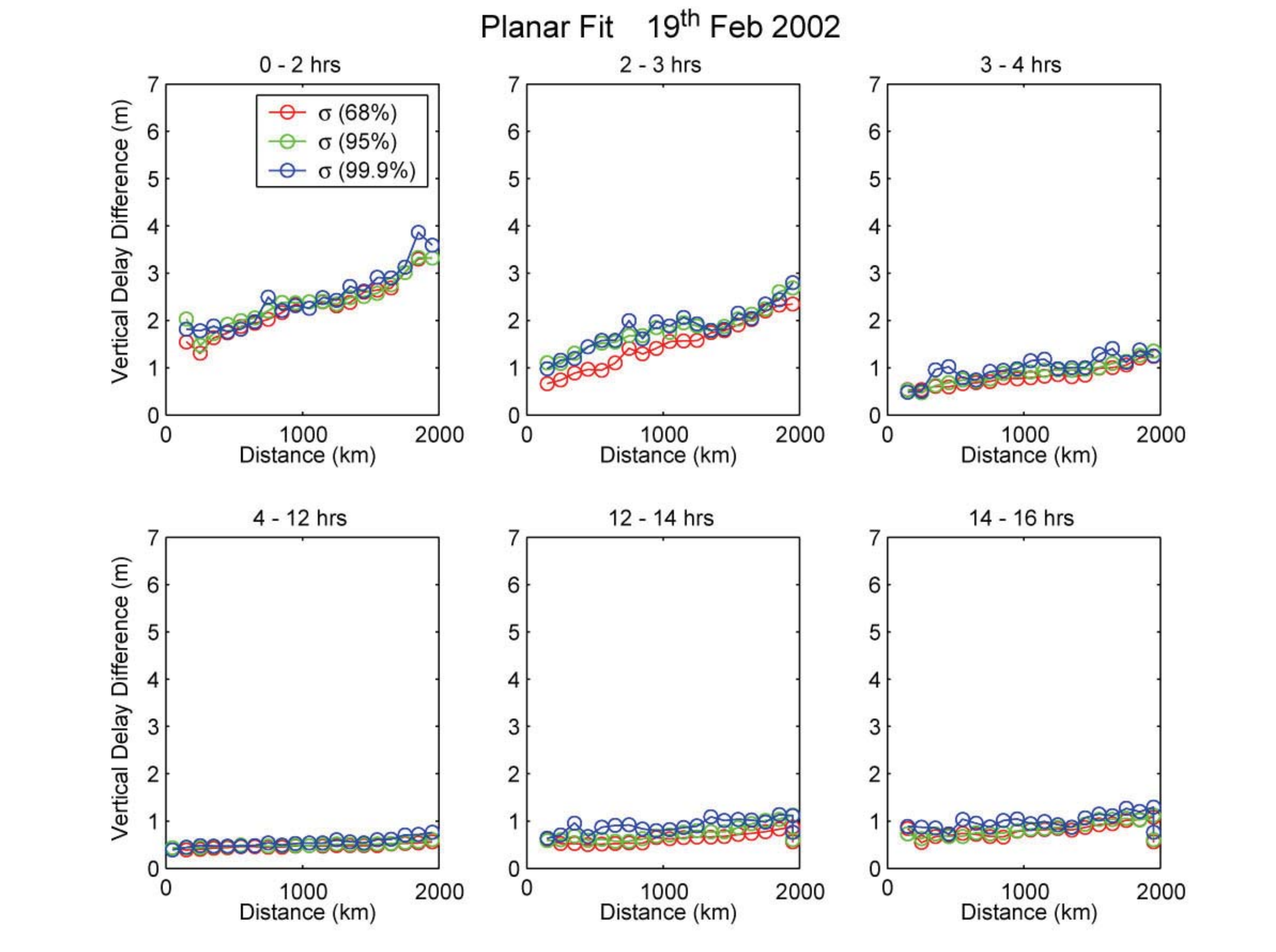
Sigma Estimate 1st Order (Sliced by Time)



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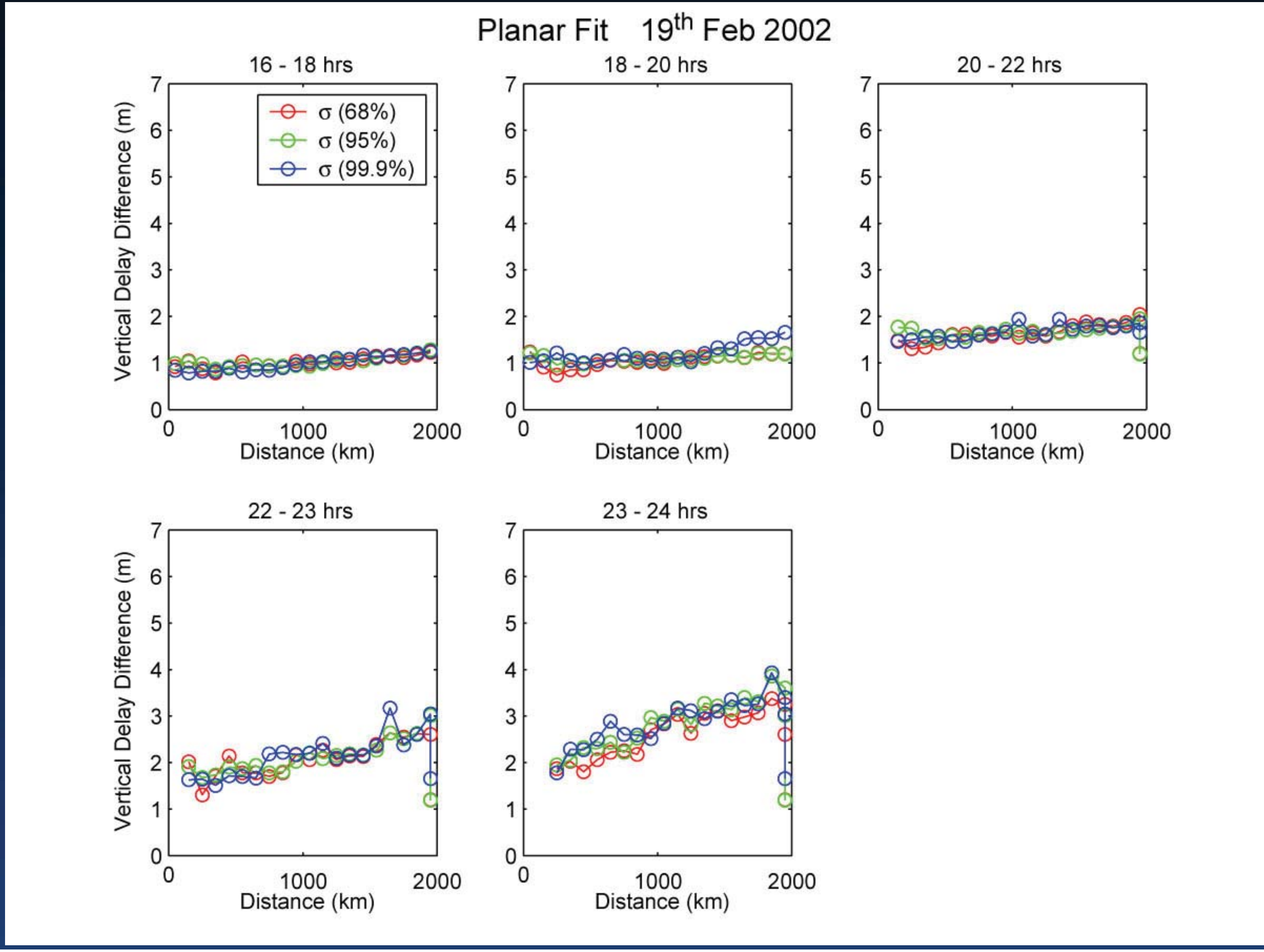
Sigma Estimate 1st Order (Sliced by Time)



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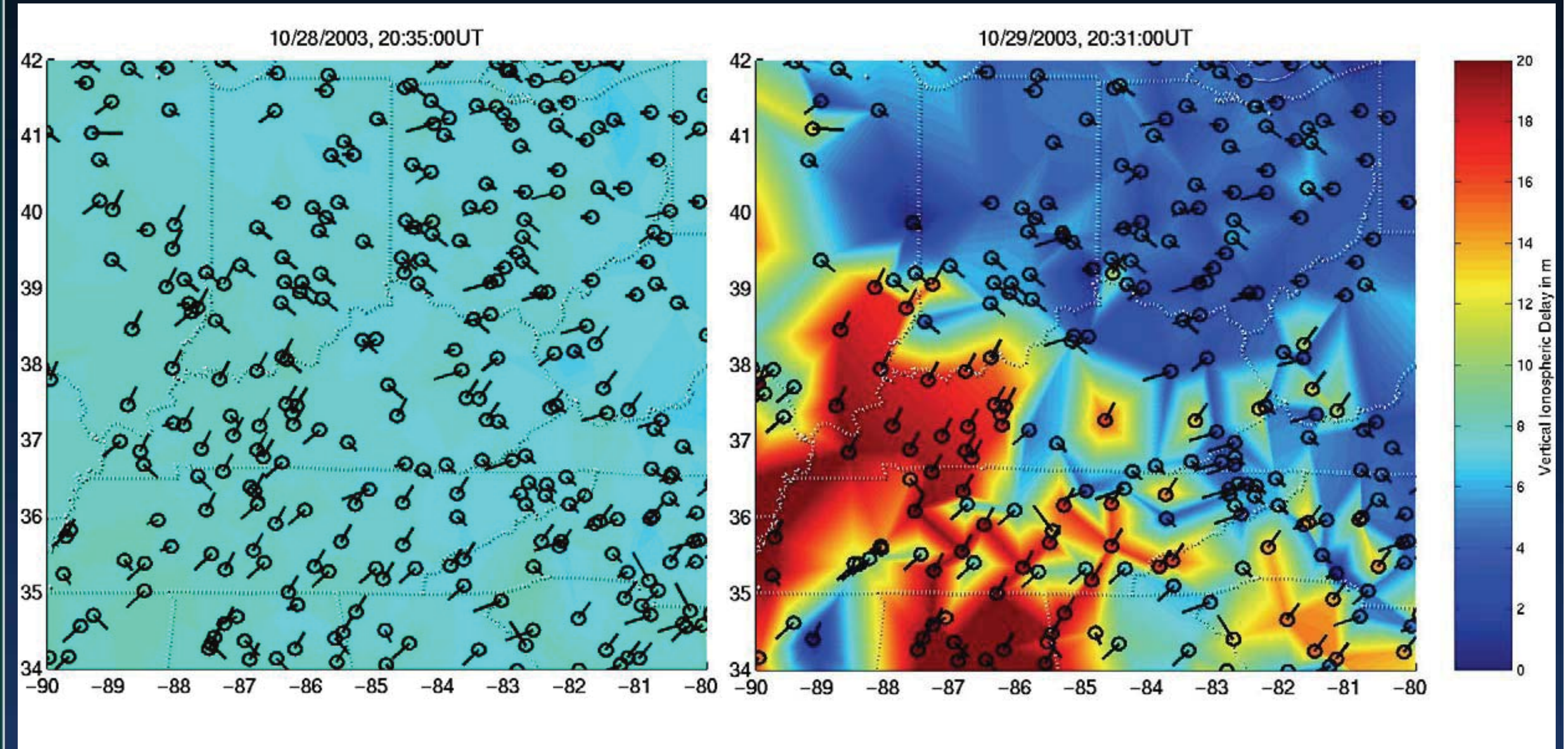
Correlation Observations

- 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*

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

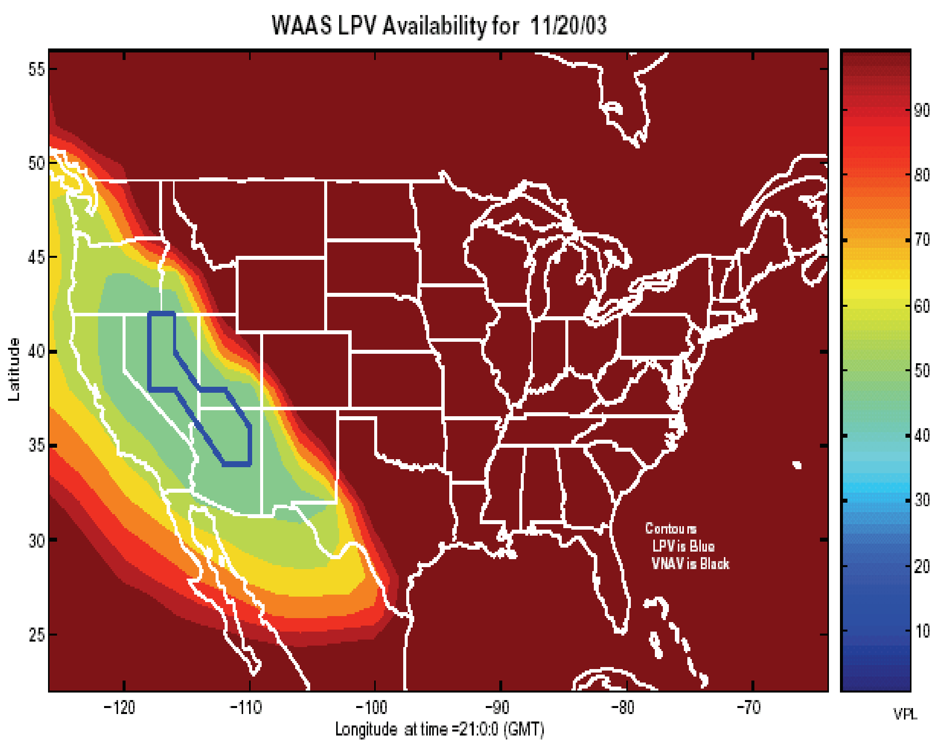
Failure of Thin Shell Model

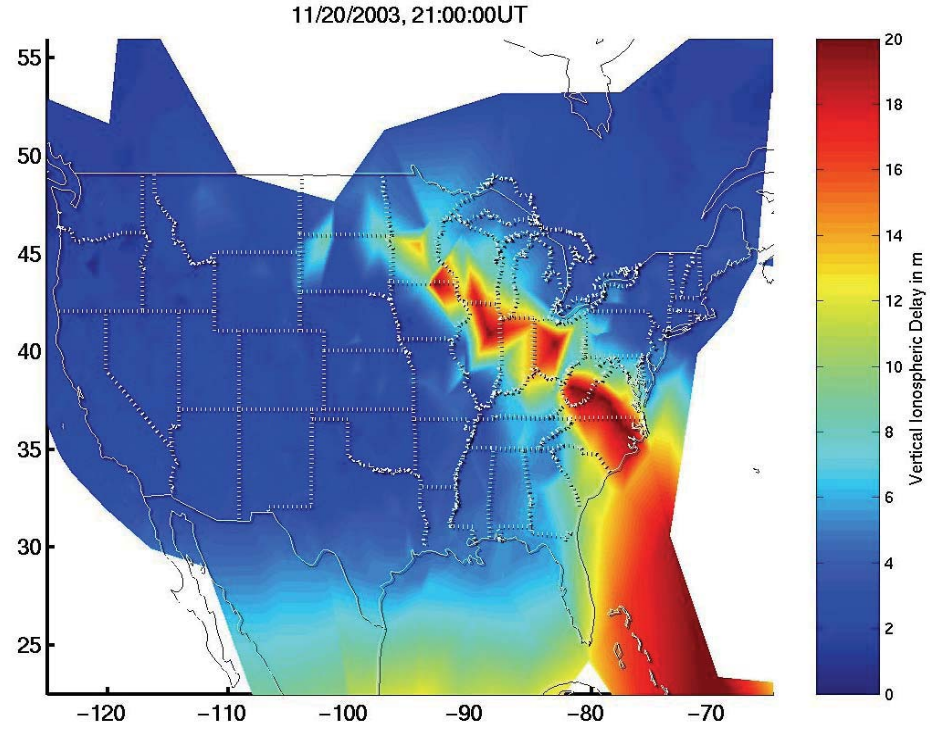


Quiet Day

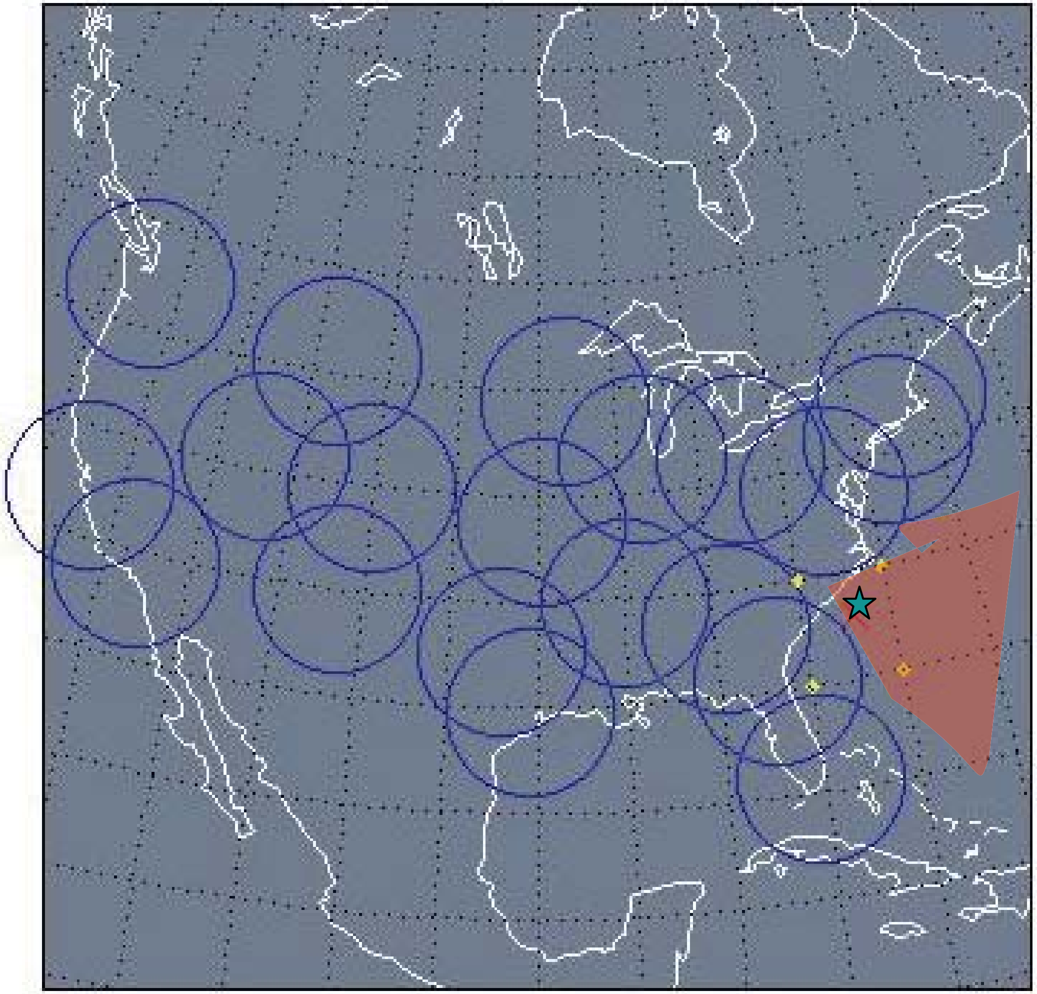
Disturbed Day

11/20/2004 21:00:00 GMT



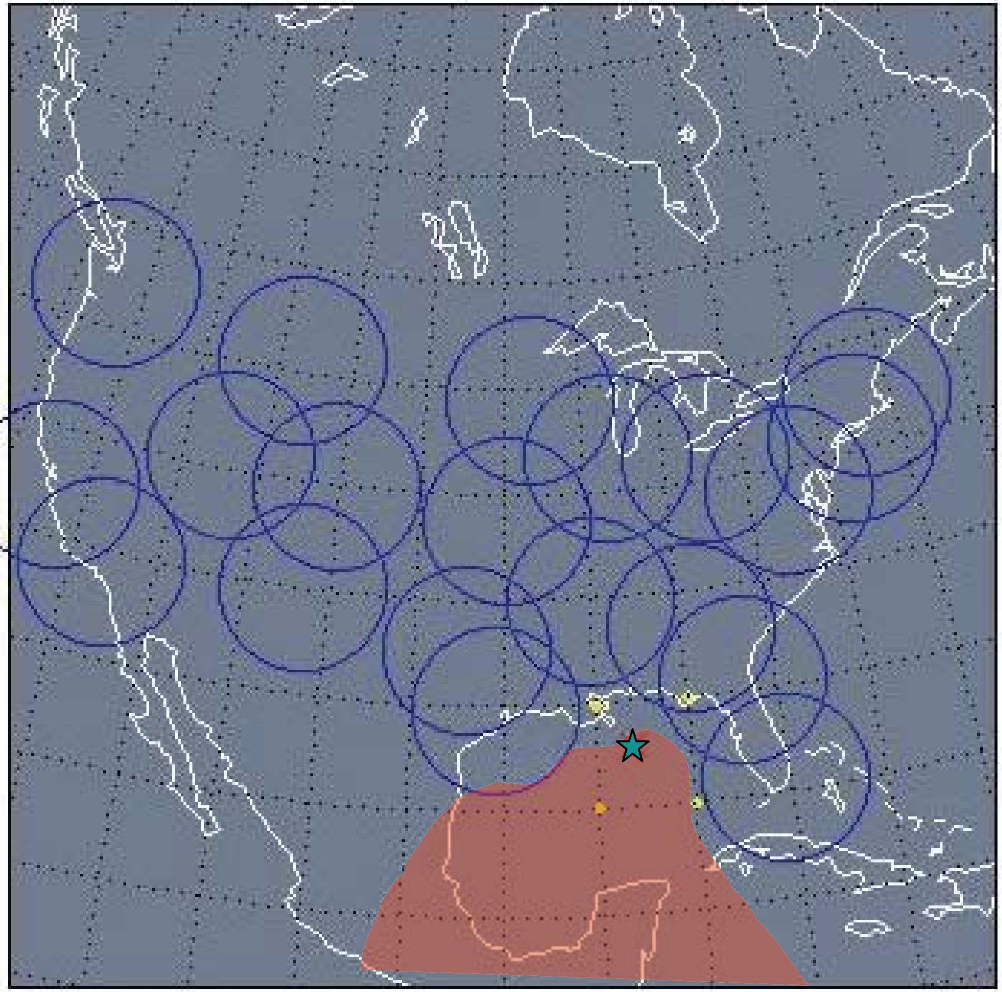


Threats at the Edge of Coverage



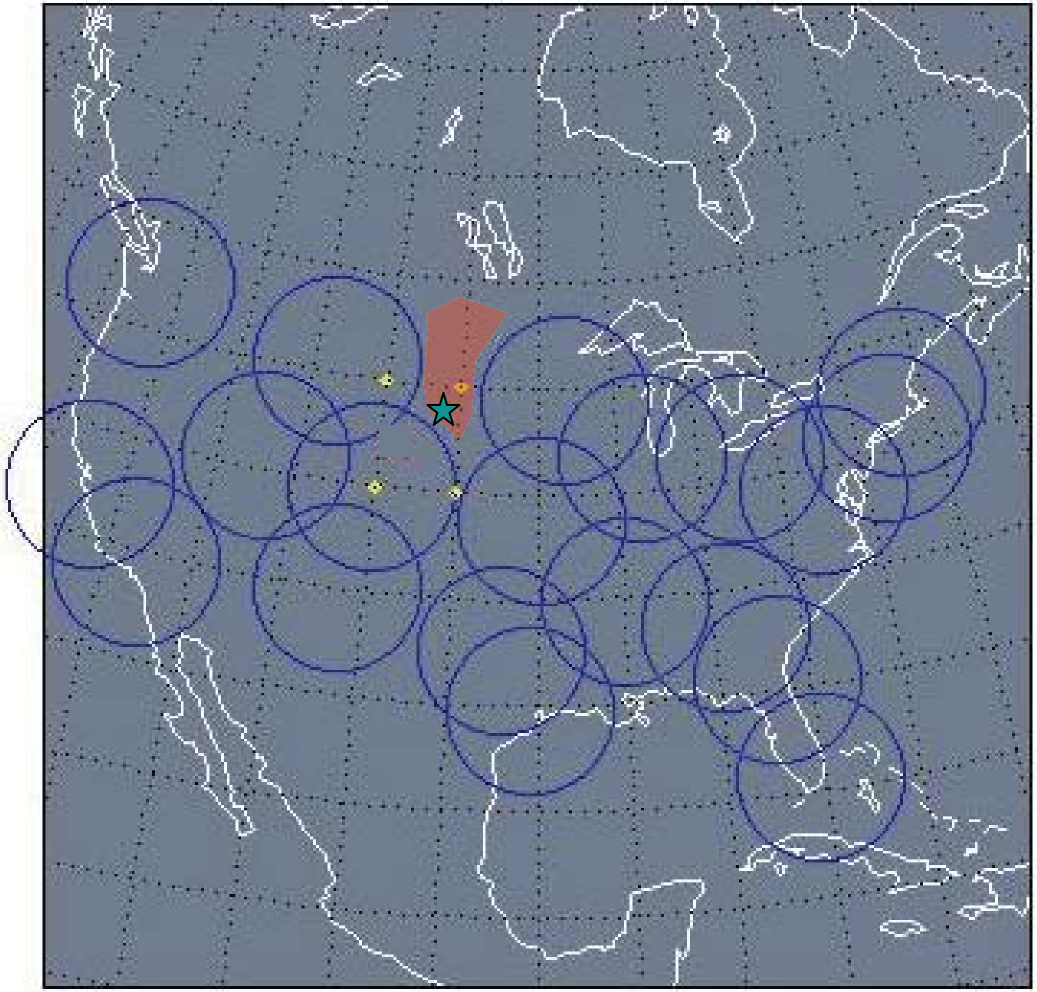
Courtesy:
Seebany
Datta-Barua

Edge of Coverage 2



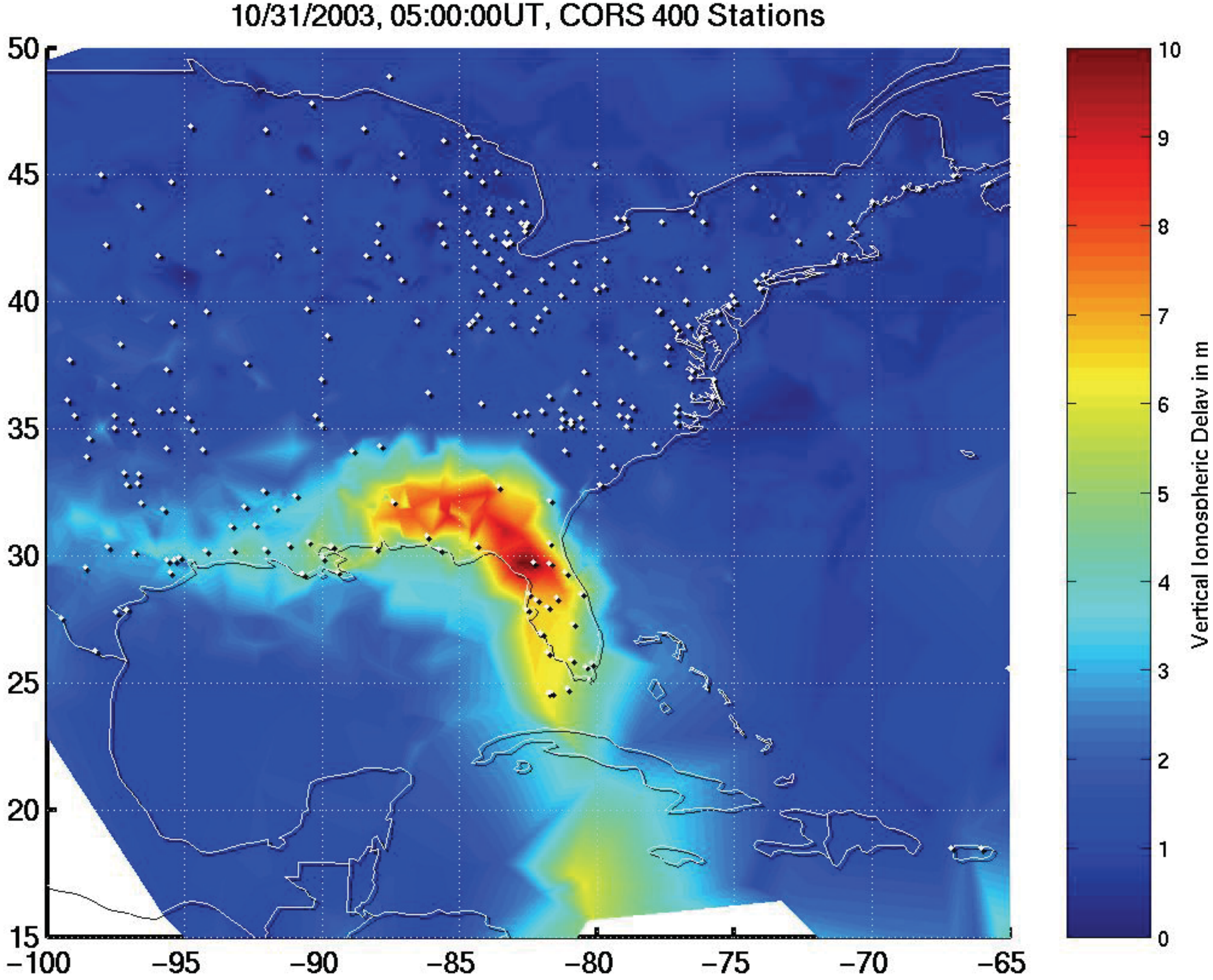
Courtesy:
Seebany
Datta-Barua

Undersampling Within CONUS



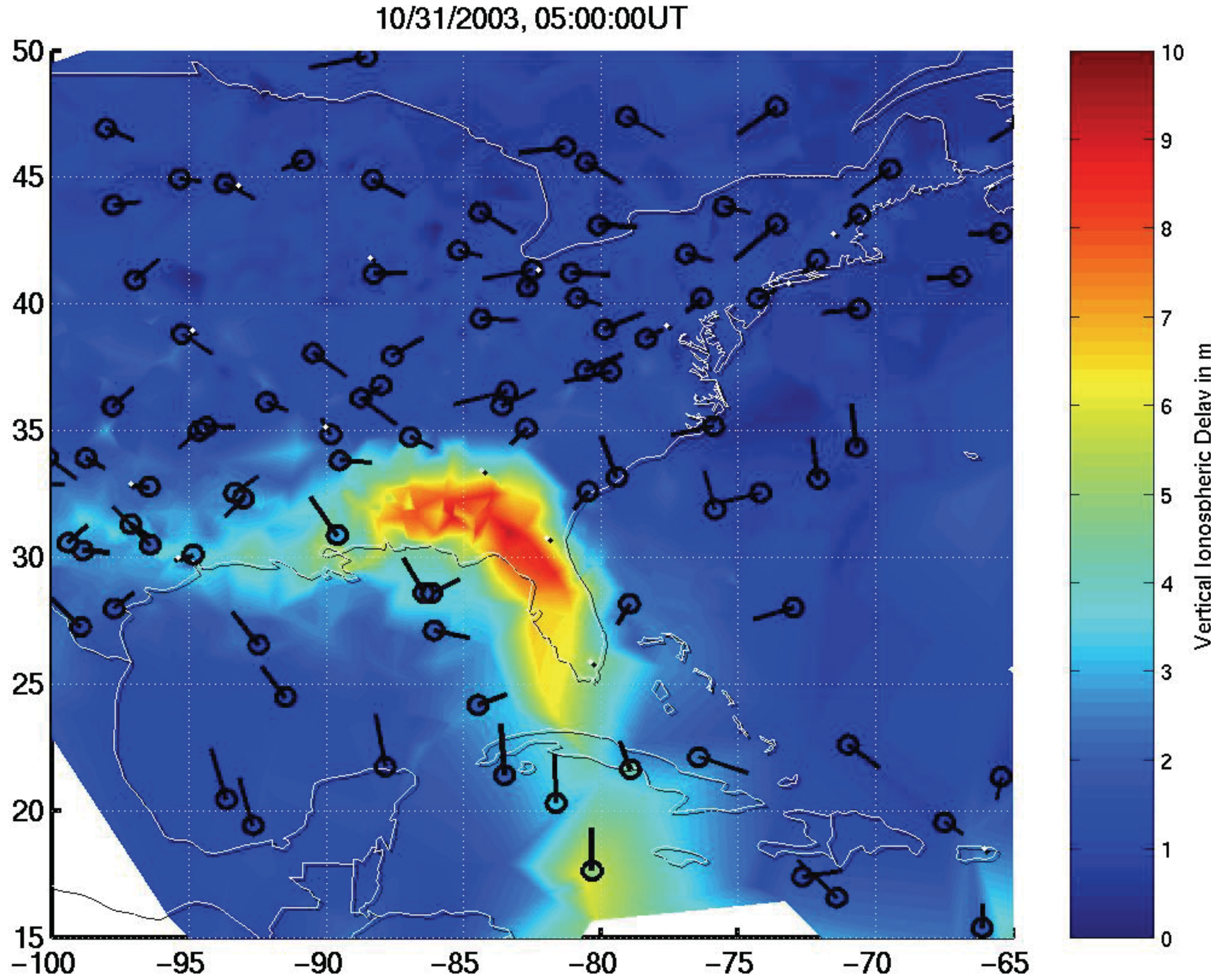
Courtesy:
Seebany
Datta-Barua

Small-scale Irregularity



Courtesy:
Seebany
Datta-Barua

Artificial Undersampled Scenario



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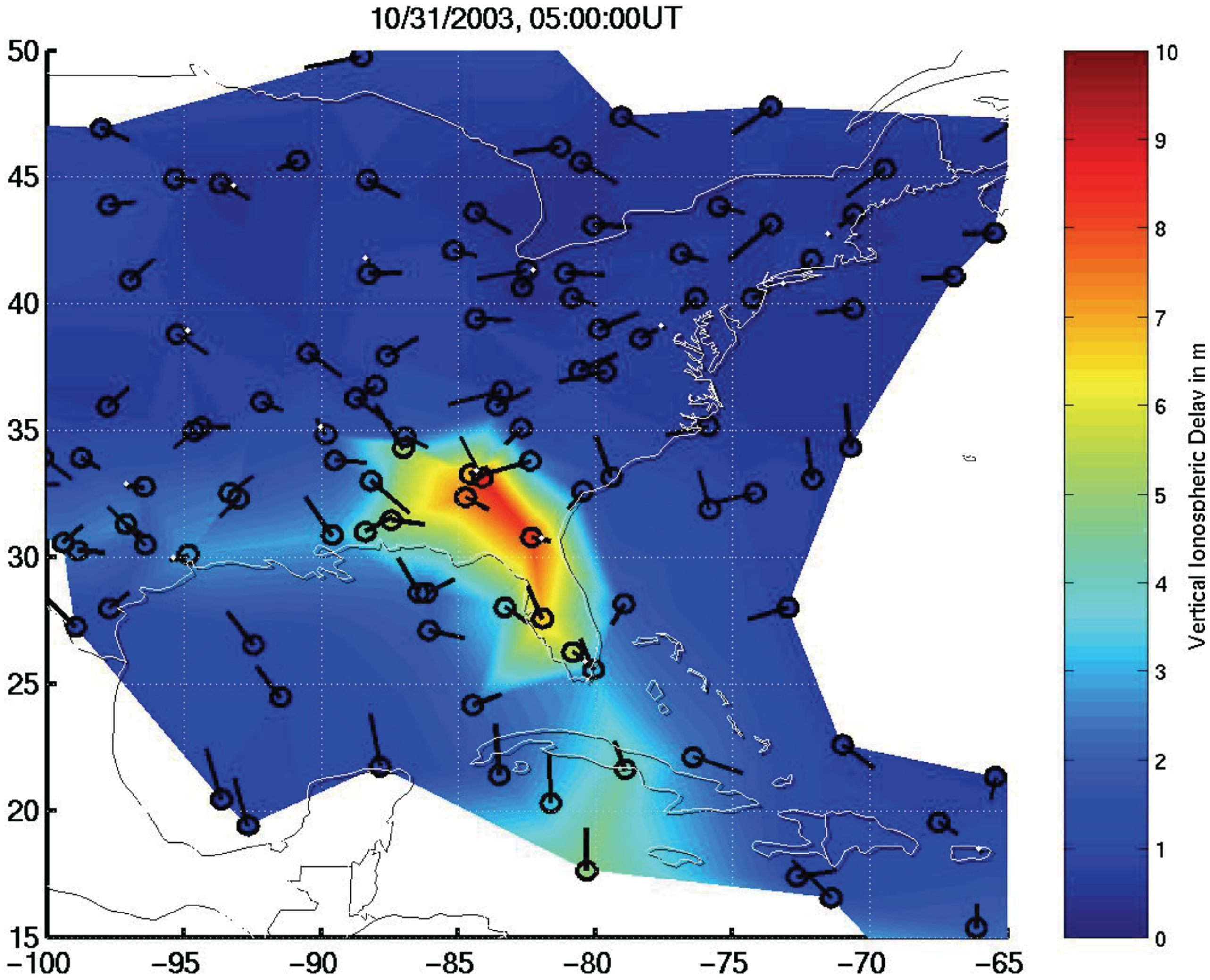
Seebany
Datta-Barua

WAAS Measurements



Courtesy:
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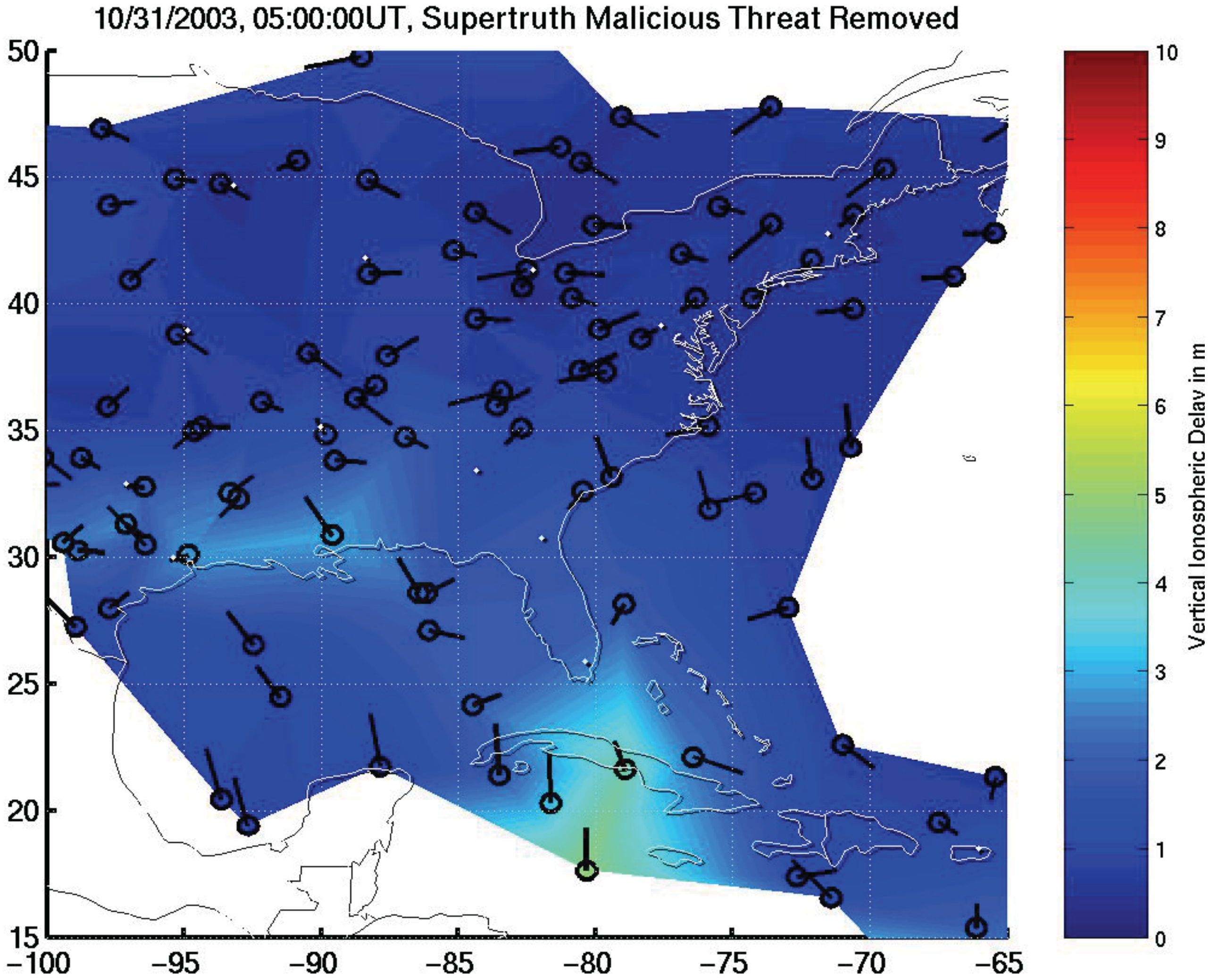
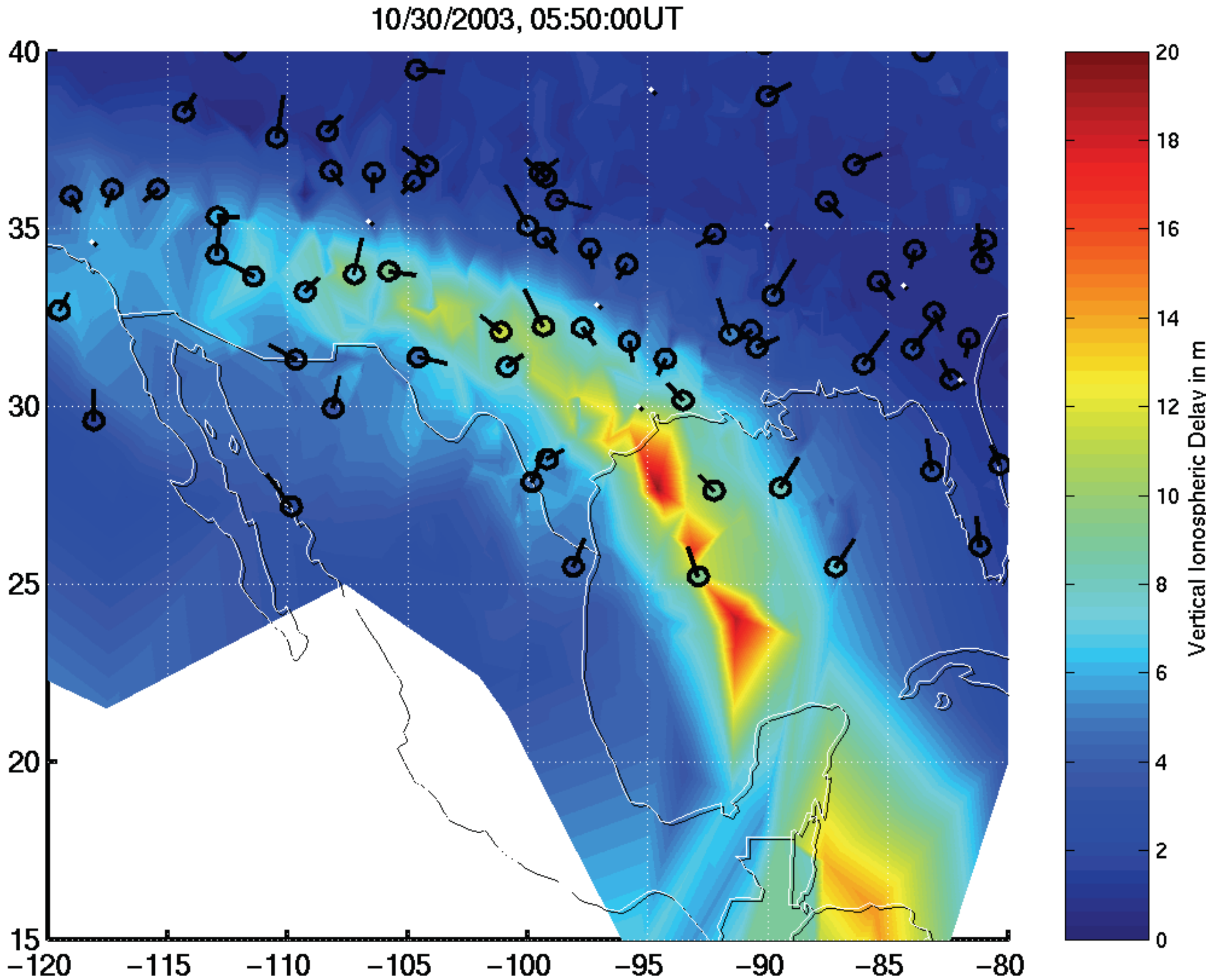
Datta-Barua

Artificial WAAS Undersampling Scenario



Courtesy: Seebany Datta-Barua

Real Undersampled Condition



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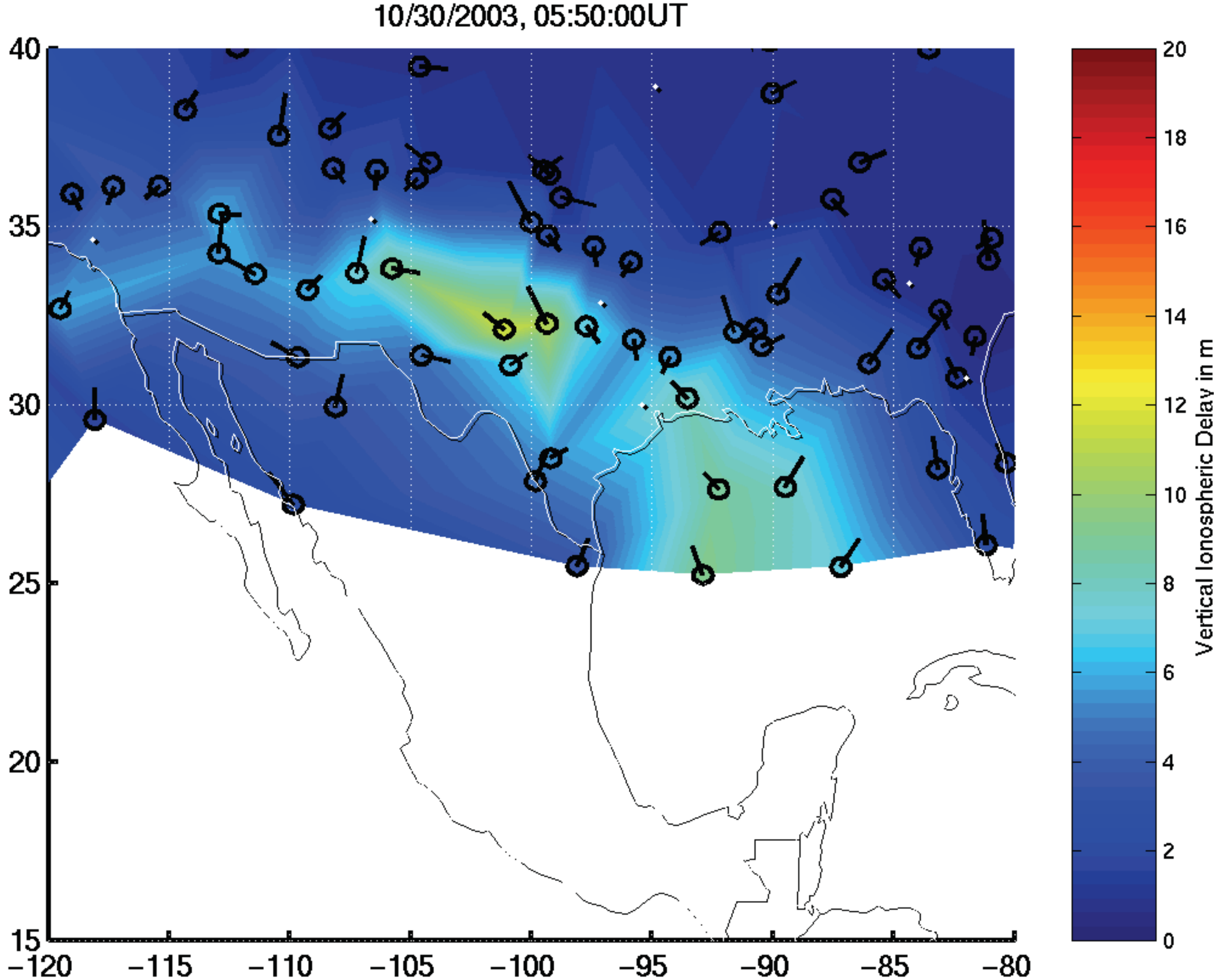
Datta-Barua

WAAS Measurements



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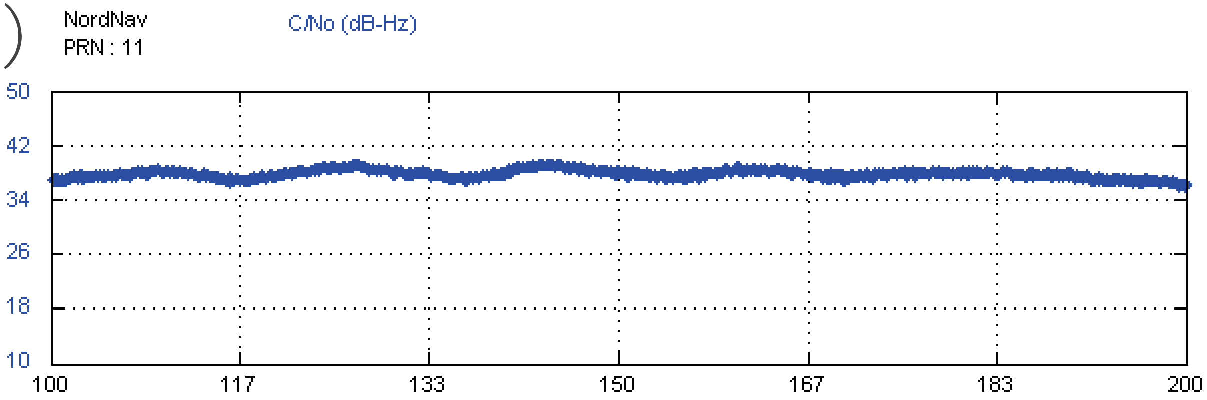
Seebany
Datta-Barua

Scintillation and Deep Signal Fading

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

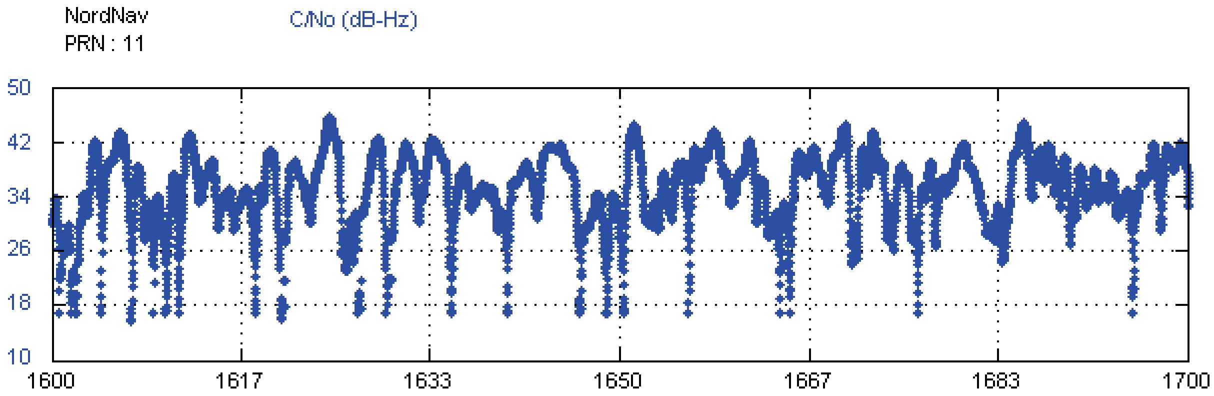
C/No

Nominal



Scintillation

(equatorial & solar max)

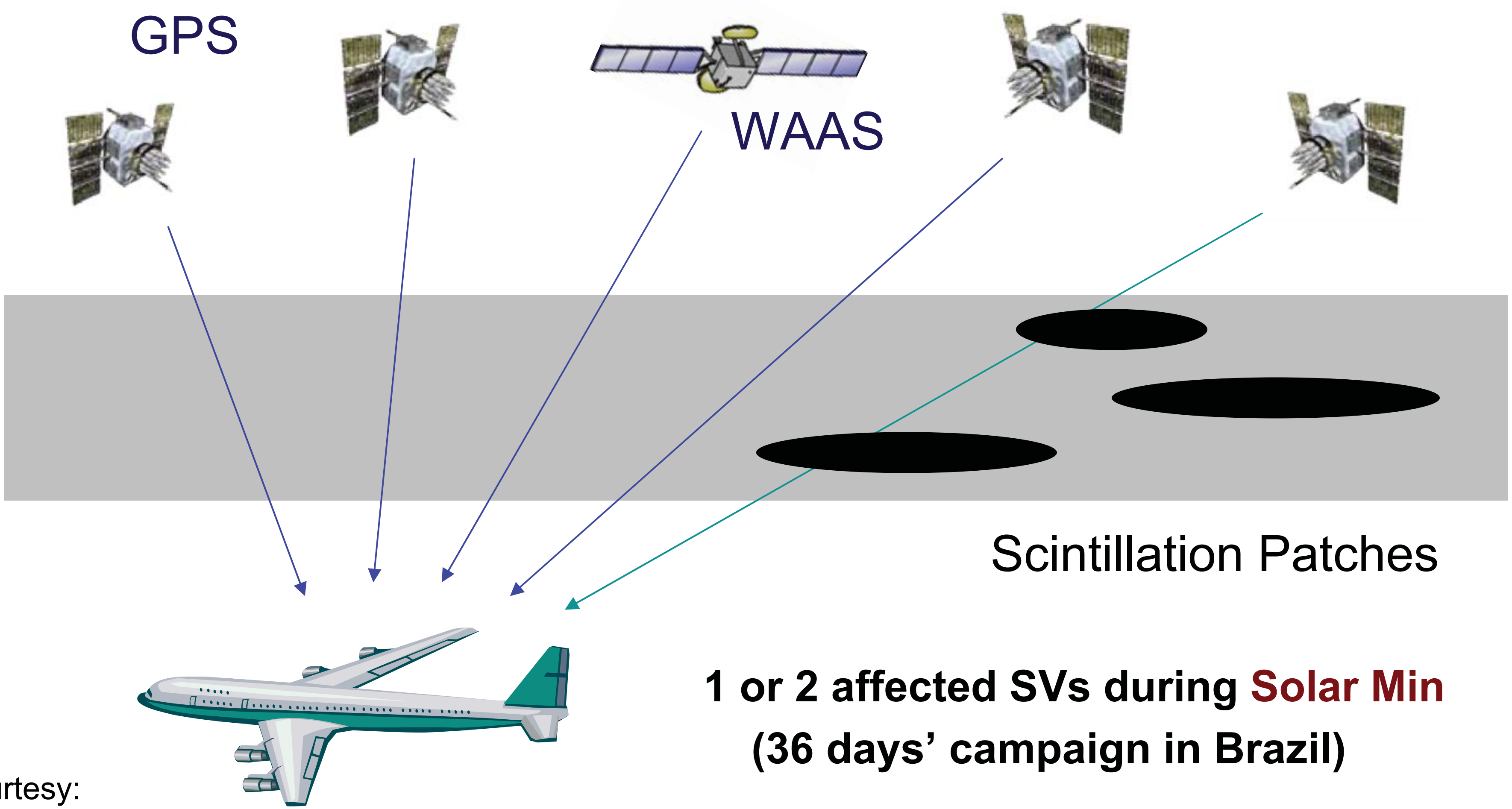


25 dB

Courtesy:
Jiwon Seo

100 sec

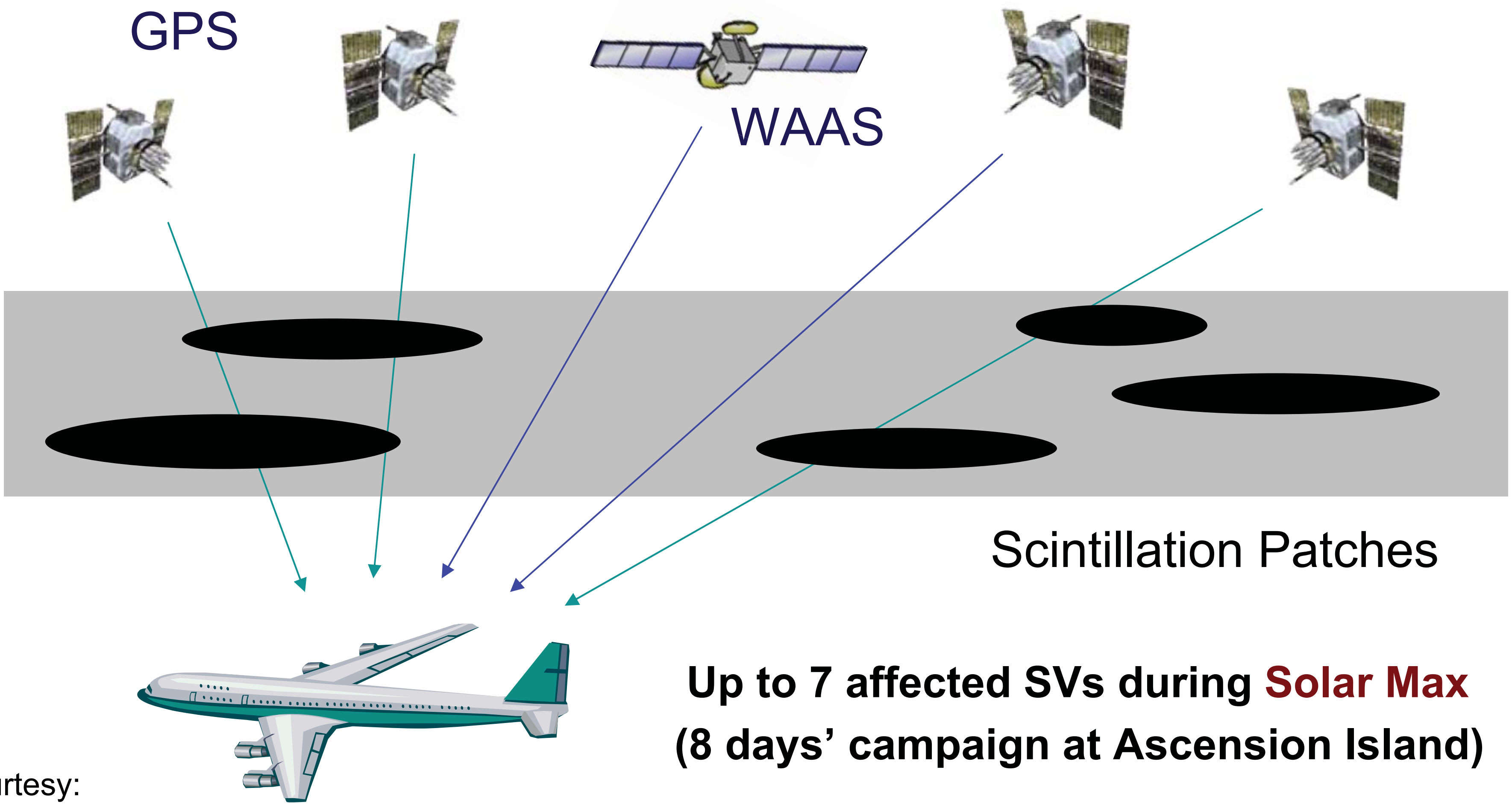
Scintillation and Navigation



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

Courtesy:
Jiwon Seo

Scintillation and Navigation

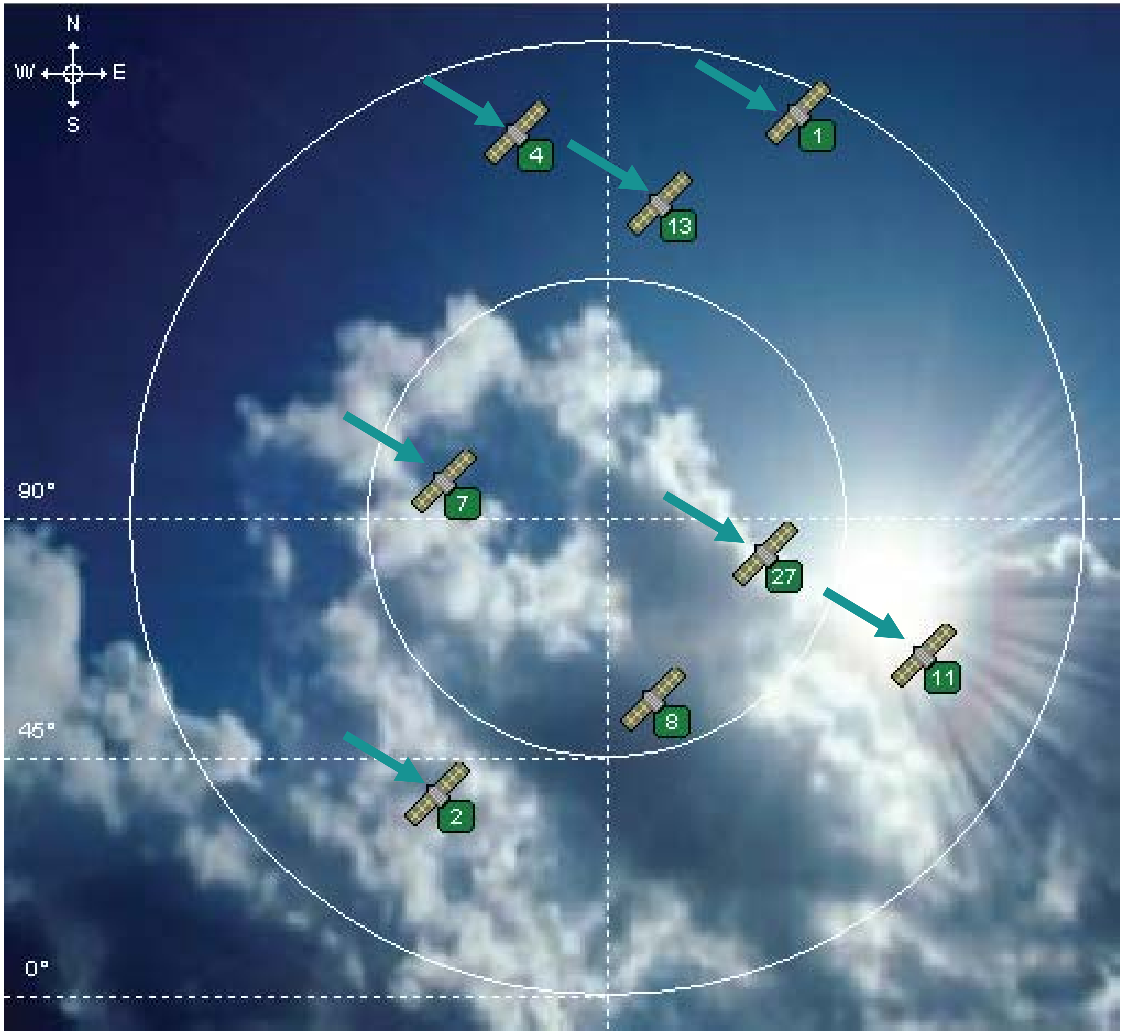


Up to 7 affected SVs during Solar Max
(8 days' campaign at Ascension Island)

Courtesy:
Jiwon Seo

Severe Scintillation Data

Solar Max
(worst 45 min
in 8 days)

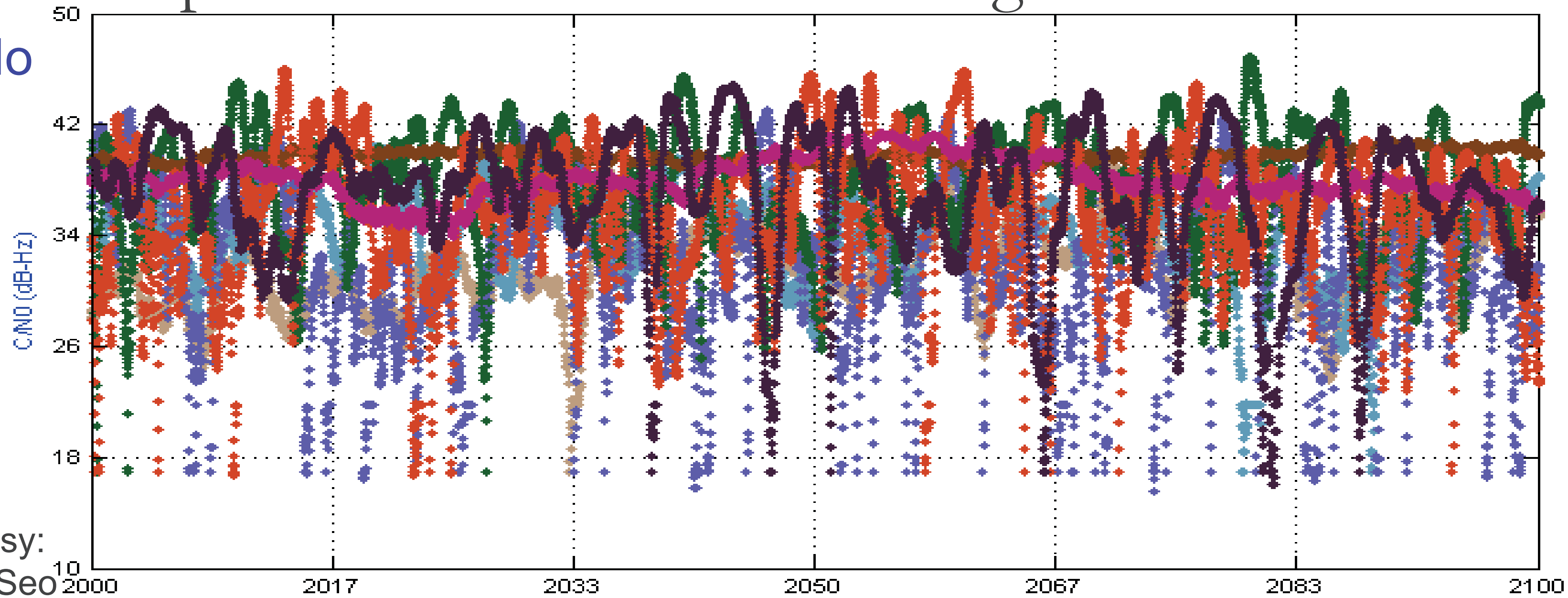


Courtesy:
Jiwon Seo

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

C/No



Courtesy: Jiwon Seo

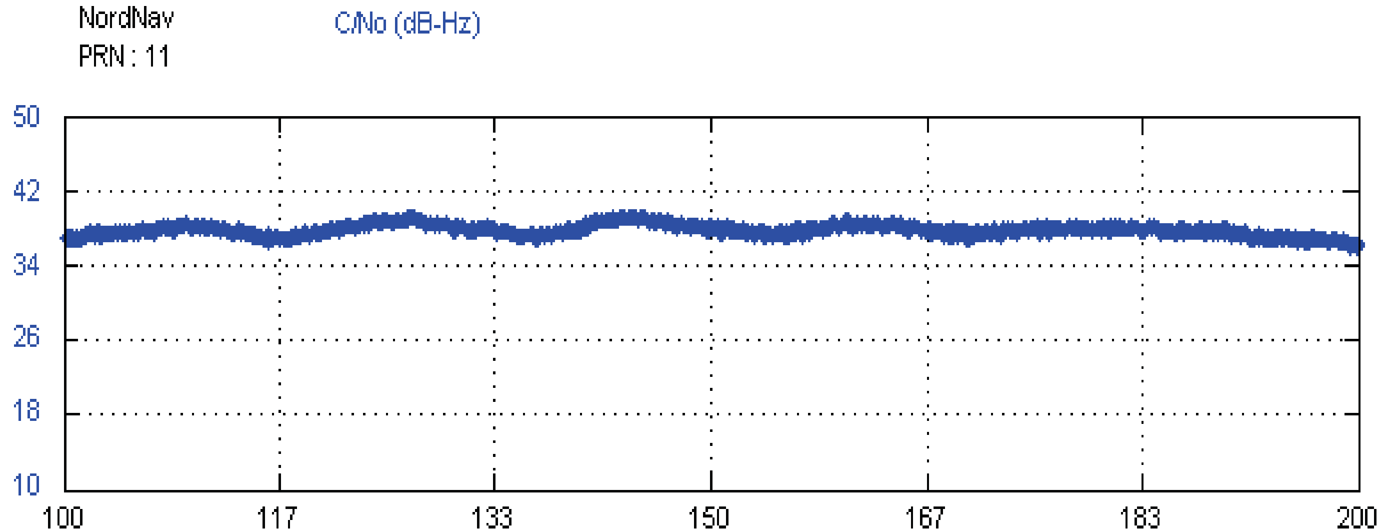
100 sec

Hatch Filter Model

50 dB-Hz

C/No

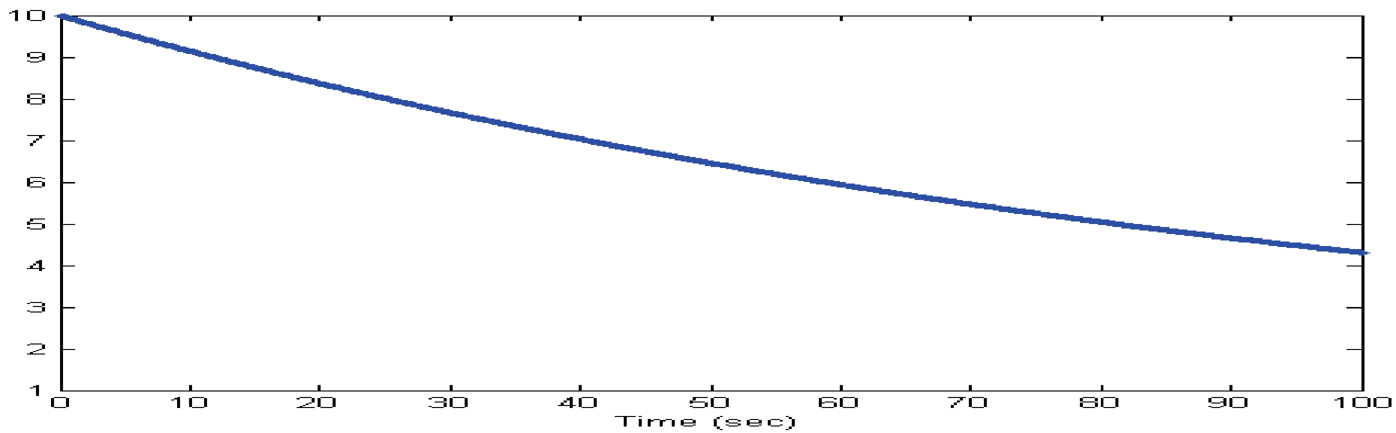
10 dB-Hz



10

Relative
Noise
Level

1



Courtesy:
Jiwon Seo

100 sec

Hatch Filter Model

50 dB-Hz

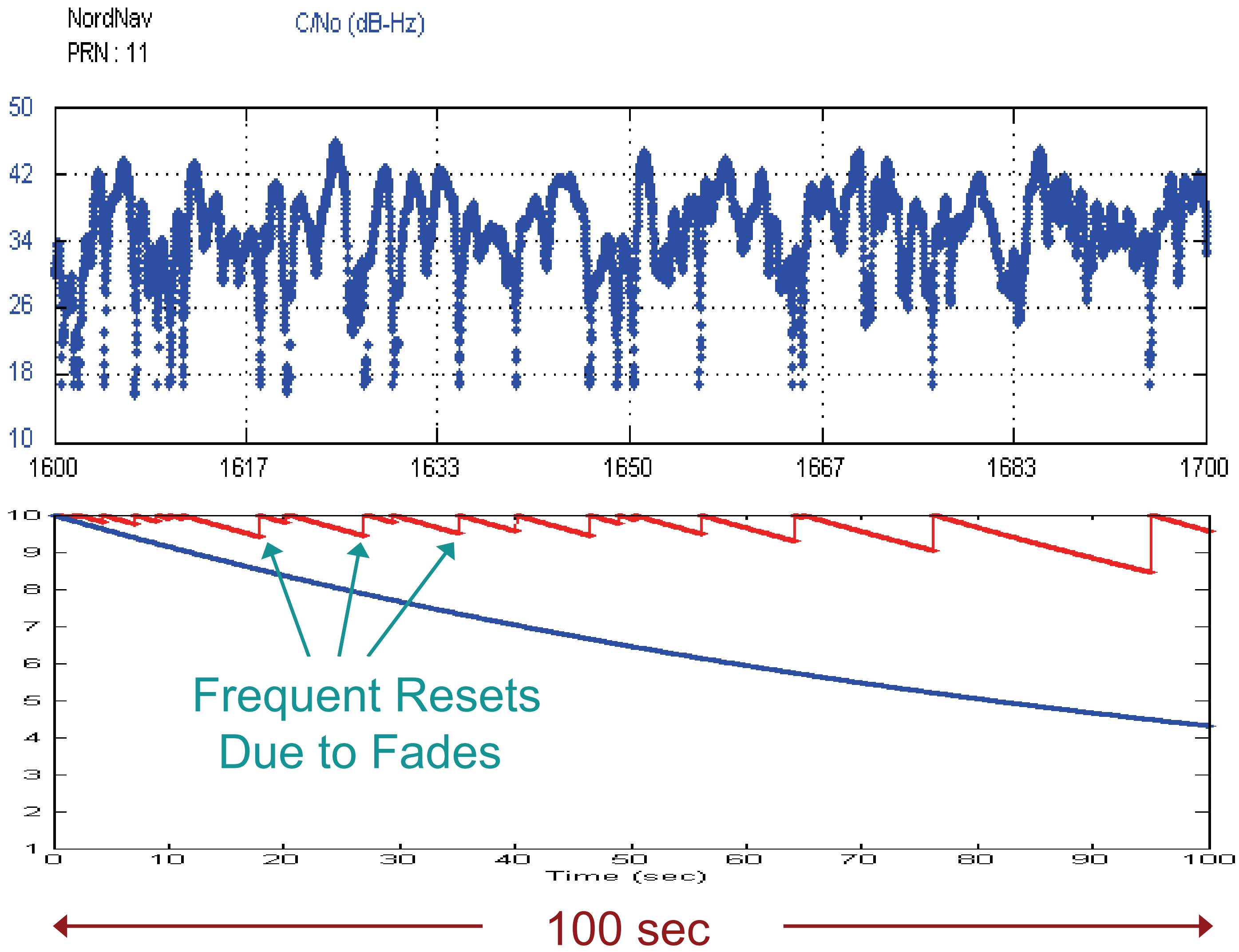
C/No

10 dB-Hz

10

Relative Noise Level

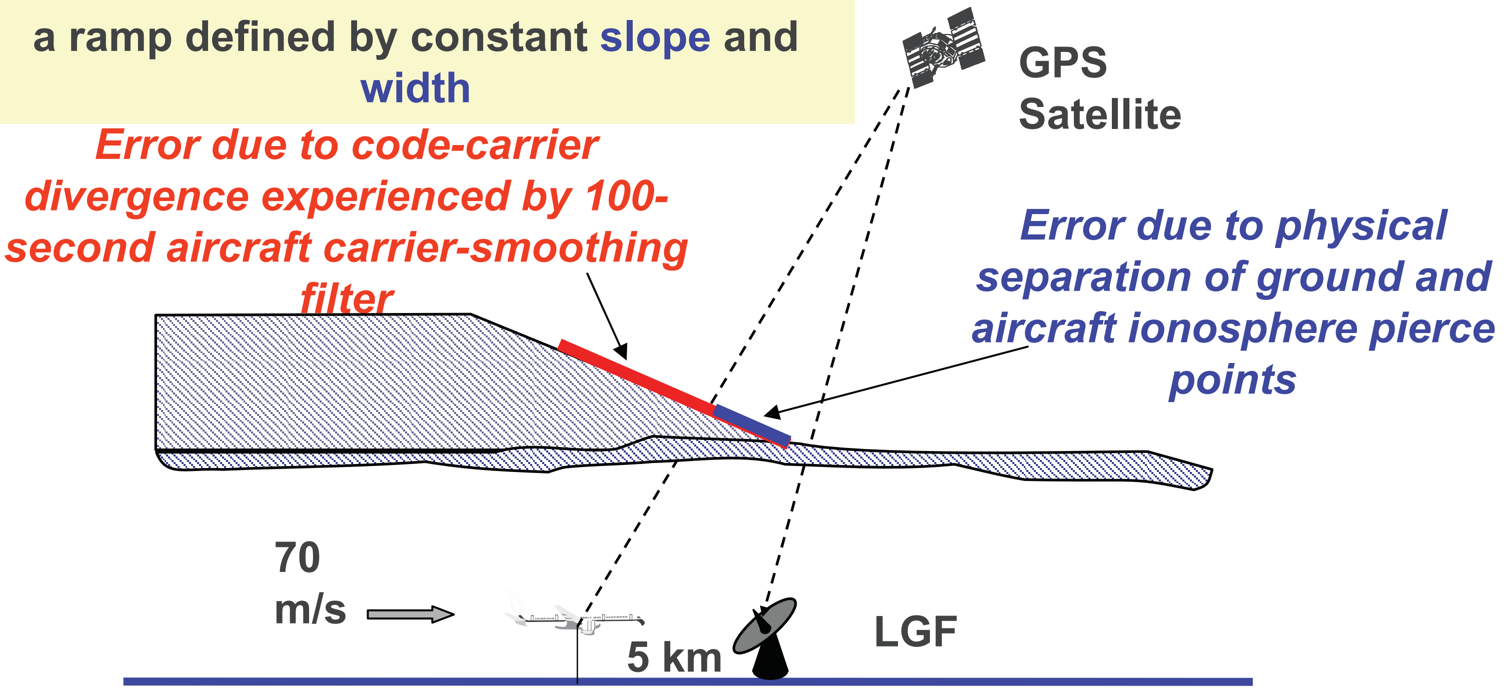
1



Courtesy:
Jiwon Seo

Contributors to Differential Ionosphere Error

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



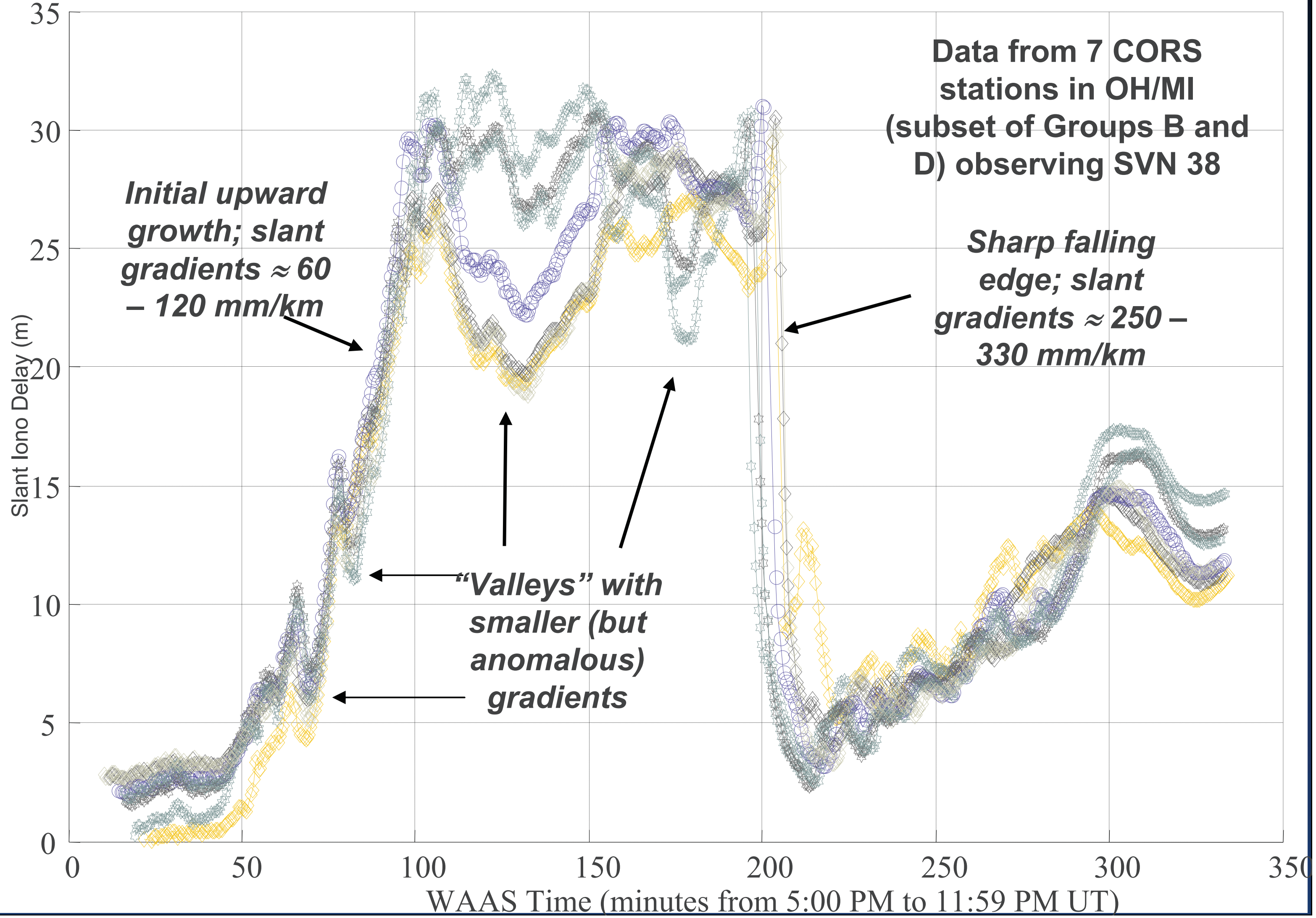
Diff. Iono Range Error = gradient slope × min{ (x + 2 τ v_{air}), gradient width}

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

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Outline

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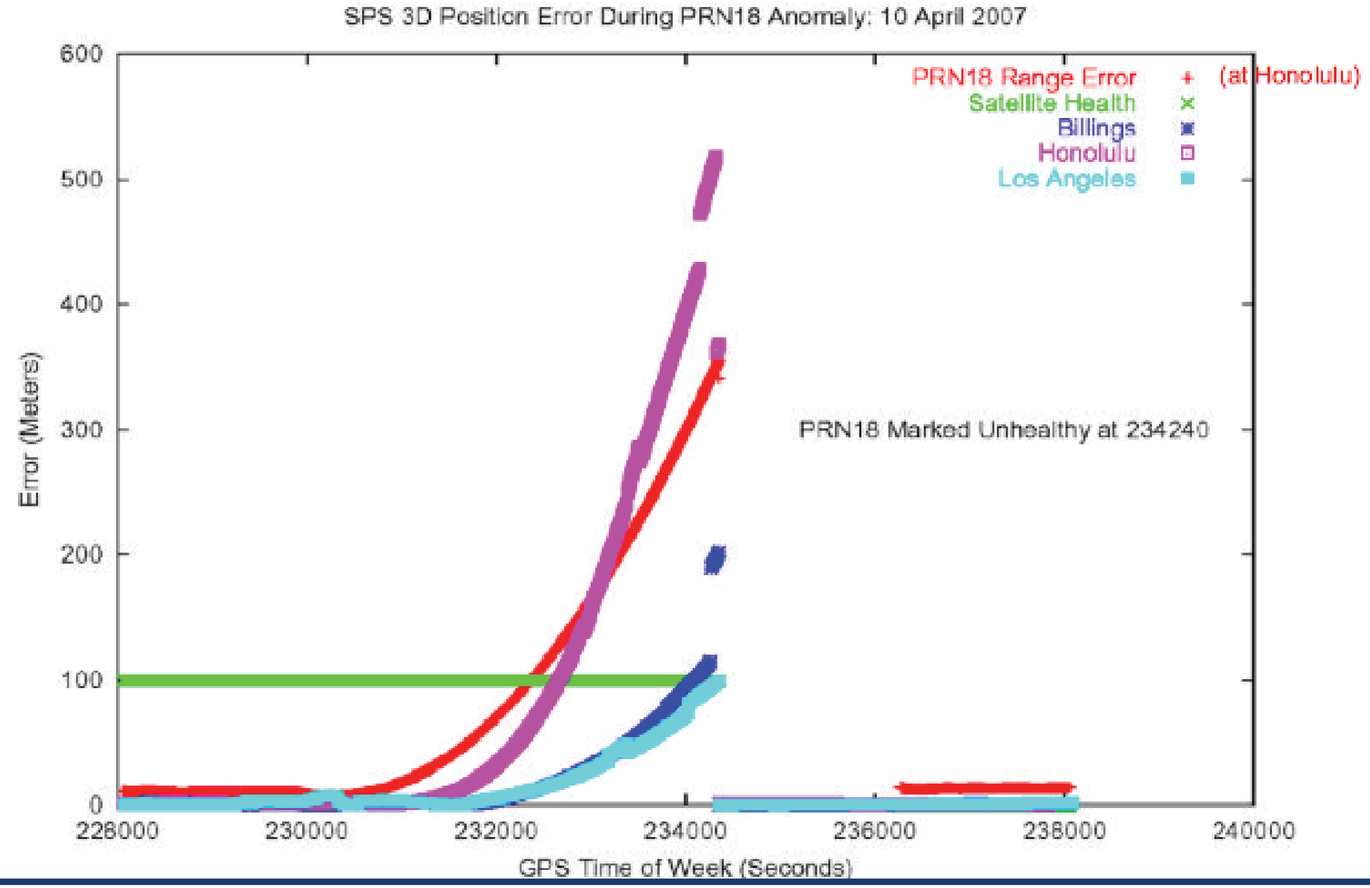
Integrity

- 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 Clock 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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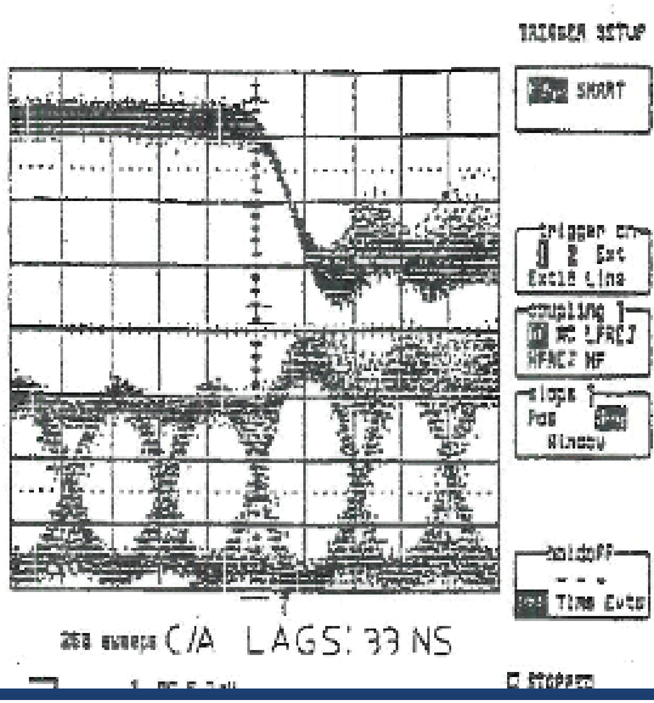
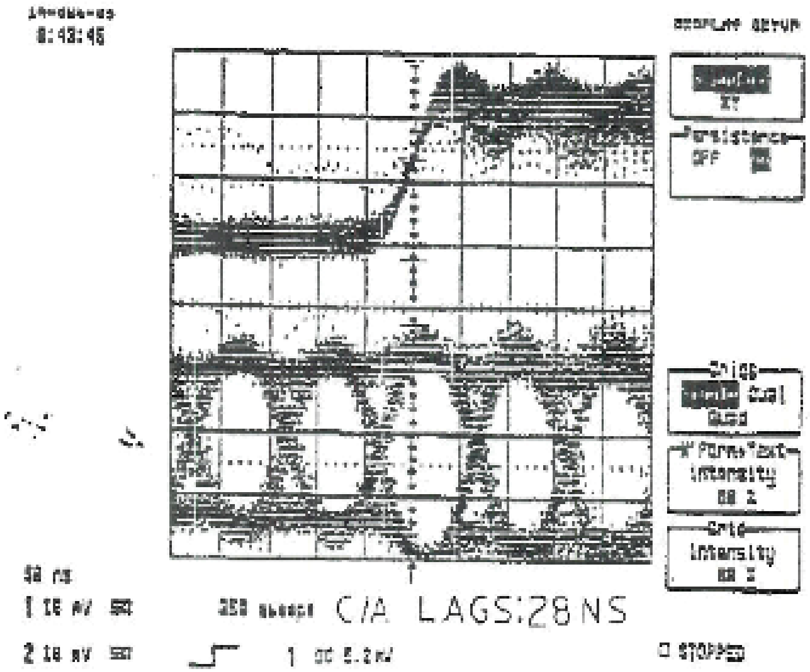
Satellite Signal Anomaly

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

Oct 13, 1993, 23:45



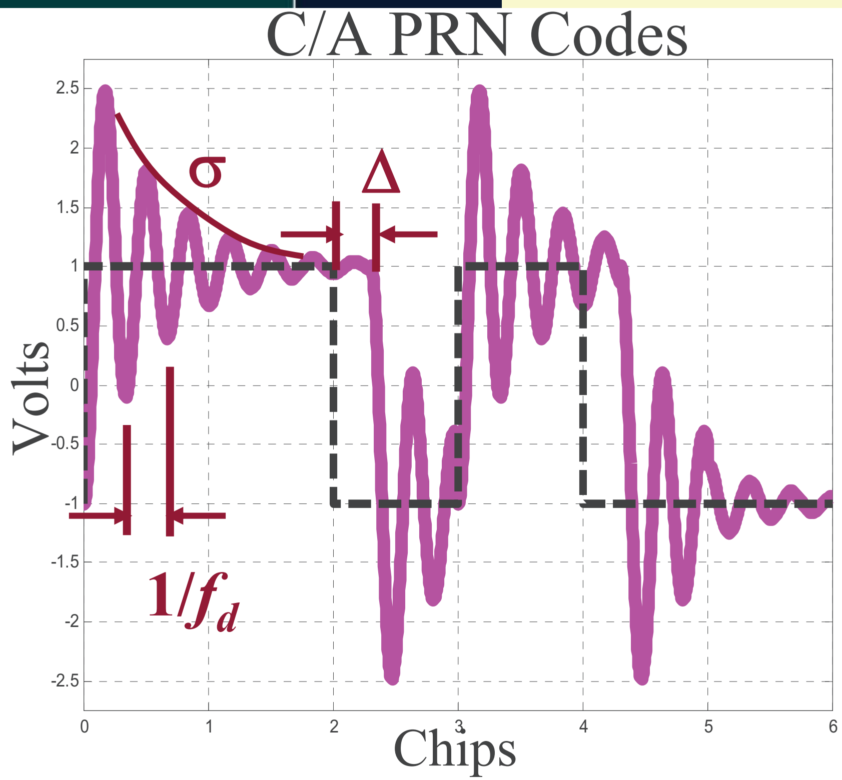
Oct 14, 1993, 08:43

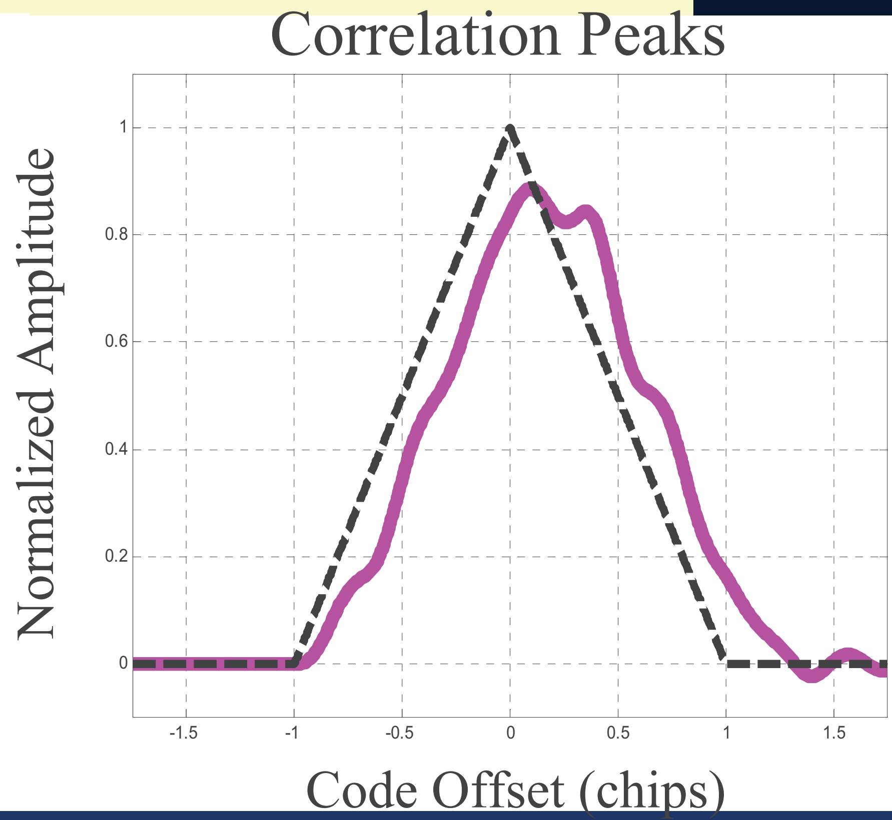


Courtesy:
Per Enge

"Evil Waveform" Failure Mode Example

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





Note:

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

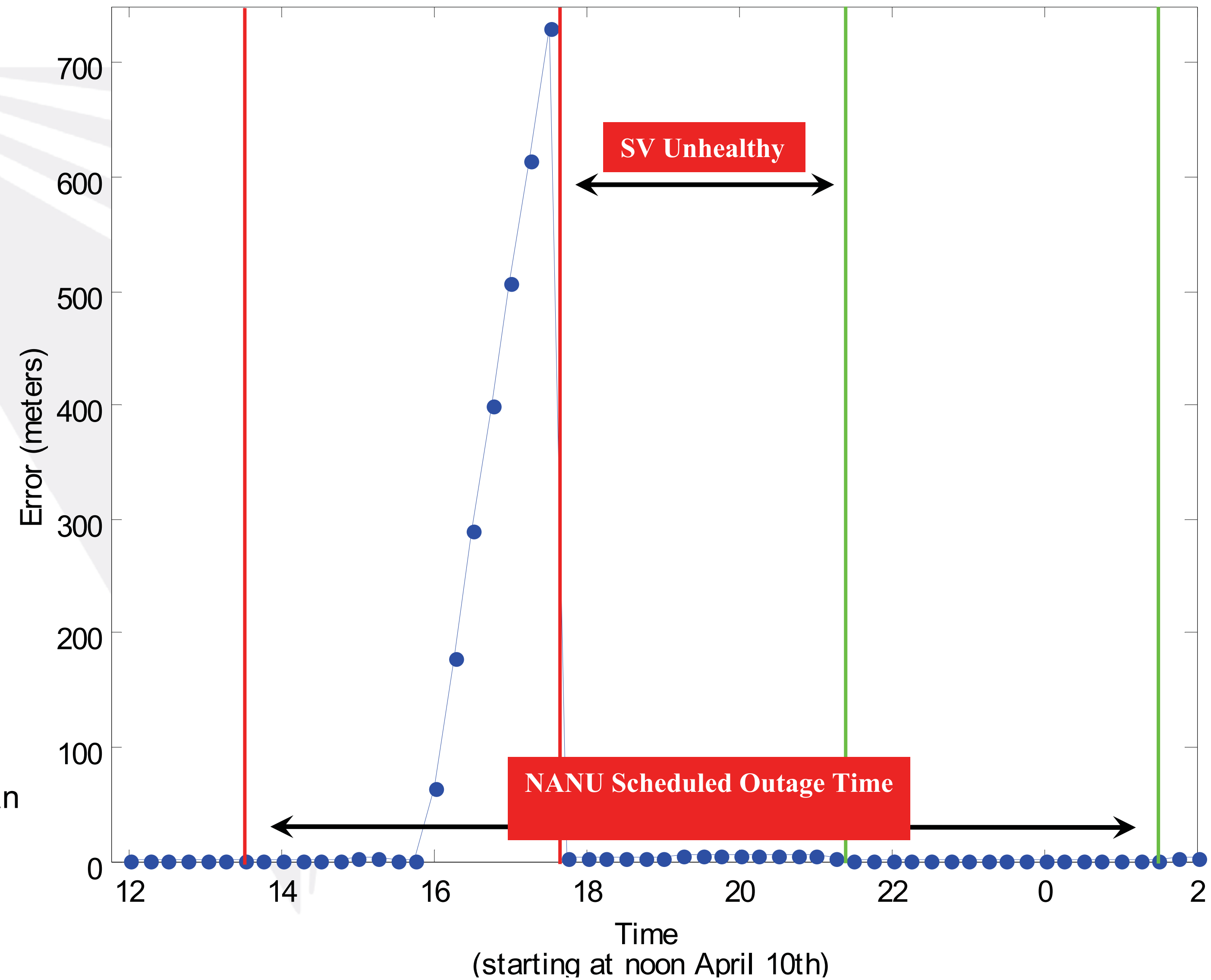
Threat Model B: Analog Failure Mode ("Ringing" Only: $f_d\sigma$)

Satellite Ephemeris Anomaly

- Scheduled NANU Outage Time
  - Start: April 10 @ 13:30
  - End: April 11 @ 1:30
- SV Health (based on broadcast ephemerides)
  - Flagged Unhealthy: April 10 @ 17:38
  - Flagged Healthy: April 10 @ 21:24
- Error > 50 meters
  - Start: April 10 @ 16:00 (63.976 meters)
  - End: April 10 @ 17:30 (731.1531 meters)

Courtesy: Boris Pervan

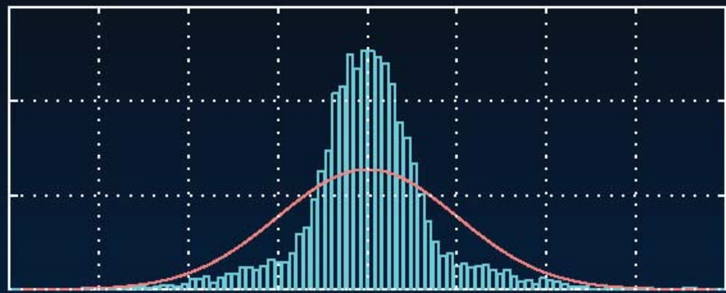
SV Position Error (norm) vs. Time



Courtesy:
Boris Pervan

Error Distribution

- Distribution of errors may be formed over many conditions
  - *Leads to "fat" tails



- Need to characterize errors for worst allowable condition
  - *Not all conditions known or recognized*
- Focus on the tail behavior as opposed to the core of the distribution
  - *For WAAS, nominal pseudorange errors are ~3 times smaller than implied by bound*
  - *Position domain errors are more than 5 time smaller*

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

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

- Specific Risk

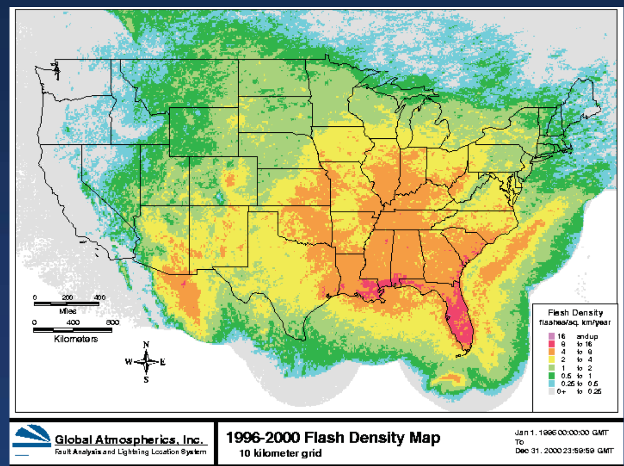
$$P(fault \mid condition)$$

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

WAAS Vertical Protection Level (VPL) correlation with Vertical Position Error (VPE)

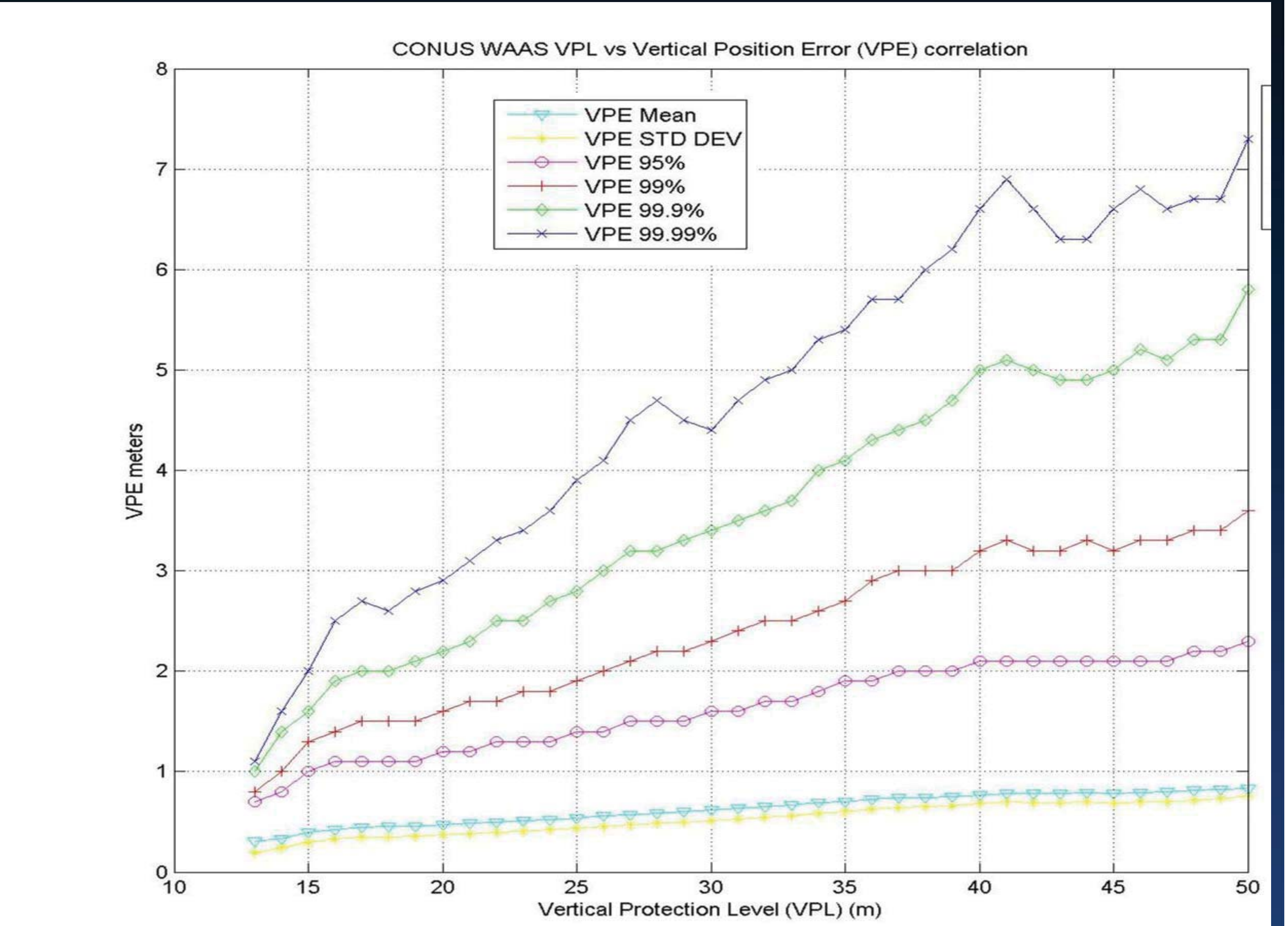
Courtesy:

FAA Technical Center

3 years

20 WRSs

1 Hz data



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WAAS LPV200 Vertical Position Error (VPE) vs. Vertical Protection Level (VPL) 2D Distribution

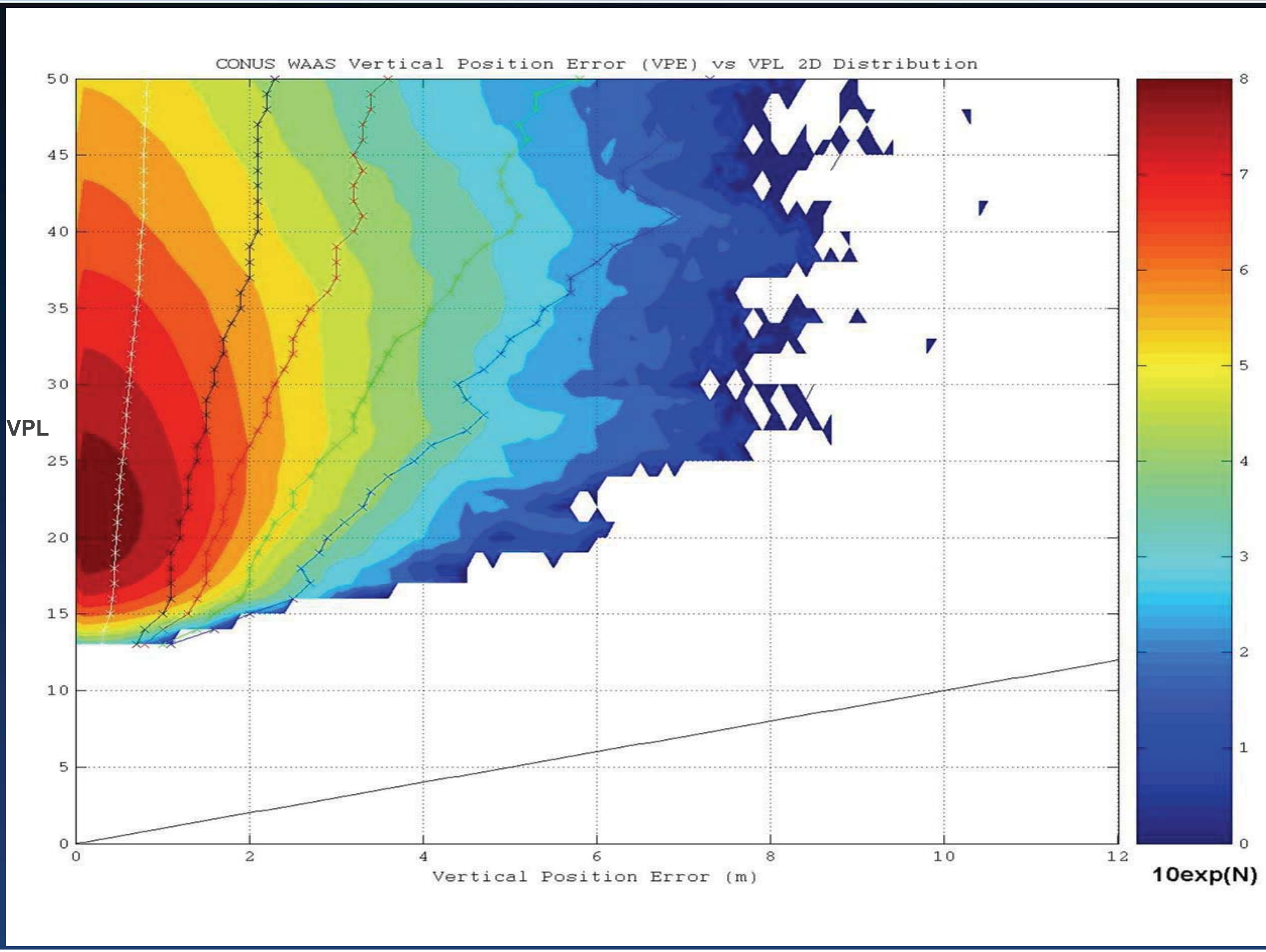
Courtesy:

FAA Technical Center

3 years

20 WRSs

1 Hz data



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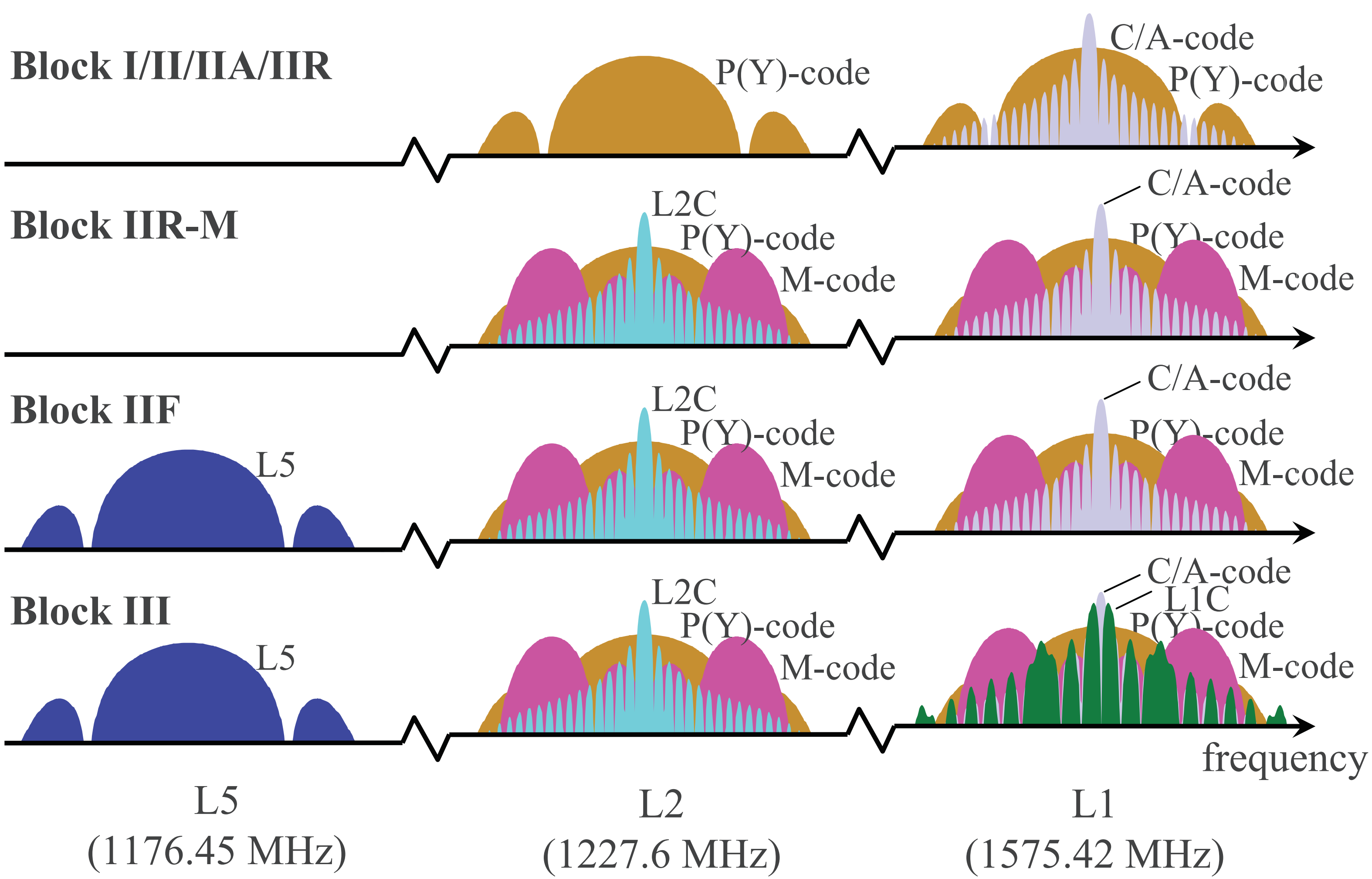
Outline

- RAIM
- Ionospheric Modeling
- Ionospheric Threats
- Other Integrity Threats
- Integrity Methodology
- **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?*

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)

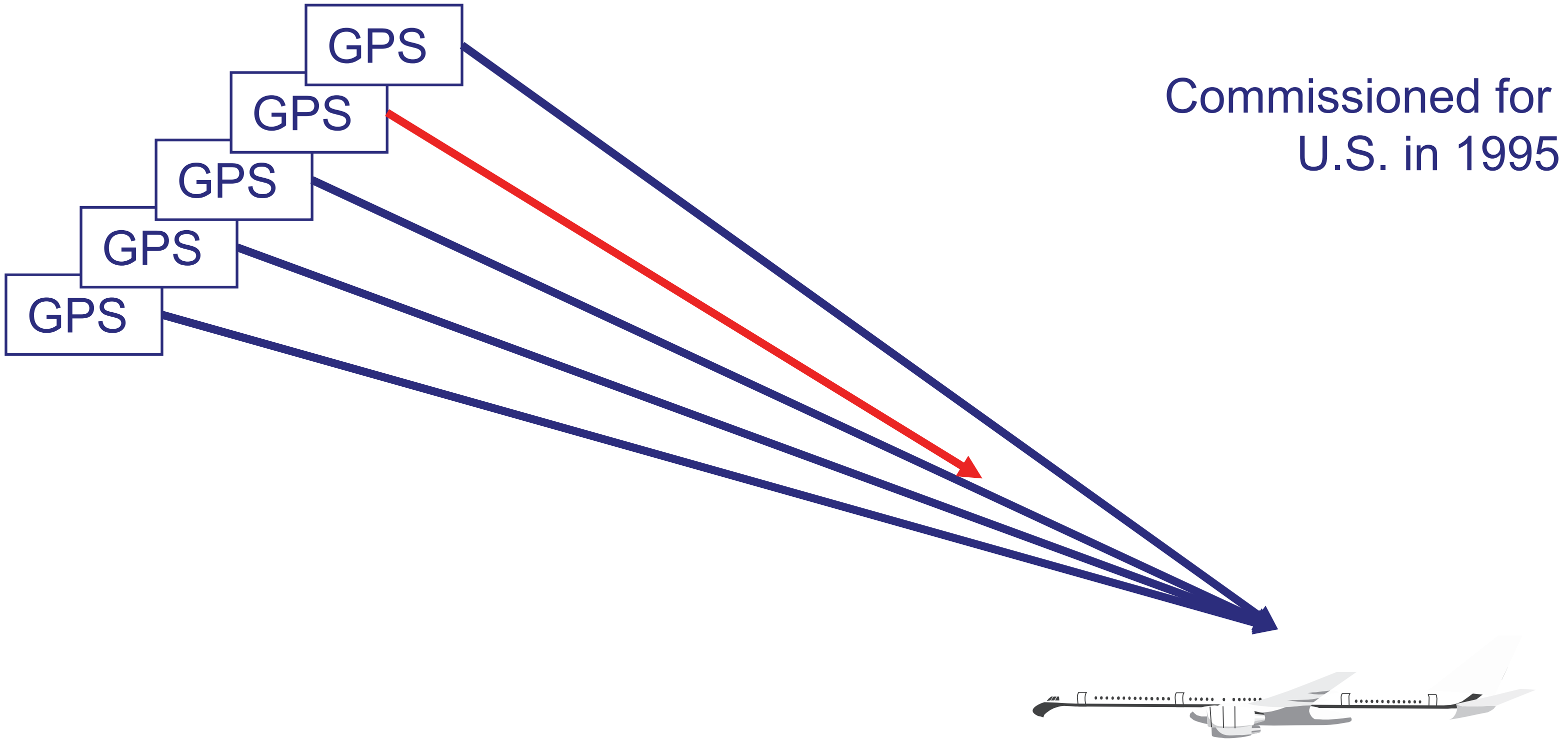
New Systems

- Galileo - Europe
  - *30 satellite in 3 planes*
  - *2 test satellites in orbit*
  - *Full constellation in 2013 (or so)*

- Compass (Beidou) - China
  - *5 GEOs*
  - *3 Inclined geosynchronous*
  - *30 MEOs*
  - *Planned operation in 2012 (or later)*

GNSS Signals

Today's Receiver Autonomous Integrity Monitoring (RAIM)



Commissioned for use in U.S. in 1995

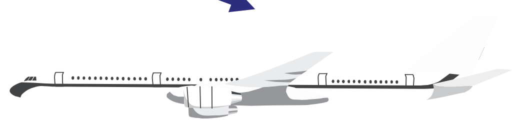
Single frequency, single constellation RAIM supports supplemental lateral navigation for en-route, terminal area & NPA

Today: SBAS & GBAS Use Ground Monitoring

GPS
- Satellite constellation
- Ground control

Today: L1

WAAS commissioned for use in U.S. in 2003
LAAS commissioned for use in U.S. in 2009



Today: L1

VHF Broadcast: TTA of 2 s
Geostationary: TTA of 6 s

GBAS & SBAS Monitors

Supports navigation for all phases of flight including vertical guidance for landing

2018: Dual Freq. SBAS & GBAS mitigate ionospheric storms & accidental RFI.

GPS
- Satellite constellation
- Ground control

Today: L1
Tomorrow: L1 & L5

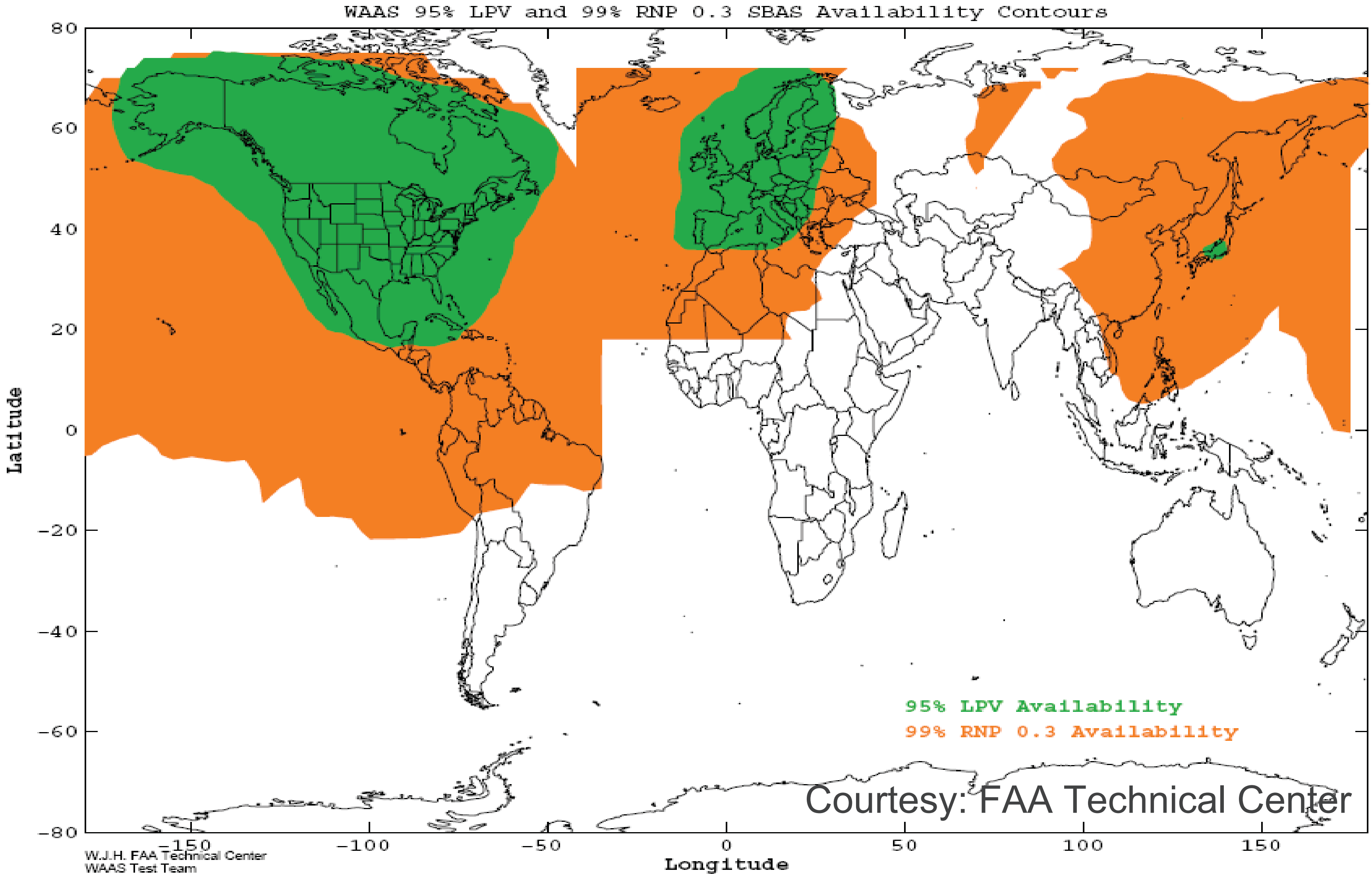
Today: L1
Tomorrow: L1 & L5

VHF Data Broadcast: TTA of 2 s
Geostationary: TTA of 6 s

GBAS & SBAS Monitors

Still requires dense network & expensive broadcast to achieve only regional coverage

2018: SBAS Orange Would Become Green & Iono/RFI Sensitivity Would Disappear



Evolution of GNSS-Based Safety

2010 2020 2030

Solar Maximum

L1 Only
- RAIM
- SBAS
- GBAS

Dual freq. SBAS & GBAS
- 24 SVs Minimum
- 10^{-4} from GNSS

Dual Frequency ARAIM
- Open service
- GPS: 30+ Slots
- Multi-constellation
- 10^{-4} from GNSS
- Failure Descriptions

GNSS Integrity Within
- GPS IIIC (1st 16) ++, or
- GNSS Safety of Life
- 24+ SVs
- not interoperable
- 10^{-7} from constellation

Benefits of Multi-Constellation RAIM

- Combining signals from multiple constellations can provide significantly greater availability and higher performance levels than can be achieved individually
- Potential to provide a safety of life service without requiring the GNSS service provider to certify each system to 10^{-7} integrity levels
- Creates a truly international solution
  - *All service providers contribute*
  - *Not dependent on any single entity*
  - *Coverage is global and seamless*

Approved GPS Aviation Operations (as of 2007)

Courtesy:
FAA

Presented at ICTP
Copyright 2009
Todd Walter

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*