FAA
GBAS System Development

for

Seminar on the Ionosphere and its Effect on GNSS Systems

Santiago, Chile
April 14-16, 2008

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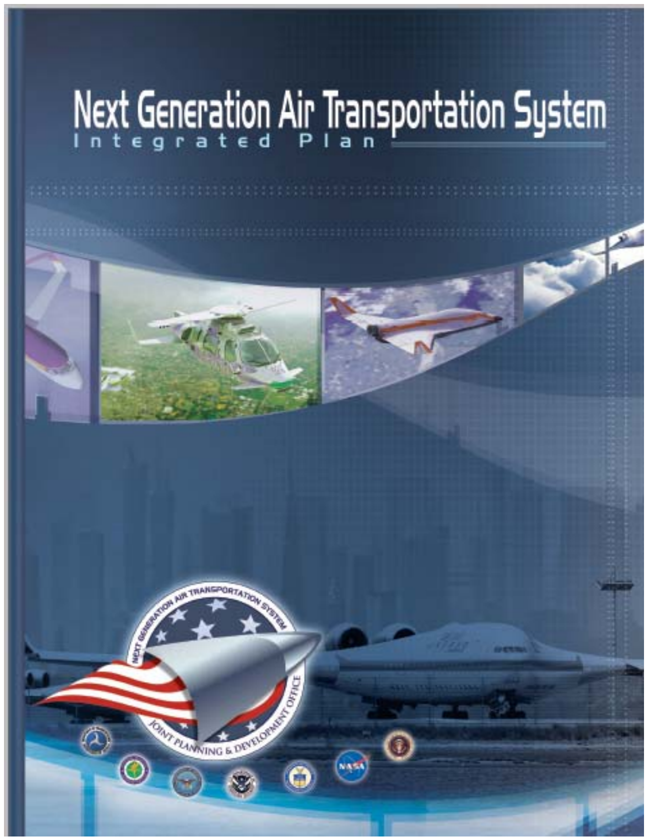
Outline

- LAAS Program Background
- Integrity Analysis and Prototype Development
- GBAS Approval Process
- International Cooperation
- CAT-III Research & Development Activities

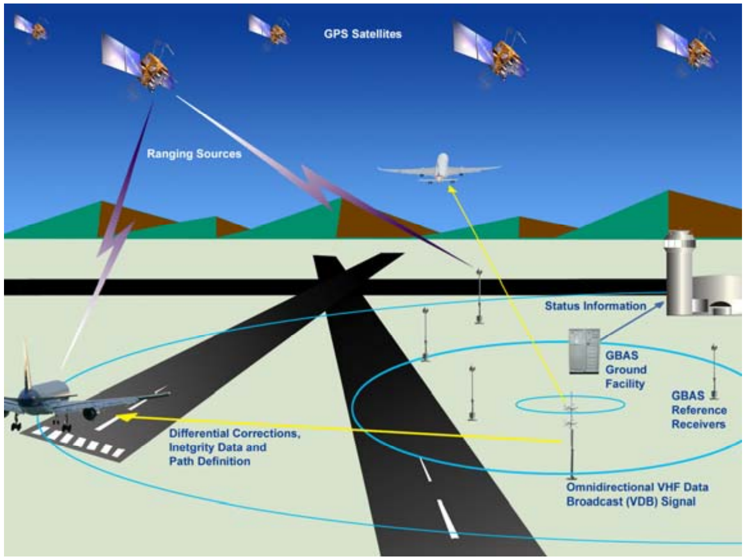
The Next Generation Air Transportation System (NextGen) Plan Defines A System That Can Meet Demands For The 21st Century



Capabilities

- Trajectory-Based Operations
- Performance-Based Operations and Services
- ***Precision Navigation***
- Weather Integration
- Network-Centric Information Sharing
- Surveillance Services
- Equivalent Visual Operations
- Super Density Operations
- Layered, Adaptive Security

LAAS and Next Gen



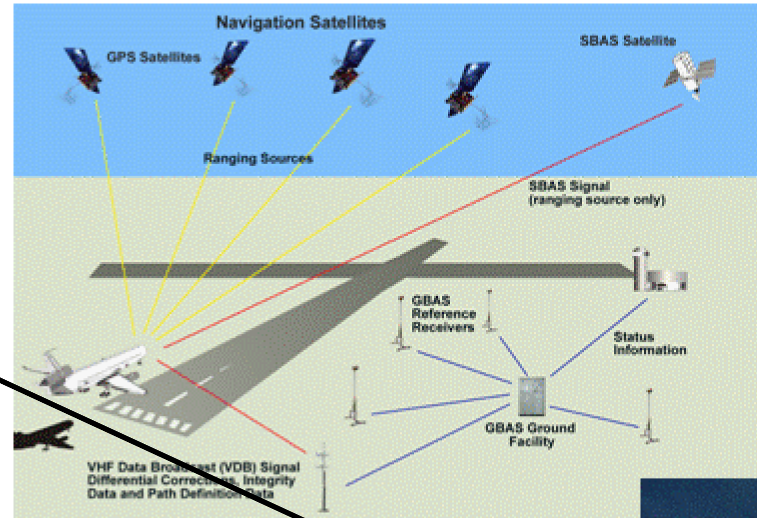
- The FAA has identified LAAS as a "Contributor" program for NextGen.
- The Operational Evolution Partnership (OEP) identified GBAS as one of the enabling technologies in the OEP plan that directly supports the transformation of the National Airspace.
- LAAS was cited as a promising solution in the New York/ New Jersey flight delay Task Force Report (December 6, 2007). <u>The report recommends accelerating the development of LAAS</u>.

LAAS Capabilities

- The Local Area Augmentation System (LAAS) Represents the U.S. Approach to the International Goal of an Interoperable GBAS Capability
- LAAS Provides a Navigation Signal That Supports the Most Demanding RNP Requirements
- LAAS is complementary to SBAS
- One LAAS Can Cover the Entire Terminal Area and Enables Precision Guidance
  - Precision approach for Category I, II & III
  - Multiple runway coverage
  - Complex procedures Guided missed approaches and departure procedures
  - Aircraft surface navigation

LAAS

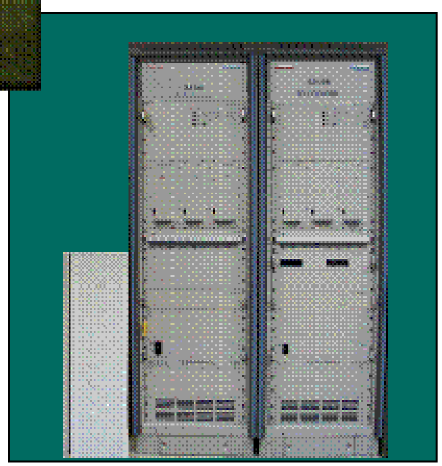
DATALINK



Antenna

GPS

Base Station Computes Differential Corrections, Provides Integrity Check & Provides Approach Coordinates



Transmitter

Encoder

Broadcast Information

Differential Corrections, Integrity Status and Approach Coordinates

Program Background

- Program Baseline Completed in 1999
- Established Government Industry Partnership (GIP) For Category-I Development in 1999
- GIP Experienced Delays Due to Integrity Issues
- In 2001, Strategy Changed To FAA Full Scale Development Contract for Category- I LAAS
- Contract Awarded To Honeywell In April 2003
  – Aggressive Schedule and Integrity Issues Resulted In Delays
- FAA Directed Program Back To R&D In February 2004
  – Lower Overall Program Risk, Resolve Integrity Issues
- Honeywell Contract Re-Structured To Resolve Integrity Risks
  – Restructure LAAS Integrity Panel & Develop Provably Safe Prototype

Current Activities

- **Integrity Analysis and Prototype Development**
  - Honeywell Contract
  - Deliver Honeywell SLS4000 GBAS
- **GBAS Approval Process**
  - System Design Approval - Audits in progress
- **LAAS Operational implementation**
  - Memphis prototype installation
- **CAT III LAAS**
  - CAT II/III ground facility specification

GBAS Integrity Method

- Integrity Analysis and Prototype Development
  - FAA GBAS prototype work under Honeywell Contract
  - Hazardous Misleading Information (HMI) Analysis underway to validate GBAS architecture/design
  - **Responsibility for GBAS Integrity resides in the Ground Facility**
    - The user (aircraft) receives a set of integrity parameters from the LGF and applies those in a set of standardized equations to determine protection levels
    - The user must check the calculated result against the requirement
  - **The Service Provider is responsible for ensuring that the uplink integrity parameters are accurate and that they provide the required function**
    - When used in the specified equations, the protection level must bound the user error

Hazardously Misleading Information (HMI) Report

- Te HMI report details the process and assumptions that demonstrate a GBAS is safe.
  - A similar process was effective in verifying FAA Wide Area Augmentation System (WAAS) integrity
  - HMI report is a detailed summary of the integrity work
  - Tool used to help the technical team communicate with the certification authority
- The core of the HMI report is a series of assertions that, when taken together and shown to be true, completely define the integrity proof
- The HMI report details the analysis used to validate the series of assertions.
  - There are three ways to perform this validation,
    - a formal mathematical proof,
    - a data driven analysis or,
    - the consensus engineering judgment of a group of subject matter experts.

Hazardously Misleading Information (HMI) Analysis

- The five steps in the HMI analysis are:
  - Formalize and obtain approval for the top level integrity architecture;
  - Approve the fault trees;
  - Approve the complete list of threats;
  - Approve specific integrity analysis methodologies for each of the monitors; and
  - Complete and obtain approval for the HMI analysis document.
- Note that much of the work on the above five steps has been accomplished under the FAA contract
  - The HMI work will focus on the formal approval and documentation of this work.

LAAS CAT I Approval Activities

- **To be approved by FAA, system or equipment must be shown to meet ICAO, FAA or other (e.g. RTCA) recognized standard.**
  - The baseline is the FAA Non-Federal LAAS Specification
  - System or equipment approval is only one of the requirements for NAS operation.
- GBAS CAT I Approval Process
  - Honeywell Submitted Application for SLS 4000 System Approval in 2006
  - System Design Approval (SDA) for Honeywell architecture in progress
  - Facility and Service Approval for Memphis planned for 2008

SYSTEM APPROVAL
- Compliance with FAA standards, FAA specification
- Software and Hardware validation

⇨

FACILITY APPROVAL
- Operational environments
- O&M Manual
- Trained maintainers
- Standard Operating Procedures

Flight Inspection

⇨

Instrument Flight Procedures

SERVICE APPROVAL
- AT and Pilot Training
- Instrument Flight Criteria

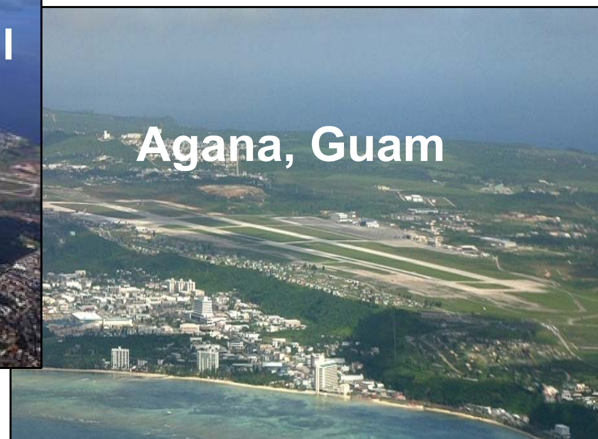
LAAS Operational Implementation

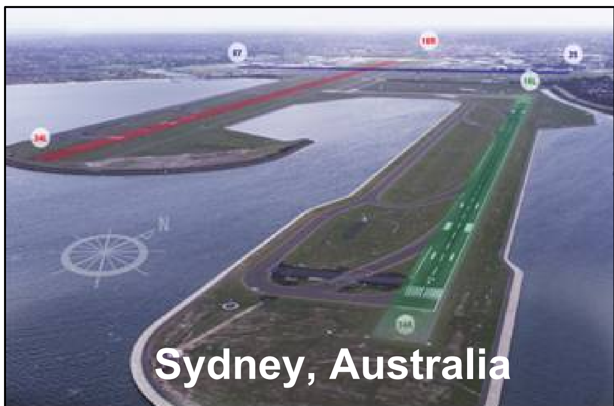
- GBAS Implementation Activities in Memphis
  - GBAS Procedures for Memphis Airport (MEM)
  - LAAS straight in procedures for all runway ends
  - Developed GBAS Terminal Area Path (TAP) procedures
  - Coordination with MEM Air Traffic Control
  - Performing flight test with FAA Technical Center Aircraft and FedEx B727 aircraft

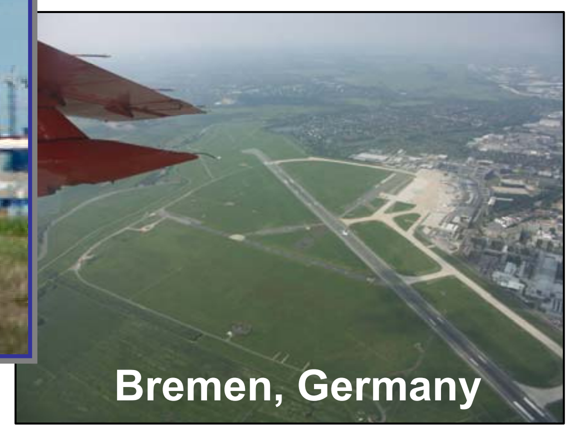
CAT II/III

- **Near term initiative for single frequency CAT II/III GBAS**
  - Ground rule: minimal changes to ground facility and transfer of some requirement responsibility to the aircraft
  - Develop requirements in line with current ILS auto-land criteria
  - Initial Requirement allocation proposal submitted by joint FAA/Boeing WG to RTCA

LAAS International Efforts







International GBAS Working Group

- **Chairpersons,**
  - FAA-EUROCONTROL
- **Scope**
  - Discuss national and international GBAS plans and identify areas of cooperation and complementary activities, like GBAS integrity analysis, ionospheric data collection, safety assessments, early operational implementation activities
- **Group Composition**
  - Nations/Service Providers: FAA, EUROCONTROL, DFS Germany, AENA Spain, Airservices Australia, JCAB Japan, Korea, China, and DECEA Brazil.
  - Industry: Honeywell, Thales, LENS/MERC, NEC, Rockwell Collins, Boeing, AIRBUS.
  - Airlines: Continental Airlines, All Nippon Airways, Japan Airlines, Qantas.
- **Accomplishments**
  - Better understanding and practice of GBAS system approval, and the use of common test cases and tools
  - Transition from information exchange to working meeting
    - Test cases and data evaluation WG
    - Local business case WG
    - Operational implementation WG
    - Siting WG

Industry/International Activities

- **Airbus**
  - A380 GBAS equipped landing at Sydney
  - A 320 GLS certified
- **Boeing**
  - B 737 New Generation GLS certified
    - Qantas, Delta, Continental, TUIfly, Sonair, Air Berlin, Air Vanuatu
  - B787 rolled out with GBAS as standard equipment

- **Multiple companies researching/developing versions of GBAS (Honeywell, Thales, Lens, NPPF Spectr)**
- **Countries planning to incorporate GBAS into their airspace (US, Australia, Germany, Spain, Italy, Brazil, Russia, Japan, Korea, China, Chile)**
- **FAA MoCs with Australia, Spain, Germany, Chile**

International GBAS FAA Cooperation Activities

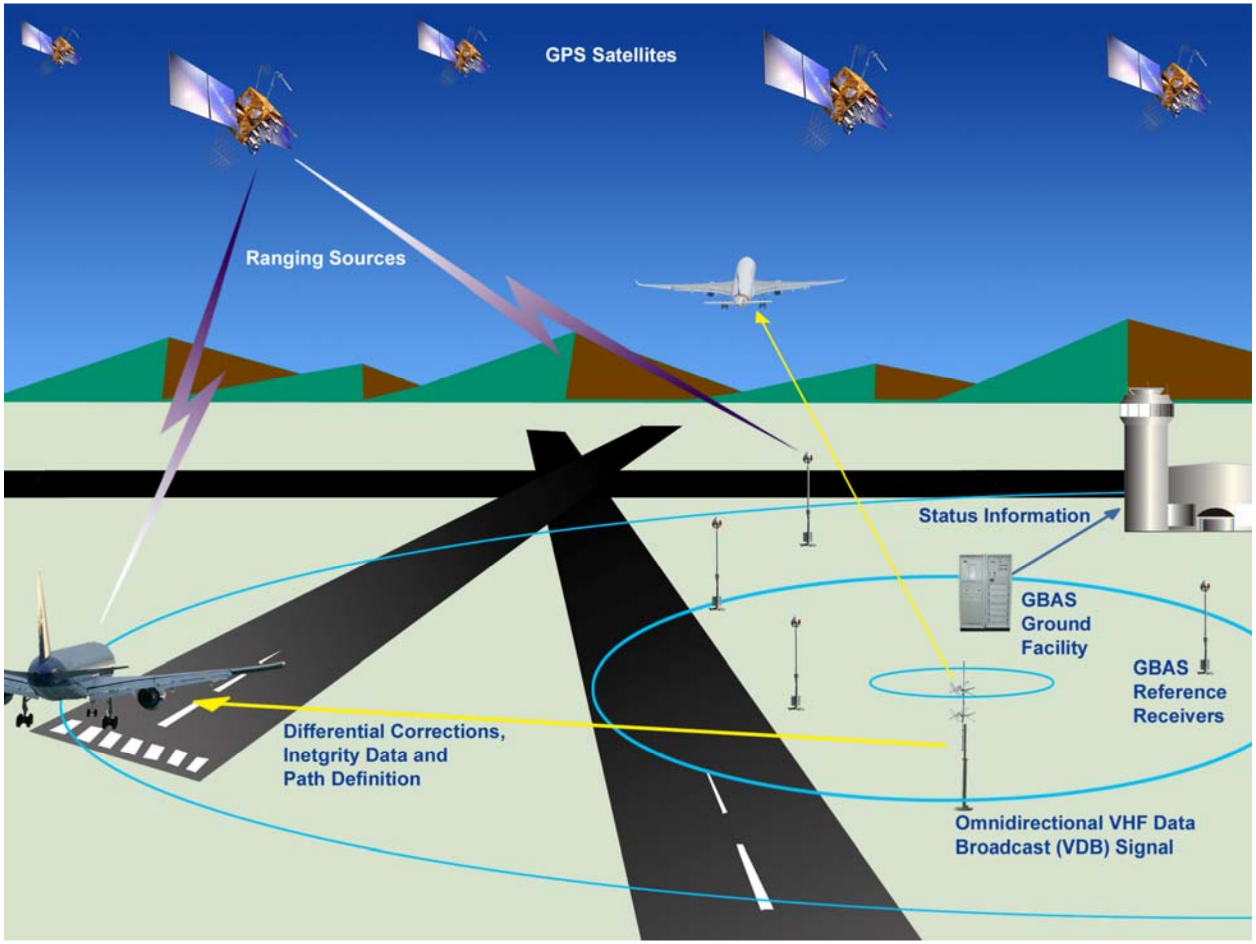
- **MOC Airservices Australia (AsA)**
  - CASA – Sydney operations
  - AsA-Honeywell Development contract
- **MOC DFS Germany**
  - TUI Flight Bremen flight trials
- **MOC AENA Spain**
  - December 2007 AENA flight trials with A 320 in Malaga
  - Coordination Meetings with AENA/Spain
- **Coordination with DECEA Brazil**
  - FAA Technical Center GBAS System
  - GBAS Flight Test
  - GBAS CONOPS
- **Chile MOC for GBAS cooperation**

Malaga A320 Flight Test

GBAS Summary

- HMI analysis to validate that the CAT I system meets integrity design requirements
- Continuation of regulatory approval for the HI LAAS at Memphis, TN in 2008
- Facility and Service Approval at Memphis in early 2009
- Continued data collection/flight test to validate operational benefits (national/international)
- Coordination of development and approval activities with International community
- R&D to develop and validate CAT II/III requirements to support a 2008 CAT II/III decision point

Questions


GPS Satellites
Ranging Sources
Status Information
GBAS
Ground
Facility
GBAS
Reference
Receivers
Differential Corrections,
Inetgrity Data and
Path Definition
Omnidirectional VHF Data
Broadcast (VDB) Signal

Seminar on the Ionosphere and its Effect on GNSS Systems

LAAS Hazardously Misleading Information (HMI) Analysis

Presented to: **Seminar on the Ionosphere and its Effect on GNSS Systems**

Location: Santiago, Chile

Date: April 16, 2008

By: John Warburton AJP-652

Overview

- **GBAS Integrity Method**
- **Current Work**
  - Completion of the HMI Report
- **Recent Accomplishments**
  - Formulation of IRCAs and issue Tiger Teams
- **Issues**
  - Technical

GBAS Integrity Method

- **Responsibility for GBAS Integrity resides in the Ground Facility**
  - The user (aircraft) receives a set of integrity parameters from the LGF and applies those in a set of standardized equations to determine protection levels
  - The user must check the calculated result against the requirement
    - A protection level bound, or Alert Limit, is transmitted from the LGF with each procedure
- **The Service Provider is responsible for ensuring that the uplink integrity parameters are accurate and that they provide the required function**
  - When used in the specified equations, the protection level must always* bound the user error
    - *The probability of not bounding is the required integrity probability, CAT I is 2.0×10^{-7} per approach

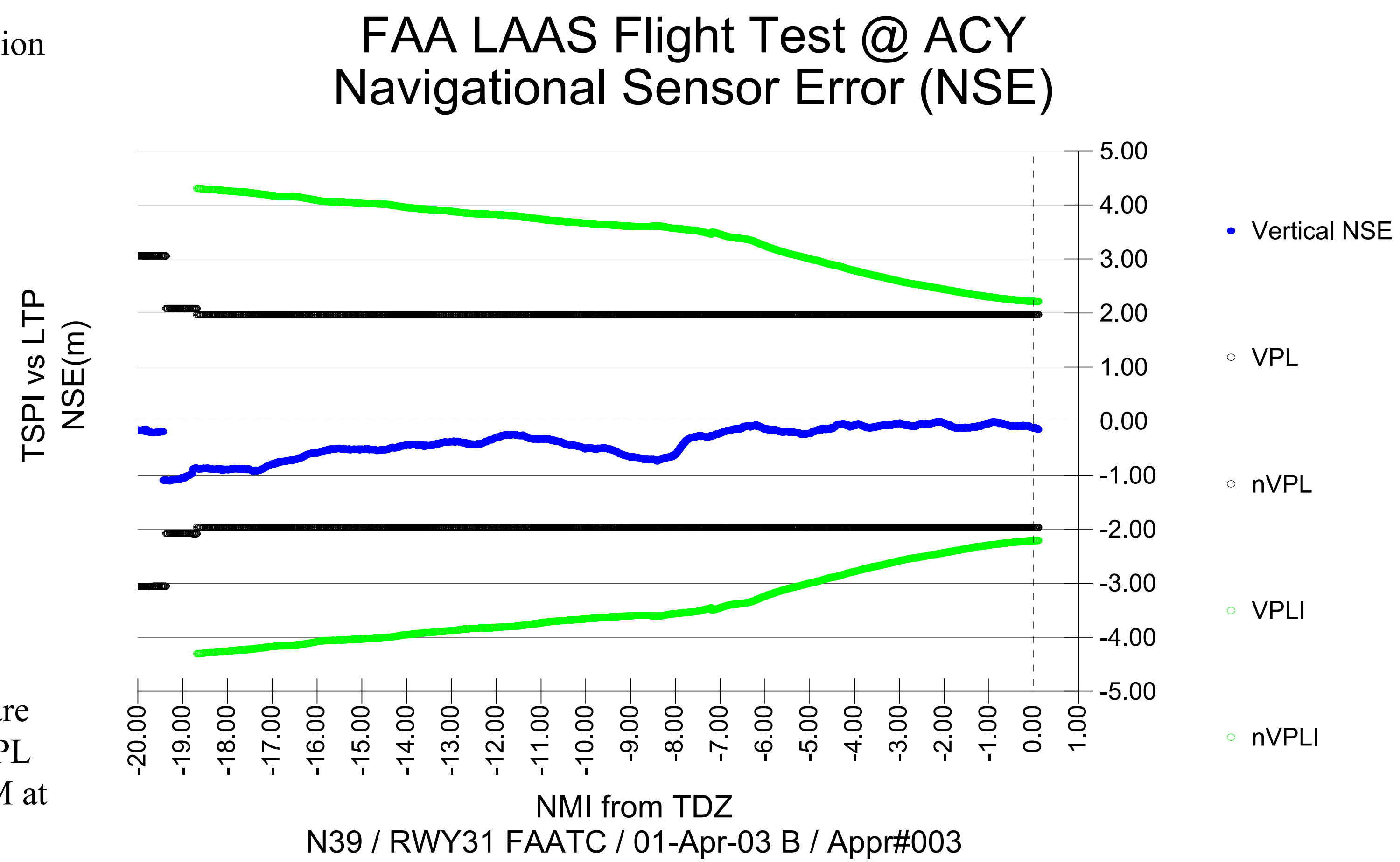
Integrity Performance Protection Level Bounding

Single Approach example of protection level bounding

Vertical NSE and vertical protection Level

Vertical NSE is always less than the calculated protection level

Navigation Flags are displayed when VPL exceeds VAL, 10M at 200 ft HAT



Current Work

Hazardously Misleading Information (HMI) Report

- **An HMI report details the process and assumptions that demonstrate a GBAS is safe.**
  - A similar process was effective in verifying FAA Wide Area Augmentation System (WAAS) integrity
  - HMI report is a detailed summary of the integrity work
  - Tool used to help the technical team communicate with the certification authority
- **The core of the HMI report is a series of statements that, when taken together and are shown to be true, completely define the integrity safety case**
  - Called the Integrity Risk Compliance Argument (IRCA)
- **The HMI report contains the IRCA list as well as a summary of the ADD material for each IRCA statement**

Hazardously Misleading Information (HMI) Analysis

- **The five steps in the HMI analysis are:**
  - Formalize and obtain approval for the top level integrity architecture;
  - Approve the fault trees;
  - Approve the complete list of threats;
  - Approve specific integrity analysis methodologies for each of the monitors; and
  - Complete and obtain approval for the HMI analysis document.
- **Note that much of the work on the above five steps has been accomplished under the FAA PSP contract**

Recent Accomplishments

- **Formulation of design-specific Integrity Risk Compliance Argument (IRCA) statements**
  - System design Algorithm Description Documents (ADDs) for the Honeywell SLS-4000 were accepted by the FAA with comments
  - Resolution of the comments remained an issue
- **Tiger teams, small focused group, were formed to resolve specific HMI issues, remaining ADD comments, and work the final design details**

HMI Report IRCA Contents

- **All sections of each IRCA compiled for the HMI report will conform to the following:**

  X.X.1 Threat Discussions (high level)
  X.X.2 Algorithm Description (high level)
  X.X.3 Integrity Risk Compliance Argument (assertions, etc.)
  X.X.3.1 Threat or Threat Model
  X.X.3.2 Method (Higher-level method techniques)
  X.X.3.3 Models / Methods (details of implementation)
  X.X.4 Justification of All X.3.3 Sections
  Detailed Algorithm
  Analyzed Data
  Validation
  X.X.5 Dependencies
  X.X.6 Conservative Methods
  X.X.7 Data Sets (locations and quantity of days….)
  X.X.8 Conclusions

Technical Issues

- **Current Tiger Team Activities**
  – Ionospheric storm integrity
- **Backup Slides**
  – Ephemeris Monitoring
  – Signal Deformation Monitoring and bounding of "Natural biases"
  – Sigma Pseudorange Ground
  – Tropospheric Error Bounding

GBAS Ionospheric Storm Integrity

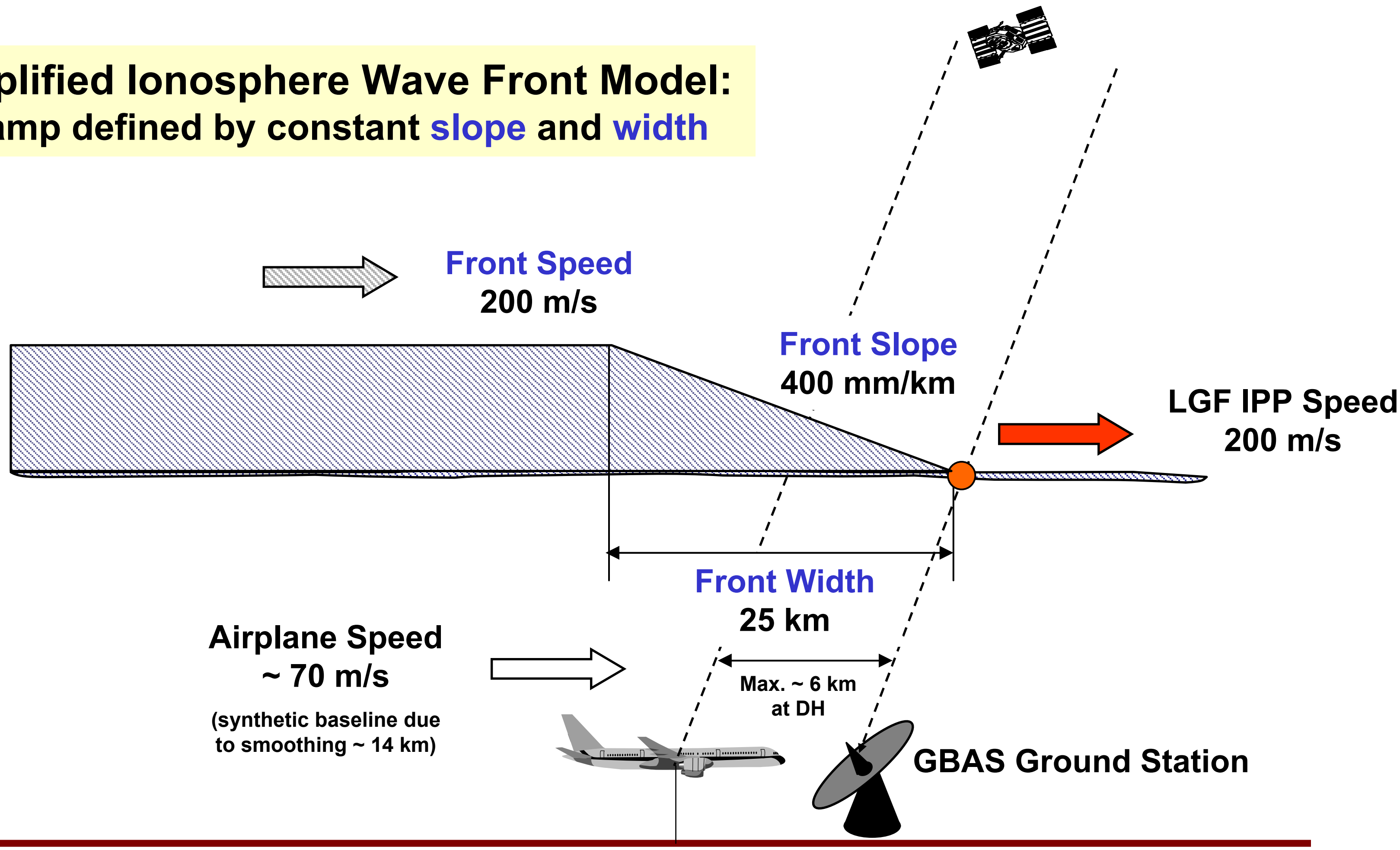
- **Ionospheric Storm Threat and Integrity**
- **Threat Model**
- **Threat Mitigation**
- **Issues**
  - DCPS
- **Summary**

Ionospheric Storm Integrity

- **Ionospheric storm activity unobservable to a GBAS station can not be mitigated by detection**
- **The GBAS airborne user can be impacted by a storm before the ground facility can see it, and integrity could be compromised**
  - These cases must be shown to be sufficiently rare, or mitigated
- **The Ionospheric tiger team has determined a solution for the CAT I system**
  - The results are based on ionospheric storm threat model created from data collected within CONUS and assumptions about how a user will be threatened
  - Other implementer must evaluate their ionospheric environment to ensure that the CONUS threat model contains potential threats in their regions of interest

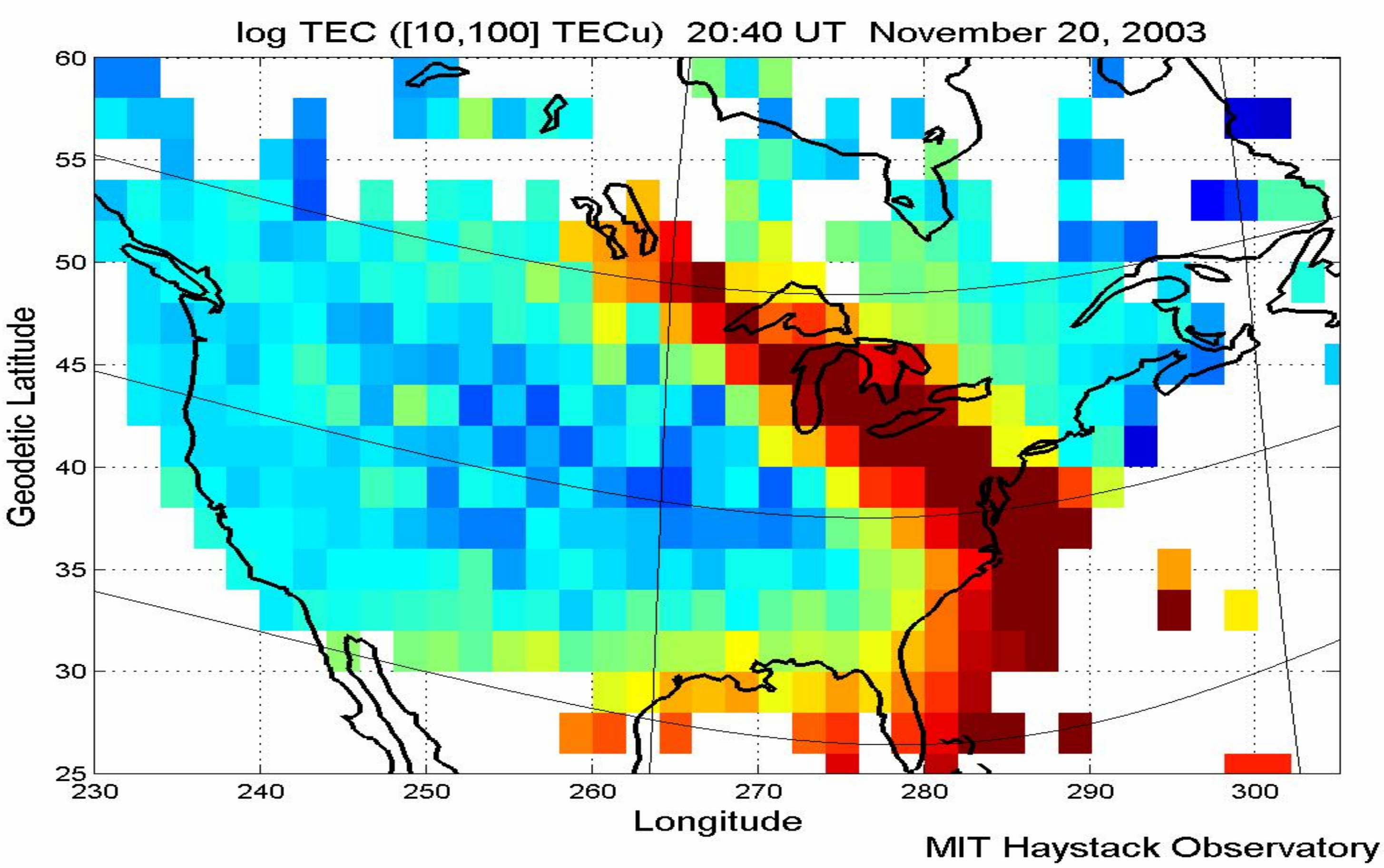
Ionosphere Anomaly Wave Front Model:
Potential Impact on a GBAS User

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



***Stationary Ionosphere Front Scenario*:**
Ionosphere front and IPP of ground station IPP move with same velocity.
Maximum Range Error at DH: 425 mm/km × 20 km = 8.5 meters

CONUS Ionospheric Anomaly November 20, 2003



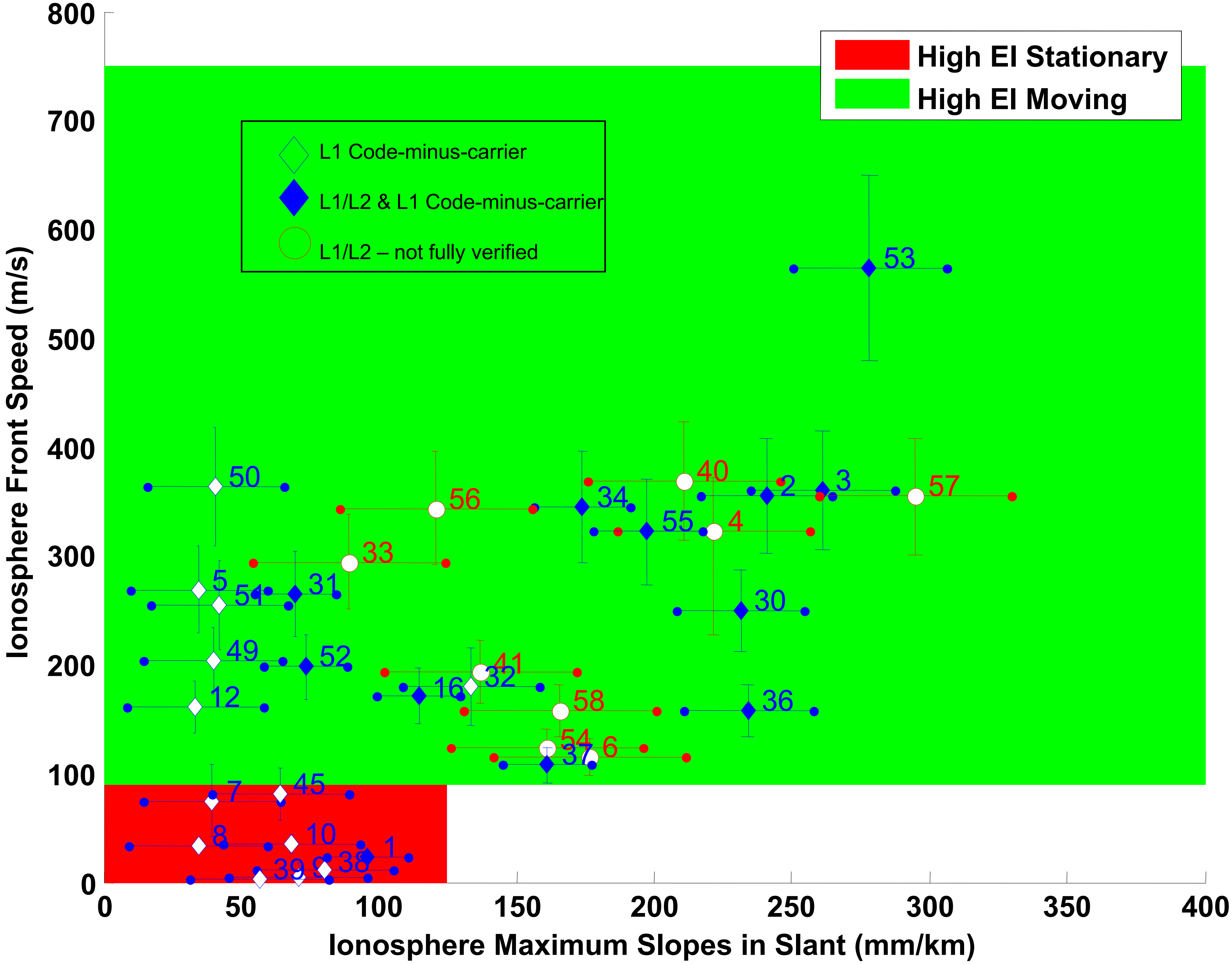
Summary of Current Ionosphere Threat Model Parameter Bounds (Revised)

Elevation	Speed	Width	Slope (slant)	Max. Error
Low elevation (< 15°)	90 – 750 m/s	25 – 200 km	30 – 375 mm/km(†)	30 m(*)
	0 – 90 m/s	25 – 200 km	30 – 125 mm/km	25 m
High elevation (≥ 65°)	90 – 750 m/s	25 – 200 km	30 – 425 mm/km(†)	50 m(*)
	0 – 90 m/s	25 – 200 km	30 – 125 mm/km	25 m

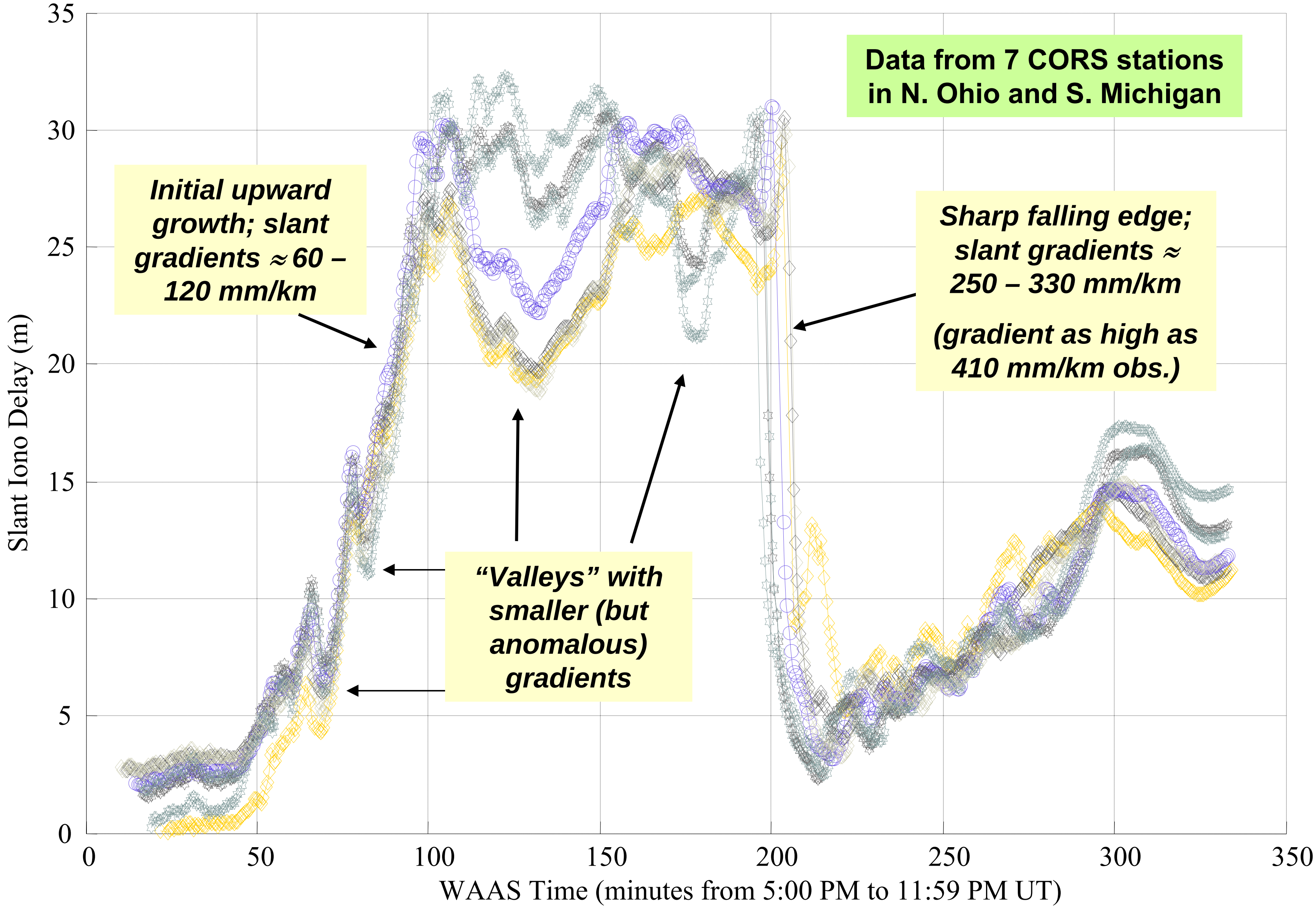
(*) ***Max. error constrains possible slope/width combinations***

(†) ***Max. gradient is linearly interpolated between 15 and 65º elevation angles***

Updated 2-D Threat Plot with All Significant, Validated Events (for Satellites above 12^o Elevation)

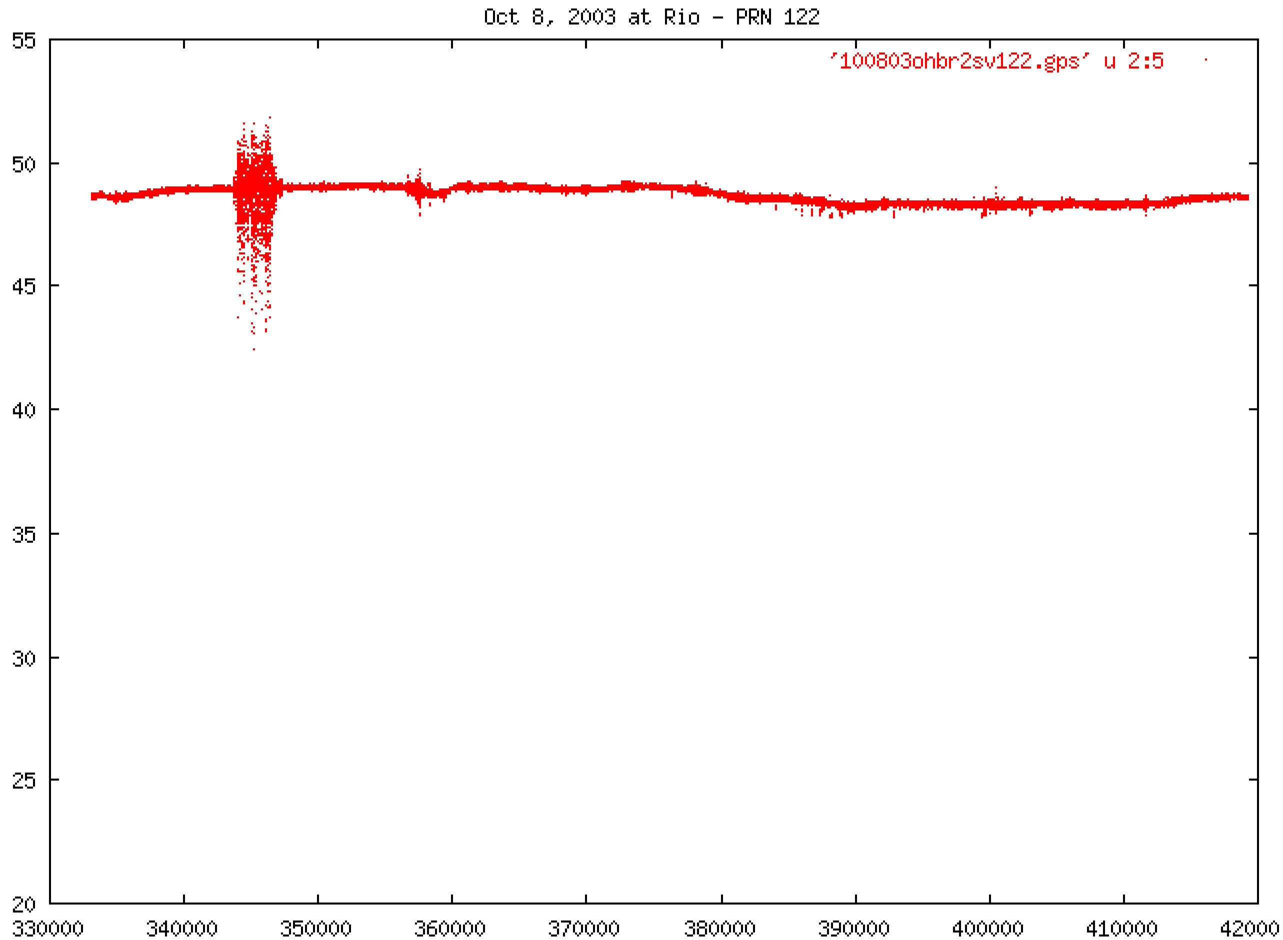


Moving Ionosphere Delay Feature in Ohio/Michigan Region on 20 Nov. 2003



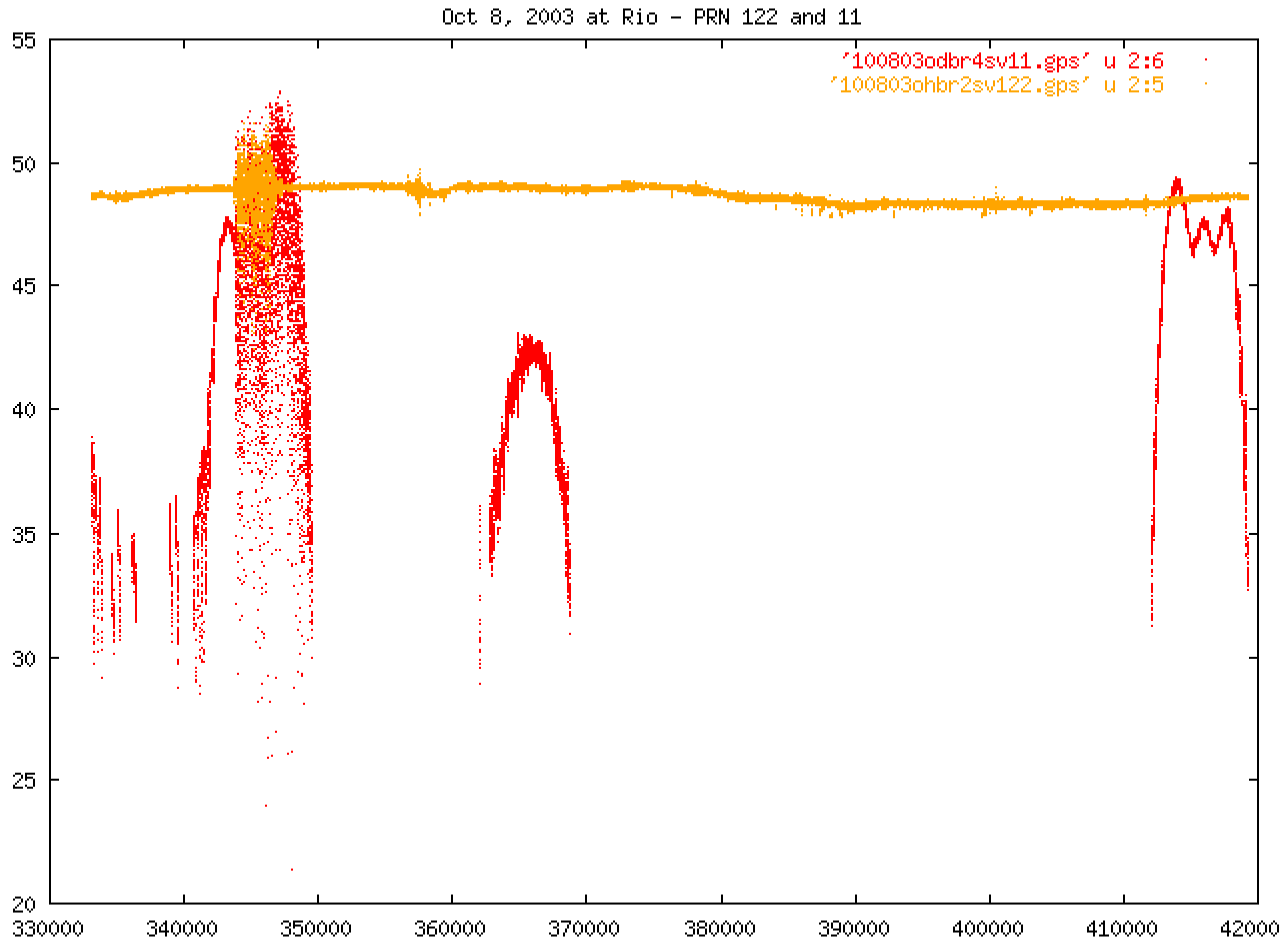
Ionosphere Depletion 10/08/2003

WAAS Geo (122) as Observed by the LTP



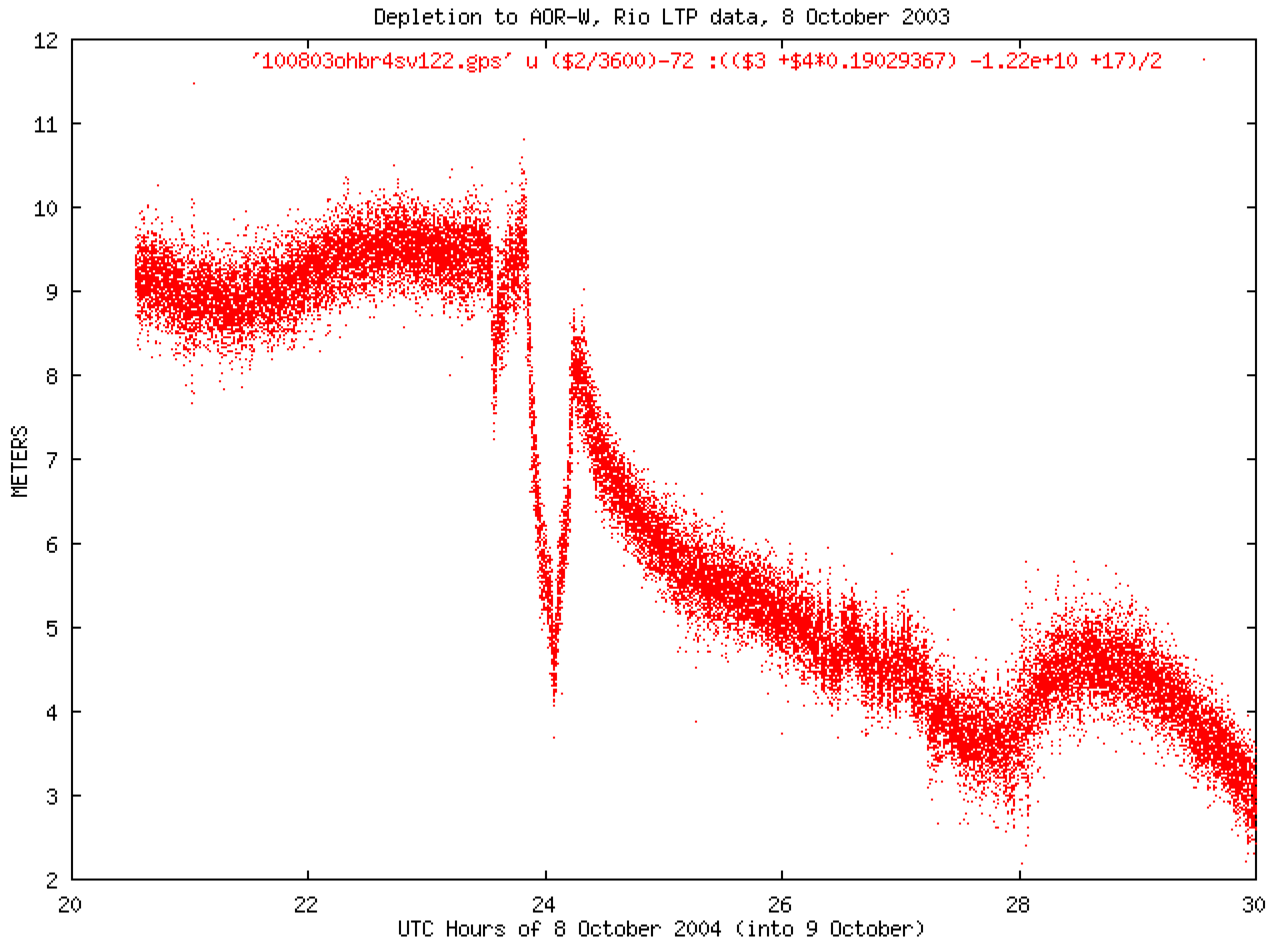
Ionosphere Depletion 10/08/2003

WAAS Geo (122) and PRN 11 as Observed by the LTP

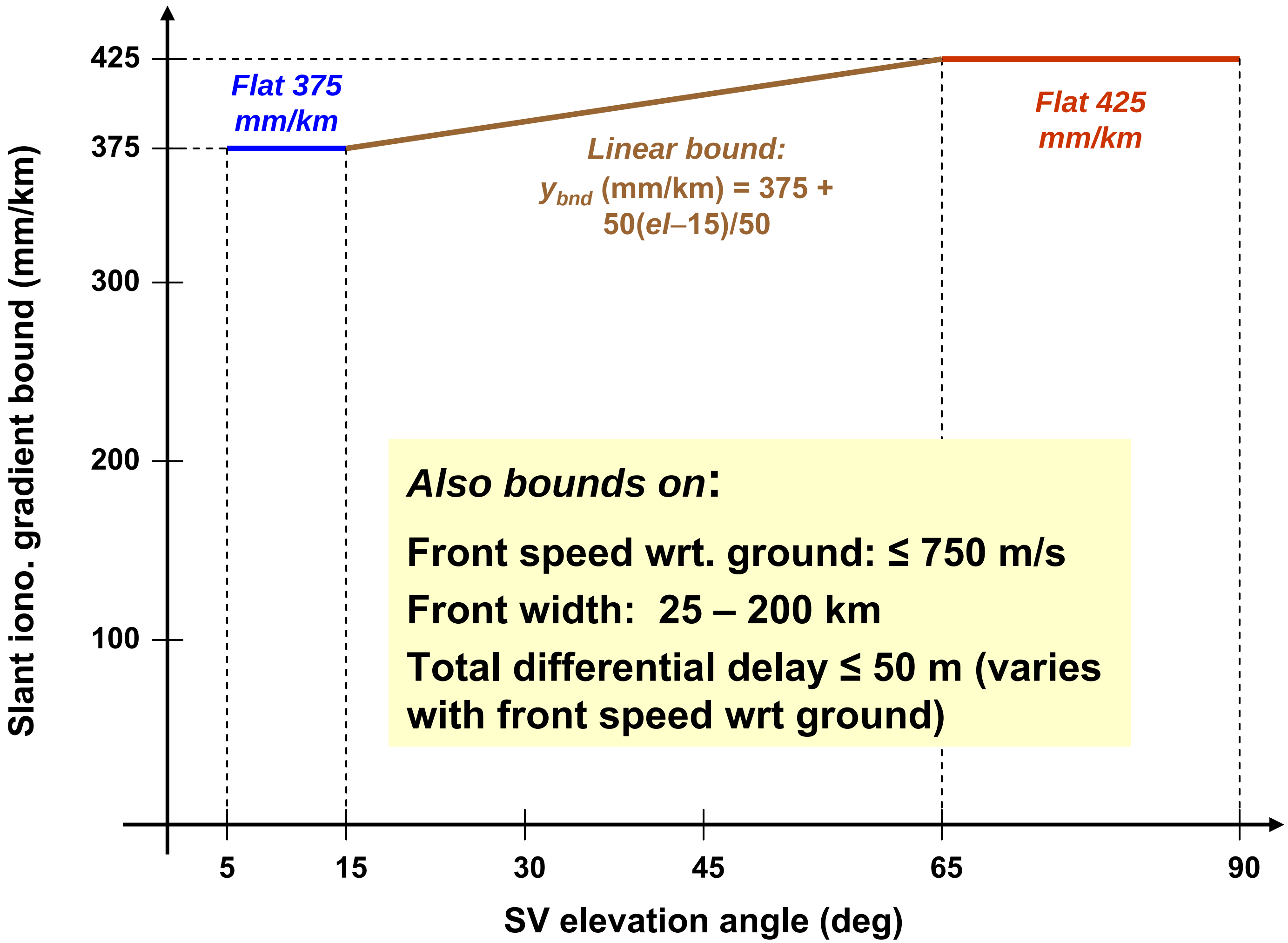


Ionosphere Depletion 10/08/2003

WAAS Geo (122) as Observed by the LTP



Final (Simplified) LAAS CAT I Ionosphere Anomaly Threat Model for CONUS



(note: plot not precisely to scale)

Mitigation of Ionosphere Anomaly Risk

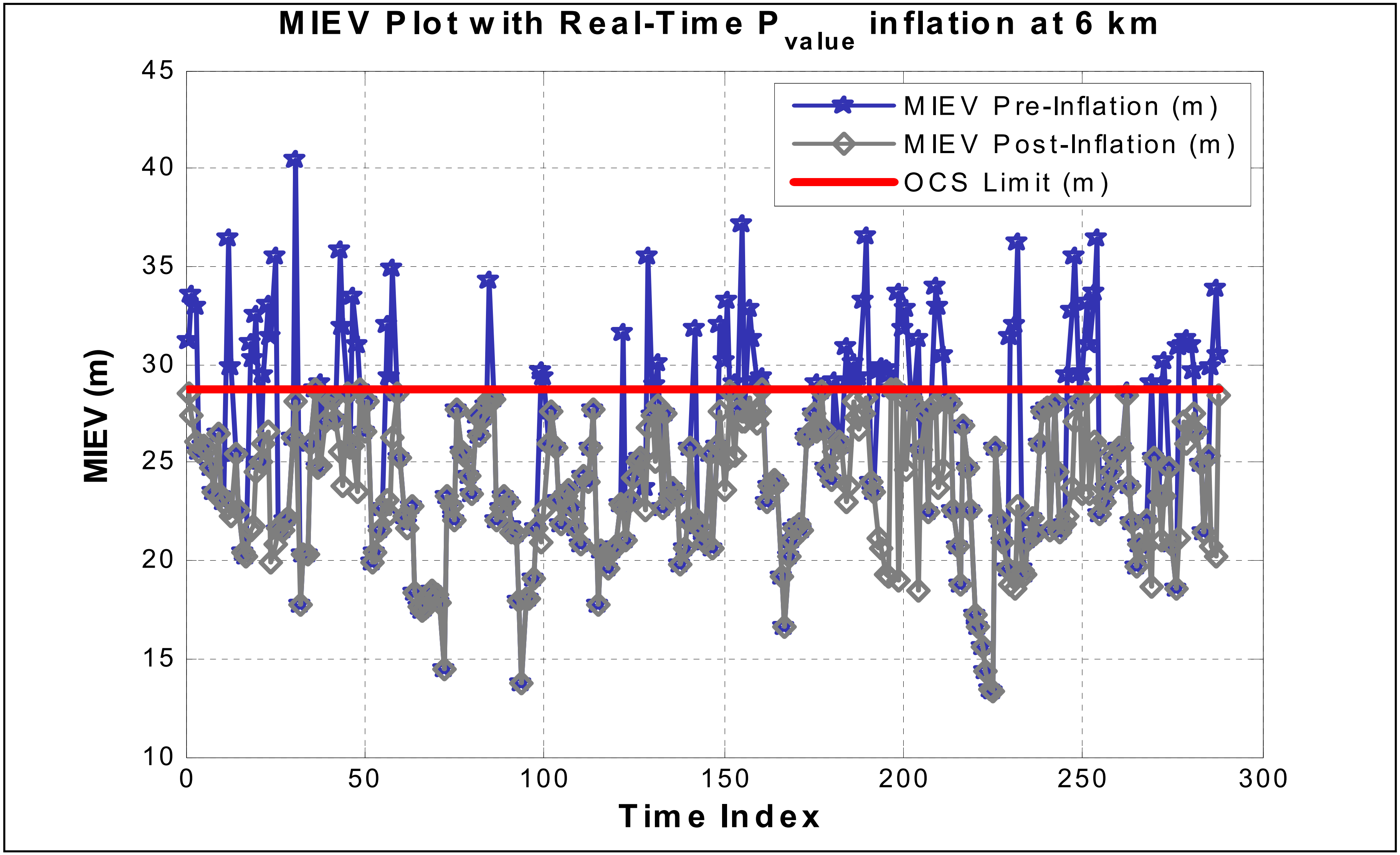
- Since the “worst-case” ionosphere anomaly cannot be detected by ground facility CCD monitoring, the ground facility must inflate broadcast integrity parameters to eliminate user subset geometries that would be unsafe (by a revised definition → vert. error $<$ 28 m at 200’ DH).

- Honeywell system achieves this by inflating appropriate broadcast parameters

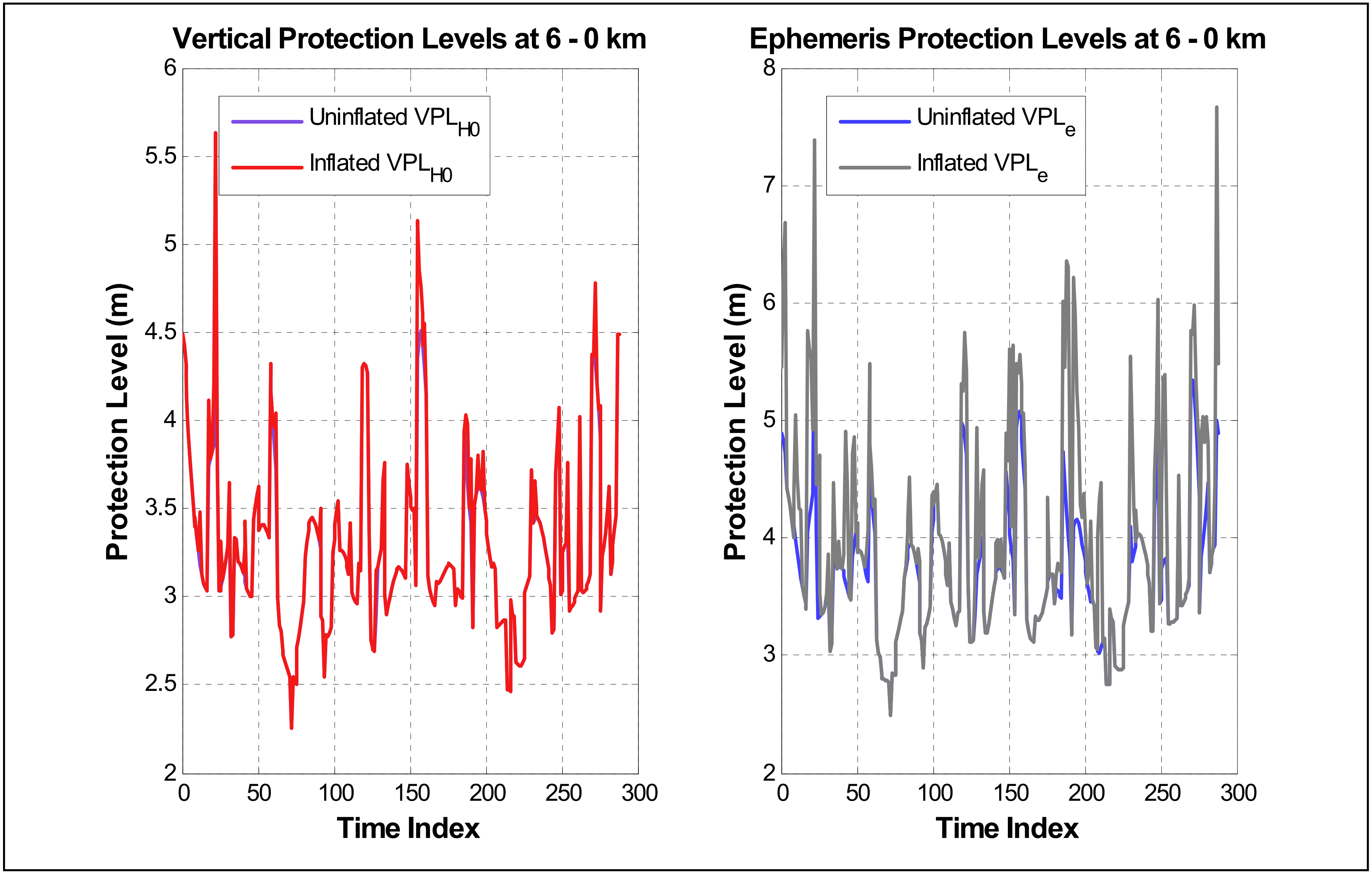
- Stanford validated a parallel approach which achieves this by targeted inflation of σ_{pr_gnd} and ephemeris P-values on a per-satellite basis (in VDB Message Type 1).

- The result of either method is lower CAT I user availability, but availability at most airports still exceeds 0.99 with all satellites healthy.

Stanford P-Value Inflation Results at Memphis Airport (RTCA 24-SV Constellation)



Stanford VPL Inflation Results at Memphis Airport (RTCA 24-SV Constellation)



Availability Estimates for 10 CONUS Airports Using Honeywell Methodology

RTCA 24-SV Constellation (No SV Outages)
All-in-View User Receiver Tracking All Satellites

Airport	DH=6km	DH=5 km	DH=4 km	DH=3 km	DH=2 km	DH=1 km
Memphis	1.000	1.000	1.000	1.000	1.000	1.000
Denver	1.000	1.000	1.000	1.000	1.000	1.000
Dallas	1.000	1.000	1.000	1.000	1.000	1.000
Newark	1.000	1.000	1.000	1.000	1.000	1.000
Washington	0.980	0.982	0.985	0.994	1.000	1.000
Los Angeles	1.000	1.000	1.000	1.000	1.000	1.000
Orlando	0.988	0.990	0.993	1.000	1.000	1.000
Minneapolis	1.000	1.000	1.000	1.000	1.000	1.000
Chicago	0.997	1.000	1.000	1.000	1.000	1.000
Tacoma	1.000	1.000	1.000	1.000	1.000	1.000

Issues

- **Anomalous ionospheric threat, when applied to the DCPS user, results in large position errors that are difficult to bound with the current definition of the protection levels**
  - There is no bound on the allowable geometries for the DCPS users
    - Precision approach users must apply a protection level check
  - There is no required airborne check for ionospheric anomalies, and since they are unobservable to the GBAS, the safety case must assume that the user will experience the error
  - There is only one set of integrity parameters, and inflation required to protect users at 60nmi would impact PA users

Ionosphere Summary

- Safety case for CAT I Precision Approach mode is complete
- DCPS safety case has been put together based on the current standards and models, and at this point would impact PA availability if implemented for all DCPS users
- Current activity at ICAO and RTCA on Dmax and CAT II/III standards may provide relief

Summary

- **Completion of the HMI report is now the priority within the LAAS Integrity Panel**
  - Completion target date June 2, 2008
- **Several issues have been identified, and are being addressed by the tiger teams**
- **Some tasks require additional analysis, but these are not expected to change the final design details and the report is expected on schedule**

Backup Slides

- **Other Tiger Team Issues**

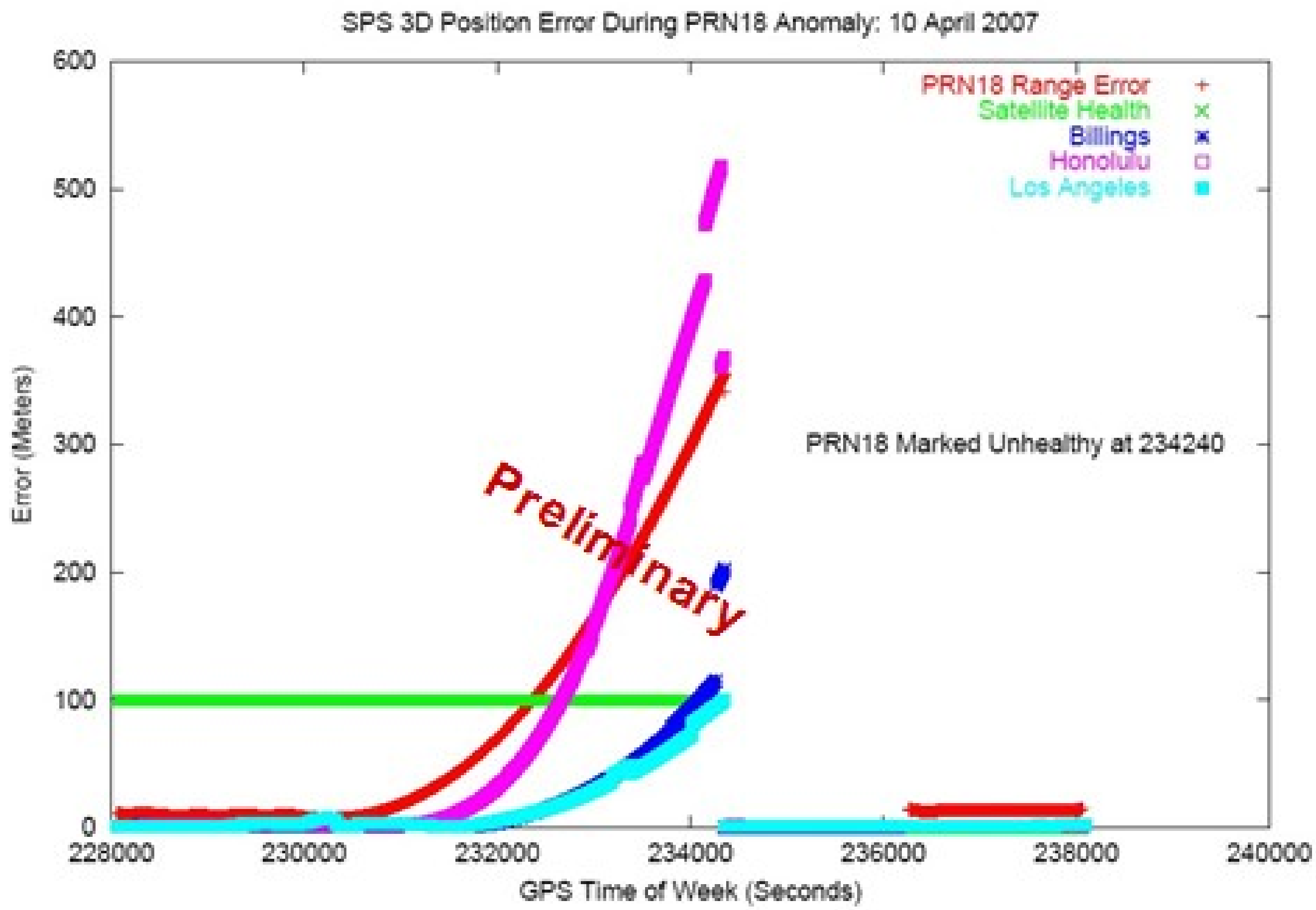
Ephemeris Monitoring

- **Ephemeris data received from each satellite provides information needed to compute the satellites position**
- **Two failure modes are associated with this data**
  - Type B faults are due to data failures, either by malfunction or failure of the satellite, or by control segment blunder
    - Data consistency checks are capable of detecting most of these failures
  - Type A faults are errors associated with movement of the satellite and include un-annunciated movement of the satellite (A2) and data failures immediately following a maneuver (A1)
- **Maneuvers that occur out of view of the GBAS are problematic for data consistency tests, and must be accounted for in the safety analysis**

Ephemeris Monitoring

- **Ephemeris A2 failures were considered sufficiently improbable to disregard for CAT I GBAS**
  - An A2 failure is an un-annunciated movement of a satellite
- **On April 10, 2007, PRN 18 was repositioned by the GPS space segment without indicating bad health status**
  - The movement was properly annunciated by a NANU
- **Complete details were published in the GPS PAN report #58, July 2007**
  - www.nstb.gps.tc.faa.gov

Ephemeris Monitoring
Observed GPS SPS Errors



Ephemeris Monitoring

Mitigation

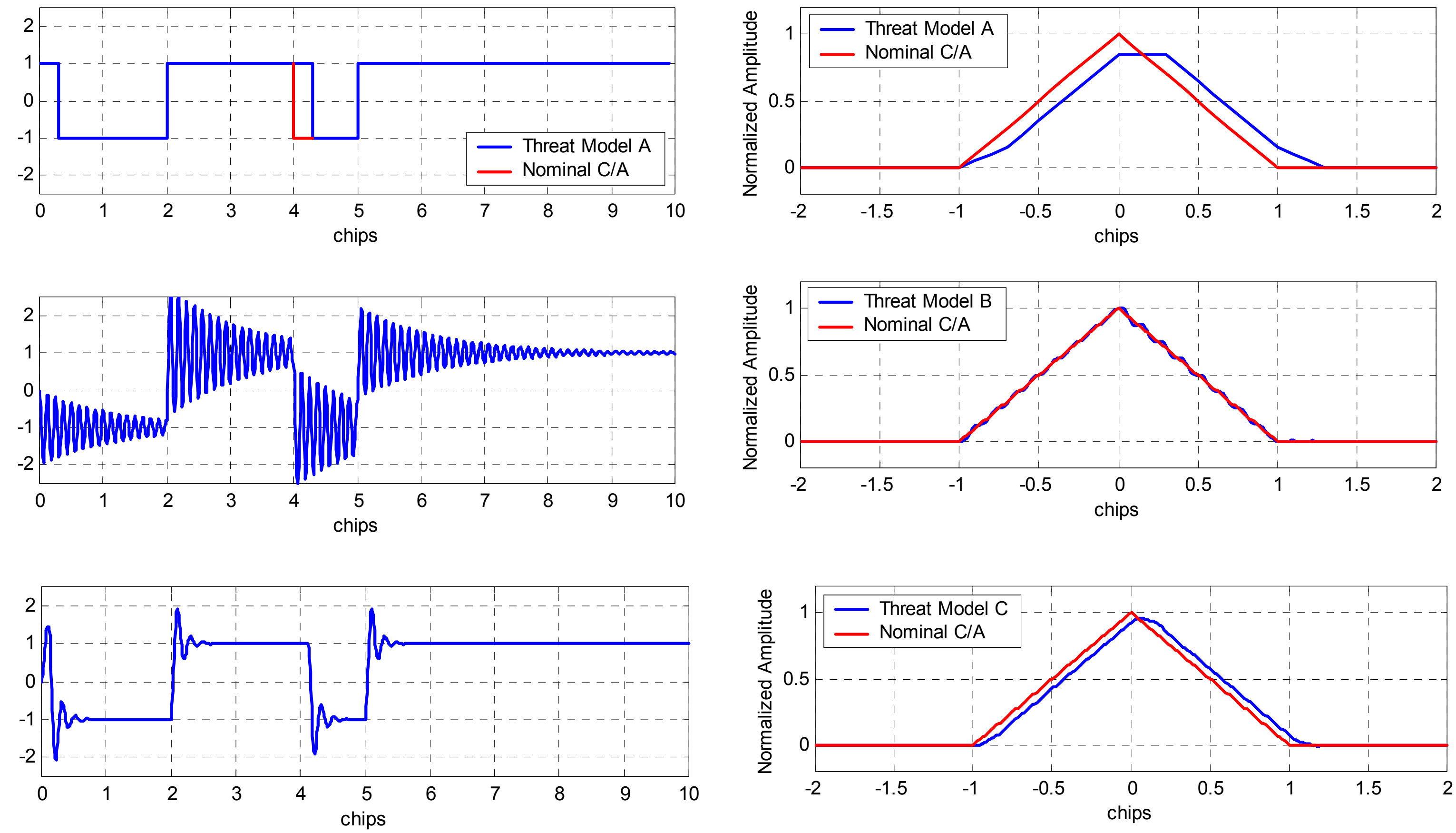
- **Several new tests were added to the design that can be used to detect satellite displacement errors**
  - The tests address the observed case without relying on monitoring NANUs
  - Also addresses problematic corner cases of the ephemeris B and A1 mitigations that were uncovered in the HMI analysis
  - Final simulations are being performed to show that all data failures following a maneuver can be detected
    - Including maneuvers out of view of the GBAS

Signal Deformation Monitoring and Natural Biases

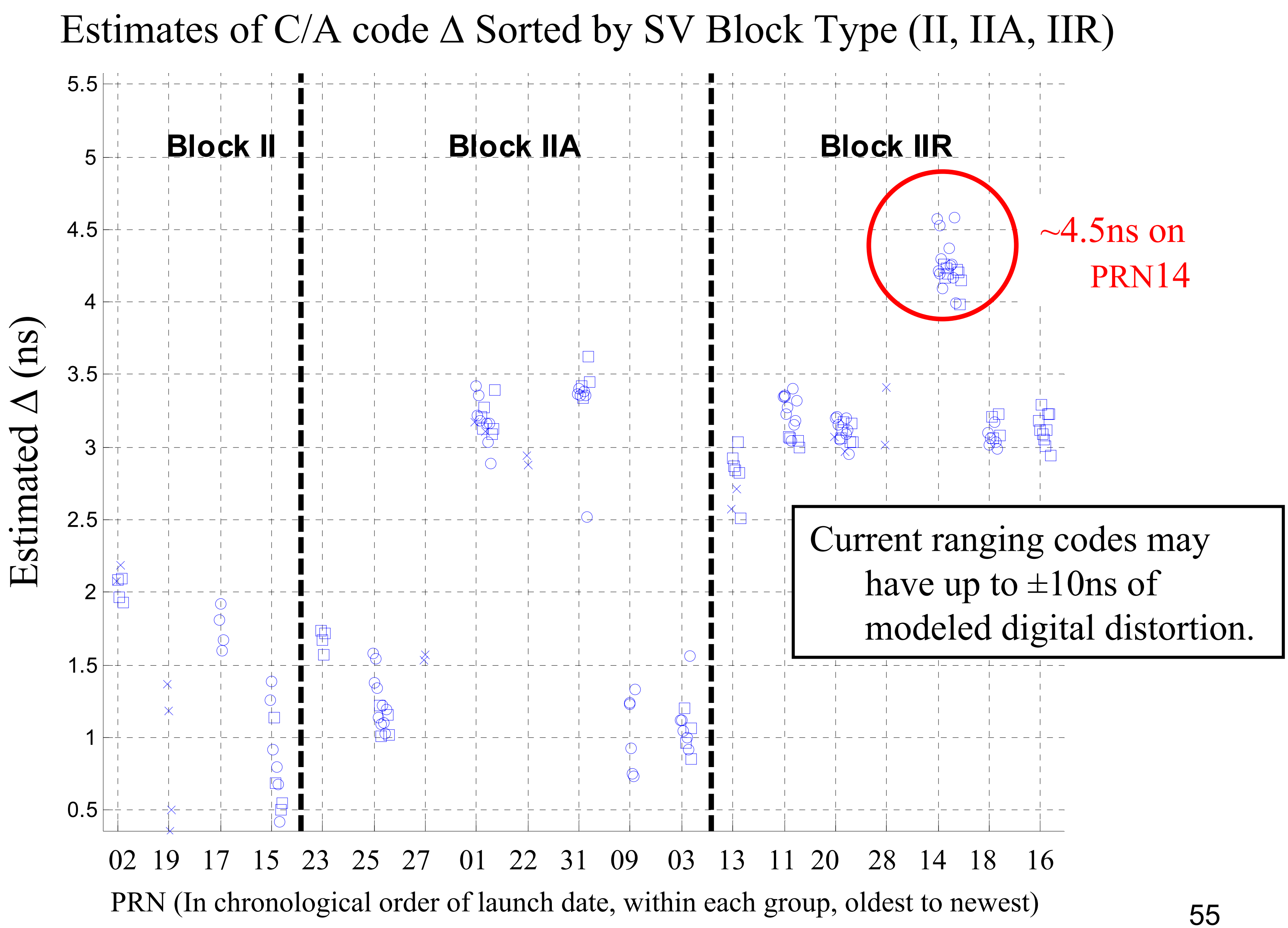
- **Satellite signals can be distorted by failures such that differential corrections will have errors for some set of users**

- **Natural (nominal, non-faulted) deformations exist**
  - The airborne user design space is limited, any difference between the ground receiver and the user receiver implementation will cause errors that must be bounded
  - Natural bias errors must be bounded by σ_{pr_gnd}
    - Already one of the existing error sources in the PSP error table

Signal Deformation Monitor Threats



Nominal Signal Deformation (Digital Only) - *Data*



Courtesy: A. Mitelman

SDM Natural Bias Actions

- **Satellites introduced into the constellation must be evaluated against the natural bias level protected by σ_{pr_gnd}**
  - Relationship between SDM test statistic biases and user errors is being more precisely simulated
- **Satellites with excessive natural bias must be additionally inflated or excluded**
  - **An additional test was added to the design to monitor the natural bias levels and perform this exclusion**
- **Details of a bias-monitoring test statistic and implementation are being completed by the tiger team**

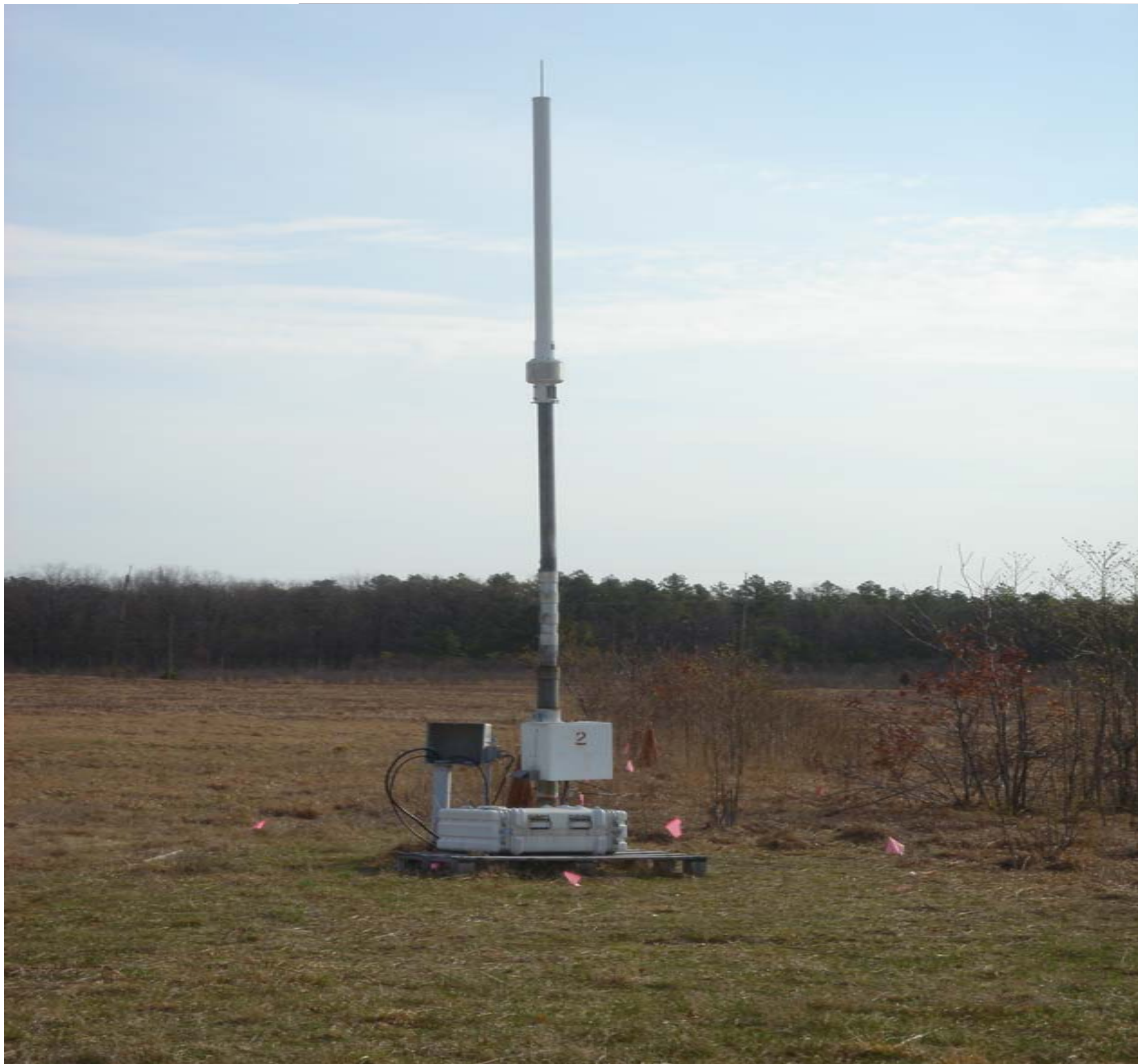
Sigma Pseudorange Ground

- **All GBAS measurement errors have been characterized by magnitude, type, time constant, and potential for correlation**
  - These must be represented in σ_{pr_gnd}
- **Several errors are/can be bias-like over the duration of an approach**
- **Primary issue is the validation of the Honeywell-developed semi-statistical overbounding methodology which combine bias-like terms and noise-like terms into the required overbounding sigma**
  - The validation approach uses a Monte Carlo simulation using selected geometries and bias error magnitudes

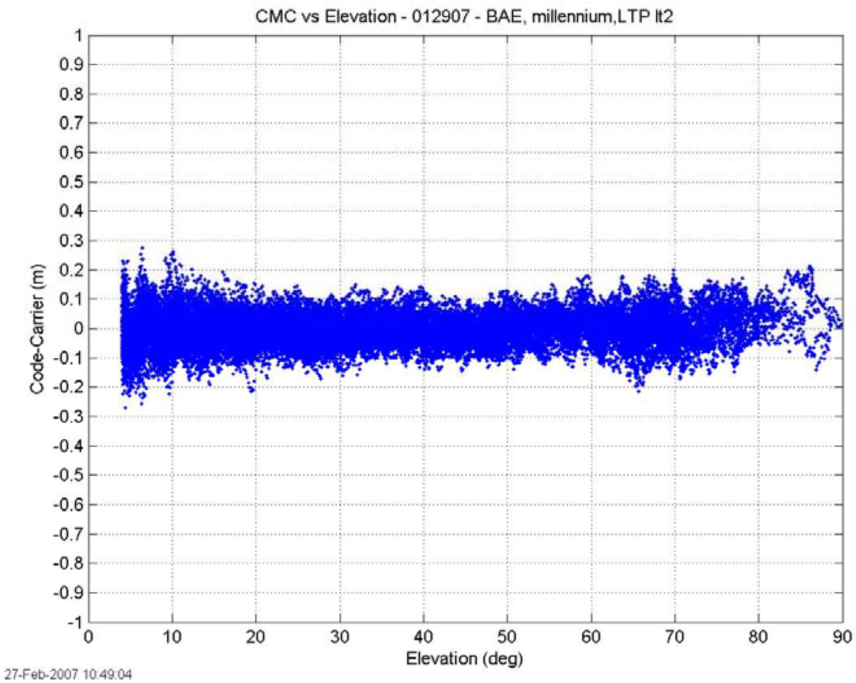
Reference Receiver Antenna Development

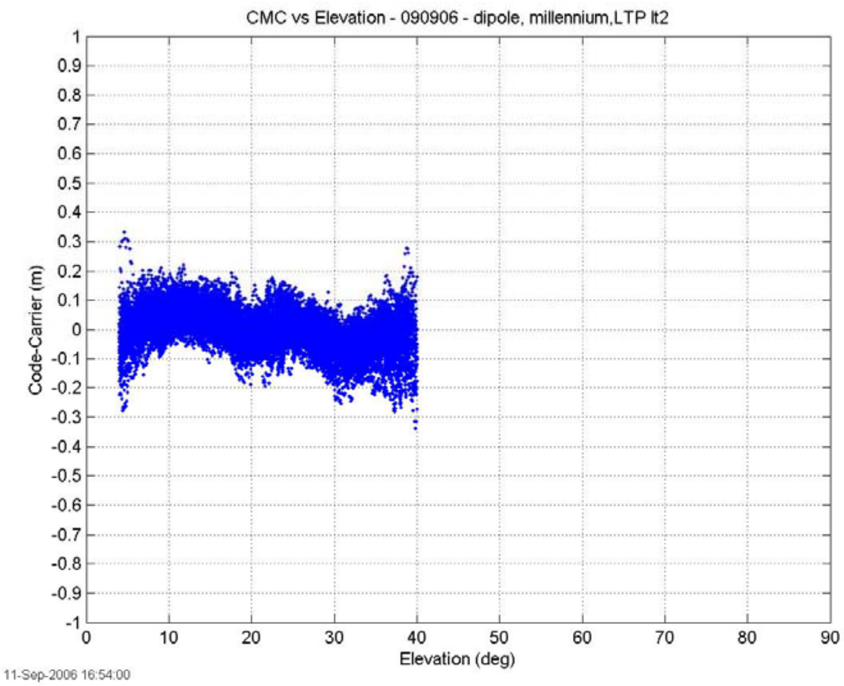
- Pseudorange measurement errors at the reference antennas are a significant portion of the errors present
- The FAA funded the development of a single-port L1/L2/L5 Right Hand Circularly polarized (RHCP) Multipath Limiting Antenna (MLA) aimed at reducing siting constraints and eliminating required bias calibration
- Ten antennas have been procured and were tested to evaluate production builds and are being used to update siting criteria

BAE ARL-1900 Production Antenna



Antenna Performance Comparison





Antenna Siting Constraint Update Testing

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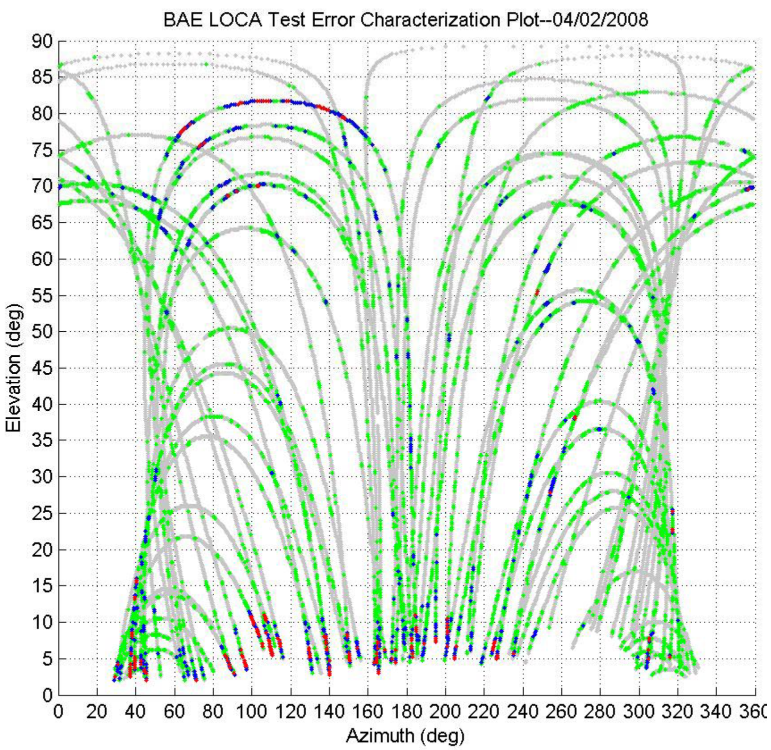

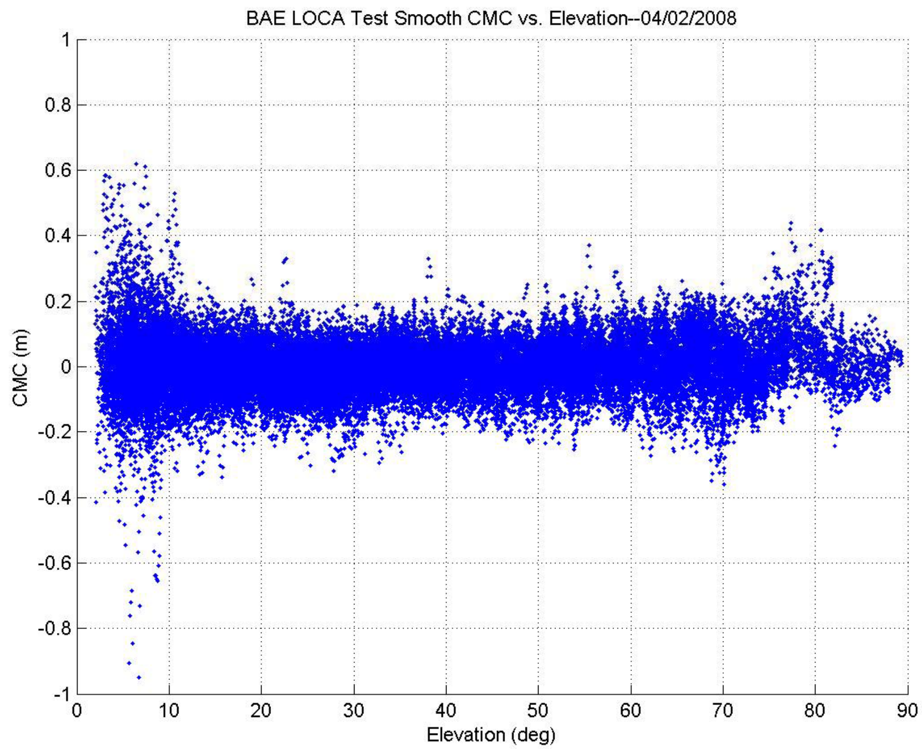

Antenna Performance Comparison

- **Both MLA designs have acceptable integrity performance**
  - Errors can be represented in σ_{pr_gnd}
  - New design has smaller error allocations
  - RHCP design also provides additional siting flexibility
- **PSP in Memphis will be upgraded with the new antenna design**

Tropospheric Error Bounding

- **A parameterized version of the LAAS tropospheric model was developed to explore the magnitude of range-domain model error**
  – Investigation of the most significant troposphere parameters and range of observed values in underway
  – Characterization of expected errors due to differences in the observed weather at the LAAS and user locations

Tropospheric Parameters

- **Areas of Responsibility**
  - Determine nominal and maximum observed variation of temperature and humidity at selected locations
    - Use the model to simulate maximum expected LAAS errors
  - Determine values for tropospheric parameters which provide integrity for all users
    - Verify with data collection and simulation
  - Gather additional verification data from available public sources
    - Requires historical observations of the region's weather activity