CAT I LAAS Ionosphere Anomaly Resolution

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Representing:

FAA/Honeywell LAAS Ionosphere Anomaly Subgroup

GBAS Working Group Meeting

Washington, D.C.

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Objectives

- Integrity in face of ionospheric threats
- No changes to CAT I (GSL C) MOPS or ICD
- Establish availability vs VAL_I trade based on ground monitor
- Optimize airborne monitoring for single frequency CAT II/III (GSL D, E, F)

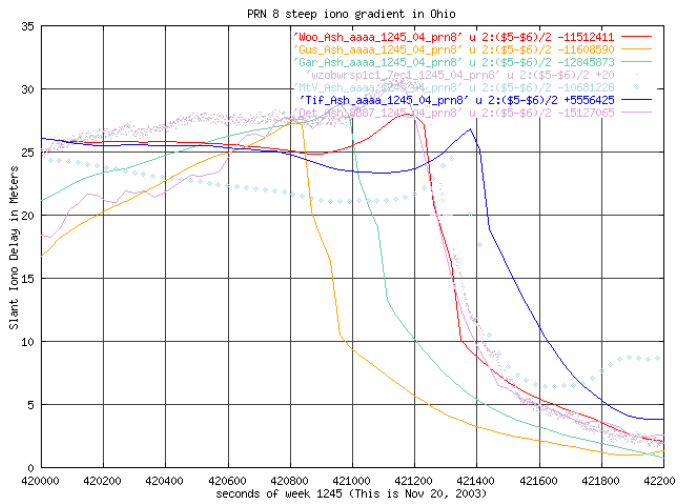
Outline

1. Summarize data analysis
2. Range domain end-around check
3. Threat model update (smaller slope for slow moving and low elevation satellites)
4. Summarize ground facility monitor capability
5. Availability vs VALI for geometry Screening
6. Ongoing Validation Work

Detailed technical briefing available from spullen@stanford.edu

Largest Gradient Observed by FAATC (L1 code minus carrier) among CORS "clusters" (in N. Ohio) on 11/20/03

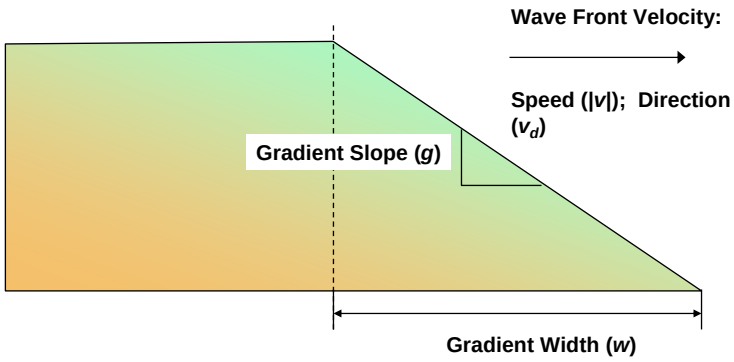
Gradient crosses GUST, then GARF, the WZOB, then TIFF
GARF to WZOB gradient ~ 20 meters in 50 km (400 mm/km)
"Wall of depletion" traveling approx. 250 m/s



Ionosphere Front Model Parameters

Max. Iono. delay diff. (*D*: given by slope and width):

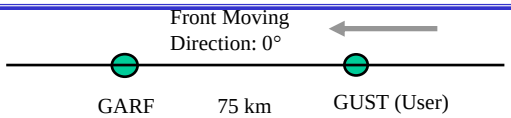
$D = wg$

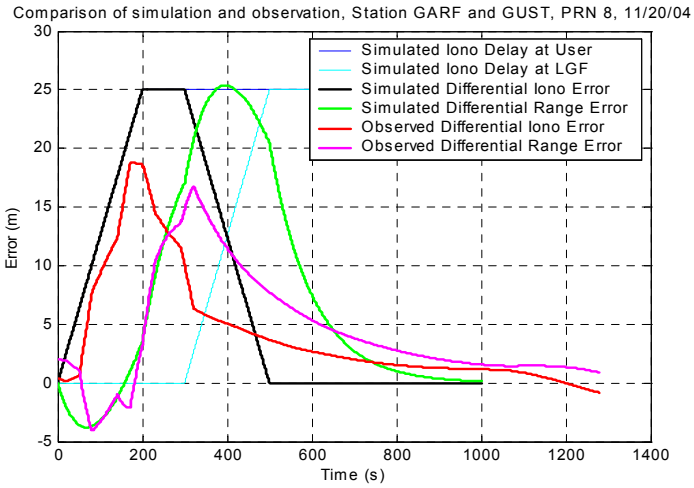


***This is a simplification of reality*:**

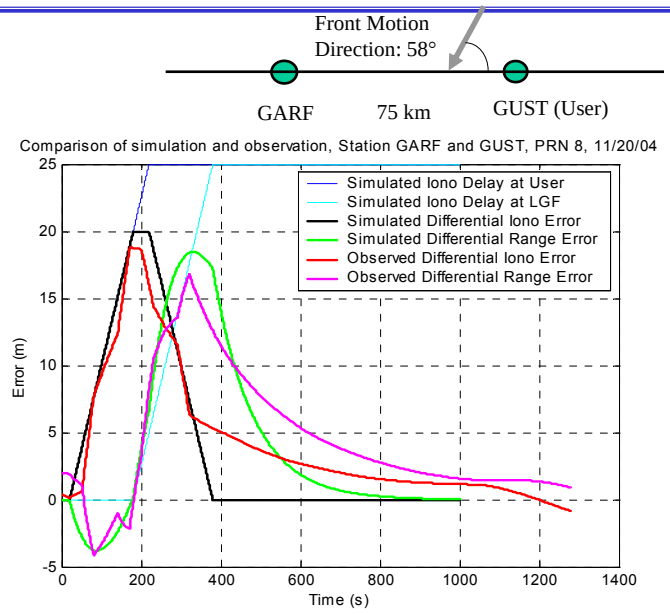
Non-linear variations appear in time series of observed anomalies, but model suffices to estimate the threat.

End-around Check in Range Domain





End-around Check in Range Domain



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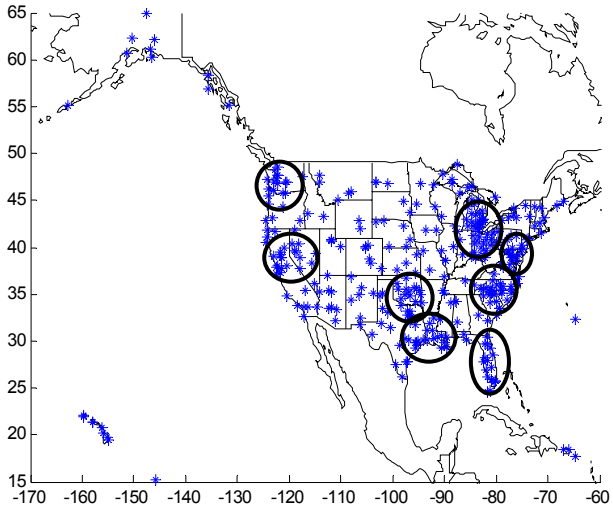
Data Analysis Summary

- Detailed tabulation of all apparent ionosphere anomalies within CORS station “clusters” during Oct. 29-30 and Nov. 20 storms has been completed
- Only points confirmed by a series of “sanity checks” and L1-L2 vs. L1 code-minus-carrier comparison are used to validate threat model
- Results suggest reduction in “maximum slope” bounds of current threat model
- Cannot yet validate width and speed parameters – analysis continues

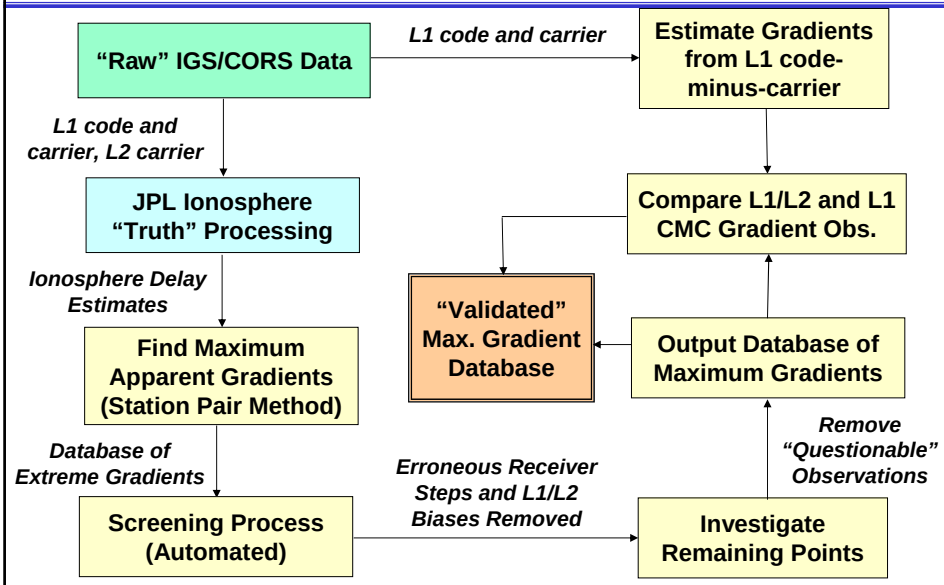
Focus on IGS/CORS Station Clusters

Ionosphere observations from "clusters" of nearby receivers are the most useful, as they most closely resemble LAAS baselines and minimize the extrapolations needed from the thin-shell model.

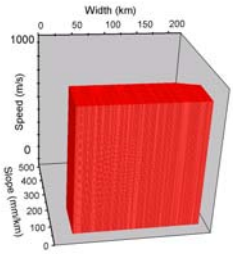


- N. California
- Seattle
- Louisiana
- OK/TX
- OH/MI
- Florida
- N. Carolina
- Wash. DC

Data Analysis and Screening Process



Revised Ionosphere Anomaly Models

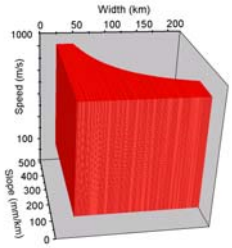


Low Elevation (El ≤ 12°)

Width: 25 – 200 km
Slope: 30 – 150 mm/km
Speed: 0 – 1000 m/s
***Max Delay* ≤ 25 m**

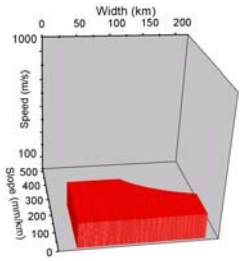
High Elevation (El > 12°) and Moving Front (> 70 m/s)

Width: 25 – 200 km
Slope: 30 – 500 mm/km
Speed: 70 – 1000 m/s
***Max Delay* ≤ 25 m**



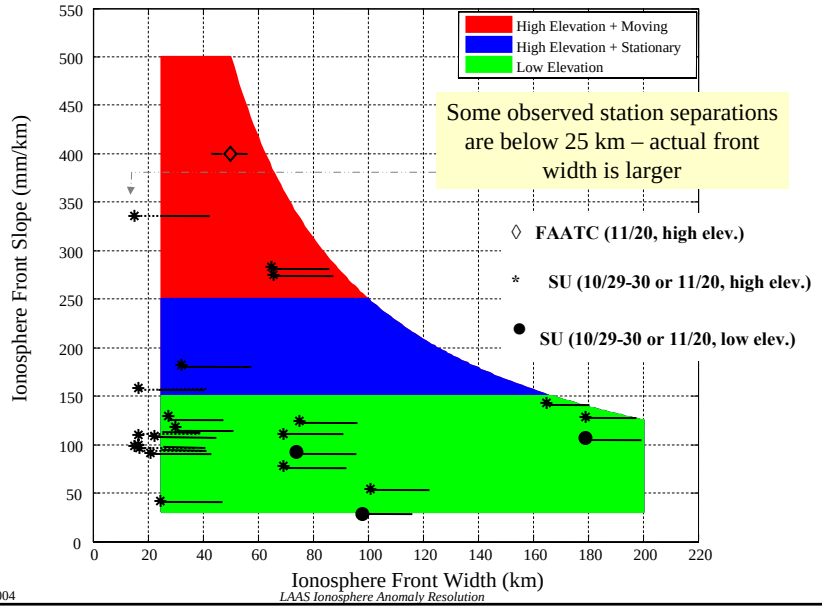
High Elevation (El > 12°) and Stationary (≤ 70 m/s)

Width: 25 – 200 km
Slope: 30 – 250 mm/km
Speed: 0 – 70 m/s
***Max Delay* ≤ 25 m**



Note: Slopes represent vertical (zenith) gradients; not slant.

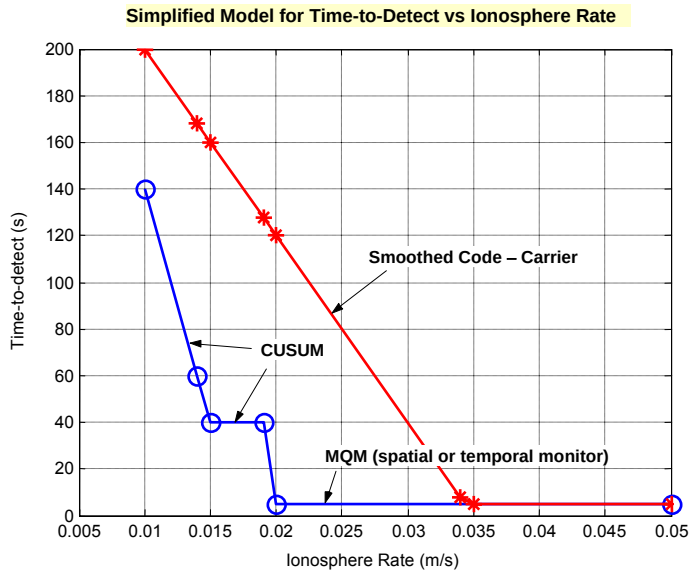
Observed Anomalies within Threat Model (29-30 October and 20 November 2003)



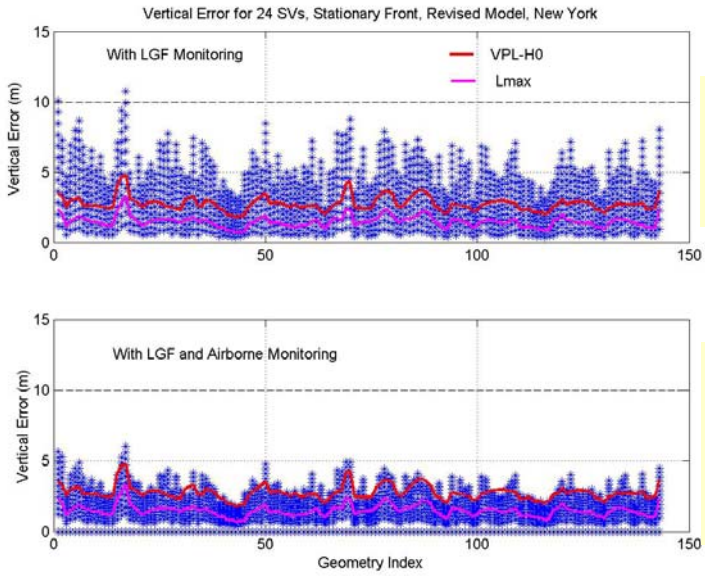
Mitigation via LGF Monitoring

- Stanford and Honeywell LGF prototypes include filtered code-minus-carrier monitoring
  - originally implemented for satellite failures
  - described in technical addendum
- Stanford LGF prototype adds:
  - CUSUM on code-minus-carrier measurements
  - tight MQM threshold for carrier-phase consistency over time
- Honeywell LGF prototype adds:
  - carrier-phase B-value calculation for consistency over space between LGF RR antennas

Time-to-detect vs. Observed Iono. Rate (from Stanford IMT)



Vertical Position Errors and VPL's for 24 SVs, Stationary Front (*New York*)



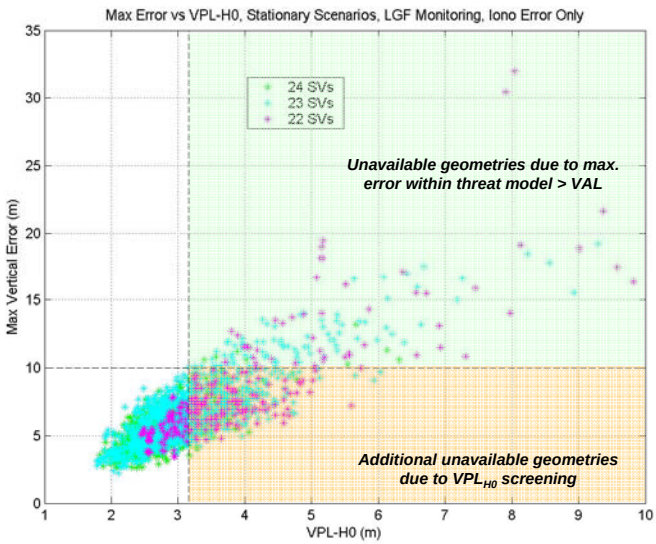
With LGF monitor only:

2 geometries (out of 143) have errors > 10 m

With LGF and airborne monitor (based on optimistic model on backup slide):

No geometry has error > 10 m.

Geometry Screening Using VPL_{H0}



LGF monitoring only:

For 10-meter VAL threshold:

$VPL_{H0} \leq 3.16$

Availability of 83%

Availability loss: 0.169

Availability versus VAL_l During Iono Event
Errors include 3.1 ♦ for non-iono errors.

VAL_l	10 m		12 m		15 m	
Monitors	LGF Only	LGF & Optimistic Airborne	LGF Only	LGF & Optimistic Airborne	LGF Only	LGF & Optimistic Airborne
Availability %	64	99.2	89.3	99.5	98.7	99.99

Way Forward for CAT I (GSL C)

- Seek sharp external means to sense iono state (SBAS or space weather service)
  - Only when threat exists, ground screens risky geometries by reducing the broadcast VAL (or increase $♦_{vig}$ or $♦_{pr_gnd}$)
- Seek further reductions in threat model (current bottleneck is slope of stationary fronts - 250 mm/km)
- Accept VAL of 15 m rather than 10 m

Way Forward for CAT II/III (GSL D,E,F)

- Require airborne monitoring and use of L_{max} screening parameter (ICD change)
- Existing requirements text in updated RTCA MASPS is acceptable given that lack of maturity is clearly noted.
- More work is needed to develop and refine a recommended airborne monitor algorithm.

Plan: Validate CAT I Parameters & Improve Availability vs VAL_I

- Refine parameters based on Oct & Nov 2003 data
  - Threat model driven by 10/29/03, 10/30/03, 11/20/03 in CONUS (two events)
- Complete analysis of 4/6-7/00, 7/15-16/00, 3/31/01, 9/7/02 to confirm threat boundaries.
  - To date, no points outside threat model have been found from these storms
  - No points threatening to LAAS have been found in Japan GEONET data (nowhere near)
- Extend end-around check to position domain
- Seek trusted external sources of iono state
  - A WAAS-based method has been proposed

Plan: *Airborne Ionosphere Monitor for Single Frequency CAT II/III*

- Use flight-test data to assess airborne monitors (SU & Honeywell) under more aircraft and ionosphere conditions
  - Complete Boeing flight data?
  - If not, process more FAATC flight data
- Consider carrier-phase relative RAIM (requires broadcast of carrier-phase corrections)
- Update availability vs VAL_I projections as airborne monitoring effectiveness results become clearer
- Dual frequency effort has begun for JPALS

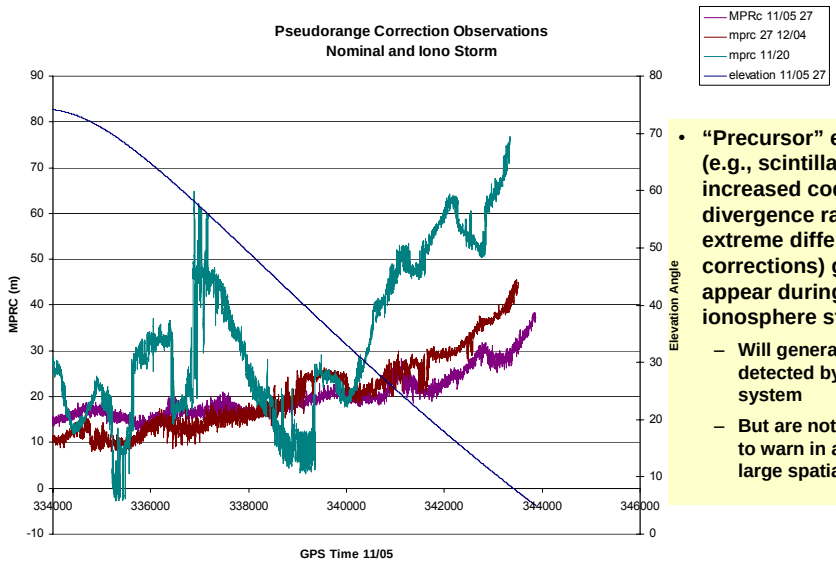
Backup Slides

- Backup slides follow…

Recommended LGF Operations Concept

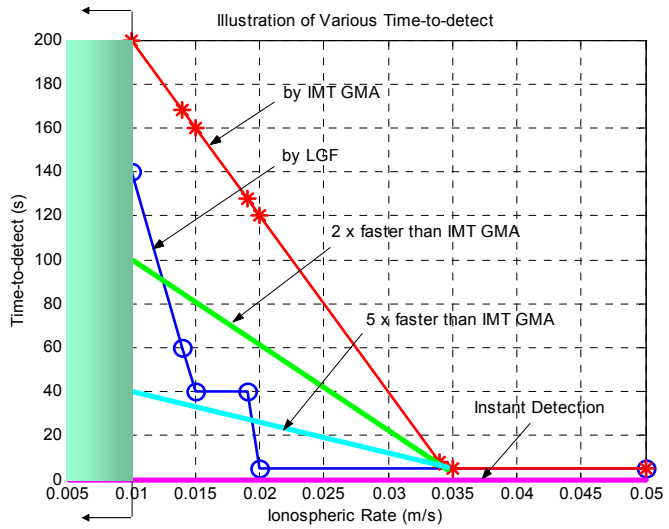
- **LGF determines when ionosphere anomaly threat exists**
  - **Ideally based on broadcast WAAS GIVE values (when LAAS site is well inside WAAS service volume)**
  - **If WAAS coverage is insufficient, use an ionosphere "almanac" (active years/seasons/locations) augmented by external K_P updates (will be much more conservative)**
  - **Most conservative approach: assume ionosphere anomaly threat is always present**
- **When iono. anomaly threat exists, LGF screens geometries based on reduced VAL (or higher σ)**
- **When threat does not exist, broadcast "normal" VAL and sigmas**
  - **Achieve nominal VPL_{H0} availability (~ 0.999+) most of the time**

Example of "Precursor" Events
(FAATC LAAS Test Prototype PR Corrections)



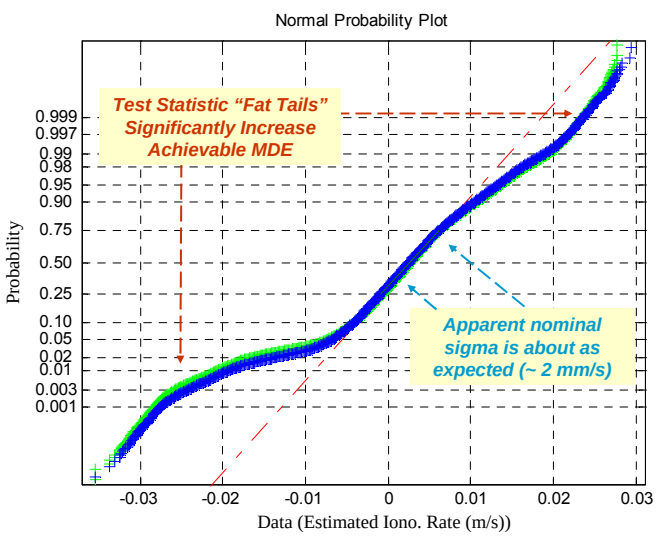
- **"Precursor" events (e.g., scintillation, increased code-carrier divergence rates, extreme differential corrections) generally appear during severe ionosphere storms**
  - **Will generally be detected by ground system**
  - **But are not guaranteed to warn in advance of large spatial gradients**

Assumed Airborne Monitor Time-to-Detect (from SU IMT Performance)



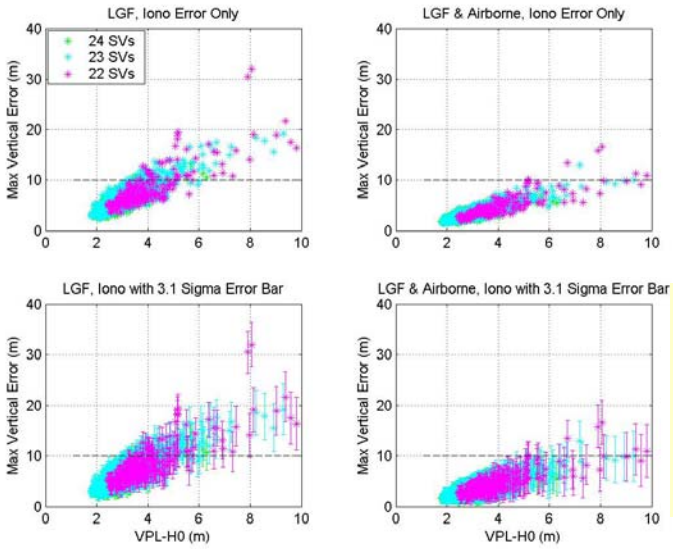
- **Estimating airborne time-to-detect is difficult (more flight data and improved airborne multipath models would help).**
- **Several hypotheses are used in this study to illustrate potential airborne monitor effectiveness.**
- **Proposed MASPS requirement approx. corresponds to the zone between the red and green lines on this plot.**
- **Note no detection in "nominal zone" below 0.01 m/s**

Example Monitor Test Statistic Distributions (from Tim Murphy's Boeing Flight Test Results)



- **Lower detection bound on slide 12 corresponds to a detectable "stationary front" slope of about 140 mm/km**
- **Monitor performance in preliminary Boeing results falls short of model on slide 26**
  - **Partially due to need to operate during active but non-threatening iono. conditions**
- **Actual detectable stationary front may not improve upon threat model upper bound of 250 mm/km**
- **Thus, benefit of current proposed monitors is questionable**

VPL_{H0} Screening Effectiveness



LGF monitor only:

- **without error bars:**

  $VPL_{H0} \leq 3.16$, Availability loss: 0.169

- **with error bars:**

  $VPL_{H0} \leq 2.83$, Availability loss: 0.359

LGF and airborne monitors:

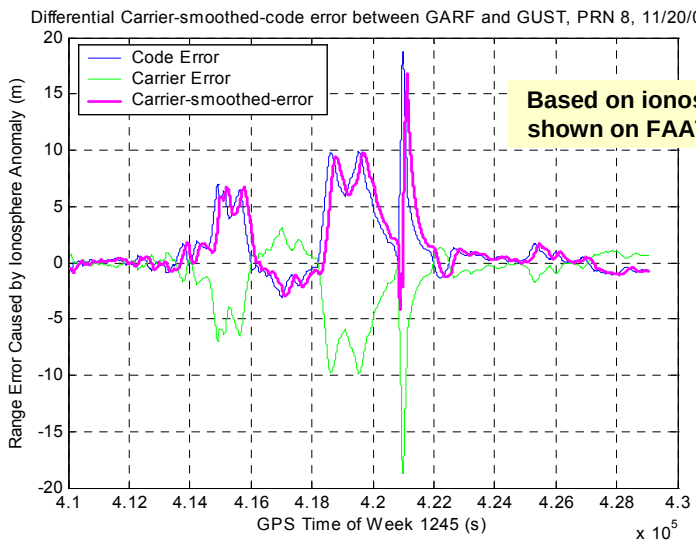
- **without error bars:**

  $VPL_{H0} \leq 5.17$, Availability Loss: 0.005

- **with error bars:**

  $VPL_{H0} \leq 4.72$, Availability Loss: 0.008

GBAS Differential Carrier-Smoothed Code Error: *N. Ohio Event on 11/20/04*



Based on ionosphere data shown on FAATC slide (?)