Ionospheric Threat Protection:

Nominal and Anomalous Ionosphere Conditions

Federal Aviation Administration

Presentation to CAAC

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John Warburton
FAA Engineering Development Services
Navigation Group AJP-652

Purpose

- Review of ionospheric requirement and threat model
- Provide the latest information on the FAA-developed Ionospheric storm threat model
- Mitigation Strategy
  - Frequency of occurrence
  - Procedural mitigation
- Nominal Ionospheric Parameter
- Summary

Current Ionosphere Anomaly Detection Requirement

3.2.1.3.5.1 Condition for Valid Sigma Ionosphere

The LGF shall detect Ionospheric conditions that result in noncompliance with the requirements in Sections 3.1.2.1 and 3.1.2.2. When the increase in system risk associated with increased ionosphere gradients exceeds design tolerances, the LGF shall exclude the offending ranging source(s) and generate alerts as appropriate. When ionospheric disturbances cannot be isolated to specific ranging sources, and system risk is not minimal (increases by more than one order of magnitude) as a result, the LGF shall generate an alarm. Self-recovery shall be accomplished after ranging source exclusions or alarms are generated once the integrity requirements in Sections 3.1.2.1 and 3.1.2.2 are again met. The probability of a false alarm shall be less than 5 x 10-8 per 15-second interval.

Note: The sigma ionosphere vertical gradient term must be valid for all users within Dmax from the LGF reference point, as identified in Section 3.1.2.

Referenced Integrity Requirement (1)

3.1.2.1.1 Category I Precision Approach The probability that the LGF transmits out-of-tolerance precision approach information for 3 seconds or longer due to a ranging source failure, LGF failure, anomalous environmental or atmospheric effects, when operating within the Radio Frequency Interference (RFI) environment defined in appendix D of RTCA/DO-253A, shall not exceed 1.5x10-7 during any 150-second approach interval. Out-of-tolerance precision approach information is defined as broadcast data that results in a position error exceeding the Category I precision approach protection level and ephemeris error bound for any user that complies with RTCA/DO-253A and is located anywhere within Dmax. Ranging source failures, as described in Appendix E, shall include:

a. Signal deformation, with a failure rate of 1.0 x 10-4 per hour per satellite during initial acquisition, and a prior probability of 4.2 x 10-6 per approach per satellite after acquisition;

Referenced Integrity Requirement (2)

b. Signal levels below those specified in Sections 3.3.1.6 and 6.3.1 of ICD-GPS-200C, for C/A code on L1 only, with a failure rate of 1.0 x 10-4 per hour per satellite during initial acquisition, and a prior probability of 4.2 x 10-6 per approach per satellite after acquisition;

c. Code/carrier divergence, with a failure rate of 1.0 x 10-4 per hour per satellite during initial acquisition, and a prior probability 4.2 x 10-6 per approach per satellite after acquisition;

d. Excessive pseudorange acceleration, such as step or other rapid change, with a failure rate of 1.0 x 10-4 per hour per satellite during initial acquisition, and a prior probability of 4.2 x 10-6 per approach per satellite after acquisition; or

e. Erroneous broadcast of GPS ephemeris data, with a failure rate of 1.0 x 10-4 per hour per satellite during initial acquisition, and a prior probability of 4.2 x 10-6 per approach per satellite after acquisition.

Threat Model Application

- Final LAAS Integrity Panel (LIP) determination
  - Due to the threat model and user impact scenario, feasibility of ground station detection of all cases is not possible
    - Assumes installation of all equipment on airport and an independent ground facility (no external inputs)
    - Storms are unpredictable, so no prior probability is assigned
      - During the storm, safety must be maintained
  - The final position error could be bounded, but not bounded by the protection levels (VPL)
  - An operationally acceptable bound could be determined based on limiting user geometries with existing airborne alert limits (VAL)

Change Process

- This information is provided in the spirit of information sharing and feedback.
- Change will be submitted with other changes in the next revision of the Non-Fed LAAS Specification
- Other standards changes/considerations/discussions will occur through the normal procedures
  - ICAO difference must be addressed

Proposed Specification Change (1)

3.2.1.3.5.1 The LGF shall set the Sigma Vertical Ionosphere Gradient Field to reflect or exceed the distribution associated with the residual ionospheric uncertainty due to spatial decorrelation under nominal ionospheric conditions.

Note: Anomalous ionosphere conditions which result in unacceptable hazardous conditions can be mitigated by monitoring external systems (e.g. WAAS) or adjusting protection level parameters values (e.g. Sigma Pseudorange Ground, Sigma Vertical Ionosphere Gradient, Ephemeris Decorrelation Parameter, etc.) to limit the maximum differential position error incurred by the airborne equipment (see Section 3.1.2.1.1 and Appendix E for additional guidance).

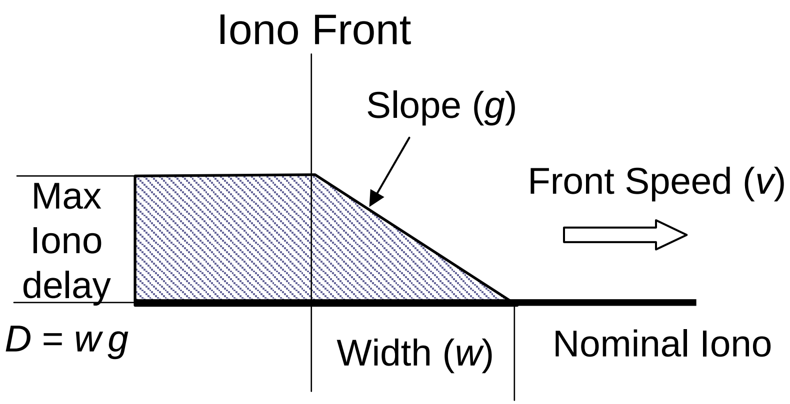
Proposed Specification Change (1)

3.1.2.1.1 Will remain unchanged except for an added condition f.

f) Anomalous ionospheric conditions

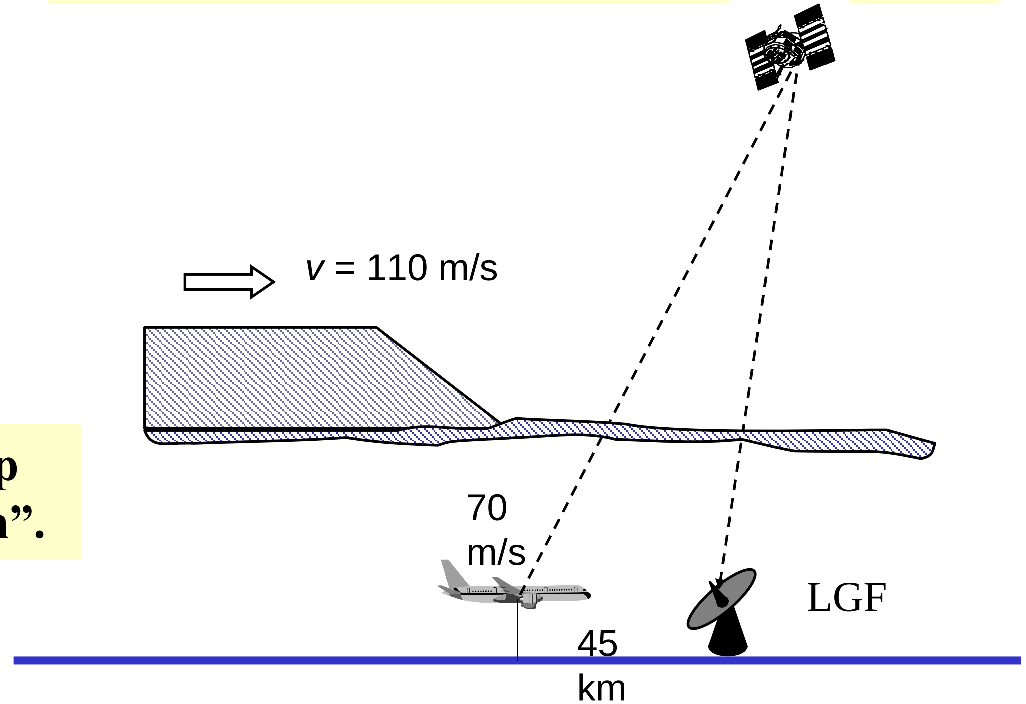
- ***For failure condition f, out-of-tolerance precision approach information is defined as broadcast data that results in a position error exceeding the values shown in Table XX (vertical position error of 28.8m at the DH) for any user that complies with RTCA/DO-253*. Failures conditions, as described in Appendix E shall include:**

Ionosphere Spatial Anomaly Model



Simplified model: a wave front ramp defined by the "slope" and the "width".

An illustration of the impact on LAAS users



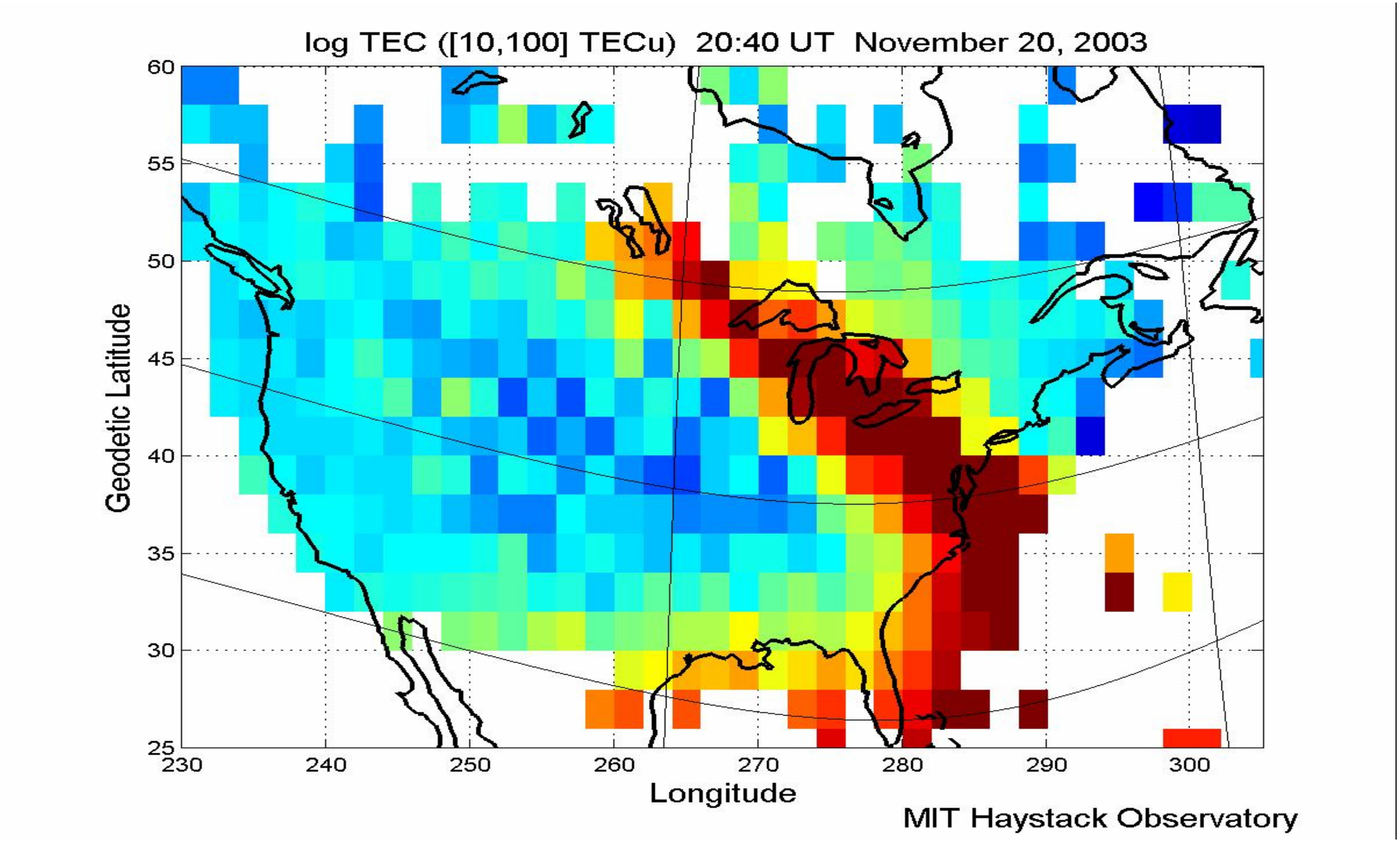
- **<u>Moving wave front scenario:</u>**
  Ionosphere wave front moves in the same direction as the airplane does and "catches" the airplane from behind before reaching the LGF
- **<u>Stationary front scenario:</u>**

  Ionosphere wave front is moving slower than aircraft approach speed and lies partially between aircraft and LGF

Current Threat Model

- Threat model was assembled based on all observed ionospheric storm data collected within CONUS United States
- The FAA effort has focused on CONUS threats
  - Leveraged data available from WAAS and CORS measurements
  - Provided a network of dense network of measurements for anomaly characterization
- Other GBAS implementers must characterize threats in their region

CONUS Ionospheric Anomaly November 20, 2003



Ionosphere Anomaly Days Analyzed

Day (UT)	K_P	D_{ST}	Geo. Storm Class	WAAS Coverage	Focus Region
4/6/2000	8.3	– 287	Severe	None (pre-IOC)	NE Corridor
4/7/2000	8.7	– 288	Extreme	None (pre-IOC)	NE Corridor
7/15/2000	9.0	– 289	Extreme	None (pre-IOC)	N/A
7/16/2000	7.7	– 301	Strong	None (pre-IOC)	N/A
9/7/2002	7.3	–163	Strong	None (pre-IOC)	N/A
10/29/2003	9.0	– 345	Extreme	~ 0%	N/A
10/30/2003	9.0	– 401	Extreme	~ 0%	TX-OK-LA-AR
10/31/2003	8.3	– 320	Severe	~ 0%	FL-GA
11/20/2003	8.7	– 472	Extreme	~ 0%	OH-MI
7/17/2004	6.0	– 80	Moderate	~ 68.8%	TX-OK-LA-AR

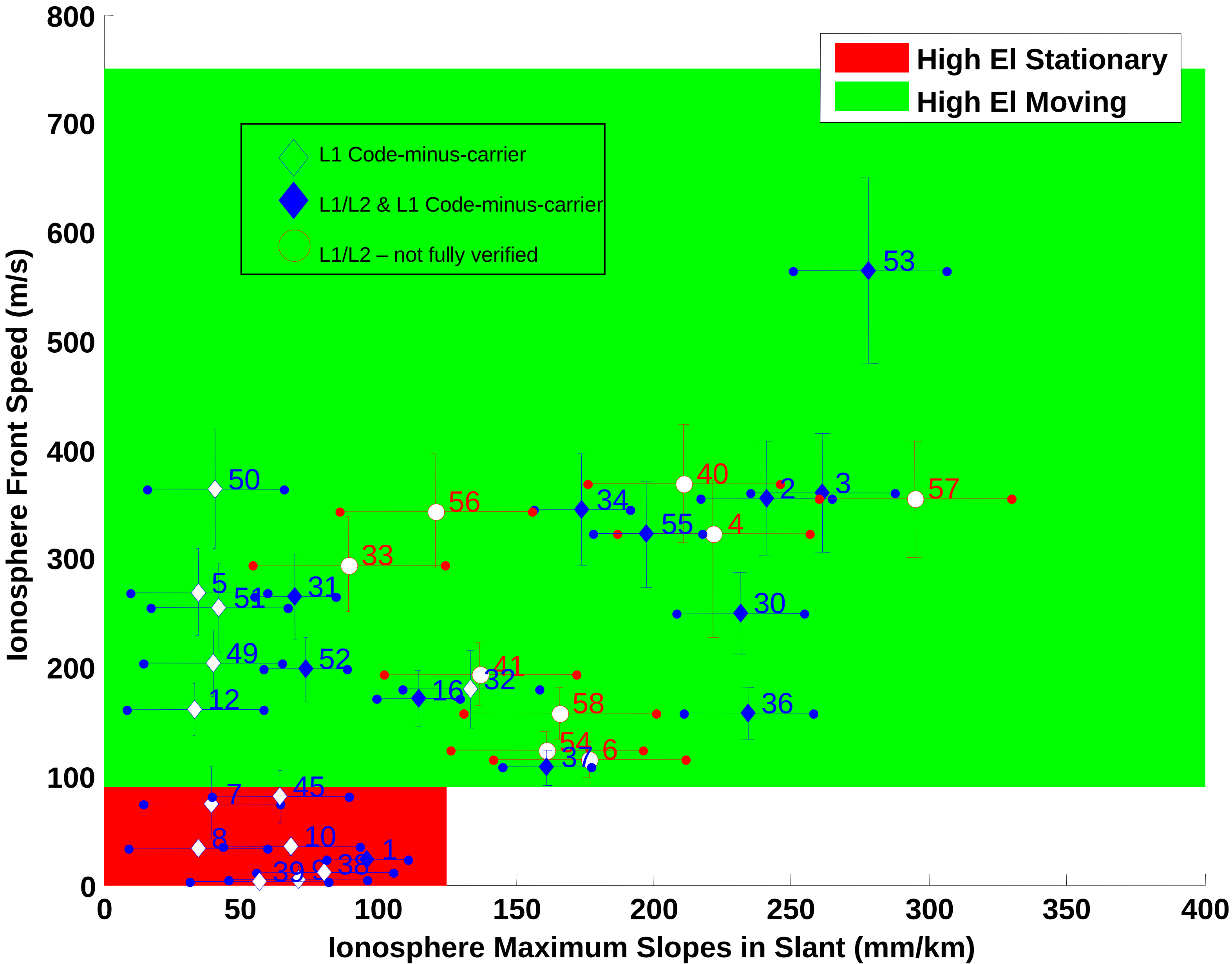
Summary of Current Ionosphere Threat Model Parameter Bounds (Revised)

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 ($\geq$ 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*

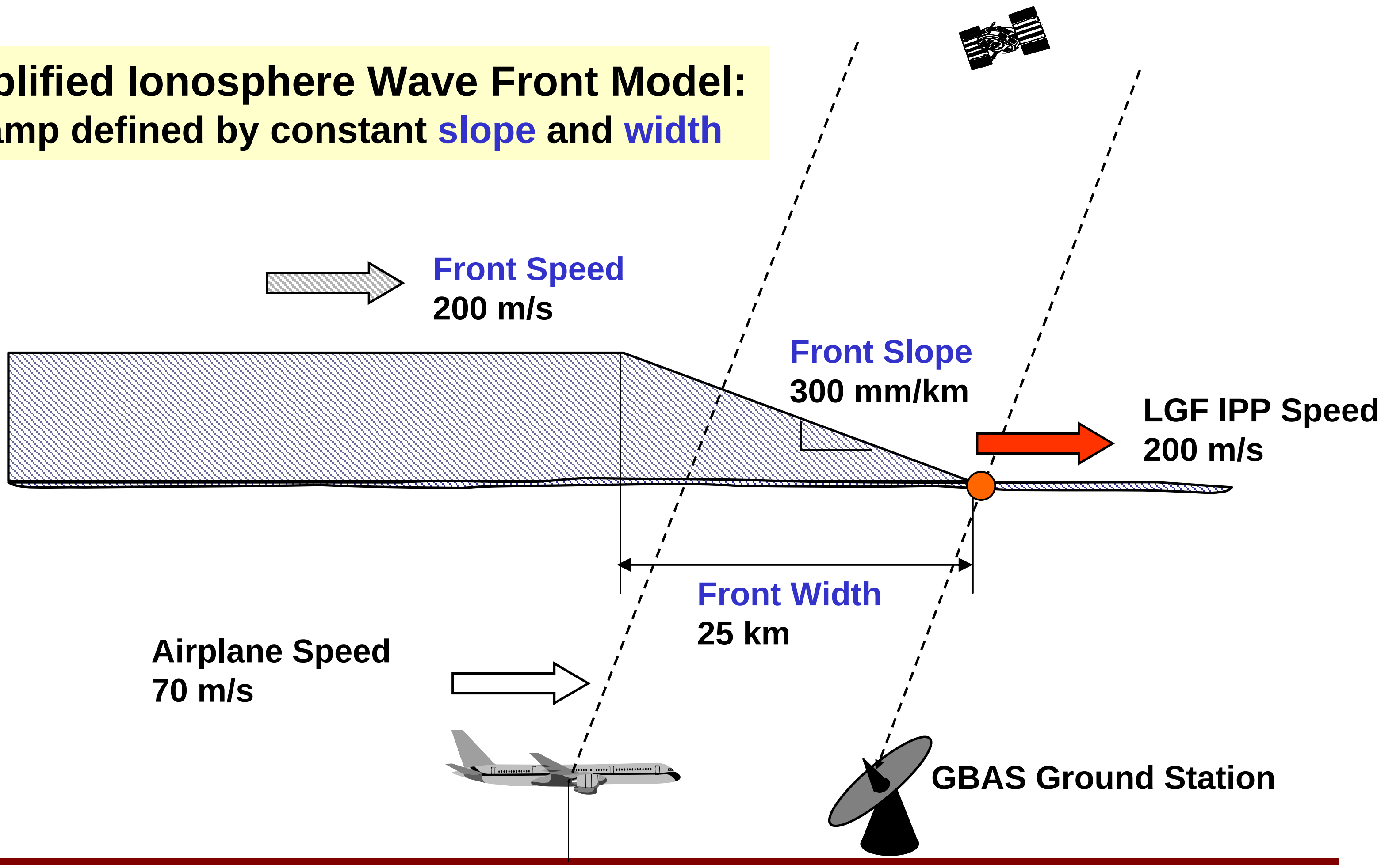
(†) *Max. gradient is linearly interpolated between 15 and 65^o elevation angles*

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



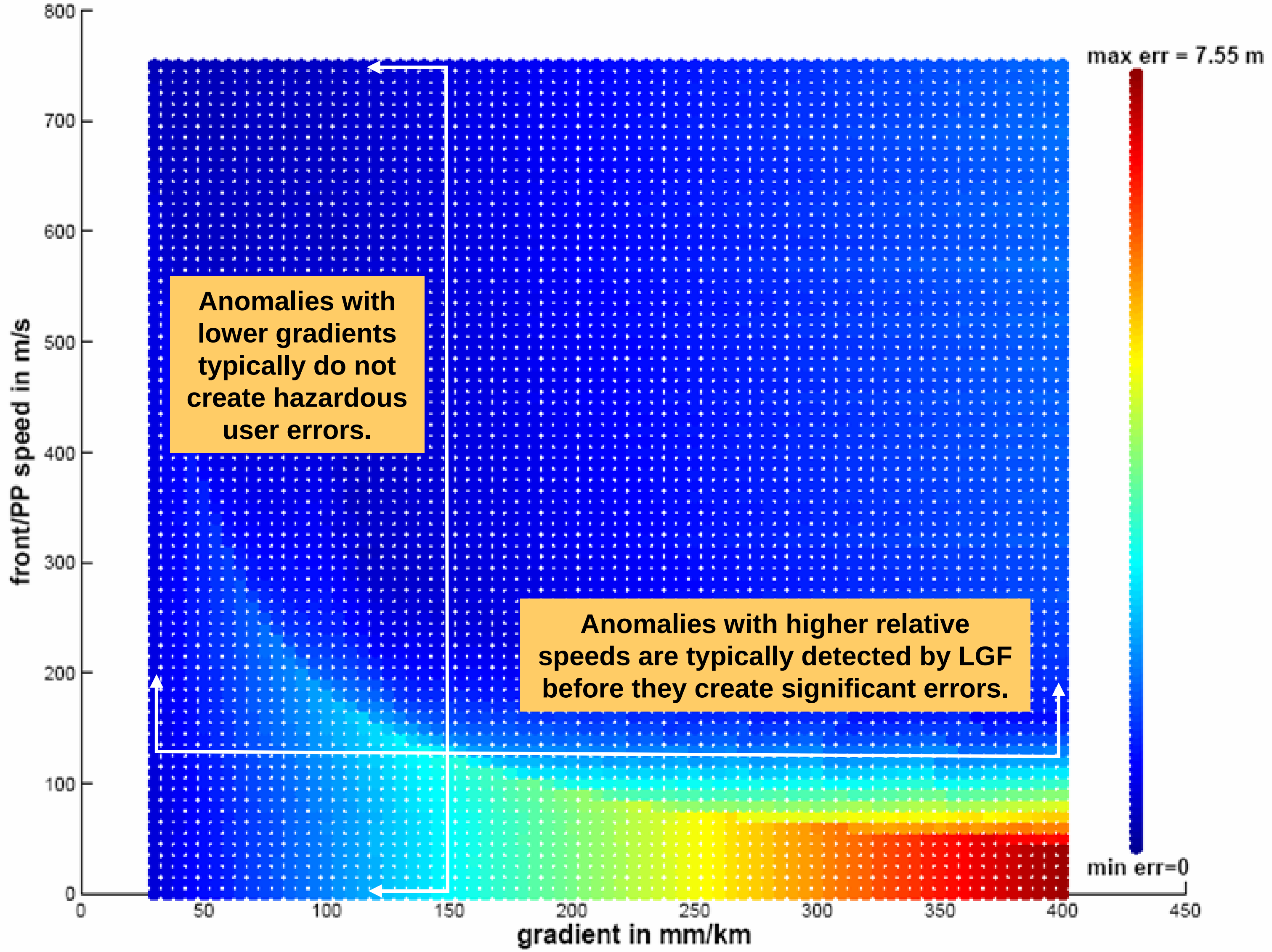
Ionosphere Anomaly Wave Front Model: *Potential Impact on a GBAS User*

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.
Estimated Range Error at DH: 300 mm/km × 19 km = 5.7 meters

Maximum Differential Range Error at Precision Approach Threshold (post-CCD Monitor)

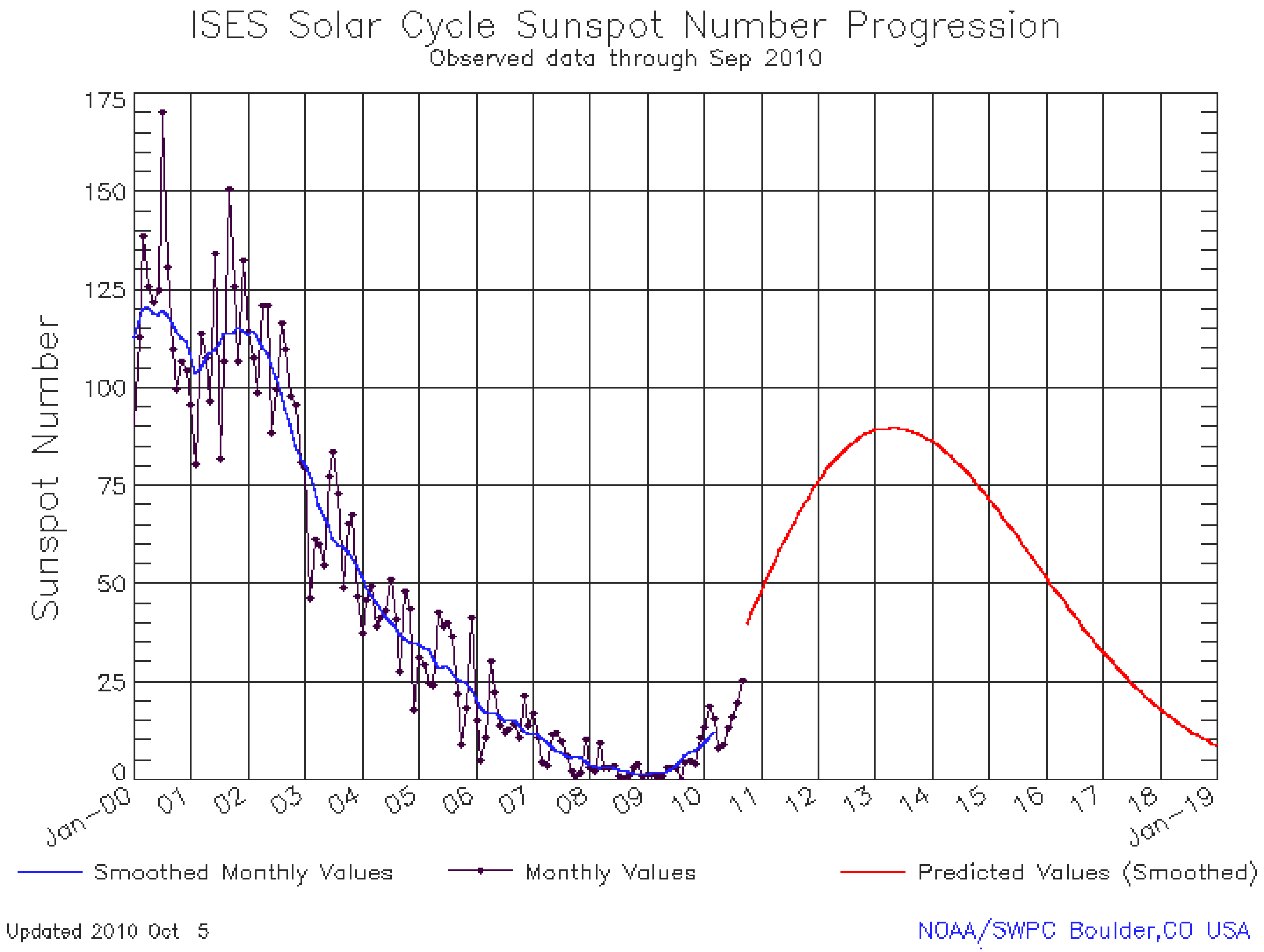


Creating a Threat Model for Outside CONUS

- Determine range of threats
  - Understand the physics of the events as much as possible
    - Depletions or bubbles (equatorial)
    - Polar scintillation and anomalies
    - Other storm events
- Identify data to be collected
  - A dense network of WAAS and CORS data was used in the US
    - Measurements are needed where more extreme activity is expected
      - Northern Latitudes and equatorial regional are more active
  - Ionospheric anomaly data must be identified
    - Typical performance data
    - Storm day performance
    - Sensitivity to the solar cycle

Solar Cycle Prediction

http://www.swpc.noaa.gov/SolarCycle/



Mitigating Ionospheric Anomalies

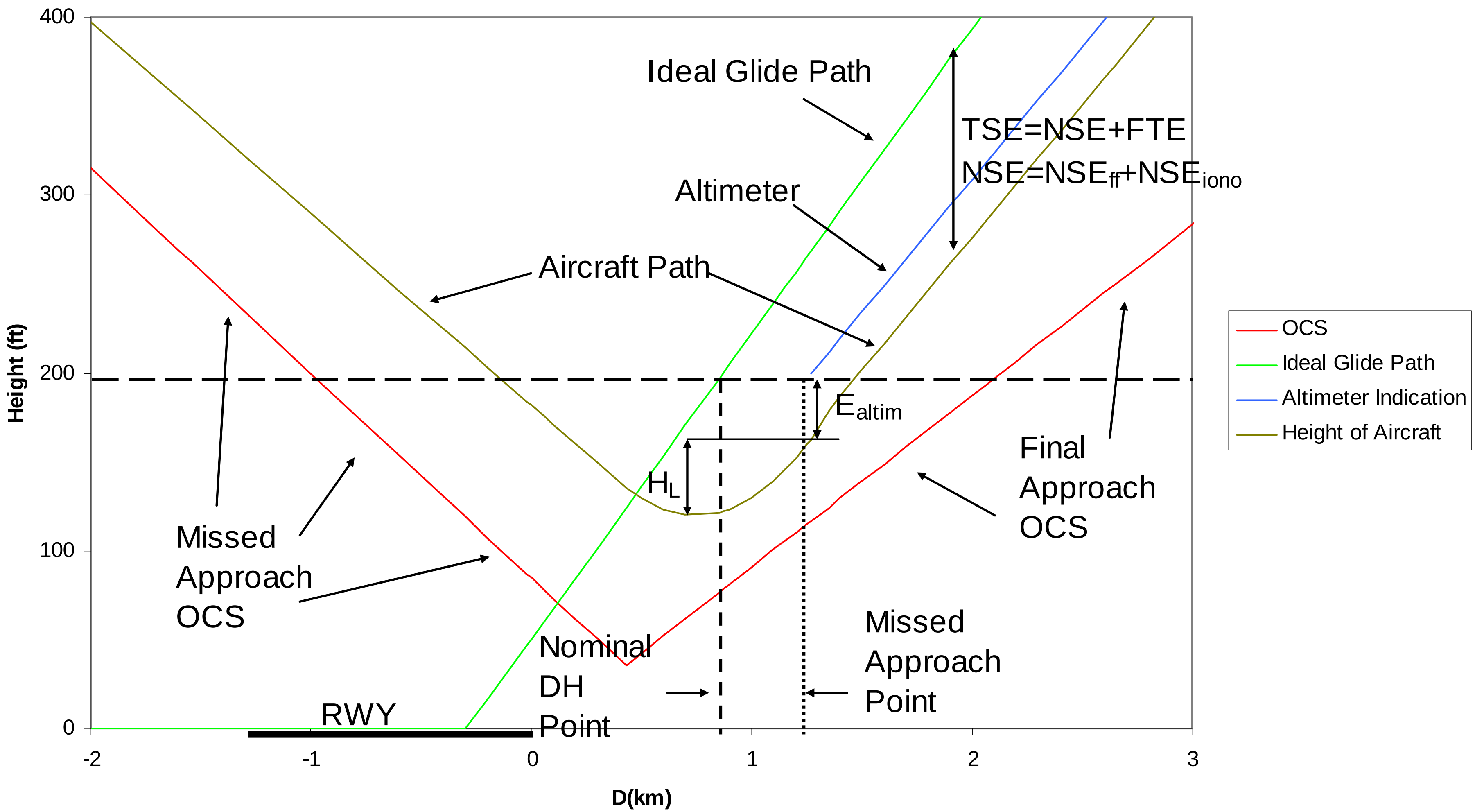
- Determine the maximum expected range error under the observed conditions
  - Use the threat model to describe the ionospheric anomaly conditions
  - Identify the user conditions in the threat environment
    - Aircraft speed and direction
    - Geometry of satellites used in the user solution
- Translate that error into user position error

Mitigating Ionospheric Anomalies

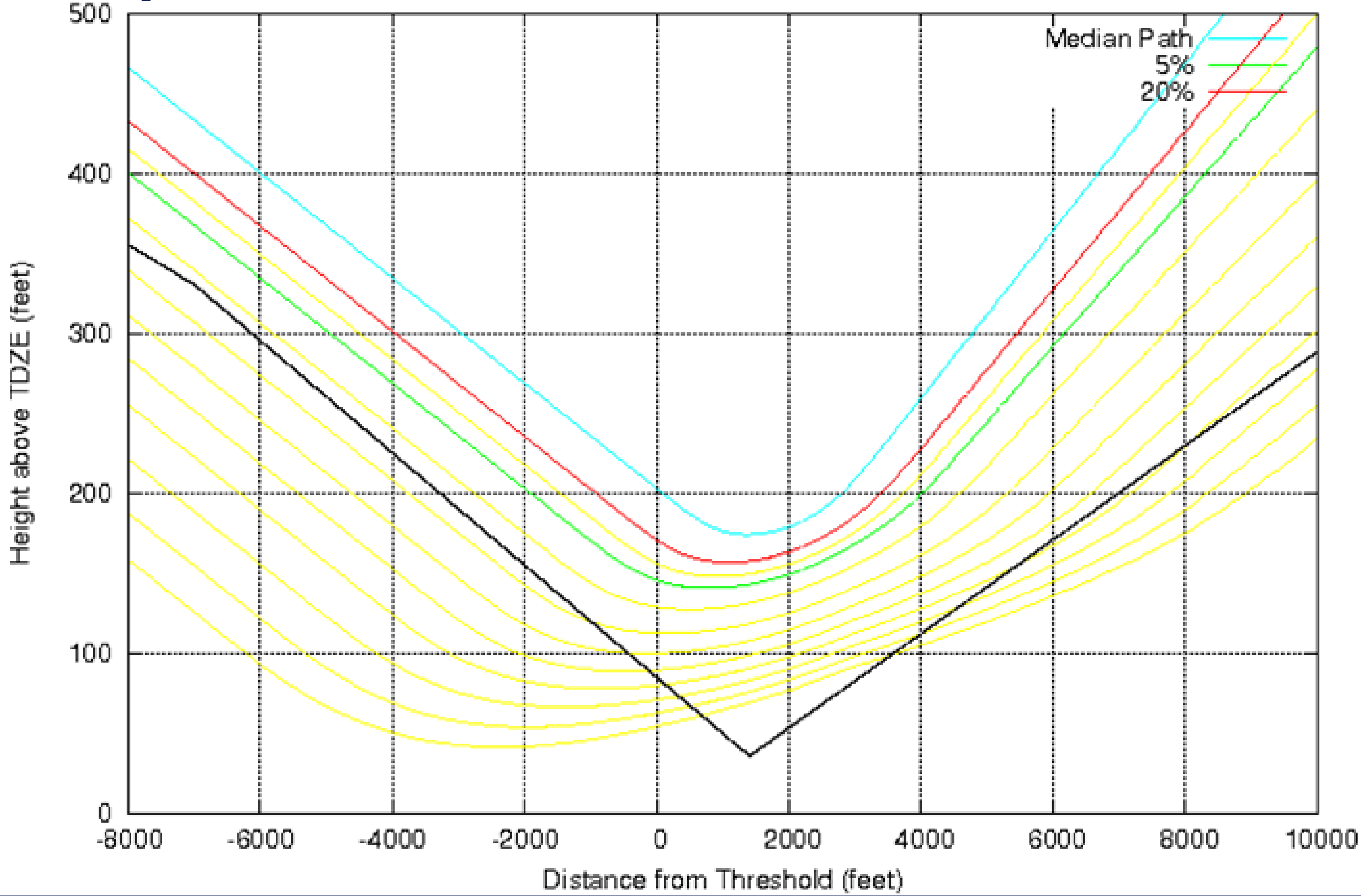
- Determine if that error is operationally acceptable
  - Weak user geometries translate into larger position errors
    - Geometries can be eliminated by inflating nominal GBAS broadcast integrity parameter
- SLS-4000 safety case examines the maximum ionospheric error induced vertical position offset and compares it to the obstacle clearance surface
- Eliminate geometries where that error can cause errors larger than operationally acceptable
  - Ground Facility requirement
  - Expected median value of this error was an important consideration in this analysis
    - What will the pilot see most (99.9%) of the time

Example Protection Surfaces

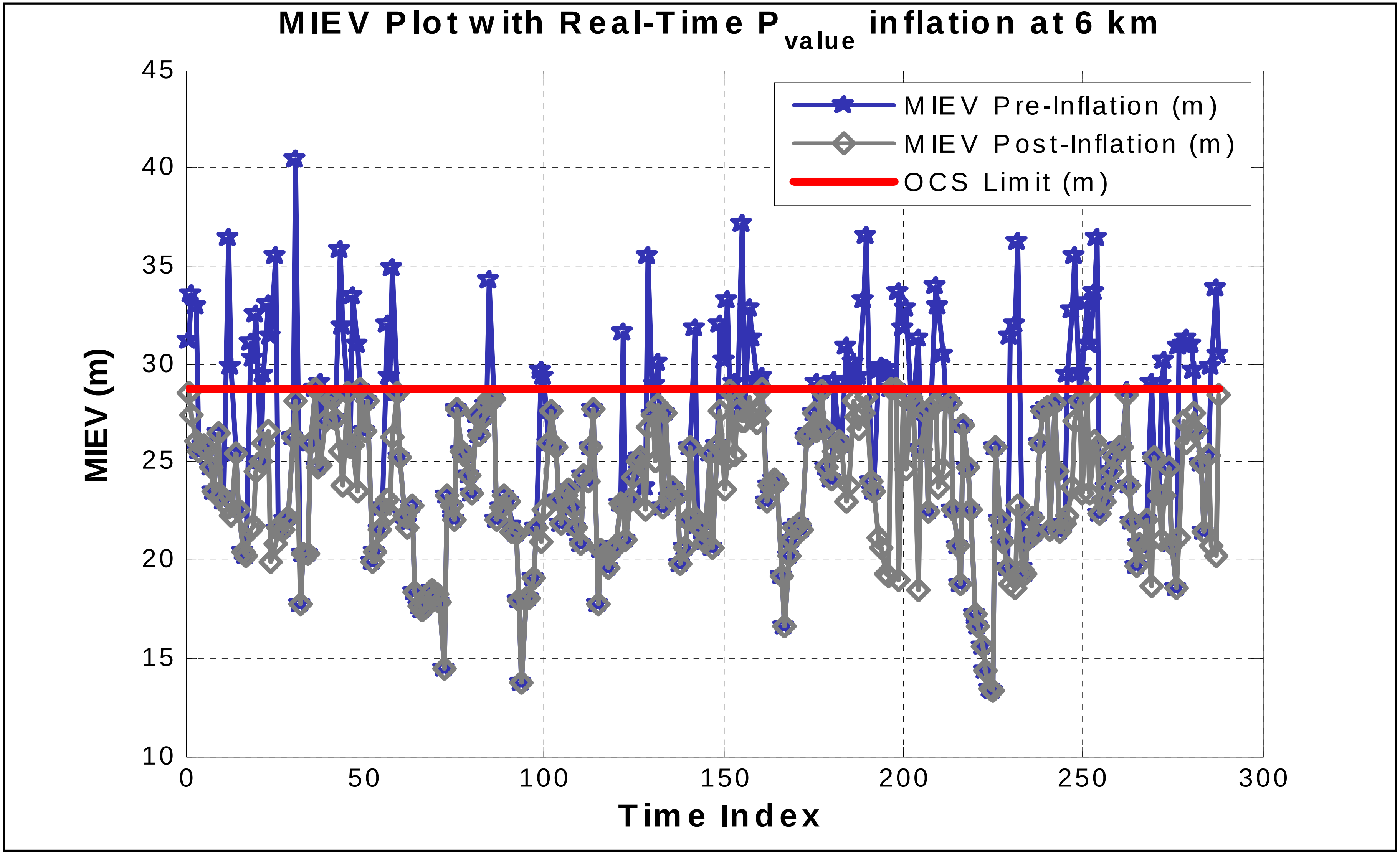
Reference Curt Shively, MITRE



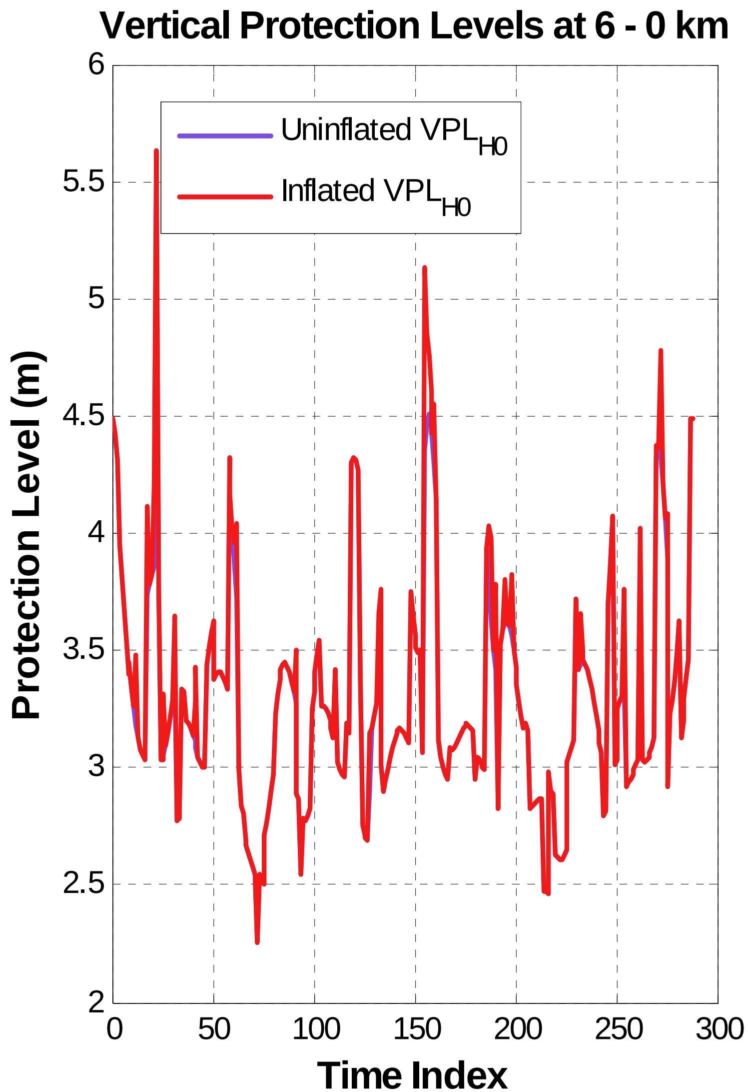
Range of User Positions Based on Maximum Ionospheric errors

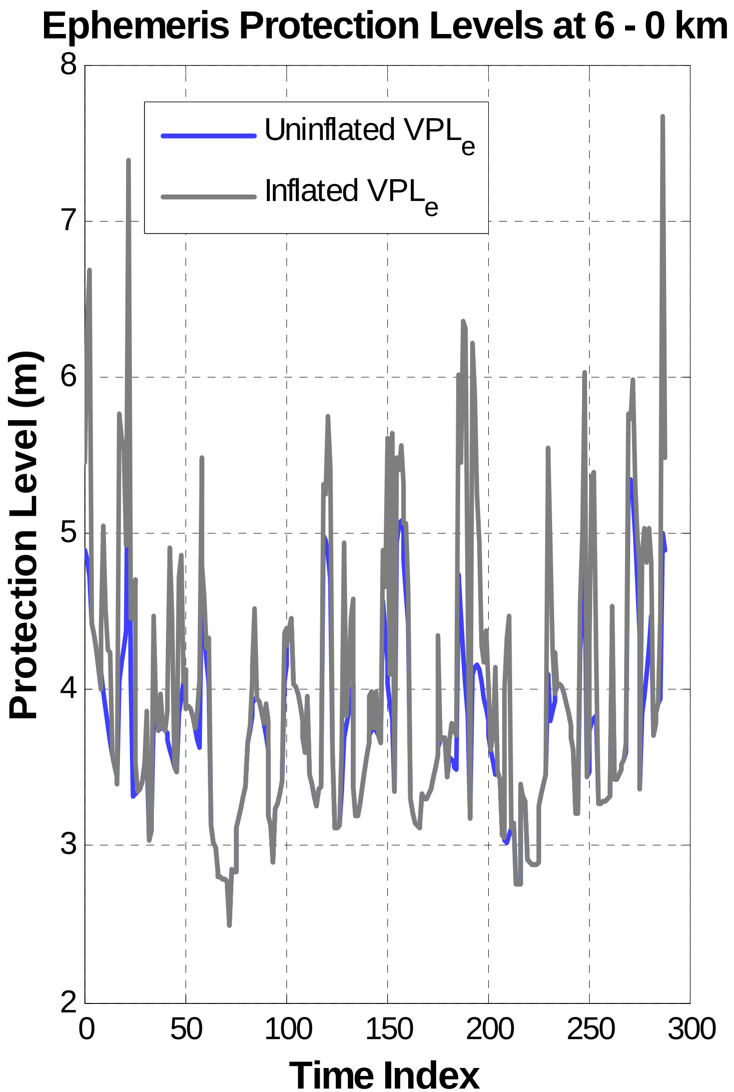


Stanford P-Value Inflation Results at Memphis Airport (RTCA 24-SV Constellation)



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

Nominal Ionospheric Divergence Parameter

- In addition to ionospheric storm bounding, the standard deviation of the nominal divergence must be determined
- The parameter was determined using data from non-storm, but "active" ionospheric days
  - Most days were well represented by 1mm/KM
  - Several days had divergence rates approaching 3-4mm/KM
  - Data included in the HMI document is used to justify a broadcast parameter of 4mm/KM for all CONUS

Summary

- Ionospheric requirements were discussed
  - Anomalous activity bounding will be clarified
- Ionospheric broadcast parameter determination and bounding requires the service provider to characterize the level of activity in the region of interest
  - Nominal divergence
  - Ionospheric storm activity
- Ionospheric error mitigation technique was described
  - Based on runway operational surfaces
  - Requires a siting restriction between the ground facility and the intended runway ends