ION GNSS 2011 TUTORIAL

Augmented GNSS: Fundamentals and Keys to Integrity and Continuity

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Outline

- Augmented GNSS Terminology
- Introduction to GNSS and GNSS Augmentation – Differential GNSS (DGNSS)
- GBAS and SBAS System Architectures
- Aviation Applications and Requirements
- Principles of Integrity and Continuity
- Specific Examples:
  - Nominal Error Bounding
  - Signal Deformation Monitoring
  - Ephemeris Monitoring
  - Ionospheric Anomaly Mitigation
- Summary

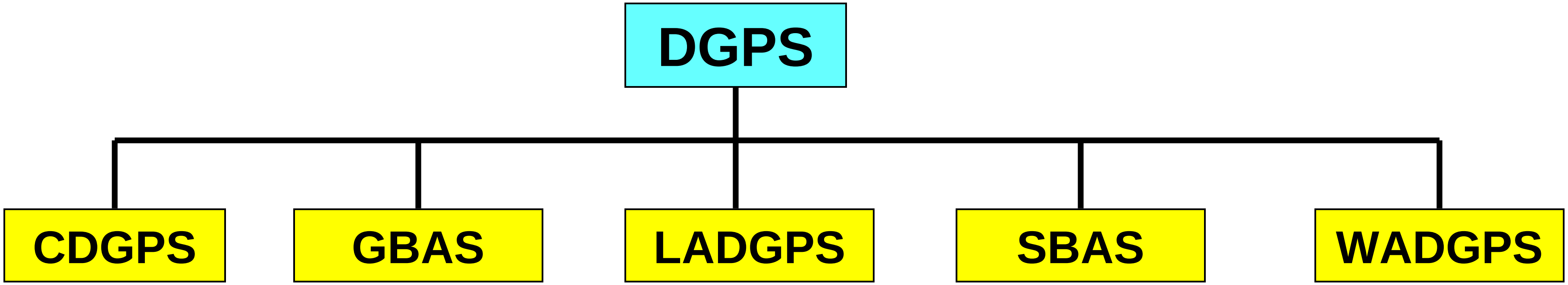
Augmented GNSS Terminology

- **GPS: Global Positioning System**
- **GNSS: Global Navigation Satellite Systems**

- **DGPS: Differential GPS (or GNSS)**
- **L(A)DGPS: Local-Area Differential GPS**
- **WADGPS: Wide-Area Differential GPS**
- **CDGPS: Carrier-Phase Differential GPS (usually a subset of Local-Area DGPS)**

- **LAAS: Local Area Augmentation System (FAA)**
- **GBAS: Ground-Based Augmentation System (international; includes LAAS)**
- **WAAS: Wide Area Augmentation System (FAA)**
- **SBAS: Space-Based Augmentation System (international; includes WAAS)**

Augmented GNSS Terminology (2)



DGPS

CDGPS

(aka "RTK")

- SB JPALS (US DOD)
- IBLS (with Pseudolites)
- Surveying
- Precision Farming
- Other cm-dm level apps

GBAS

- SLS-4000 LAAS (Honeywell)
- DGRS 610/ 615 (Thales)
- KIX GBAS (NEC, Japan)
- LCCS-A-2000 (NPPF Spectr, Russia)
- SELEX-SI GBAS

LADGPS

- LD JPALS (US DOD)
- ParkAir SCAT-I
- NDGPS (US Coast Guard)
- Commercial services
- Many other meter-level apps

SBAS

- WAAS (FAA, USA)
- EGNOS (ESA, Europe)
- MSAS (JCAB, Japan)
- GAGAN (India)
- SNAS (China)

WADGPS

- WAGE (GPS Wing, DOD)
- OmniSTAR (Trimble)
- StarFire (NavCom)
- Other commercial services

Augmented GNSS Classifications

Global Category ***(ICAO SARPS)***	**GBAS**	**SBAS**
National Program ***(e.g., FAA; RTCA Standards for U.S.)***	**LAAS**	**WAAS** **EGNOS** **MSAS** **etc.**
Contractor Systems	**Honeywell SLS-4000** **Thales DGRS-615** **KIX GBAS** **etc.**	**Raytheon** **Thales Alenia** **NEC/Raytheon** **etc.**

Aviation GNSS Terminology

- **ICAO:** **International Civil Aviation Organization**
- **SARPS:** **Standards and Recommended Practices (ICAO Requirements)**
- **MASPS:** **Minimum Acceptable System Performance Standards (sys. arch.)**
- **MOPS:** **Minimum Operational Performance Standards (user avionics)**
- **ICD:** **Interface Control Document**

Used by RTCA

- **NPA:** **Non-Precision Approach (2-D horizontal)**
- **LNAV/VNAV:** **Lateral/Vertical Navigation Approach**
- **LPV:** **Lateral Position Vertical Approach**
- **CAT-I** **Category I Precision Approach (200 ft DH)**
- **CAT-II** **Category II Precision Approach (100 ft DH)**
- **CAT-III** **Category III Precision Approach (0-50 ft DH)**

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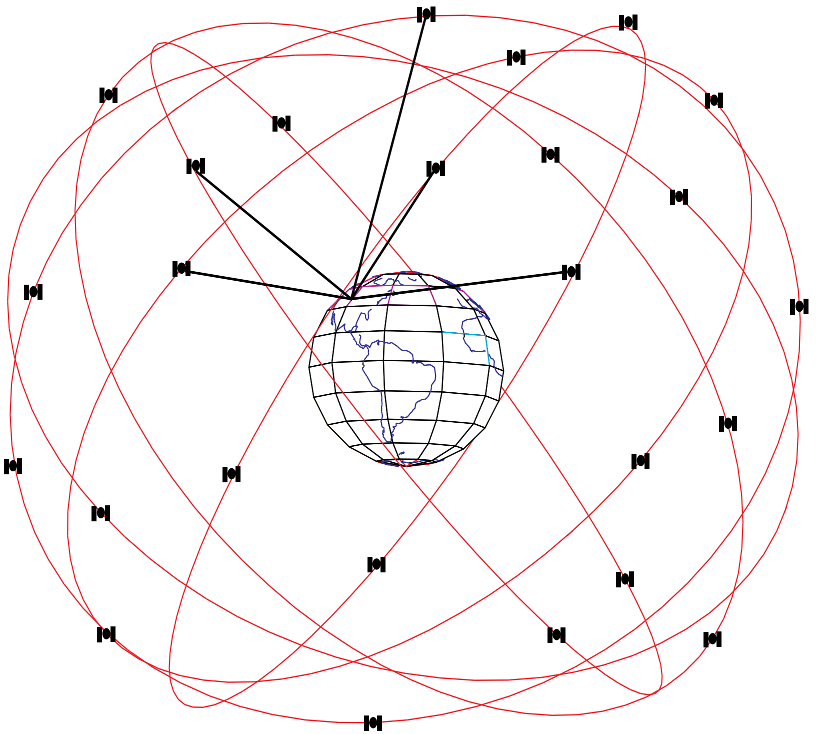
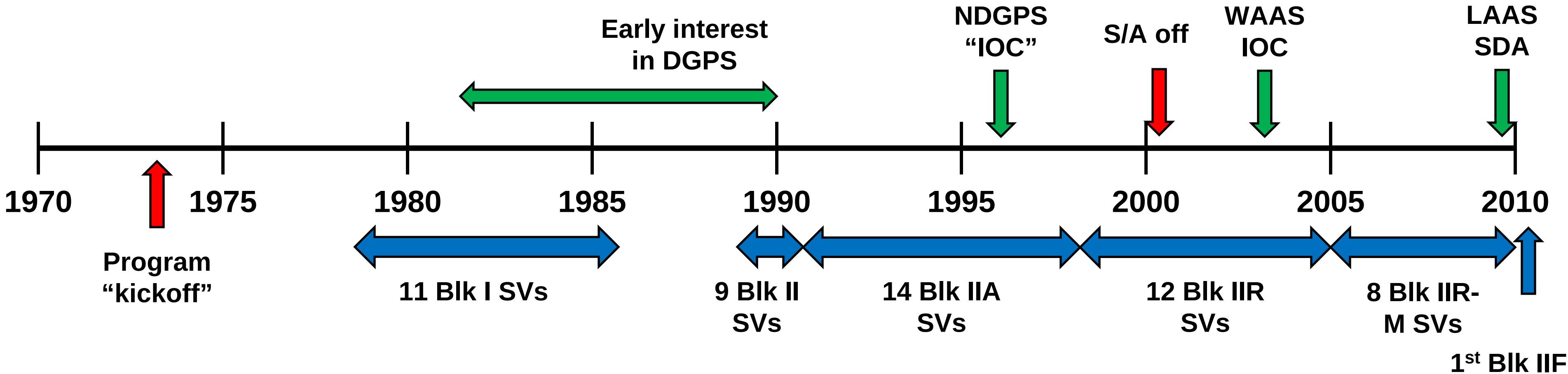
The Evolution of GPS



- 24+ Satellites since FOC in 1995 (space vehicles, or SVs)
- 6 orbit planes, 60 degrees apart
- 55 degrees inclination
- 12-hour (11 hr, 58 min) orbits
- 26,560 km from earth’s center
- 20,182 km mean altitude
- moving ~ 2.7 km/sec



Early interest in DGPS

NDGPS “IOC”

S/A off

WAAS IOC

LAAS SDA

1970 1975 1980 1985 1990 1995 2000 2005 2010

Program “kickoff”

11 Blk I SVs

9 Blk II SVs

14 Blk IIA SVs

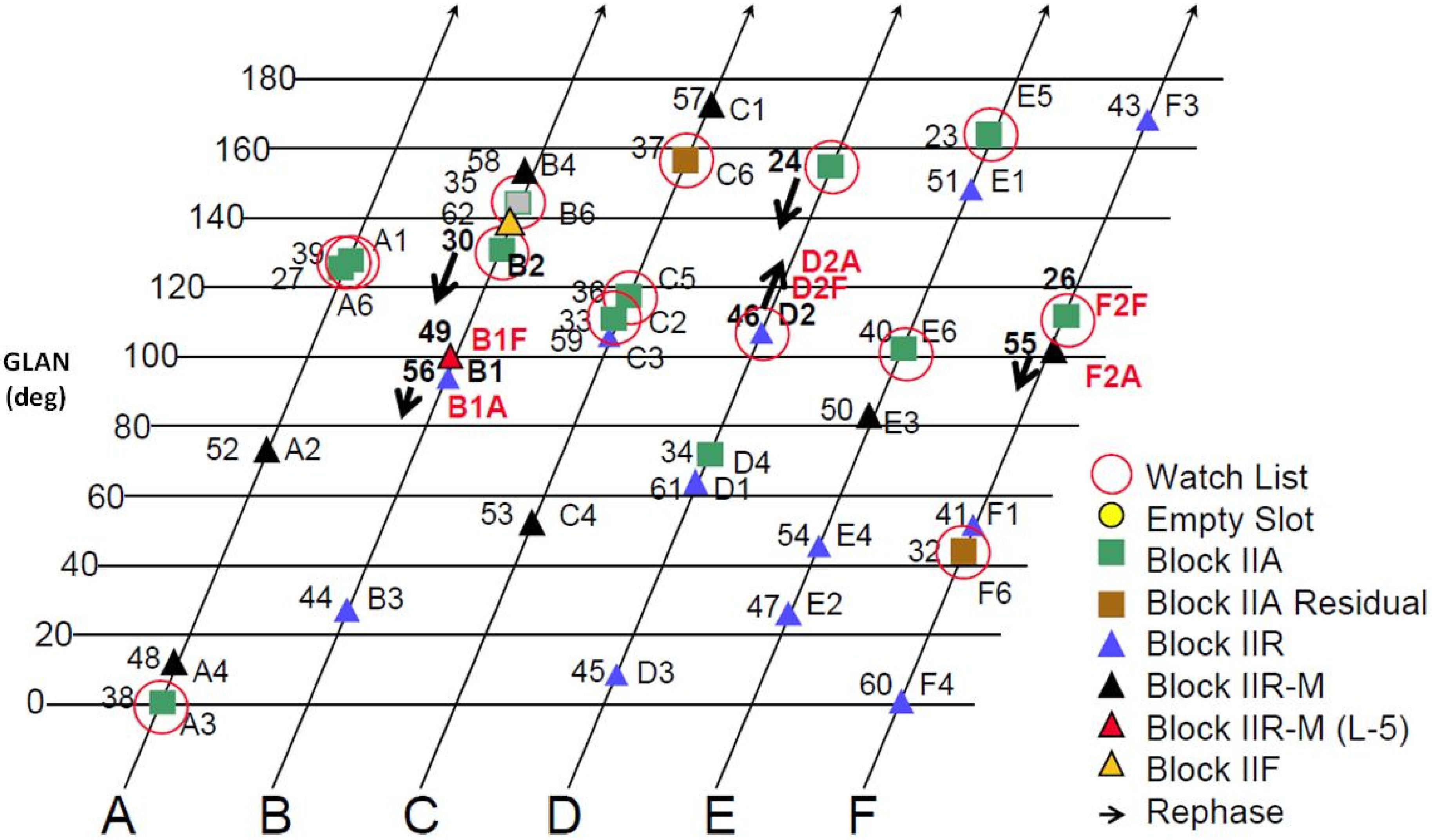
12 Blk IIR SVs

8 Blk IIR-M SVs

1st Blk IIF

The GPS Space Segment
(as of Sept. 2010)

***Source*: Lt. Col M. Manor, "GPS Status (Const. Brief)," CGSIC, Sept. 2010**



The GPS Ground Segment Today

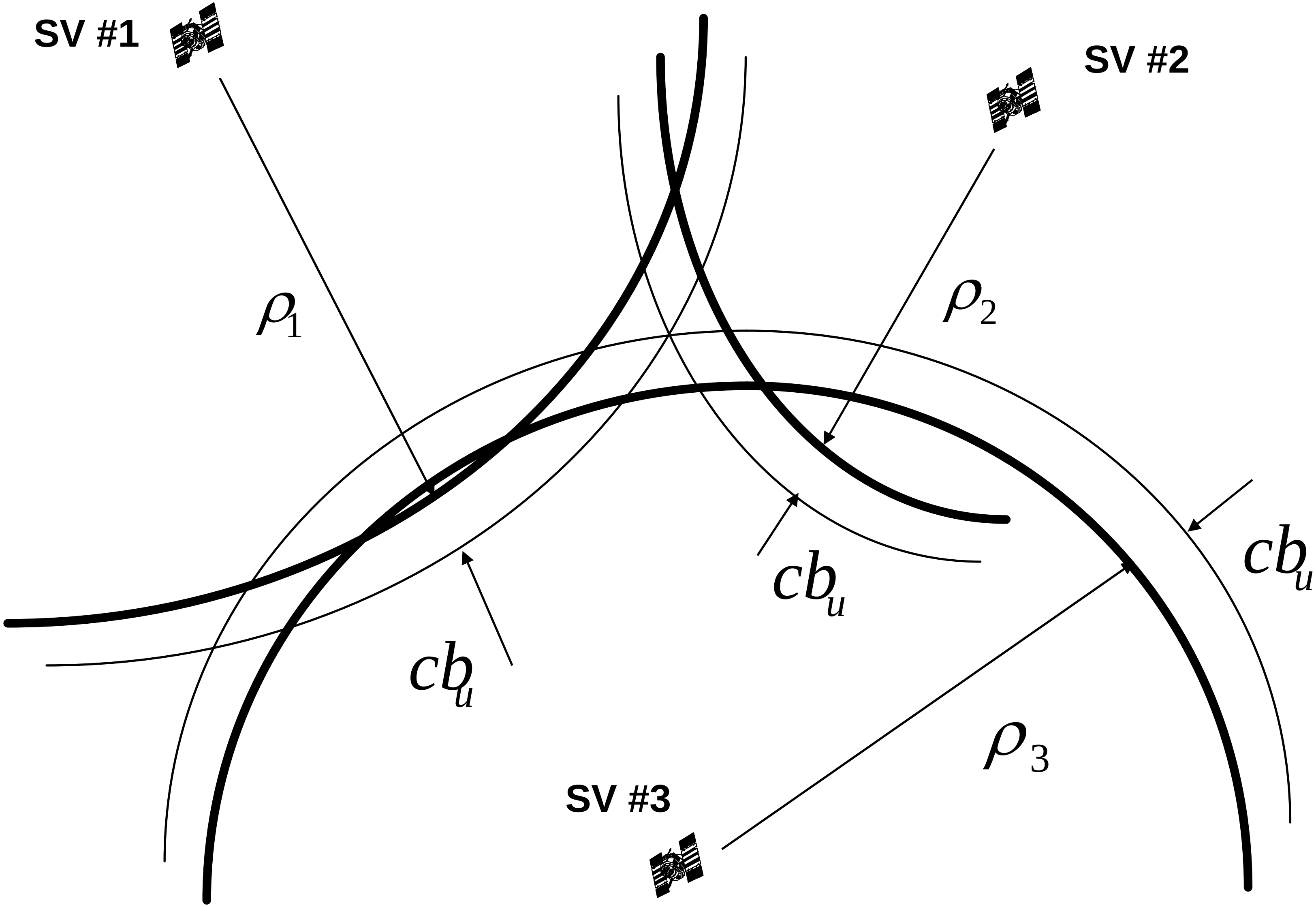
***Source*: Col. B. Gruber, “GPS Mod. & Prog. Upd.,” Munich SatNav Summit, March 2011**

🟧 MCS at Schriever AFB, CO
& Alternate MCS at VAFB

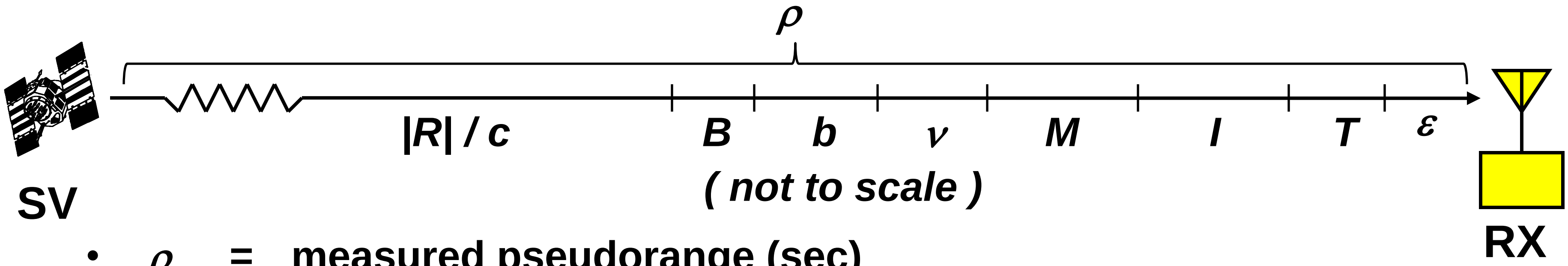
● 16 Monitor Stations
6 OCS + 10 NGA

▲ ▲ 12 Ground Antennas
● 4 GPS + 8 AFSCN

GPS Measurements: "Pseudoranging"



Elements of a Pseudorange

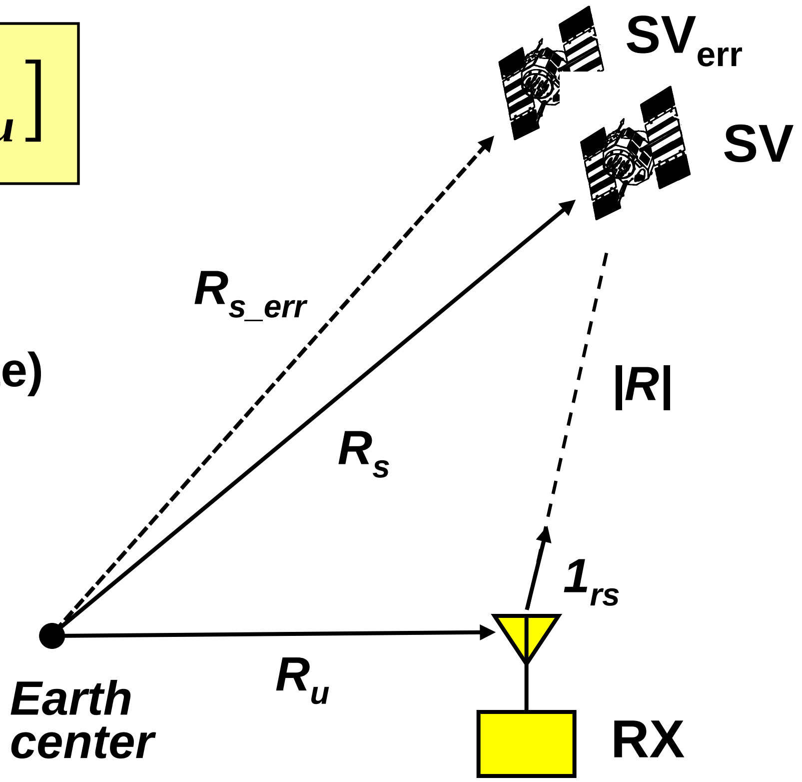


- ρ = **measured pseudorange (sec)**
- c = **speed of light in vacuum ≅ 3 × 10^8 m/s**
- $|R|$ = **true (geometric) range from RX to SV (m)**
- B = **SV clock error (previously included S/A) (sec)**
- b = **RX clock error (sec)**
- ν = **RX noise error (sec)**
- M = **RX multipath error (sec)**
- I = **Ionospheric delay at RX location (sec)**
- T = **Tropospheric delay at RX location (sec)**
- ε = **other receiver errors (sec)**

True Range and Ephemeris Error

$$\left|R\right| = \left|R_s - R_u\right| = 1_{rs} \bullet \left[R_s - R_u\right]$$

- R = true vector from RX to SV ($\equiv R_{rs}$)
- 1_{rs} = true unit vector along R ($1'$ = estimate)
- R_s = true vector from Earth center to SV
- R_u = true vector from Earth center to RX



- R_s' (estimate of R_s) derived from broadcast navigation data (ephemeris messages)
- R_u' (estimate of R_u) is derived from estimated user position improved by iteration during position determination (meter-level accuracy not needed)
- *What is the impact of errors in R_s? (Come back to this later…)*

"Corrected" Pseudorange and Position Solution

$$\boxed{\rho_c = \rho + c\,B_{est} - c\,(T_{est} + I_{est})}$$

- ρ_c = "corrected" pseudorange measurement (sec)
- B_{est} = SV clock error correction from navigation data (m)
- I_{est} = ionospheric error correction based on Klobuchar model with parameters included in navigation data (m)
- T_{est} = tropospheric error correction based on external meteorology model (temp., pressure, humidity inputs) (m)

Iterate and Linearize: $x = x_0 + \delta x$ $b = b_0 + \delta b$ $\delta X \equiv [\,\delta x \;\; \delta b\,]^T$

$$\boxed{\delta\rho_c = G\,\delta X + \xi_\rho}$$

where

$$G = \begin{bmatrix} -1'^{T}_{rs\_1} & 1 \\ -1'^{T}_{rs\_2} & 1 \\ \vdots & \vdots \\ -1'^{T}_{rs\_N} & 1 \end{bmatrix}$$

$$\Downarrow$$

$$\boxed{\delta X_{est} = (G^T W G)^{-1} G^T W \,\delta\rho_c}$$

$$W \equiv \text{diag}\,[\,w_1, w_2, \ldots, w_N\,]$$

(default: $w_1 = w_2 = \ldots = w_N = 1$)

Range-Domain Error Breakdown

- **Examine pseudorange error relative to "perfect" range, meaning range to true satellite position:**

$$\rho_{err} \equiv c\,(-\Delta B + \Delta b + \Delta T + \Delta I + C) + \Delta A\,(S - U) + A\,\Delta S$$

- ρ_{err} ≡ **pseudorange error relative to perfect range**
- ΔY = **residual error in (generic) vector/matrix *Y* after applying correction or broadcast information (sec)**
- C ≡ $M + \nu + \varepsilon$ **(sum of uncorrected receiver errors) (m)**

$$A_{(N\times 3N)} = \begin{bmatrix} -\mathbf{1}'^{T}_{s\_1} & 0 & 0 & 0 \\ 0 & -\mathbf{1}'^{T}_{s\_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & -\mathbf{1}'^{T}_{s\_N} \end{bmatrix} \qquad S_{(3N\times 1)} = \begin{bmatrix} R_{s1}' \\ R_{s2}' \\ \vdots \\ R_{sN}' \end{bmatrix} \qquad U_{(3N\times 1)} = \begin{bmatrix} R_{u1} \\ R_{u2} \\ \vdots \\ R_{uN} \end{bmatrix}$$

$$\Delta X_{est} = (G^T W G)^{-1} G^T W \rho_{err}$$

“Dilution of Precision” (DOP)

- A very useful (if imprecise) result comes from taking an idealized covariance of the position state error estimate ΔX_{est} from the previous slide
- For default weighting matrix ($W = I_{NxN}$) and case where ρ_{err} for each satellite is zero-mean and i.i.d.:

$$\text{Cov}\,(\Delta X_{est}) = (\,G^T G\,)^{-1}\,\text{Cov}\,(\rho_{err}\,) = (\,G^T G\,)^{-1}\,\sigma_\rho^{\,2}$$

  - Where $\sigma_\rho^{\,2}$ = variance of i.i.d., zero-mean pseudorange error

$$H_{(N\times N)} \equiv \left(G^T G\right)^{-1} \equiv \left.\begin{bmatrix} XDOP^2 & \bullet & \bullet & \bullet \\ \bullet & YDOP^2 & \bullet & \bullet \\ \bullet & \bullet & VDOP^2 & \bullet \\ \bullet & \bullet & \bullet & TDOP^2 \end{bmatrix}\right\}$$

Only a function of SV geometry

$$HDOP^2 \equiv XDOP^2 + YDOP^2 \qquad PDOP^2 \equiv XDOP^2 + YDOP^2 + VDOP^2$$

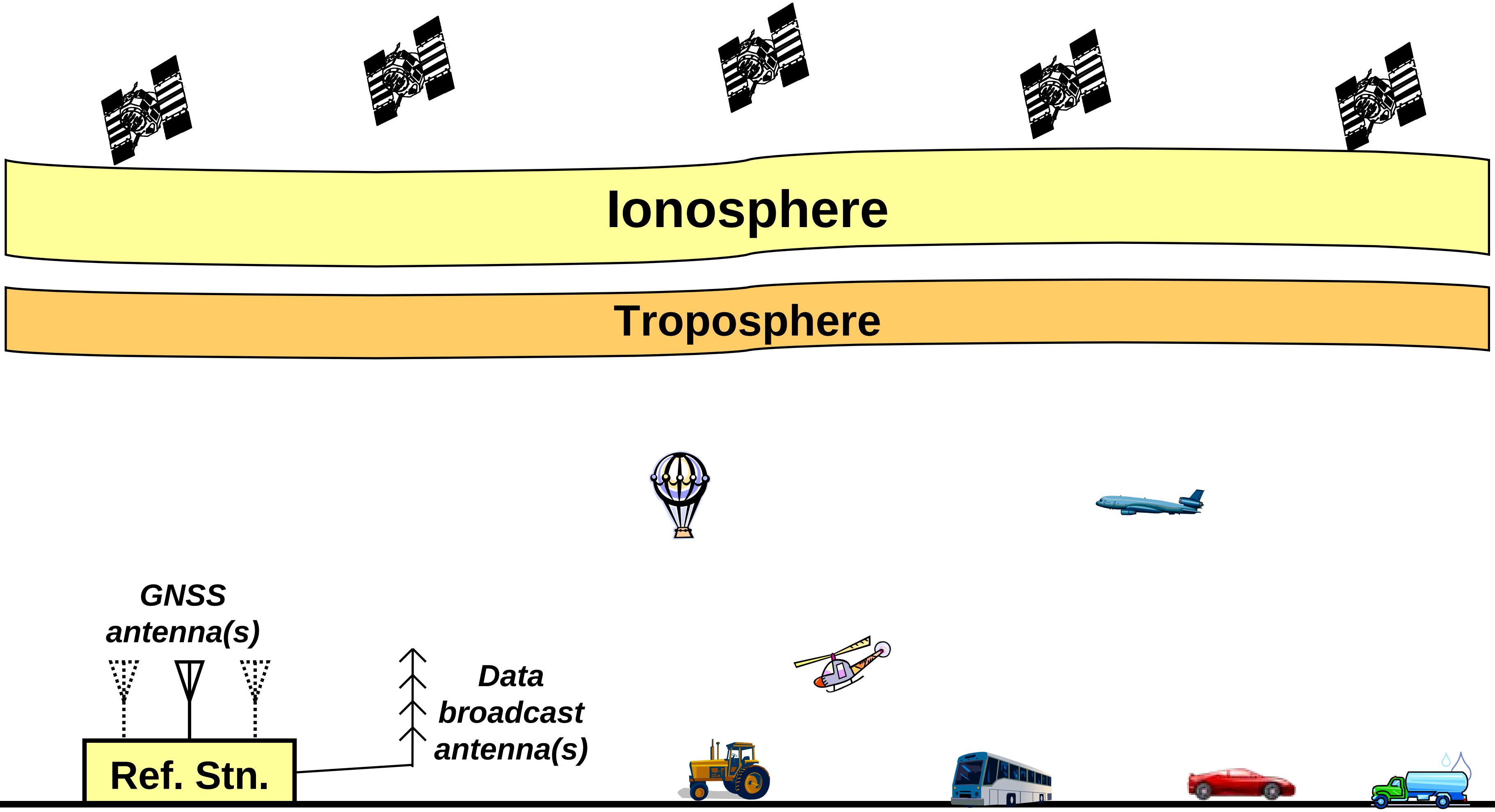
$$GDOP^2 \equiv XDOP^2 + YDOP^2 + VDOP^2 + TDOP^2$$

The Usefulness of DOP

- **(Unweighted) DOP separates the two primary sources of GNSS errors:**
    1. **Errors in ranging measurements**
    2. **Impact of satellite geometry**
- **Differential GNSS primarily addresses the first error source by eliminating common-mode range errors.**
    - **One exception in SBAS: additional ranging measurements from GEO satellites**
- **GNSS modernization addresses both error sources, but the second one is typically of more benefit to differential GNSS users.**

Local Area DGNSS: The Basic Concept

- **Exploit the spatial and temporal correlation of several GNSS error sources to (mostly) remove them from user range measurements.**



Ionosphere

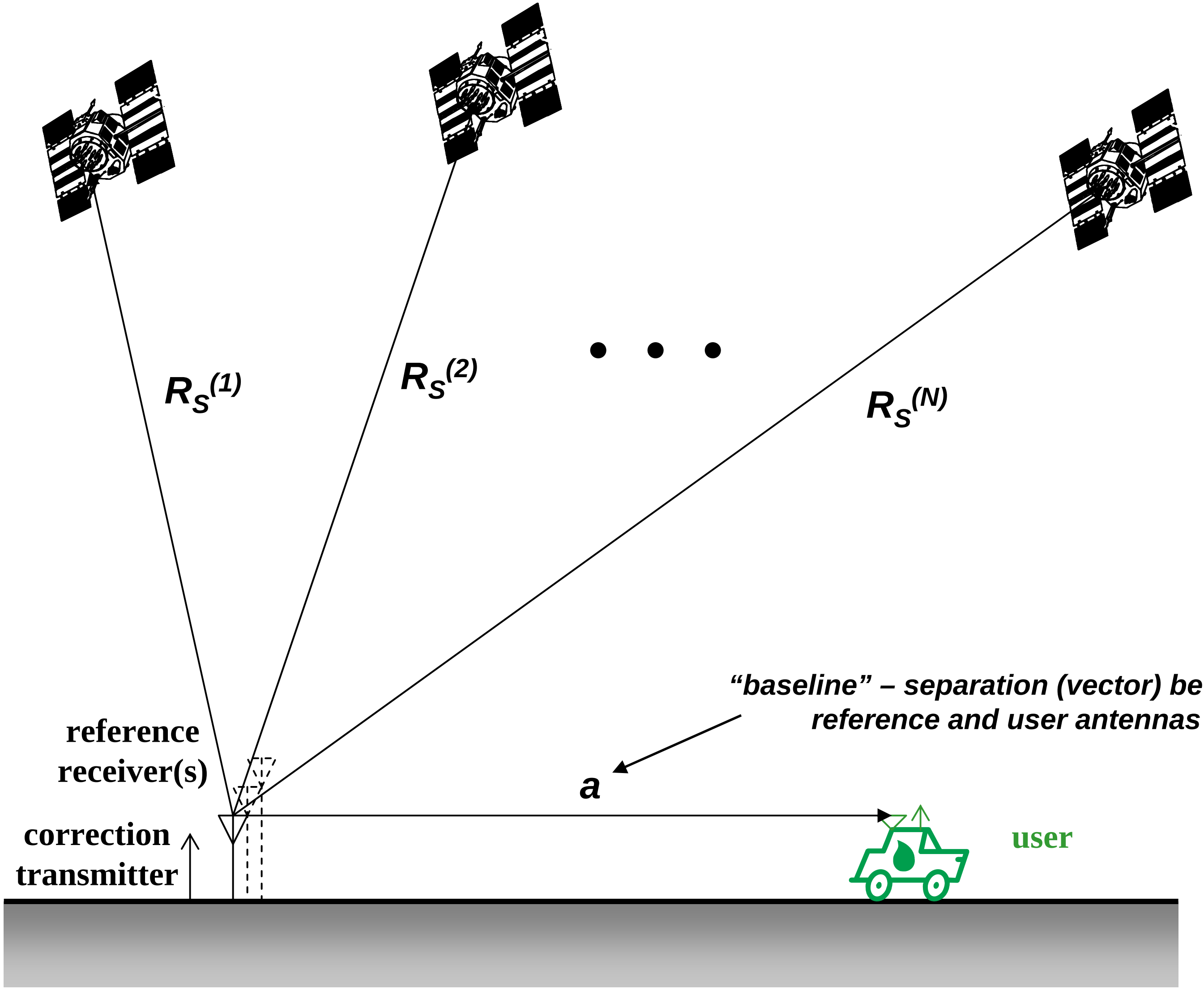
Troposphere

GNSS antenna(s)

Data broadcast antenna(s)

Ref. Stn.

Local Area DGNSS: The Basic Concept (2)



"baseline" – separation (vector) between reference and user antennas

GPS Range Error Sources

Error Source	Approx. 1Π Error for Standalone GPS Users	Approx. 1Π Error for LADGPS Users (*a* = 50 km)
SV Clock	**1 – 2 m**	**Π2 – 3 cm**
SV Ephemeris	**1 – 3 m**	**1 – 5 cm**
Troposphere	**2 – 3 m (uncorrected) 0.1 – 0.5 m (corrected by atmospheric model)**	**1 – 5 cm**
Ionosphere	**1 – 7 m (corrected by Klobuchar model)**	**10 – 30 cm**
Multipath (ref. and user receivers)	**PR: 0.5 – 2 m(*) Π: 0.5 – 1.5 cm**	**PR: 0.5 – 2 m(*) Π: 0.5 – 1.5 cm**
Receiver noise (ref. and user receivers)	**PR: 0.2 – 0.35 m(†) Π: 0.2 – 0.5 cm**	**PR: 0.2 – 0.35 m(†) Π: 0.2 – 0.5 cm**
Antenna survey error/motion	**N/A**	**0.2 – 1 cm**

Ref. – User Correlation

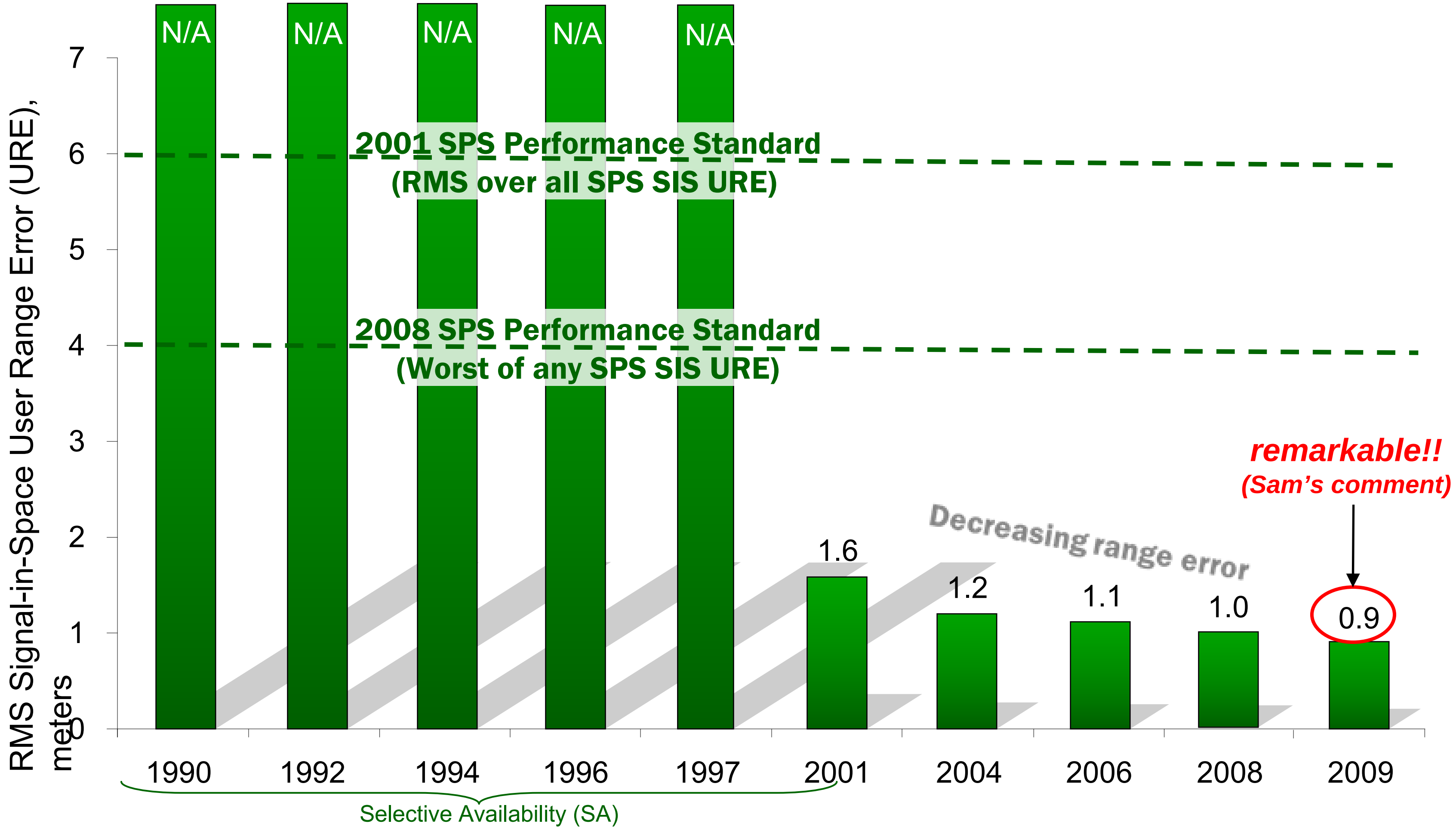
(*) In obstructed scenarios with many large reflectors, multipath errors can be significantly larger.

(†) This number represents "raw" PR noise, prior to any carrier smoothing.

GPS (SPS) SIS Error Reduction

***Source*: Lt. Col S. Steiner, “GPS Program Update,” CGSIC, Sept. 2010**

SIS URE: Signal-in-Space contribution to User Range Error (combined SV clock and ephemeris error)



remarkable!!
(Sam’s comment)

Errors Sensitivity to Satellite Geometry

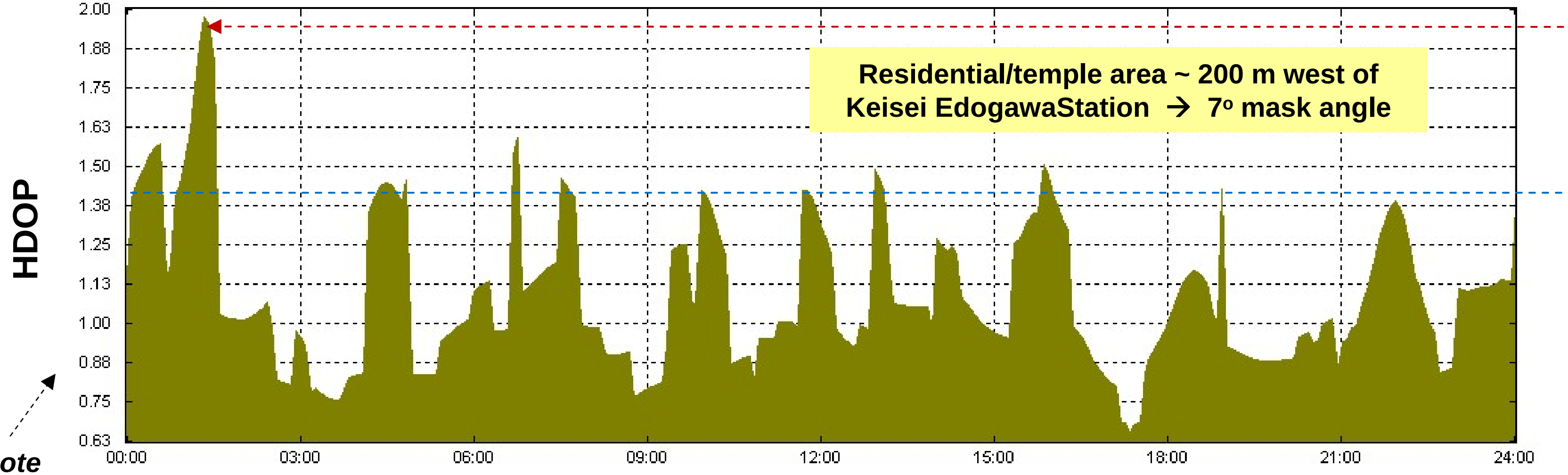
- **Under nominal conditions, GPS satellite geometry quality (as approximated by DOP) varies more than ranging errors and thus drives user accuracy**

- **Examine variability of 2-D horizontal DOP (HDOP) over one repeatable day of GPS geometries at a typical mid-latitude location**

- **Use "off-the-shelf" (and highly recommended) Trimble Planning Software (version 2.9 for Windows)**
  - **used to help schedule observations for periods of "good" satellite geometry**
  - **http://www.trimble.com/planningsoftware.shtml**

Typical Horizontal DOPs in Tokyo

***Lat*: 35.737º N *Long*: 139.895º E *Altitude*: 100 m**



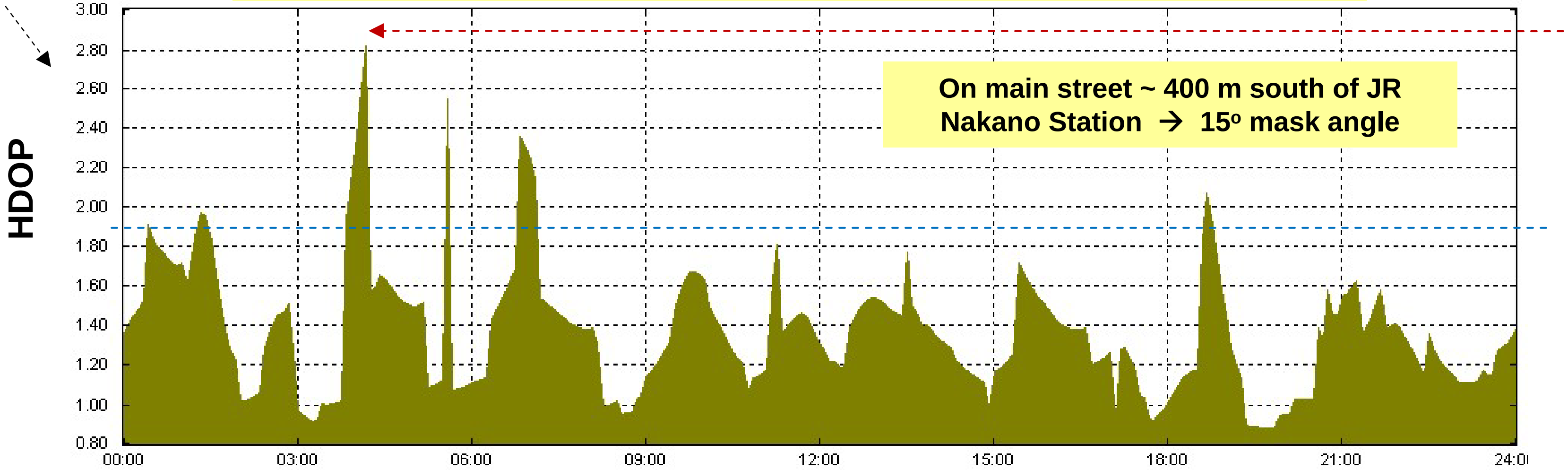
Residential/temple area ~ 200 m west of Keisei EdogawaStation → 7º mask angle

Max. ~ 1.98

Most < 1.4

Note change of scale

***Lat*: 35.703º N *Long*: 139.6655º E *Altitude*: 100 m**



On main street ~ 400 m south of JR Nakano Station → 15º mask angle

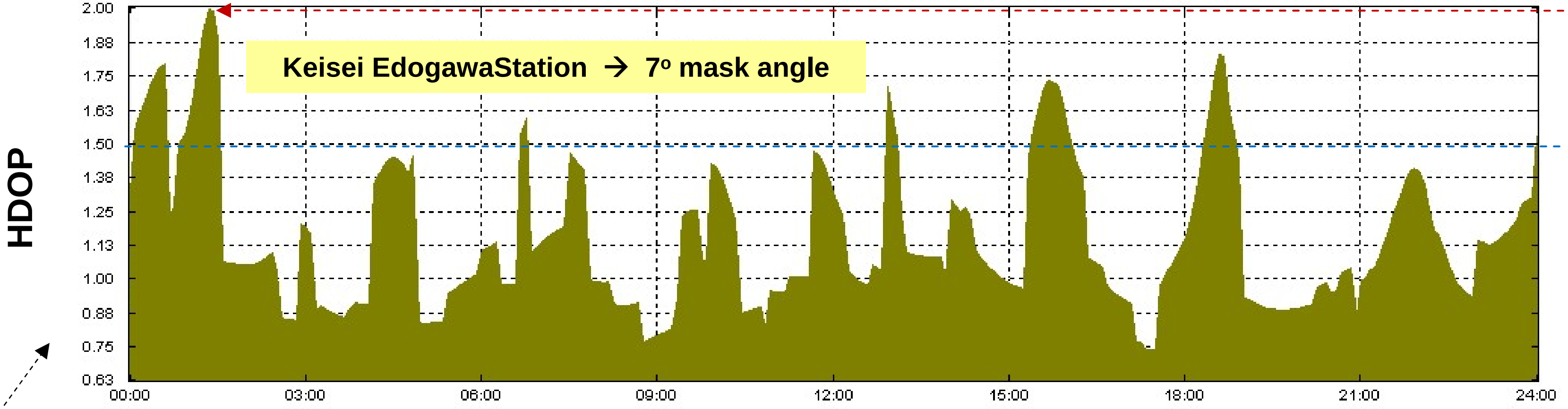
Max. ~ 2.8

Most < 1.8

Local Time (from midnight on 08/22/11)

Typical Horizontal DOPs in Tokyo (with SV Losses)

***Lat*: 35.737° N *Long*: 139.895° E *Alt*: 100 m**
***Remove 3 “spare” SVs*: PRN 06 (C5), PRN 07 (A6), PRN 32 (E5)**

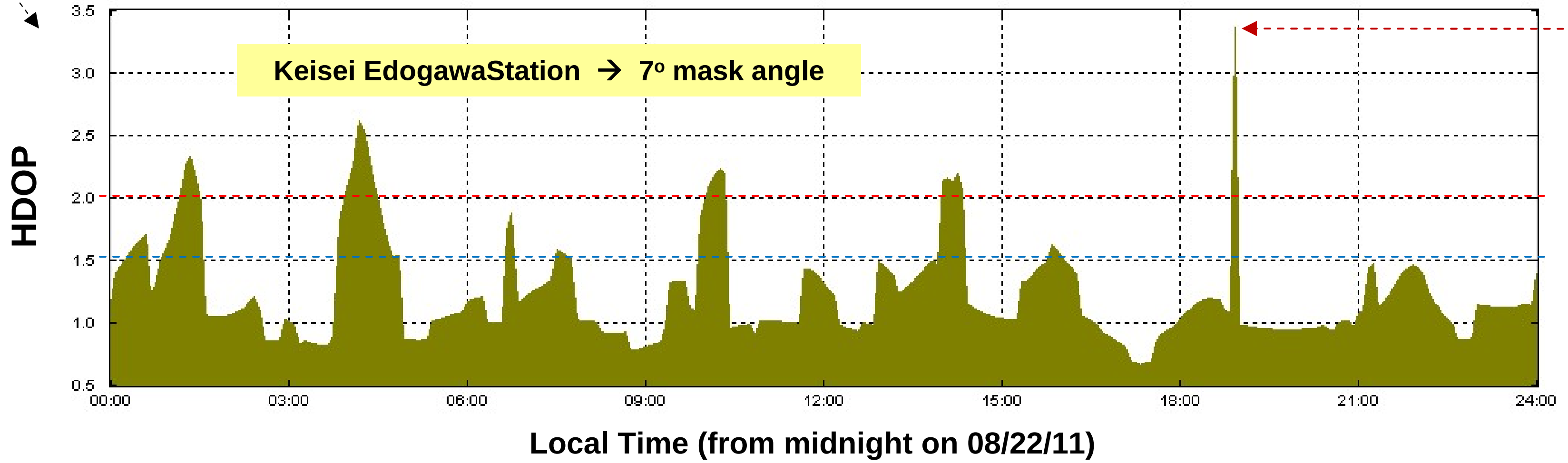


Max. ~ 1.99

Most < 1.4

Note change of scale

***Lat*: 35.737° N *Long*: 139.895° E *Alt*: 100 m**
***Remove 3 “primary” SVs*: PRN 03 (C2), PRN 09 (A1), PRN 10 (E3)**



Max. ~ 3.37

Some > 2.0

Most < 1.5

Horizontal Errors with Typical HDOPs

- **From pseudorange error table on slide 20, absent unusual multipath:**
  - **"standalone" SPS error ≈ 2 – 3 m (1σ)**
  - **LADGPS error (unsmoothed) ≈ 50 – 80 cm (1σ)**
  - **LADGPS error (smoothed) ≈ 25 – 40 cm (1σ)**

SV Geometry Quality	"Typical" HDOP (Approx.)	SPS horizontal error (1σ)	LADGPS horiz. error (1σ, unsmoothed)	LADGPS horiz. error (1σ, smoothed)
Good	1.0	2 – 3 m	50 – 80 cm	25 – 40 cm
Fair	1.3	2.5 – 4 m	75 – 120 cm	30 – 55 cm
Poor	1.8	3.5 – 6 m	0.9 – 1.5 m	40 – 75 cm
Very Poor	3.0	6 – 10 m	1.5 – 2.5 m	70 – 130 cm

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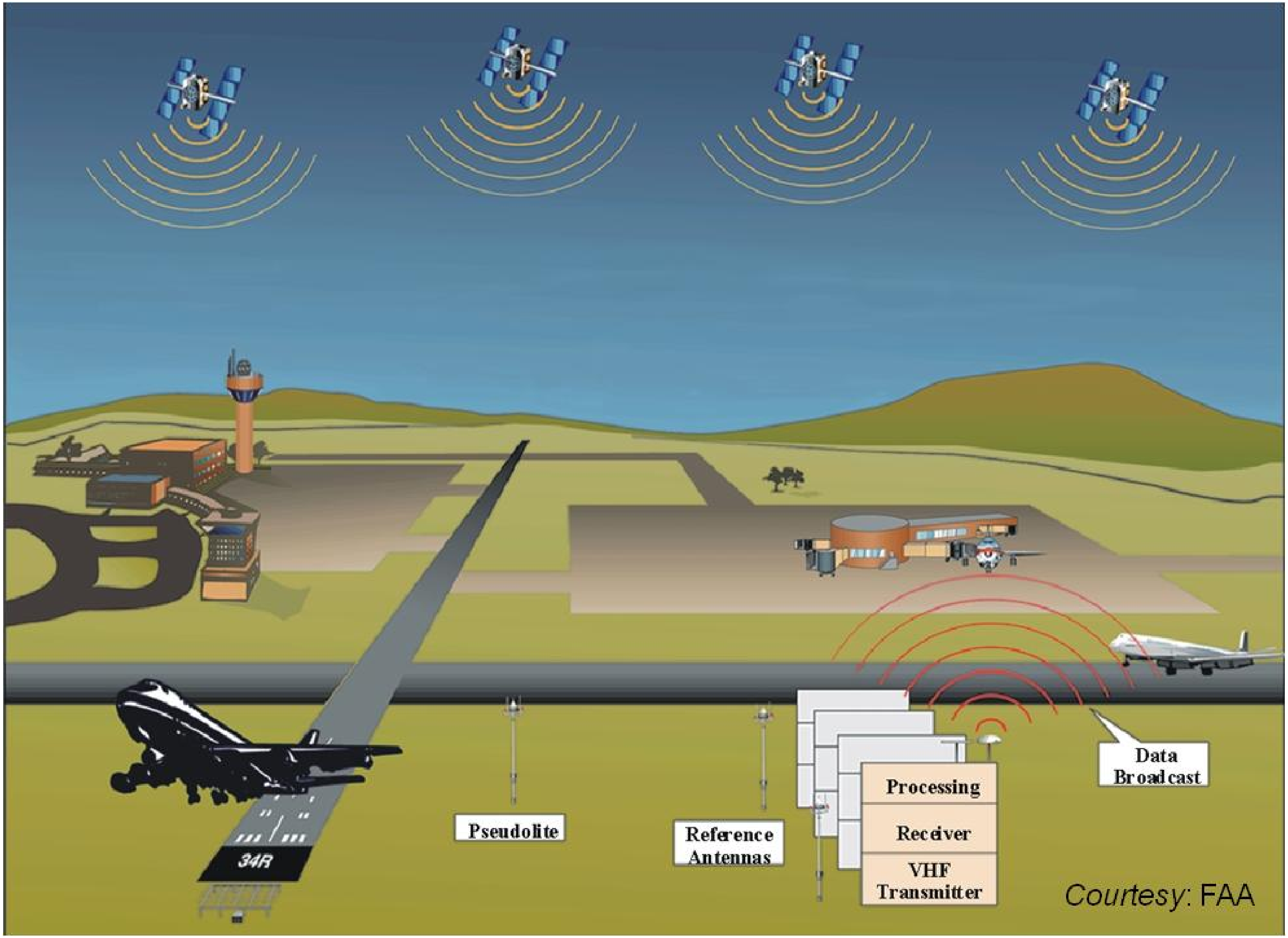
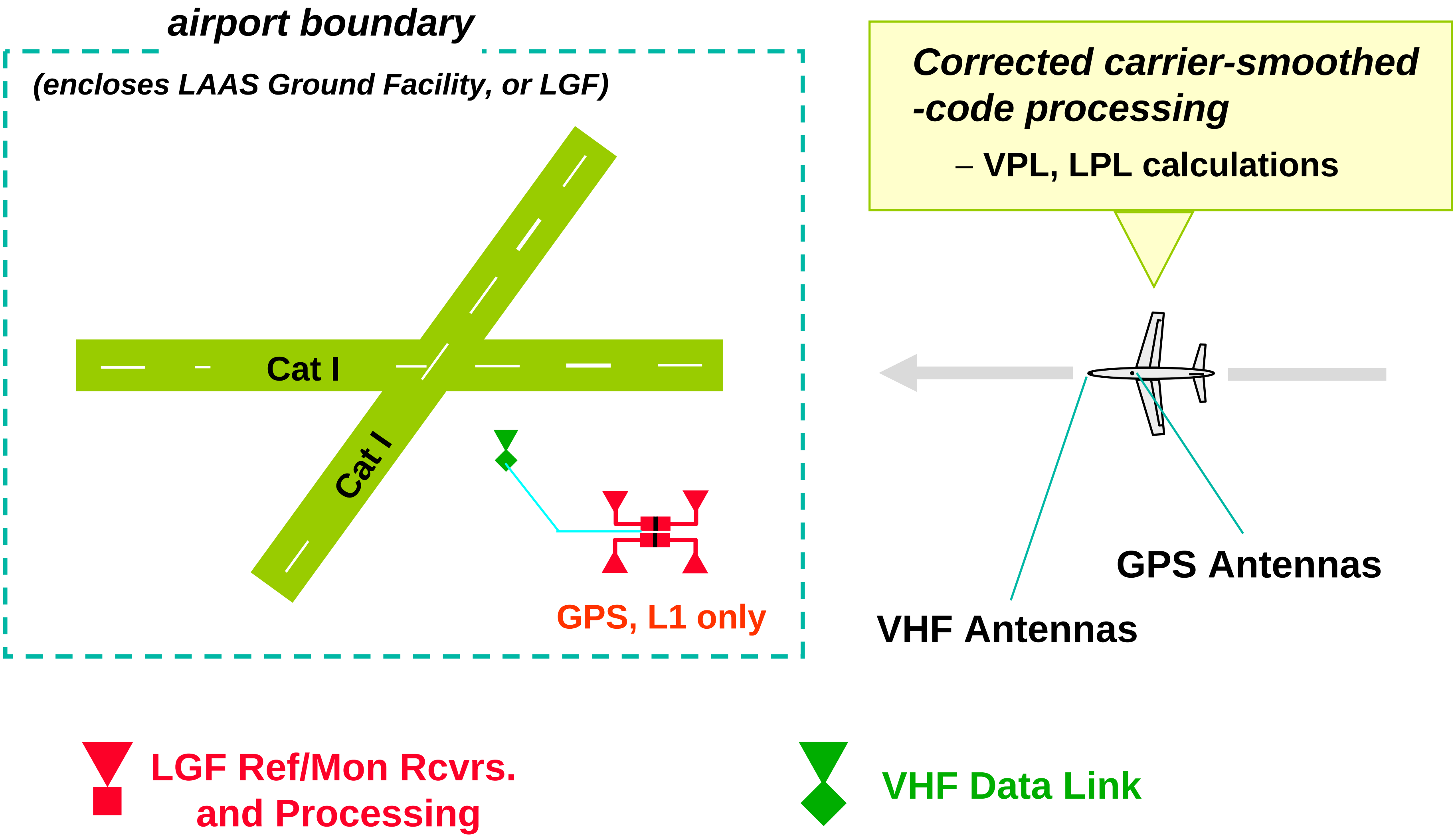
GBAS (LAAS) Architecture Pictorial



Courtesy: FAA

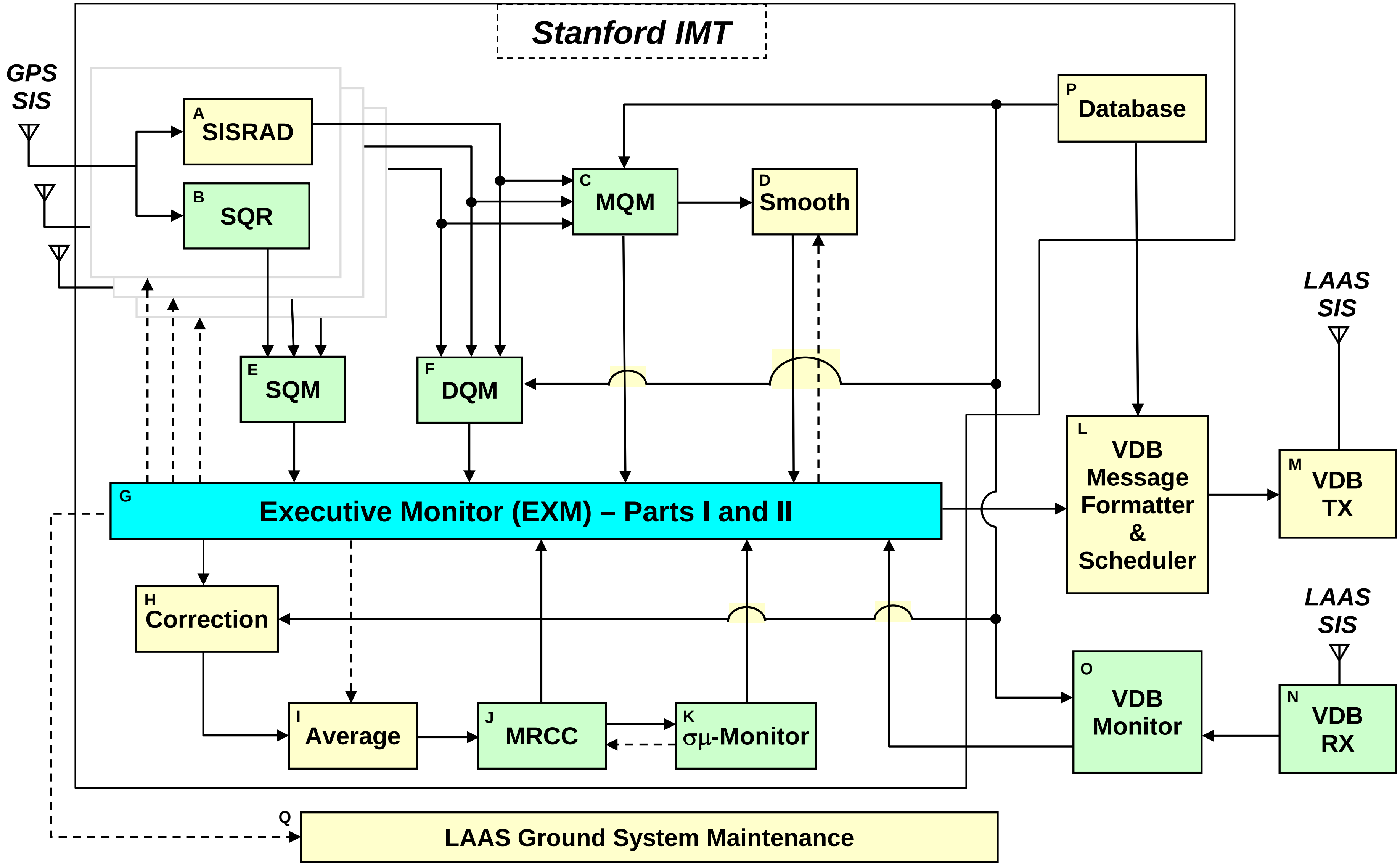
GBAS Architecture Overview (supports CAT I Precision Approach)



Corrected carrier-smoothed -code processing

- **VPL, LPL calculations**

GBAS Ground System Processing



Stanford IMT

GPS SIS

A SISRAD

B SQR

C MQM

D Smooth

E SQM

F DQM

G Executive Monitor (EXM) – Parts I and II

H Correction

I Average

J MRCC

K σμ-Monitor

L VDB Message Formatter & Scheduler

M VDB TX

N VDB RX

O VDB Monitor

P Database

Q LAAS Ground System Maintenance

LAAS SIS

LAAS SIS

Fundamental GBAS Processing: *Carrier Smoothing*

- **Carrier smoothing of "raw" pseudorange ("code") measurements is key to both GBAS and SBAS**
  - **Attenuates receiver noise and high-freq. multipath errors**

- **GBAS requires (nearly) matched smoothing filters in ground and avionics to limit sensitivity to ionospheric divergence:**

$$PR_s(k) = \left(\frac{1}{N}\right) PR_r(k) + \left(\frac{N-1}{N}\right)\left[PR_s(k-1) + \phi(k) - \phi(k-1)\right]$$

$$N = S / T$$

filter time constant (100 sec)

epoch duration (0.5 sec)

- **SBAS can smooth for much longer, as it removes divergence on ground using L2 measurements**

Fundamental GBAS Processing: *Scalar PR Corrections*

- **GBAS (smoothed) PR corrections use the following standard equations:** (n = SV index, m = RR index)

$$PR_{sc}(n,m) = R(n,m) - PR_{s}(n,m) - t_{sv\_gps}(n)$$

smoothed PR correction

predicted range (from SV navigation data)

smoothed PR (see slide 30)

SV clock correction (from SV navigation data)

$$PR_{sca}(n,m) \equiv PR_{sc}(n,m) - \frac{1}{N_c} \sum_{n \in S_c} PR_{sc}(n,m)$$

Smoothed, "clock-adjusted" PR correction

Number of satellites in "common set" (common to all RR's)

$$PR_{corr}(n) \equiv \frac{1}{M(n)} \sum_{m \in S_n} PR_{sca}(n,m)$$

Broadcast PR correction (per SV, averaged over RRs)

Number of RR's with valid measurements for SV *n*

***Source*: FAA Category I LGF Specification, FAA-E-2937A, Apr. 17, 2002**

Fundamental GBAS Processing: *B-Value Calculations*

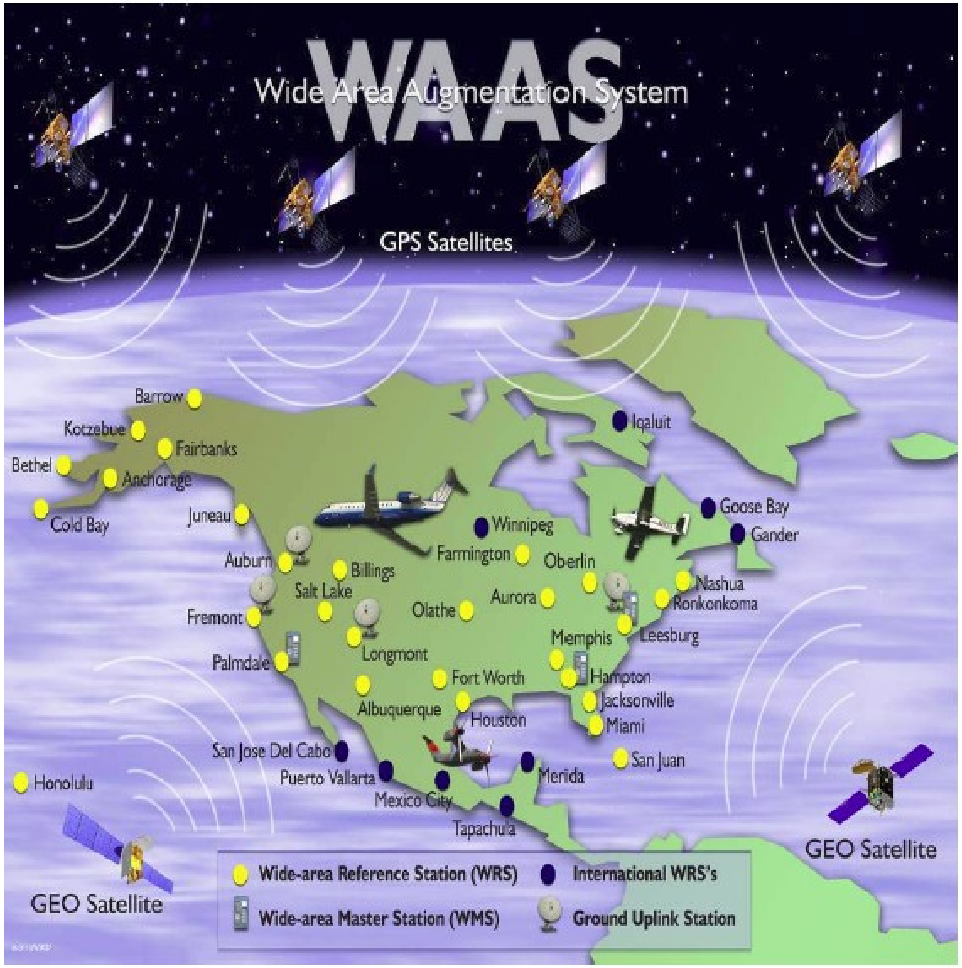
- **Averaged PR corrections are compared with corrections from each RR to generate "B-values"**
- **B_{nm} ≡ Error in PR correction error for SV *n* if RR *m* has failed (meaning that all measurements from RR *m* are invalid)**

$$B_{PR}(n,m) \equiv PR_{corr}(n) - \frac{1}{M(n)-1} \sum_{\substack{i \in S_n \\ i \neq m}} PR_{sca}(n,i)$$

- **B-values are used to:**
  - **Detect failed RRs and channels (one SV tracked by one RR)**
  - **Account for possible RR failures in airborne calculation of protection levels ("H1 hypothesis")**
  - **Feed statistical tests that monitor correction error means and sigmas over time ("sigma-mean monitoring")**

SBAS (WAAS) Architecture Pictorial

***Source*: Leo Eldredge, “WAAS and LAAS Program Status,” CGSIC, Sept. 2010**



38 Reference Stations

3 Master Stations

4 Ground Earth Stations

2 Geostationary Satellite Links

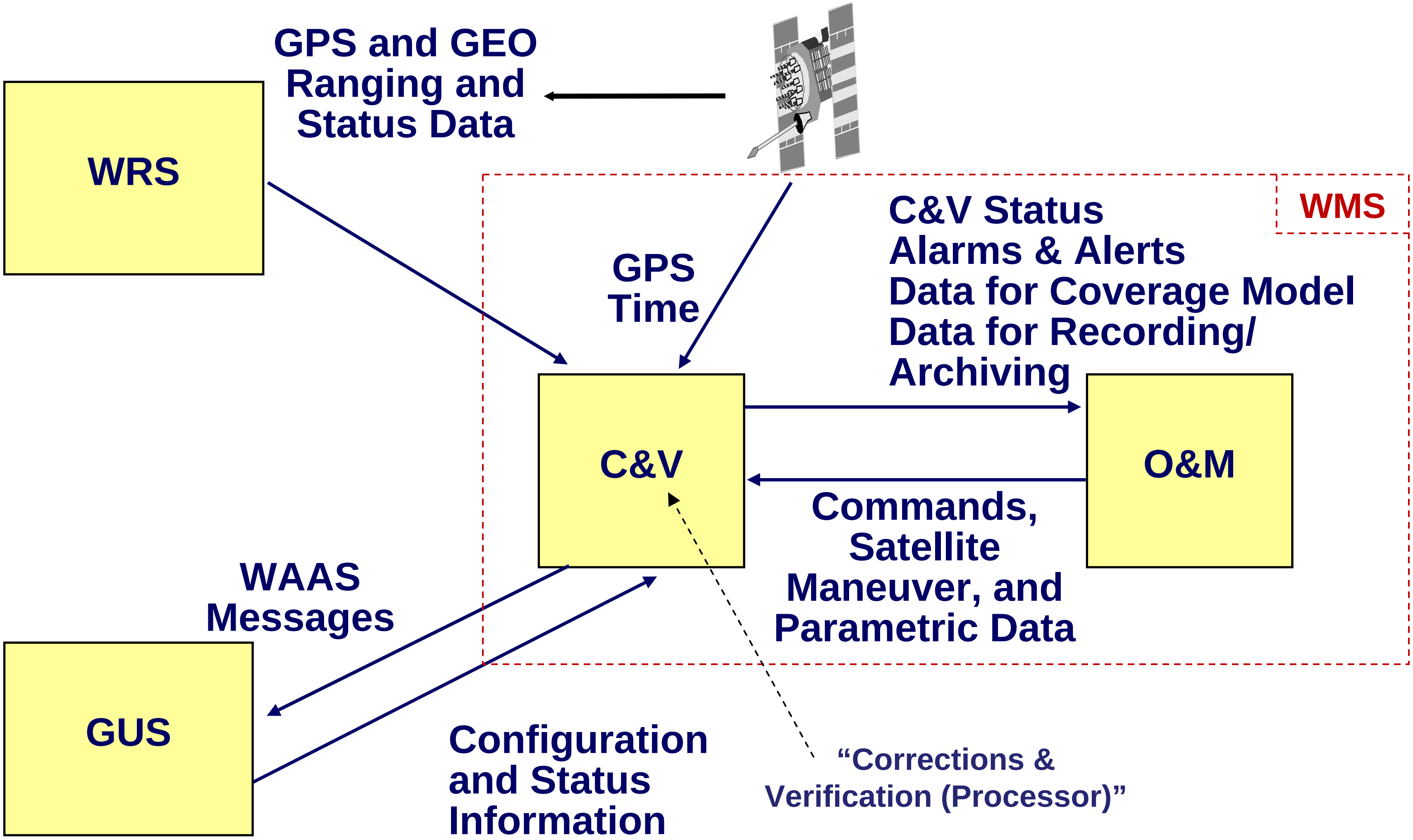
2 Operational Control Centers

SBAS: Key Differences from GBAS

- **Many widely-spread reference stations (RSs) provide coverage over very large areas**
  - **Observability of individual satellites and ionospheric behavior is *far better* than for independent GBAS sites**
- **RSs send measurements to master stations, where corrections and integrity bounds valid for the entire coverage area are created**
  - ***Vector* corrections separate fast-changing SV clock/ephemeris from slower ionospheric behavior**
- **L1-compatible correction/integrity messages are uplinked to GEO satellites to cover user space**
- **Significant latency in RS-MS, MS-GEO, and correction message scheduling make timely alerts *much more challenging* for SBAS**

FAA WAAS: System Overview

***Source*: B. Mahoney, FAA SBAS Tutorial, Feb. 2001**



WRS

GPS and GEO Ranging and Status Data

WMS

GPS Time

C&V Status
Alarms & Alerts
Data for Coverage Model
Data for Recording/ Archiving

C&V

O&M

Commands, Satellite Maneuver, and Parametric Data

WAAS Messages

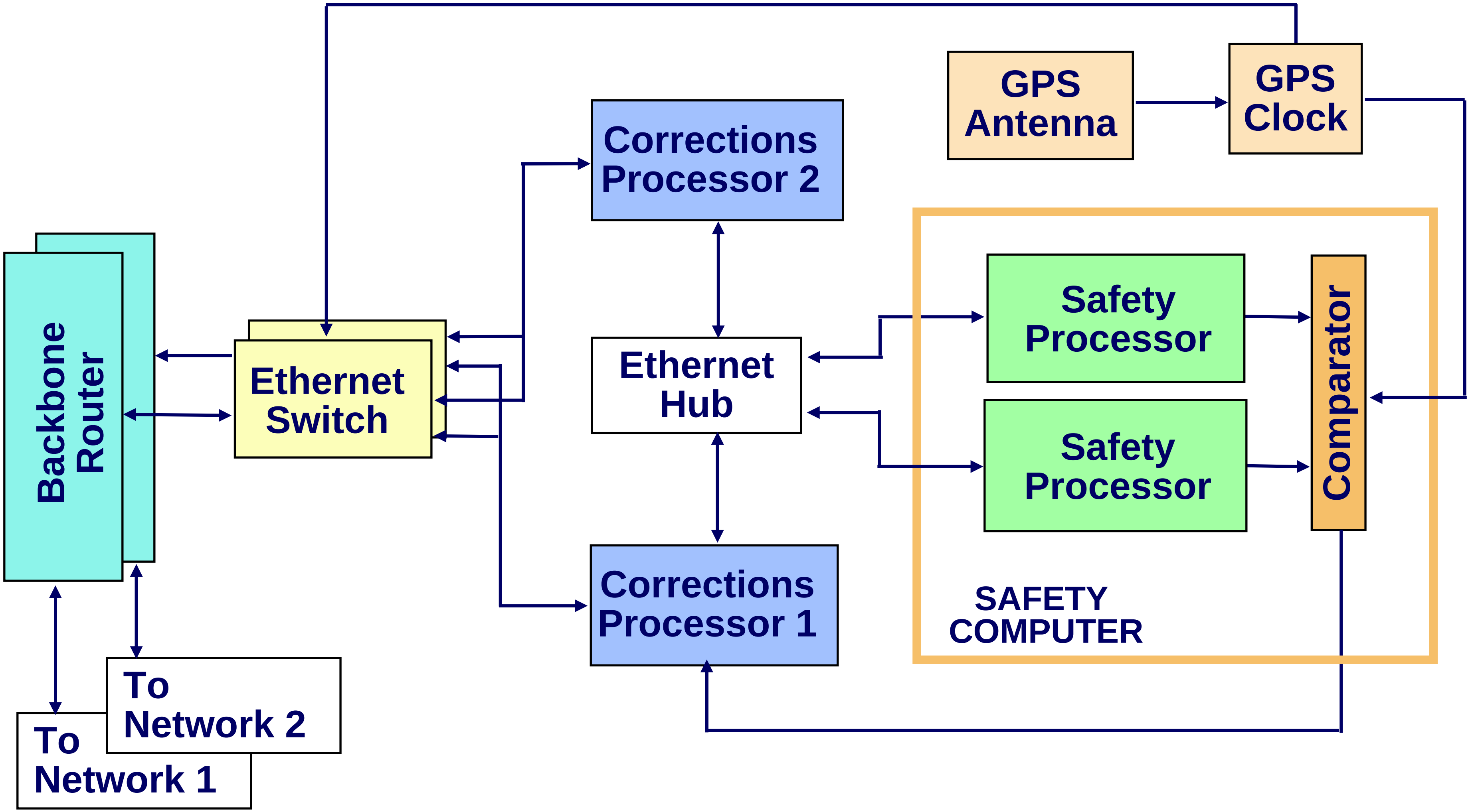
GUS

Configuration and Status Information

"Corrections & Verification (Processor)"

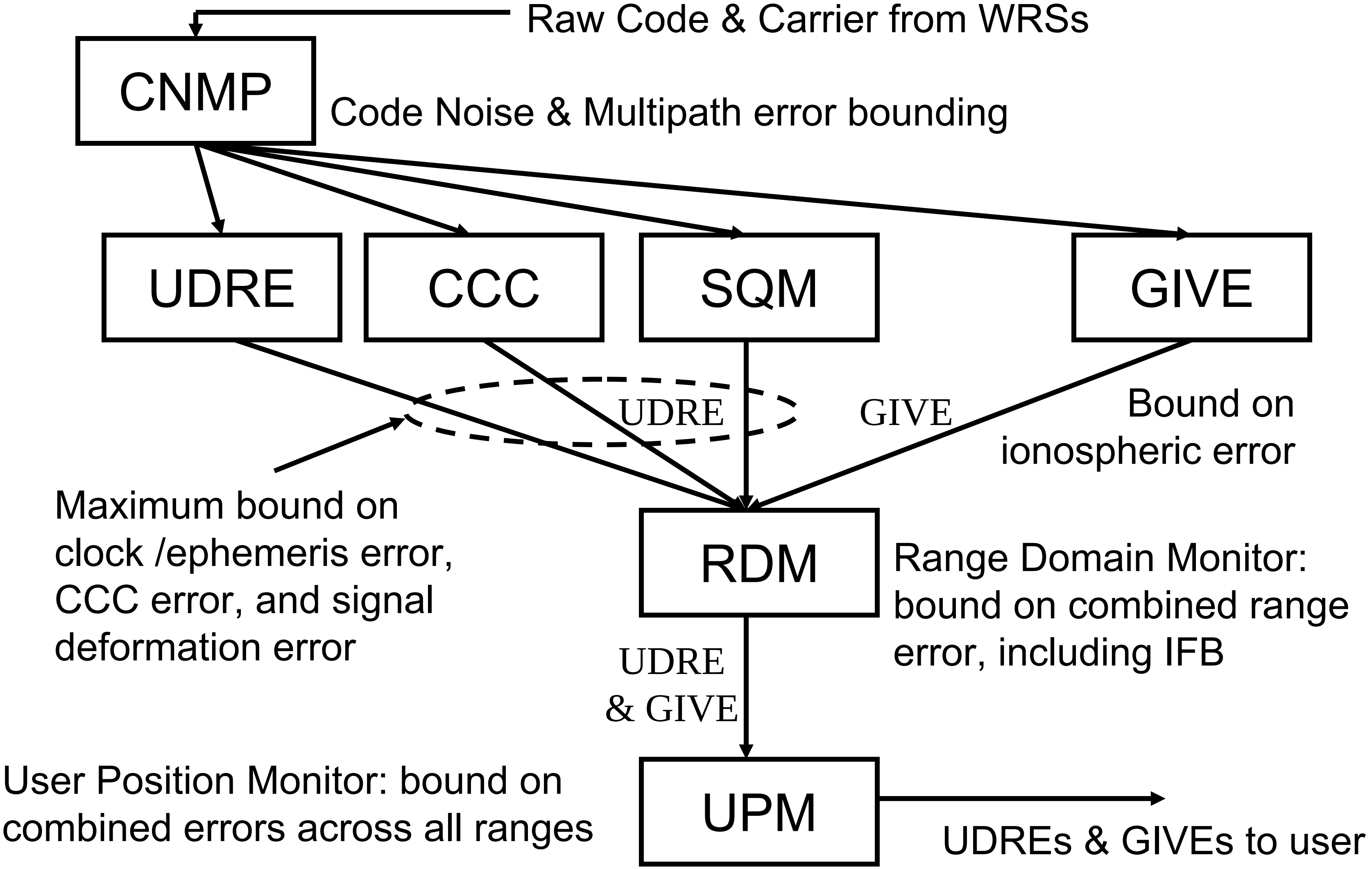
FAA WAAS: C&V Block Diagram

Source: B. Mahoney, FAA SBAS Tutorial, Feb. 2001



FAA WAAS: Safety Processor Flow Diagram

***Source*: T. Walter, *et al*, “Evolving WAAS to Serve L1/L5 Users,” ION GNSS 2011.**



Raw Code & Carrier from WRSs

CNMP

Code Noise & Multipath error bounding

UDRE

CCC

SQM

GIVE

UDRE

GIVE

Bound on ionospheric error

Maximum bound on clock /ephemeris error, CCC error, and signal deformation error

RDM

Range Domain Monitor: bound on combined range error, including IFB

UDRE & GIVE

User Position Monitor: bound on combined errors across all ranges

UPM

UDREs & GIVEs to user

WAAS vs. LAAS: Another Key Difference

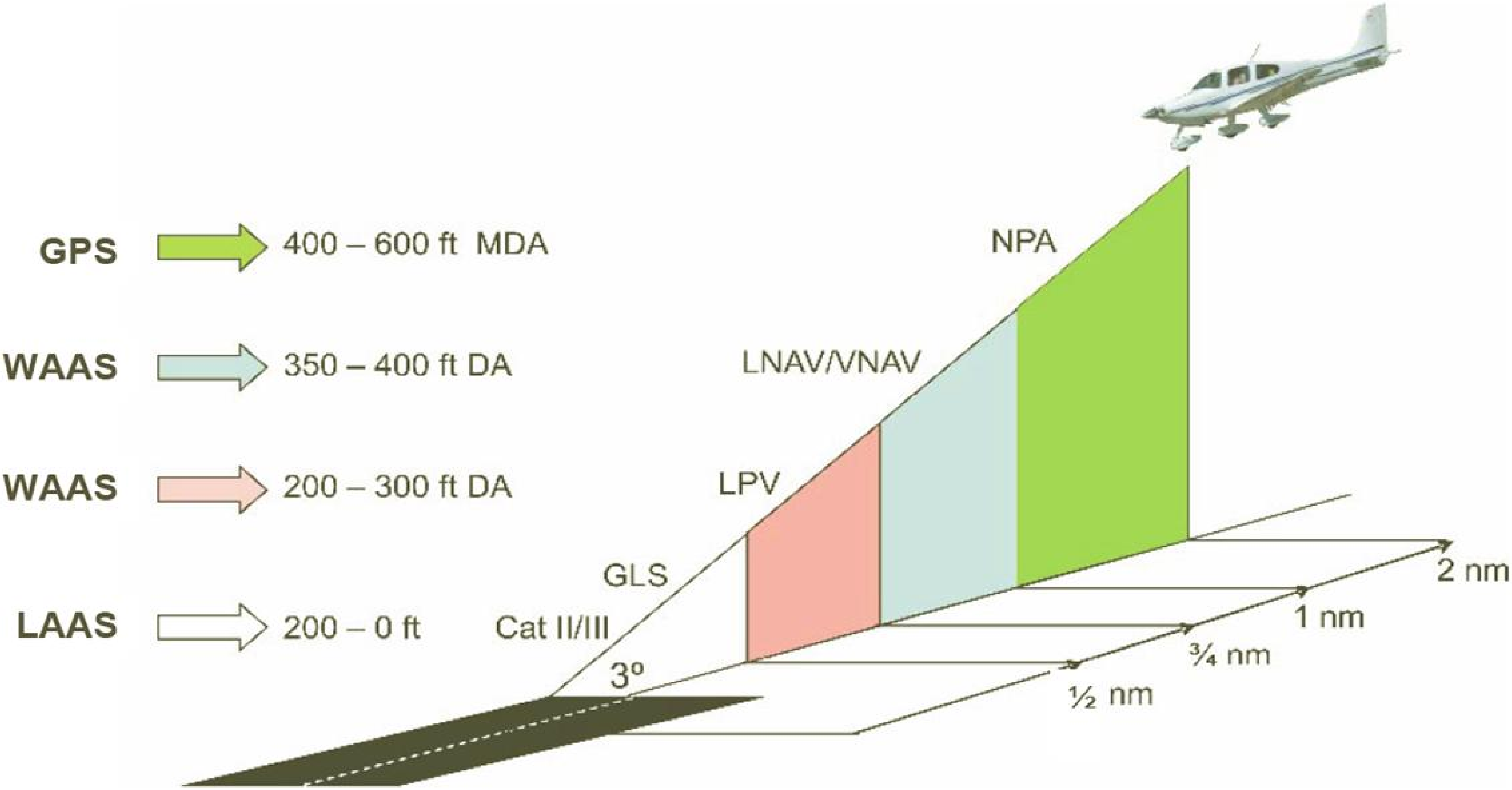
- **“Calculate then Monitor”**
  - **In Raytheon WAAS implementation, “Corrections Processor” (CP) performs all calculations required to generate corrections and integrity information, but in uncertified (“COTS”) software**
  - **Separate “Safety Processor” (SP) is required to perform “final” integrity checks (that determine broadcast error bounds) in “certified” software**
  - **SP integrity checks must assume that outputs from CP are misleading with probability of 1.0 (!!)**
- **“Monitor then Calculate”**
  - **In Honeywell LGF implementation (and in all other GBAS ground systems), *all* software is “certified”**
  - **Calculation of corrections and integrity monitoring can be mixed without “CP” penalty**

Outline

- **Augmented GNSS Terminology**
- **Introduction to GNSS and GNSS Augmentation – Differential GNSS (DGNSS)**
- **GBAS and SBAS System Architectures**
- **Aviation Applications and Requirements**
- **Principles of Integrity and Continuity**
- **Specific Examples:**
  - **Nominal Error Bounding**
  - **Signal Deformation Monitoring**
  - **Ephemeris Monitoring**
  - **Ionospheric Anomaly Mitigation**
- **Summary**

GPS (SPS), WAAS, and LAAS Approach Minima

***Source*: L. Eldredge, "WAAS and LAAS Update," CGSIC 47th Meeting, Sept. 2007.**



GBAS Service Level (GSL) Definitions

Table 1-1 (Section 1.5.1) of RTCA LAAS MOPS (DO-245A)

GSL	**Typical Operation(s) which may be Supported by this Level of Service**
A	Approach operations with vertical guidance (performance of APV-I designation)
B	Approach operations with vertical guidance (performance of APV-II designation)
C	Precision approach to lowest Category I minima
D	Precision approach to lowest Category IIIb minima, *when augmented with other airborne equipment*
E	Precision approach to lowest Category II/IIIa minima
F	Precision approach to lowest Category IIIb minima

GSL Requirements Table

Table 2-1 (Section 2.3.1) of RTCA LAAS MOPS (DO-245A), Dec. 2004

GSL	Accuracy		Integrity				Continuity
	95% Lat. NSE	**95% Vert. NSE**	**Pr(Loss of Integrity)**	**Time to Alert**	**LAL**	**VAL**	**Pr(Loss of Continuity)**
A	16 m	20 m	2×10^{-7} / 150 sec	6 sec	40 m	50 m	8×10^{-6} / 15 sec
B	16 m	8 m	2×10^{-7} / 150 sec	6 sec	40 m	20 m	8×10^{-6} / 15 sec
C	16 m	4 m	2×10^{-7} / 150 sec	6 sec	40 m	10 m	8×10^{-6} / 15 sec
D	5 m	2.9 m	10^{-9} / 15 s (vert.); 30 s (lat.)	2 sec	17 m	10 m	8×10^{-6} / 15 sec
E	5 m	2.9 m	10^{-9} / 15 s (vert.); 30 s (lat.)	2 sec	17 m	10 m	4×10^{-6} / 15 sec
F	5 m	2.9 m	10^{-9} / 15 s (vert.); 30 s (lat.)	2 sec	17 m	10 m	2×10^{-6} / 15 s (vert.); 30 s (lat.)

Navigation Performance Parameters

- ***ACCURACY*:** Measure of navigation output deviation from truth.

- ***INTEGRITY*:** Ability of a system to provide timely warnings when the system should not be used for navigation. ***INTEGRITY RISK is the probability of an undetected, threatening navigation system problem.***

- ***CONTINUITY*:** Likelihood that the navigation signal-in-space supports accuracy and integrity requirements for duration of intended operation. ***CONTINUITY RISK is the probability of a detected but unscheduled navigation interruption after initiation of an operation.***

- ***AVAILABILITY*:** Fraction of time navigation system is usable (as determined by compliance with accuracy, integrity, and continuity requirements) before approach is initiated.

Accuracy

- ***Accuracy*** **is a statistical quantity associated with the Navigation Sensor Error (NSE) distribution.**
  - **most commonly cited as a 95th-percentile error bound**
  - ***Also*****: Flight Technical Error (FTE) and Total System Error (TSE), where TSE = NSE + FTE**

- ***Requirement*****: the 95% position accuracy shall not exceed the specified value at every location over 24 hours within the service volume *when the navigation system predicts that it is available.***

- ***Note*****: for augmented GPS systems, accuracy is rarely the limiting performance parameter.**
  - **integrity and continuity requirements normally dictate tighter system accuracy than the actual accuracy requirement demands.**

Integrity

- ***Integrity*** **relates to the trust that can be placed in the information provided by the navigation system.**

- ***Misleading Information (MI)*** **occurs when the true navigation error exceeds the appropriate alert limit (i.e., an unsafe condition).**

- ***Time-to-alert*** **is the time from when an unsafe condition occurs to when an alerting message reaches the pilot (or guidance system)**

- **A *Loss of Integrity (LOI)* event occurs when an unsafe condition occurs without annunciation for a time longer than the time-to-alert limit, given that the system predicts it is available.**

Continuity

- *Continuity* **is a measure of the likelihood of unexpected loss of navigation during an operation.**

- ***Loss of Continuity*** **occurs when the aircraft is forced to abort an operation during a specified time interval after it has begun.**
  - **system predicts service was available at start of operation**
  - **alert from onboard integrity algorithm during operation due to:**
    - » **loss of GPS satellites**
    - » **loss of DGPS datalink**
    - » **degradation of measurement error accuracy**
    - » **unusual noise behavior under normal conditions (i.e., false alarm)**

- ***Requirement*****: the probability of Loss of Continuity must be less than a specified value over a specified time interval (15 seconds – 1 hour).**

Availability

- **A navigation service is deemed to be *available* if the accuracy, integrity, and continuity requirements are all met.**
  - ***Operationally*, checked shortly before service is utilized**
  - ***Offline*, evaluated via simulation for locations of interest (over lengthy or repeating time periods)**

- ***Service Availability:* the fraction of time (expressed as a probability over all SV geometries and conditions) that the navigation service is available (determined offline).**

- ***Operational Availability* refers to typical or maximum periods of time over which the service is unavailable (determined offline – important for flight and ATC planning).**

- ***Requirement*: a range of values is usually given – actual requirement depends on operational needs of each location.**

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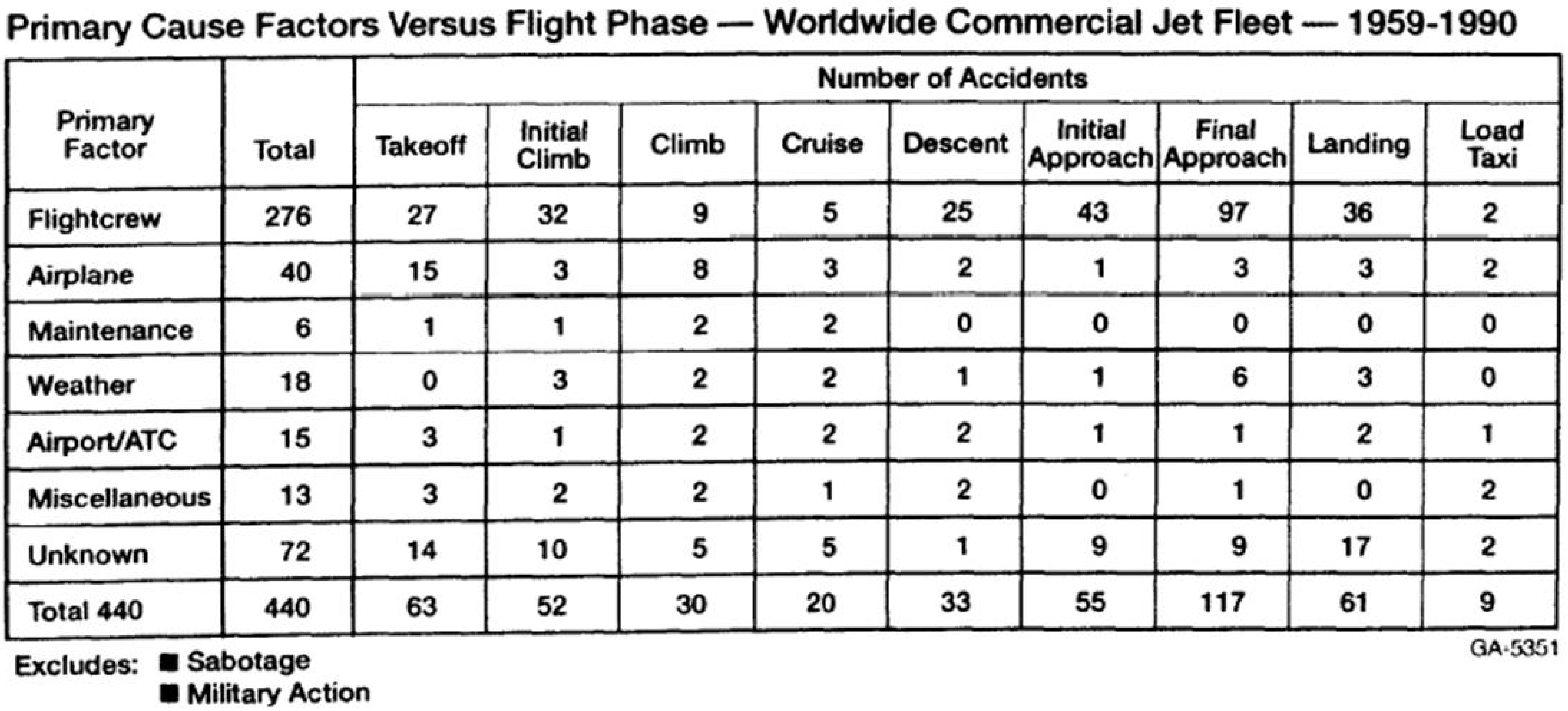
  - **Ionospheric Anomaly Mitigation**
- **Summary**

Breakdown of Worldwide Accident Causes: 1959 – 1990 (from ICAO Oct. 1990 Study)



Primary Cause Factors Versus Flight Phase — Worldwide Commercial Jet Fleet — 1959-1990

Primary Factor	Total	Number of Accidents								
		Takeoff	Initial Climb	Climb	Cruise	Descent	Initial Approach	Final Approach	Landing	Load Taxi
Flightcrew	276	27	32	9	5	25	43	97	36	2
Airplane	40	15	3	8	3	2	1	3	3	2
Maintenance	6	1	1	2	2	0	0	0	0	0
Weather	18	0	3	2	2	1	1	6	3	0
Airport/ATC	15	3	1	2	2	2	1	1	2	1
Miscellaneous	13	3	2	2	1	2	0	1	0	2
Unknown	72	14	10	5	5	1	9	9	17	2
Total 440	440	63	52	30	20	33	55	117	61	9

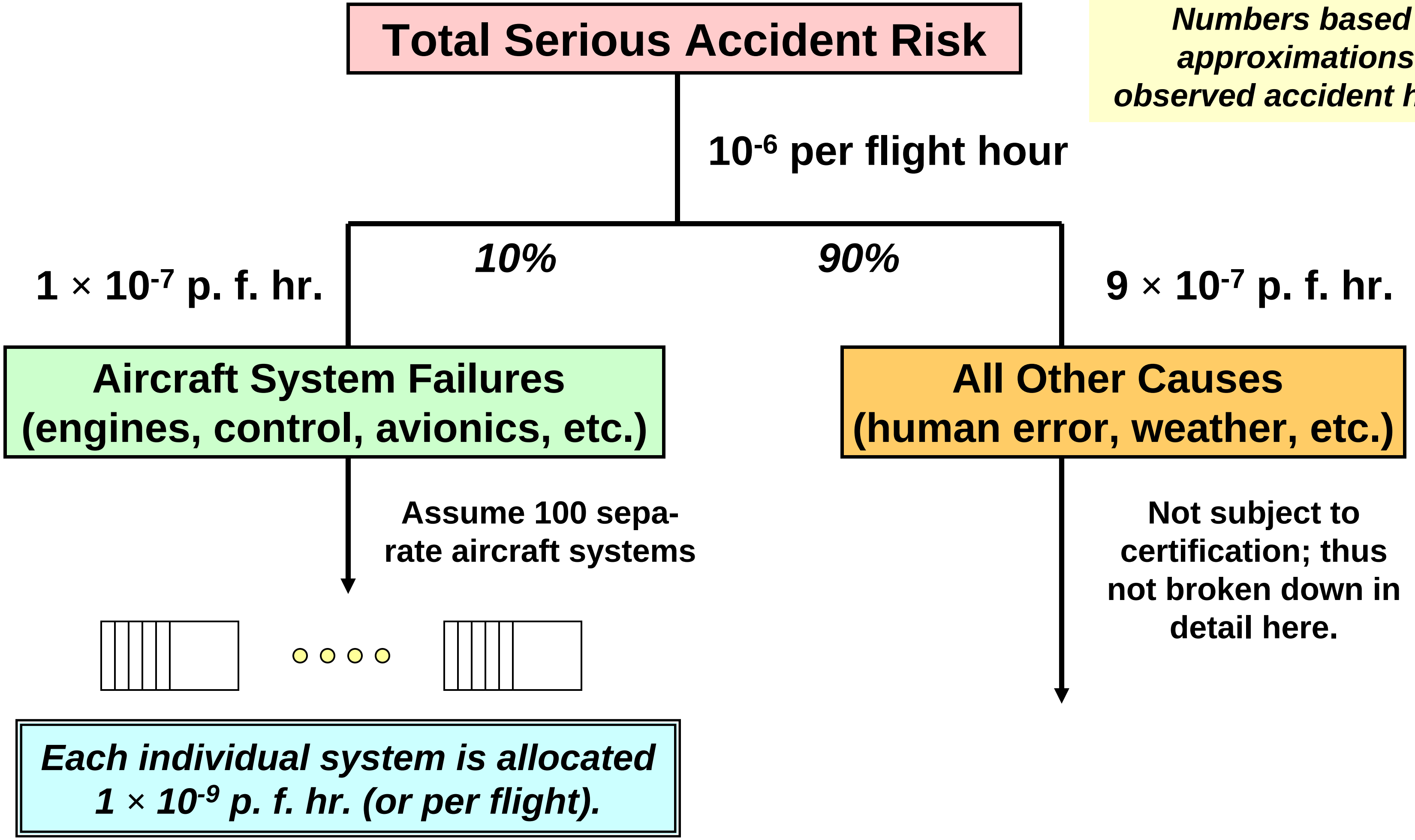
Excludes:
- Sabotage
- Military Action

GA-5351

- **Total hull loss probability per flight as of 1990 = 1.87 × 10^{-6}**
- **Current probability per commercial departure in U.S. = 2.2 × 10^{-7} (3-year rolling average, March 2006 update)**
  - **http://faa.gov/about/plans_reports/Performance/performancetargets/details/2041183F53565DDF.html**

Unofficial “Serious Accident” Risk Allocation (from 1983 SAE paper[†])

Numbers based on approximations of observed accident history.



Total Serious Accident Risk

10^{-6} per flight hour

10%

1 × 10^{-7} p. f. hr.

Aircraft System Failures (engines, control, avionics, etc.)

Assume 100 separate aircraft systems

Each individual system is allocated 1 × 10^{-9} p. f. hr. (or per flight).

90%

9 × 10^{-7} p. f. hr.

All Other Causes (human error, weather, etc.)

Not subject to certification; thus not broken down in detail here.

[†] D.L. Gilles, “The Effect of Regulation 25.1309 on Aircraft Design and Maintenance,” SAE Paper No. 831406, 1983.

FAA Risk Severity Classifications*

- **Minor**: failure condition which would not significantly reduce airplane safety, and which involve crew actions that are well within their capabilities

- **Major**: failure condition which would **significantly**:
  - (a) Reduce safety margins or functional capabilities of airplane
  - (b) Increase crew workload or conditions impairing crew efficiency
  - (c) Some discomfort to occupants

Cat I

- **Severe Major** ("**Hazardous**" in ATA, JAA): failure condition resulting in more severe consequences than Major:
  - (a) Larger reduction in safety margins or functional airplane capabilities
  - (b) Higher workload or physical distress such that the crew could not be relied upon to perform its tasks accurately or completely
  - (c) Adverse effects on occupants

Cat III

- **Catastrophic**: failure conditions which would prevent continued safe flight and landing (with probability –> 1)

* Taken from AC No. 25.1309-1A, AMJ 25.1309, SAE ARP4761 (JHUAPL summary)

FAA Hazard Risk Index (HRI) Table

- **Several versions exist, all with essentially the same meaning**
- ***Source of this version*: 1999 Johns Hopkins Applied Physics Laboratory "GPS Risk Assessment Study" final report**
  http://www.faa.gov/asd/international/GUIDANCE_MATL/Jhopkins.pdf

Consequence Prob. Of Occurance	Catastrophic	Hazardous	Major	Minor	No Effect
Frequent (>10^{-2})	1	3	6	10	21
Reasonably Probable (10^{-2} to 10^{-5})	2	5	9	14	22
Remote (10^{-5} to 10^{-7})	4	8	13	17	23
Extremely Remote (10^{-7} to 10^{-9})	7	12	16	19	24
Extremely Improbable (<10^{-9})	11	15	18	20	25

Cat. III ILS case

Cat. I ILS case

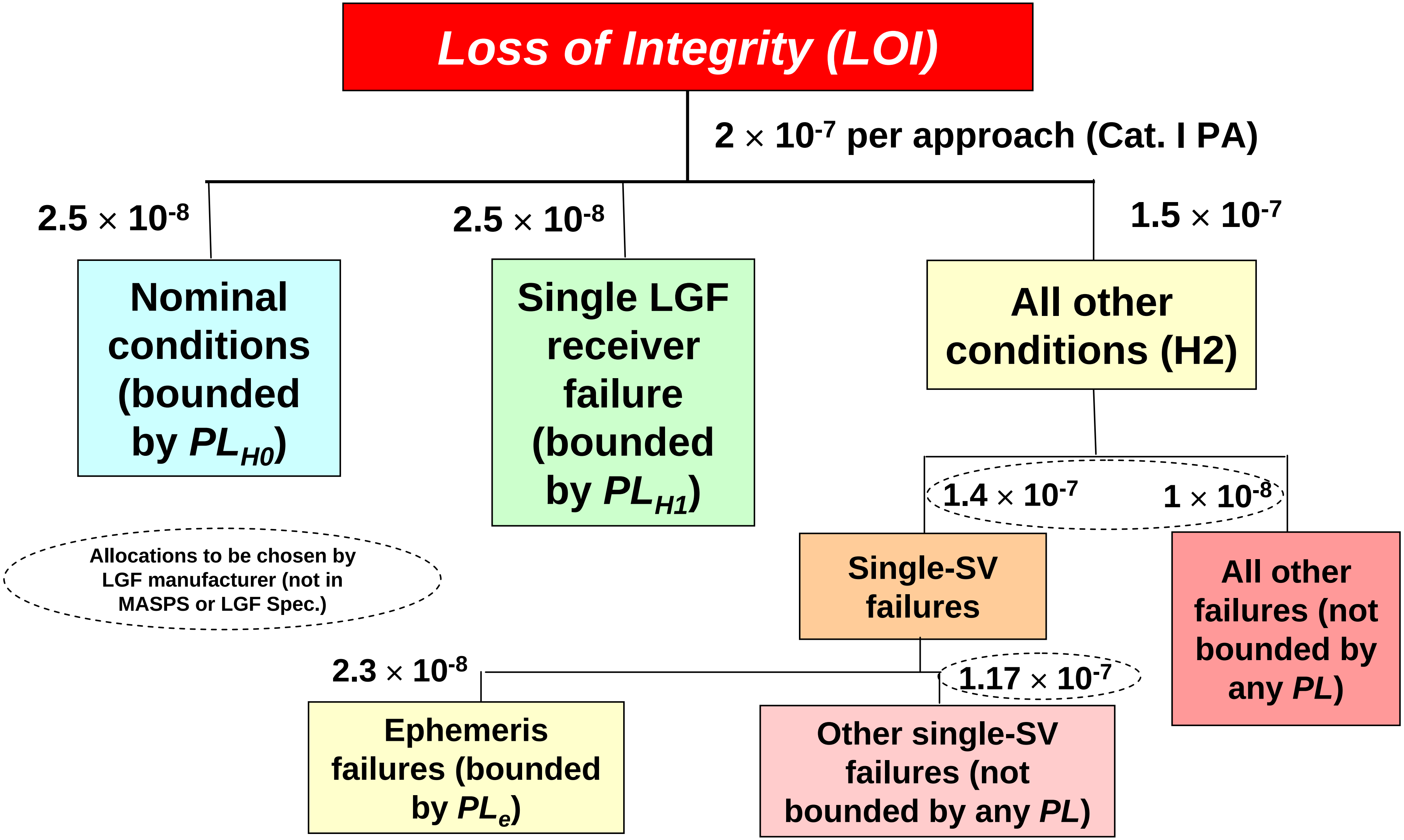
Hazard Risk Index	Acceptance Criteria
1-6	Unacceptable
7-10	Undesirable
11-18	Acceptable, but FAA review required
19-25	Acceptable

RTCA DO-178B Software Classifications

- **DO-178B defines five software levels, from A (most critical) to E (least critical – includes COTS software)**
- **Each level is linked to a specific failure consequence from the Hazard Risk Index model**

Failure Consequence	***Required Software Level***
Catastrophic	**Level A**
Hazardous/Severe-Major	**Level B**
Major	**Level C**
Minor	**Level D**
No Effect	**Level E**

Integrity Fault Tree for CAT I LAAS



Loss of Integrity (LOI)

2×10^{-7} per approach (Cat. I PA)

2.5×10^{-8}

Nominal conditions (bounded by PL_{H0})

2.5×10^{-8}

Single LGF receiver failure (bounded by PL_{H1})

1.5×10^{-7}

All other conditions (H2)

1.4×10^{-7}

1×10^{-8}

Single-SV failures

All other failures (not bounded by any *PL*)

Allocations to be chosen by LGF manufacturer (not in MASPS or LGF Spec.)

2.3×10^{-8}

1.17×10^{-7}

Ephemeris failures (bounded by PL_e)

Other single-SV failures (not bounded by any *PL*)

Fundamental Integrity Risk Model

- **For a given fault mode (or anomaly) *i*:**

$$P_{LOI,i} \geq \underbrace{P_{PL,i}}\,\underbrace{P_{MD,i}}\,\underbrace{P_{prior,i}}$$

(unconditional) prior probability of event *i*

(conditional) probability of missed detection of event *i* given that event *i* occurs

Probability of loss of integrity due to event *i* → must be sub-allocated out of total integrity risk requirement (2 × 10^{-7} per approach for LAAS CAT I)

(conditional) probability of unsafe error (protection level violation) given that event *i* occurs and is not detected (depends on bias due to event *i* and normal error variation)

GNSS Protection Levels: *Introduction*

- **To establish integrity, augmented GNSS systems must provide means to validate in real time that integrity probabilities and alert limits are met.**

- **This cannot easily be done offline or solely within ground systems because:**
  - **Achievable error bounds vary with GNSS SV geometry.**
  - **Ground-based systems cannot know which SV's a given user is tracking.**
  - **Protecting all possible sets of SV's in user position calculations is numerically difficult.**

- **Protection level concept translates augmentation system integrity verification *in range domain* into user position bounds *in position domain.***

GBAS Protection Level Calculation (1)

- **Protection levels represent *upper confidence limits* on position error (out to desired integrity risk probability):**
  - **H_0 case:**

    (***nominal conditions***)

    $$VPL_{H0} = K_{ffmd}\sqrt{\sum_{i=1}^{N} s_{i,vert}^{2}\sigma_i^{2}}$$

    Nominal range error variance

    Nominal UCL multiplier (for Gaussian dist.)

    Geom. conversion: range to vertical position (~ VDOP)

  - **H_1 case:**

    (***single-reference-receiver fault***)

    $$VPL_j = \left|B_{j,vert}\right| + K_{md}\sigma_{vert,H1}$$

    Vert. pos. error std. dev. under H_1

    B-value converted to Vertical position error

    H_1 UCL multiplier (computed for Normal dist.)

  - **Ephemeris:**

    (***single-satellite ephemeris fault***)

    From weighted p-inverse of user geometry matrix

    LGF-user baseline vector

    Missed-detection multiplier

    $$VPLe_j = \left|S_{3,j}\right|\left|x\right|\frac{MDE_e}{R_j} + K_{md_e}\sqrt{\sum_{k=1}^{N} S_{3,k}^{2}\sigma_k^{2}}$$

    SV index

    Differential ranging error variance

    (S index “3” = vertical axis)

GBAS Protection Level Calculation (2)

- **Fault-mode VPL equations (VPL_{H1} and VPL_{e}) have the form:**

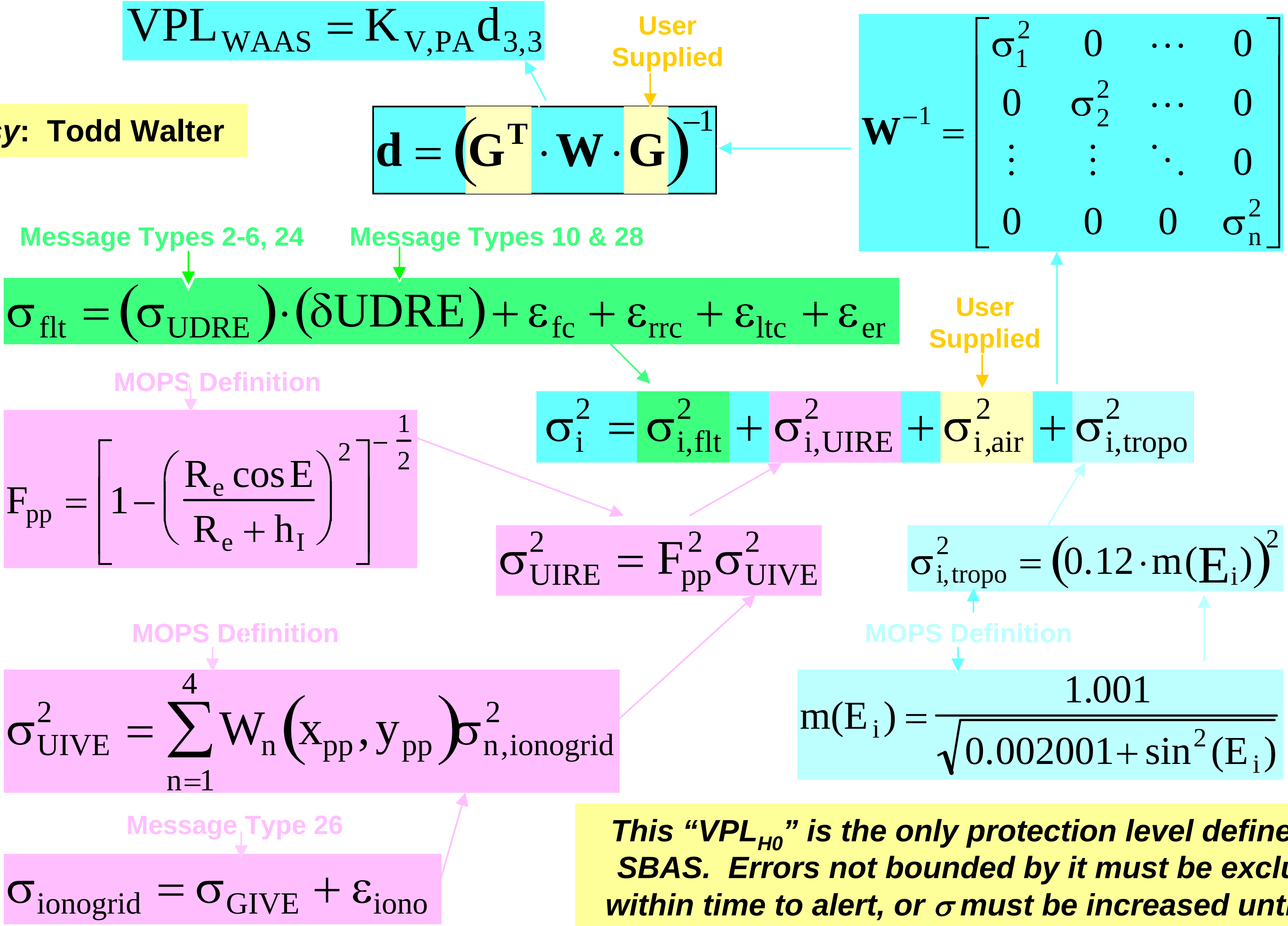
$$VPL_{fault} = \text{Mean impact of fault on vertical position error} + \text{Impact of nominal errors, } \textit{de-weighted by prior probability of fault}$$

- **LAAS users compute VPL_{H0} (one equation), VPL_{H1} (one equation per SV), and VPL_{e} (one equation per SV) in real-time**
  - **warning is issued (and operation may be aborted) if maximum VPL over all equations exceeds VAL**
  - **absent an actual anomaly, VPL_{H0} is usually the largest**

- **Fault modes that do not have VPL's must:**
  - **be detected and excluded such that VPL_{H0} bounds**
  - **residual probability that VPL_{H0} does not bound must fall within the "H2" ("not covered") LAAS integrity sub-allocation**

SBAS Protection Level Calculation

***Courtesy*: Todd Walter**



$$VPL_{WAAS} = K_{V,PA} d_{3,3}$$

User Supplied

$$\mathbf{d} = \left(\mathbf{G}^T \cdot \mathbf{W} \cdot \mathbf{G}\right)^{-1}$$

$$\mathbf{W}^{-1} = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \sigma_n^2 \end{bmatrix}$$

Message Types 2-6, 24

Message Types 10 & 28

$$\sigma_{flt} = \left(\sigma_{UDRE}\right) \cdot \left(\delta UDRE\right) + \varepsilon_{fc} + \varepsilon_{rrc} + \varepsilon_{ltc} + \varepsilon_{er}$$

User Supplied

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

MOPS Definition

$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

$$\sigma_{UIRE}^2 = F_{pp}^2 \sigma_{UIVE}^2$$

$$\sigma_{i,tropo}^2 = \left(0.12 \cdot m(E_i)\right)^2$$

MOPS Definition

$$\sigma_{UIVE}^2 = \sum_{n=1}^{4} W_n\left(x_{pp}, y_{pp}\right) \sigma_{n,ionogrid}^2$$

MOPS Definition

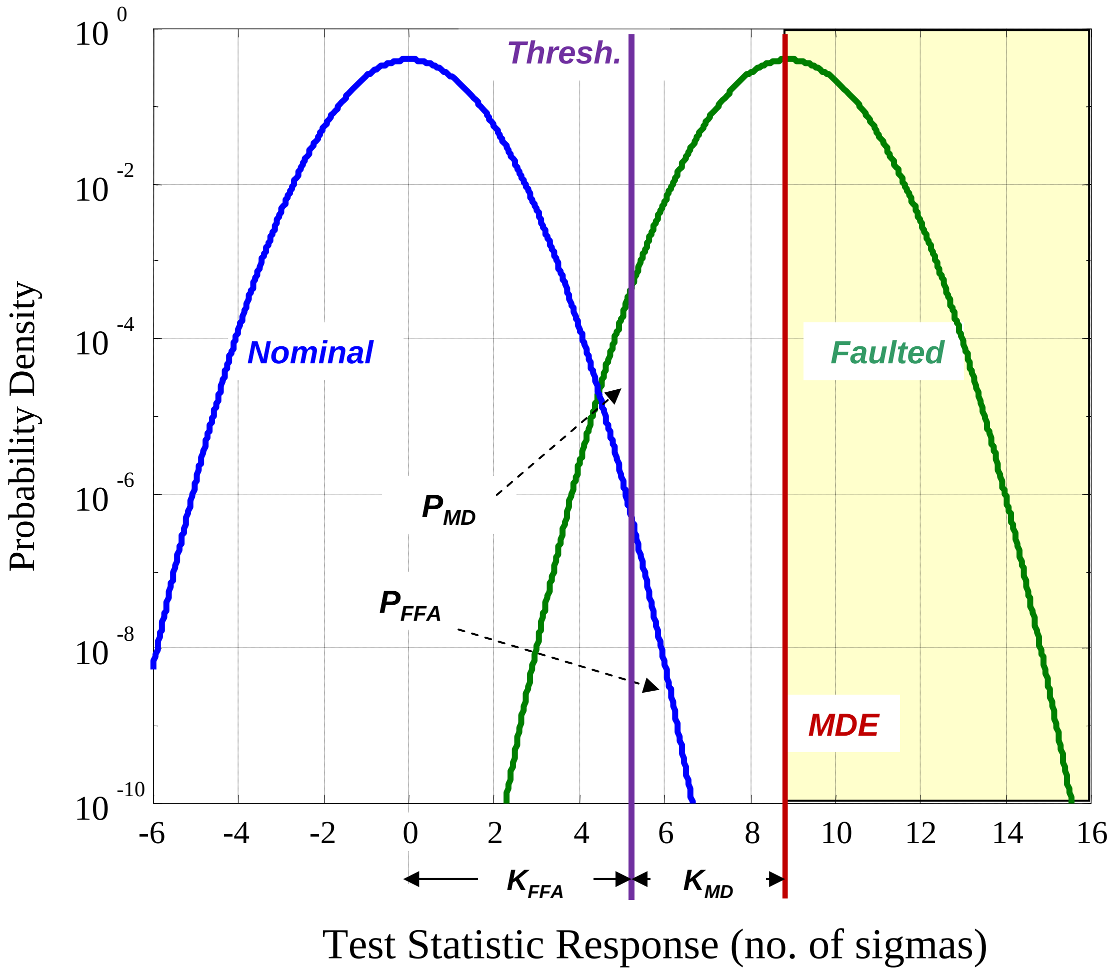
$$m(E_i) = \frac{1.001}{\sqrt{0.002001 + \sin^2(E_i)}}$$

Message Type 26

$$\sigma_{ionogrid} = \sigma_{GIVE} + \varepsilon_{iono}$$

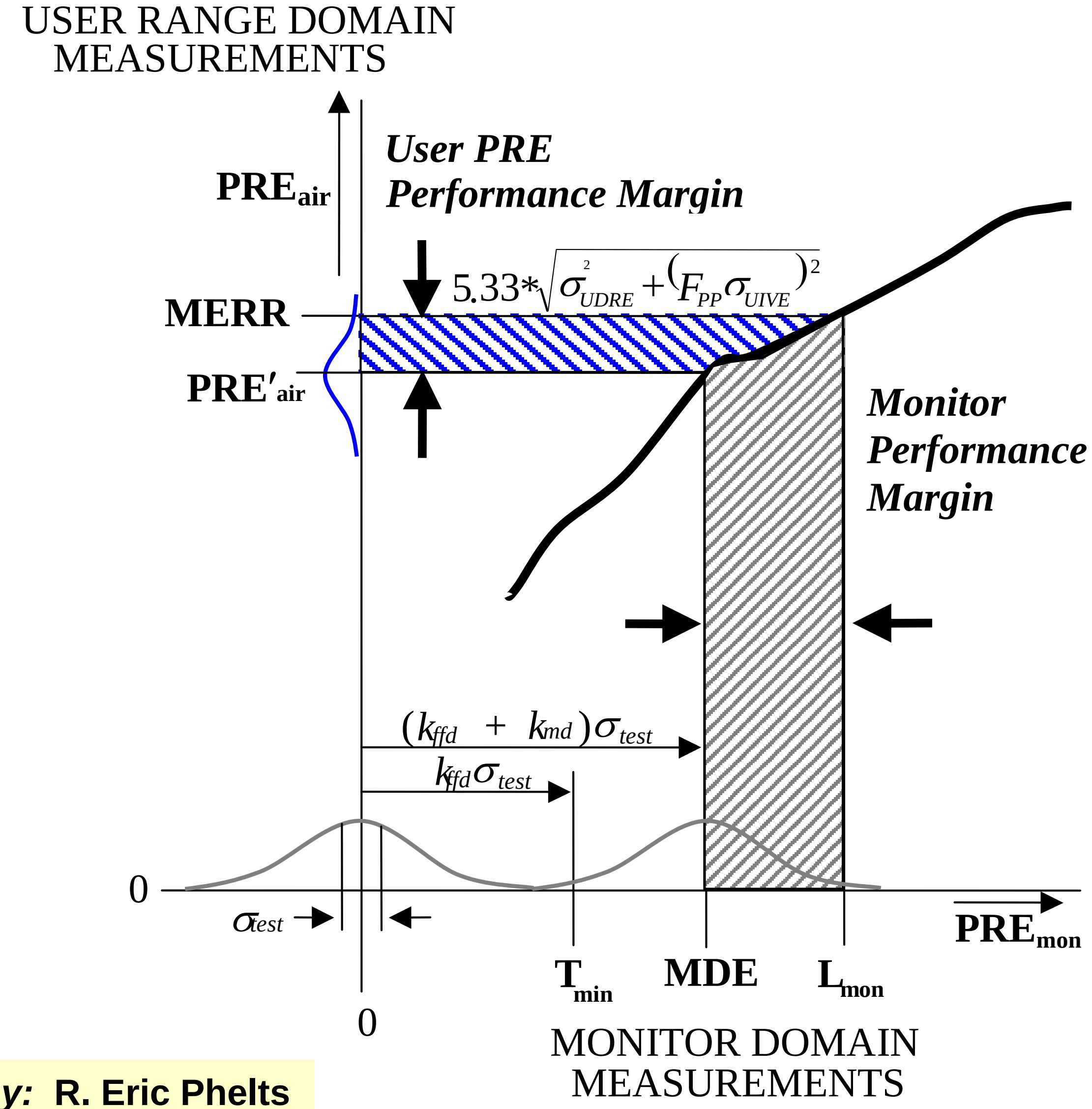
This "VPL$_{H0}$" is the only protection level defined for SBAS. Errors not bounded by it must be excluded within time to alert, or σ must be increased until this VPL is a valid bound.

Threshold and MDE Definitions



Failures causing test statistic to exceed *Minimum Detectable Error* (MDE) are mitigated such that both integrity and continuity requirements are met.

MDE Relationship to Range Domain Errors



- **MDE in test domain corresponds to a given PRE in user range domain depending on differential impact of failure source**
- **If resulting PRE ≤ MERR (required range error bound), system meets requirement with margin**
- **If not, MDE must be lowered (better test) or MERR increased (higher sigmas → loss of availability)**

***Courtesy:* R. Eric Phelts**

Assumptions Built Into Protection Level Calculations

- **Distributions of range and position-domain errors are assumed to be Gaussian in the tails**
  - **"K-values" used to convert one-sigma errors to rare-event errors are computed from the standard Normal distribution**
- **All non-faulted conditions are "nominal" and have one zero-mean Gaussian distribution with the same sigma**
- **Under faulted conditions, a known bias (due to failure of a single SV or RR) is added to a zero-mean distribution with the same sigma**
- **Weighted-least-squares is used to translate range-domain errors into position domain**
  - **Broadcast sigmas are used in weighting matrix, but these are not the same as truly "nominal" sigmas.**

Use of "Prior Probabilities"

- **Prior probabilities of potentially threatening failures and anomalies are needed to complete fault tree allocation and verification.**
  - **K_{MD} values in fault-mode protection level equations are derived based on estimated prior probabilities (for satellites) or required prior probabilities (for ground equipment).**

- **For CAT I LAAS:**
  - **H1 requirement (to support VPL_{H1} and KMD $\approx$ 2.9): probability of faults threatening integrity of reference receiver corrections must be *lower than 10^{-5} per approach (over all RRs)*.**
  - **For comparison, continuity requirement on reference receiver failures (which includes all causes of loss of function, not just integrity faults), is similar: *2.3×10^{-6} per 15 sec (over all RRs).***
  - **Satellite failure probabilities and atmospheric anomaly probabilities are beyond designers' control → *these must be conservatively estimated*.**

Two Failure Probabilities of Interest

- **Failure *Onset* Probability (probability of transition from "nominal" to "failed" state per unit time)**
  - **Poisson approx.: not valid at beginning and end of SV life**

$$P_{F,onset} \cong \frac{number\ of\ observed\ fault\ events}{total\ observation\ time}$$

$$MTBF \cong \frac{1}{P_{F,onset}} \equiv \text{Mean Time Between Failures}$$

- **Failure *State* Probability (long term average probability of being in fault state)**
  - **exponential queuing approximation**

$$P_{F,state} \cong \frac{MTTR}{MTBF + MTTR}$$

$$MTTR \equiv \text{Mean Time To Repair (following failure onset)}$$

SV Failure Probability Estimate from SPS Performance Standard

- **From *GPS SPS Performance Standard* (4th Ed, 2008): No more than three (3) GPS service failures per year (across GPS constellation) for a maximum constellation of 32 satellites.**
  - ***Service failure*: SV failure leading to SPS user range error > 4.42 URA without timely OCS warning or alert**

- **Assuming 3 failures per year over a 32-SV constellation:**

$$\frac{3 \text{ events/year}}{8766 \text{ hours/year}} \; \frac{1}{32 \text{ satellites}} = \boxed{1.07 \times 10^{-5} \text{ events/SV/hour}}$$

$$1.07 \times 10^{-5} \frac{\text{events/SV}}{\text{hour}} \; \frac{150 \text{ sec/approach}}{3600 \text{ sec/hour}} = 4.46 \times 10^{-7} \text{ events/SV/approach}$$

SV Fault Probabilities Assumed by LAAS

- **SPS definition of service failure does not cover all faults of concern to LAAS.**
  - **LAAS users could be threatened by differential range errors of 1 meter or less ("peak risk" concept).**
- **SV prior failure probability for LAAS integrity analyses was conservatively set to 10^{-4} per SV per hour (or 4.2×10^{-6} per SV per approach).**
  - **This is *9.4 times larger* than probability on previous slide.**
- **Furthermore, given lack of detail regarding failure types in SPS Performance Standard, *each* SV failure mode was assigned this entire probability (rather than dividing probability among them).**

Interpretations of "MI" and "HMI"

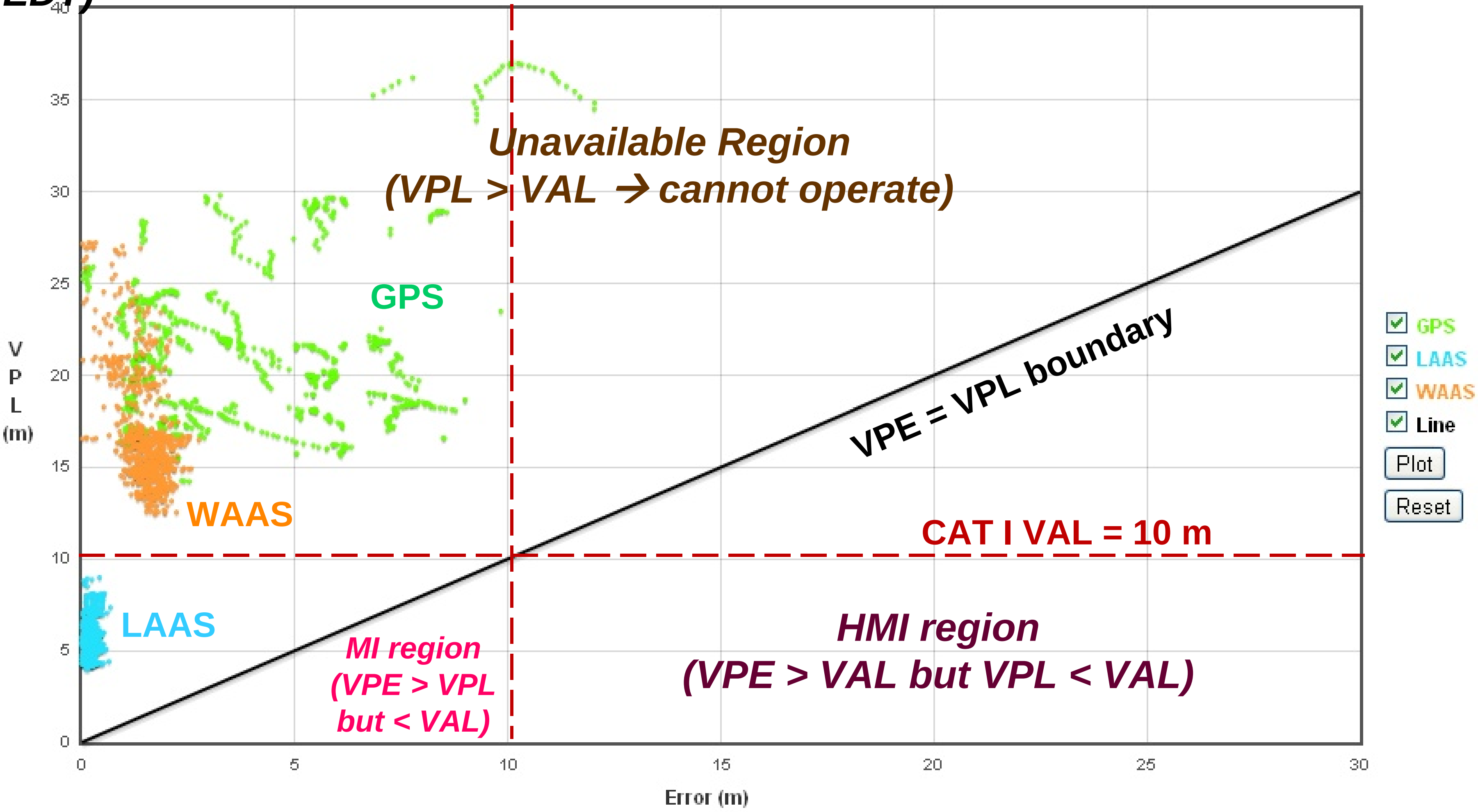
- **Recall that *Misleading Information (MI)* refers to a condition where the actual error exceeds a safe limit without annunciation within the time to alert.**

- **For WAAS, and in the GBAS SARPS, the "safe limit" is defined as the *protection level*, not the alert limit.**
  - **Therefore, protection level error bounding is required to avoid loss of integrity**
  - **This avoids limiting applicability to particular operations (which define alert limits), but it is much harder to achieve.**

- **MI in which the alert limit is also exceeded can be defined as *Hazardously Misleading Information* (HMI).**
  - **Note that "Hazardous" does not specify consequence in Hazard Risk Index.**

"Triangle Chart" Error Bounding Illustration

VPE and VPL at Newark Airport from 9/12/11 (10 AM EDT) to 9/13/11 (8 PM EDT)



Unavailable Region (VPL > VAL → cannot operate)

VPE = VPL boundary

CAT I VAL = 10 m

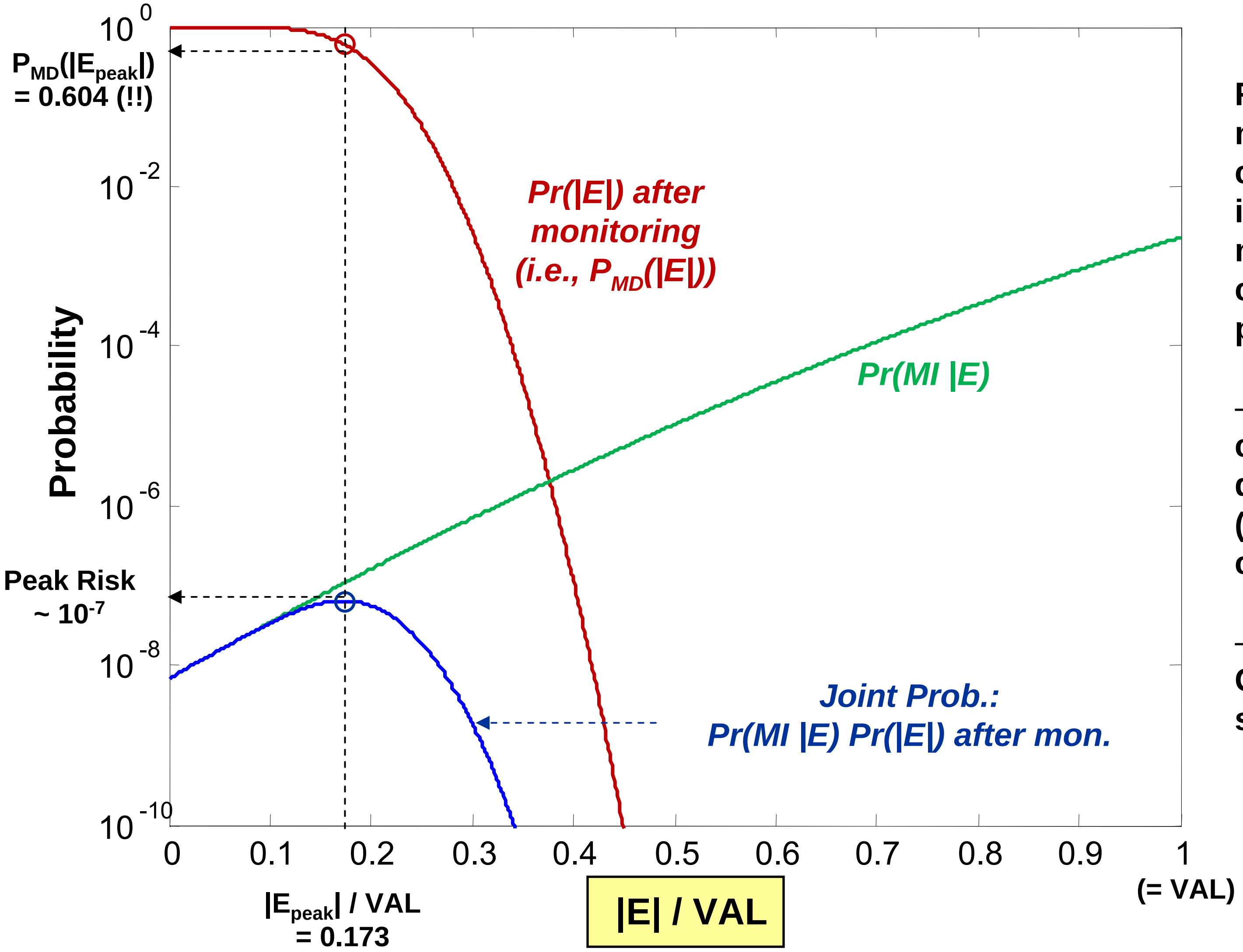
MI region (VPE > VPL but < VAL)

HMI region (VPE > VAL but VPL < VAL)

Source: **FAA Technical Center,** http://laas.tc.faa.gov/EWR_Graph.html

The “Peak Risk” Model

GAST-D Ephemeris Error Monitor Example



Results are mathematically correct, but errors in assumptions make conclusions conservative in practice:

– (VAL + δ) is completely dangerous, while (VAL – δ) is completely safe

– P_{MD}(E) based on Gaussian test statistic behavior

The Role of "Threat Models"

- **Faults and anomalies are rare events that are often difficult to characterize by theory or data.**
  - **For example, anomalous signal deformation has only been observed once, on GPS SVN 19 in 1993.**

- **Most engineers prefer deterministic models for fault behavior, including min. and max. parameter bounds.**

- **Therefore, *threat models* that bound extent and behavior are developed for each fault mode or anomaly of concern.**

- ***Big Problem*: the uncertainty created by lack of information does not go away.**
  - **Very conservative modeling may sacrifice performance.**
  - **The temptation of non-conservative modeling (when facing difficult threats) has led to unpleasant surprises for both WAAS and LAAS.**

The Role of “Assertions”

- **As shown on the previous slides, imperfect knowledge of rare events requires that (conservative) assumptions be made to make modeling and mitigation practical.**
- **Assumptions like these are often called “*assertions*,” which carries a subtle difference in meaning.**
- **An “assertion” typically represents an assumption that is being “asserted” as true for the purposes of integrity or continuity validation.**
  - **This clarifies that the subsequent validation is dependent on the assertion and its rationale.**
  - **The degree of justification for a given assertion varies with its “reasonableness” and its “criticality.”**
- **As you can imagine, assertions are easy to abuse, and they often are – *be careful* !!**

Documentation of Results

- **WAAS and LAAS have developed a specific approach to documenting integrity validation in support of system design approval (SDA, aka "certification").**
- **The key elements:**
  - ***Algorithm Description Documents (ADDs)* – these describe each algorithm in complete detail, sufficient to allow DO-178B-qualified coding by someone unfamiliar with the algorithm.**
  - ***"HMI" Document* – this show in detail how the system and its monitors mitigate all identified integrity threats (it addresses continuity and availability to a much lesser extent).**
- **These documents support the existing FAA safety-assurance process.**
  - **FAA System Safety Handbook:** http://www.faa.gov/library/manuals/aviation/risk_management/ss_handbook/

The Challenge of Continuity

- **Two causes of continuity loss:**
  - **Actual faults or anomalies**
  - **“Fault-free” alerts: monitor alerts due to excessive measurement noise under “nominal” conditions**
- **Actual faults may directly cause loss of service (e.g., loss of satellite or VDB signal) or trigger monitor alert and measurement exclusion.**
  - **In latter case, monitor protects integrity as designed, but at the price of continuity.**
- **Loss of individual satellites (or reference receivers) do not necessarily cause loss of continuity…**
  - **Protection levels computed from remaining measurements may still be acceptable**

Critical Satellites

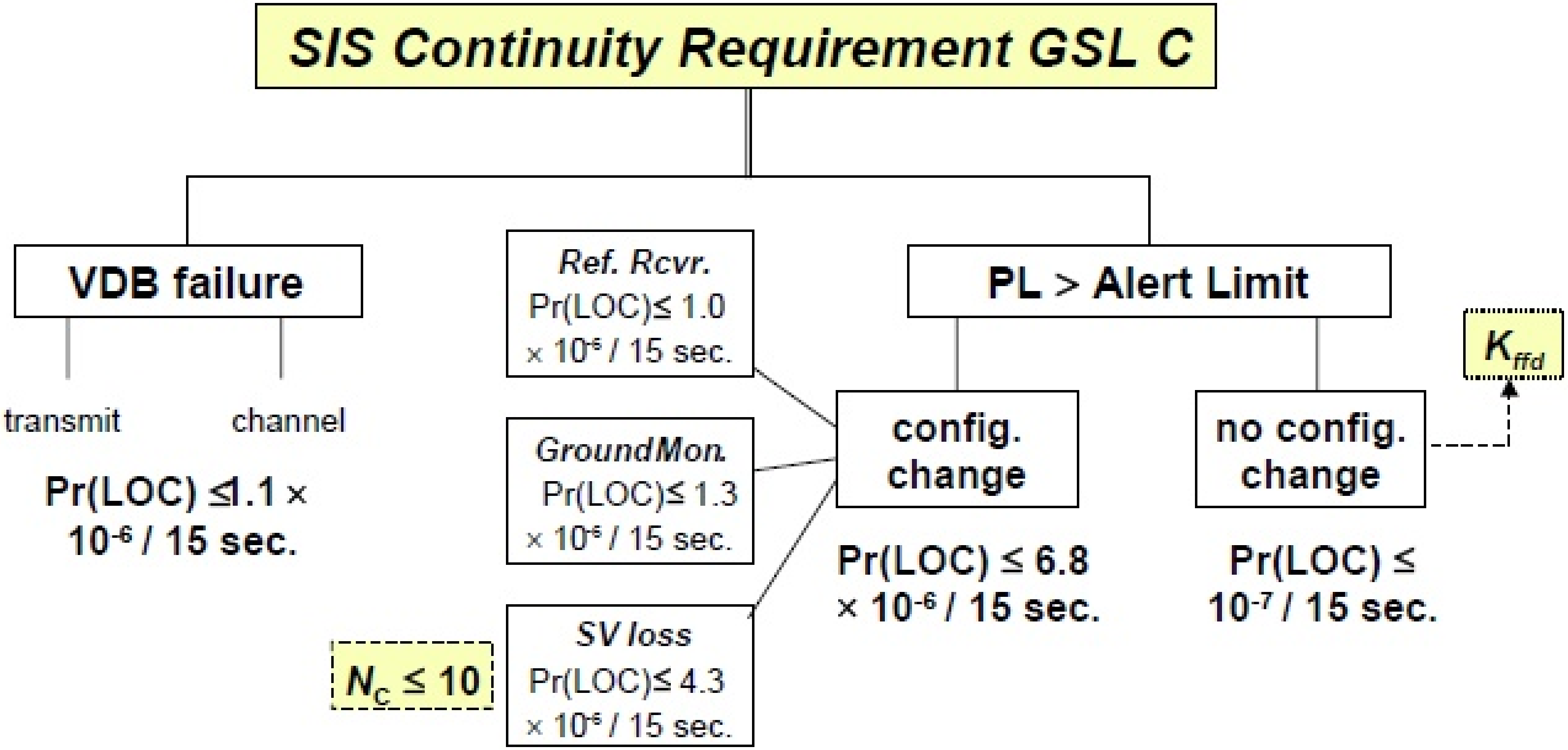
- A ***critical satellite*** **is one whose loss (or exclusion due to monitor alert) leads to loss of continuity.**
  - **VPL with critical satellite included is below VAL**
  - **With critical satellite excluded, VPL now exceeds VAL, requiring operation to be aborted**

Critical Satellites in CAT I LAAS (Original RTCA Error Model, 1998)

Number of Usable SV in View	Fraction of Avail. Geometries	Average Number of Critical Satellites
3 or less	0	N/A
4	0.0022	4.0 (by definition)
5	0.0516	1.2083
6	0.2531	0.2543
7	0.4136	0.0326
8 or more	0.2795	$<$ 0.001

CAT I LAAS SIS Continuity Allocation

Source: **RTCA LAAS MASPS, DO-245A, Dec. 2004.**



- **Required Mean Times to Failure (assuming Exponential distribution of failure times) for each function and component can be derived from this allocation.**
- **Assumed GPS satellite MTTF ≥ 9740 hrs (beyond spec. → historical performance)**

What Makes Continuity So Hard?

- **The key difficulty to meeting the continuity requirement is doing so while meeting the (higher-visibility) integrity requirement *at the same time*.**
  - **Meeting integrity with high confidence requires a great deal of conservatism to account for threat uncertainty.**
  - **Thresholds are generally set as tight as false-alert allocations from continuity requirement allow.**
  - **However, as will be seen, monitor test statistics do not follow assumed Gaussian distributions at low probabilities.**
  - **As a result, *measurements will be excluded much more often than necessary* if perfect information were available.**
- **Required MTTFs are difficult to meet with real HW.**
- **Budget has *no allocation* for RF interference.**

Specific vs. Average Probabilities

- ***Average Risk (my definition)*: the probability of unsafe conditions based upon the convolved ("averaged") estimated probabilities of all unknown events.**

- ***Specific Risk (my definition)*: the probability of unsafe conditions subject to the assumption that *all (negative but credible) unknown events that could be known occur with a probability of one*.**
  - ***Required for aviation integrity* → must meet requirements under worst-case conditions that are deemed safe for use ("available").**

- ***Key Question:* when can continuity be evaluated under "average risk" criteria?**
  - **WAAS LPV continuity is evaluated this way → loss of continuity deemed to be of "Minor" consequence.**
  - **LAAS CAT I may follow the same approach, but loss of continuity for CAT III is likely to be deemed "Major" or higher.**

Outline

- Augmented GNSS Terminology
- Introduction to GNSS and GNSS Augmentation – Differential GNSS (DGNSS)
- GBAS and SBAS System Architectures
- Aviation Applications and Requirements
- Principles of Integrity and Continuity
- Specific Examples:
  - Nominal Error Bounding
  - Signal Deformation Monitoring
  - Ephemeris Monitoring
  - Ionospheric Anomaly Mitigation
- Summary

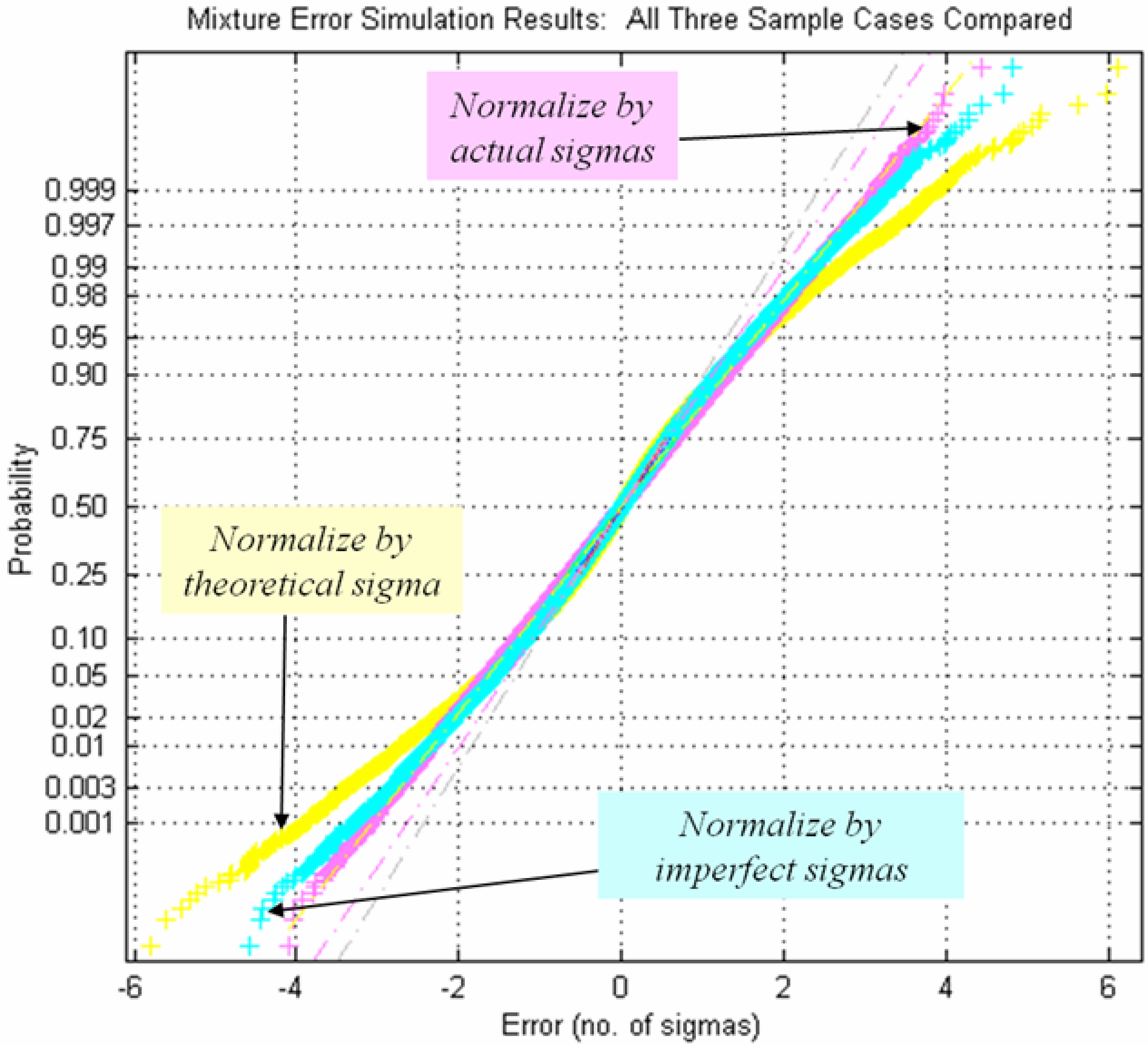
Nominal Error Bounding: *Problem Statement*

- **As shown previously, an important component of integrity risk is HMI under "nominal conditions"**
  - **For GBAS, integrity risk under "H0 hypothesis"**
- ***In principle*, "nominal" refers to the error model that reflects normal working conditions.**
  - **No system faults or anomalies are present**
  - ***Integrity risk is given by the tail probabilities of the nominal error distribution***
- ***In practice*, this division between "nominal" and "faulted" or "anomalous" conditions is too simple.**
  - **Multiple degrees of "off-nominal" conditions also exist**
  - **No one error distribution applies, and the tails of the distributions that might apply are *fatter than Gaussian***

Nominal Error Bounding: *Requirements*

- **SARPS and RTCA standards require that nominal error distribution be Gaussian with zero mean.**
  - **Recall previous slides on protection level equations**
- ***Therefore,* SBAS and GBAS must develop “overbounding” zero-mean Gaussian distributions that bound the cumulative distribution function (cdf) of the actual (unknown) nominal error distribution in the tails.**
  - **“Tails” refers to probabilities out to integrity risk allocated to “HMI under nominal conditions” (~ 6 × 10^{-9} for CAT I GBAS)**
- **When the “nominal error distribution” is actually a family of off-nominal, non-Gaussian distributions of unknown form and magnitude, *proving* a bound at the ~ 10^{-7} – 10^{-9} probability level is not possible.**
  - **What can we do, short of that?**

Theoretical Impact of Sampling Mixtures on Gaussian Tails

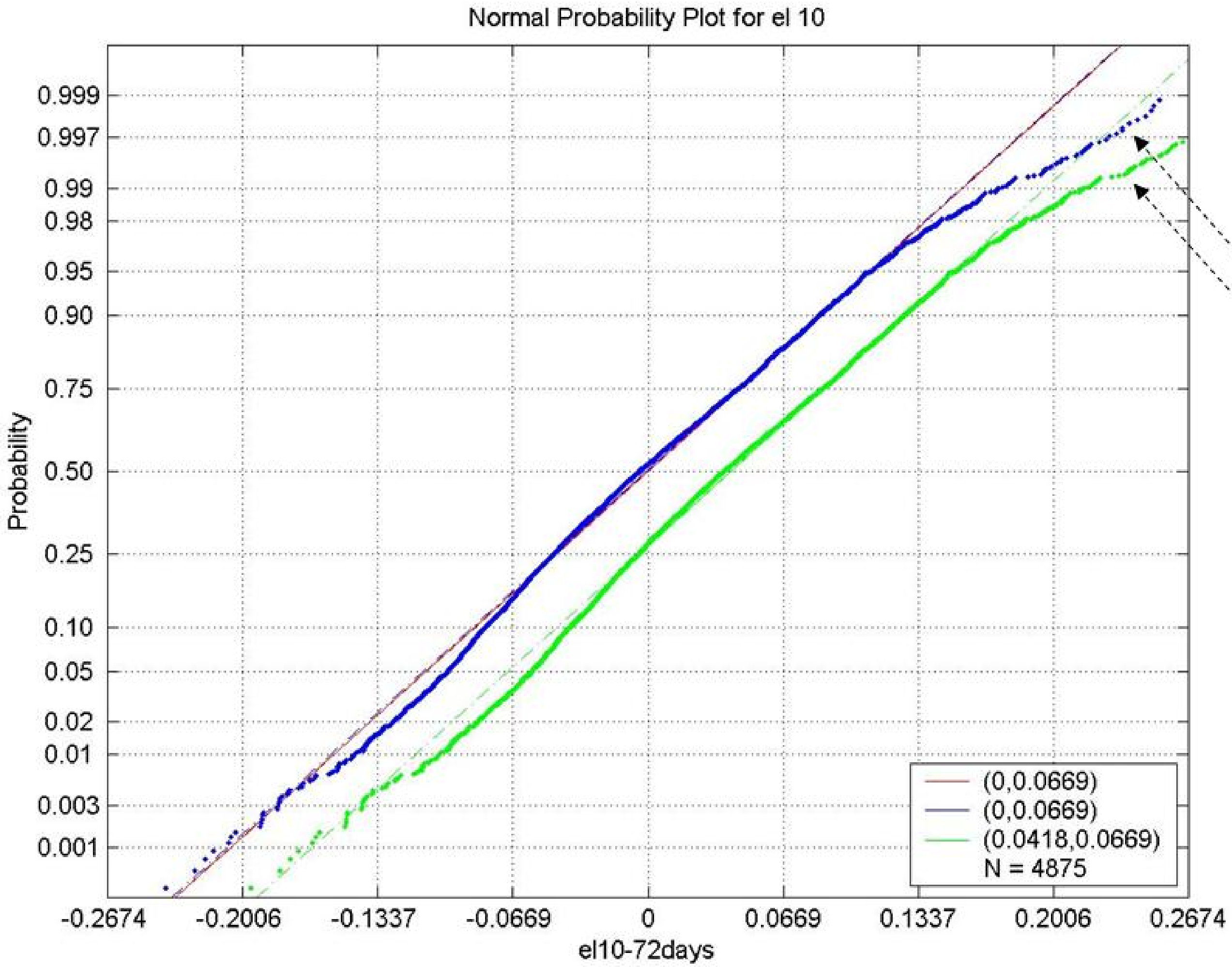


"Mixing" of Gaussian distributions with different sigmas results in non-Gaussian tail behavior)

- **Result trends toward double-exponential dist. (J.B. Parker, 1960's)**
- **Corresponds to combinations of many varieties of "off-nominal" conditions, even if their tails were Gaussian**
- **Since each input dist. is actually fatter-than-Gaussian in the tails, resulting distribution is unknown.**

LAAS Test Prototype Error Estimates
(9.5 – 10.5 degree SV elevation angle bin)

72 days of data: June 1999 – June 2000
200 seconds between samples

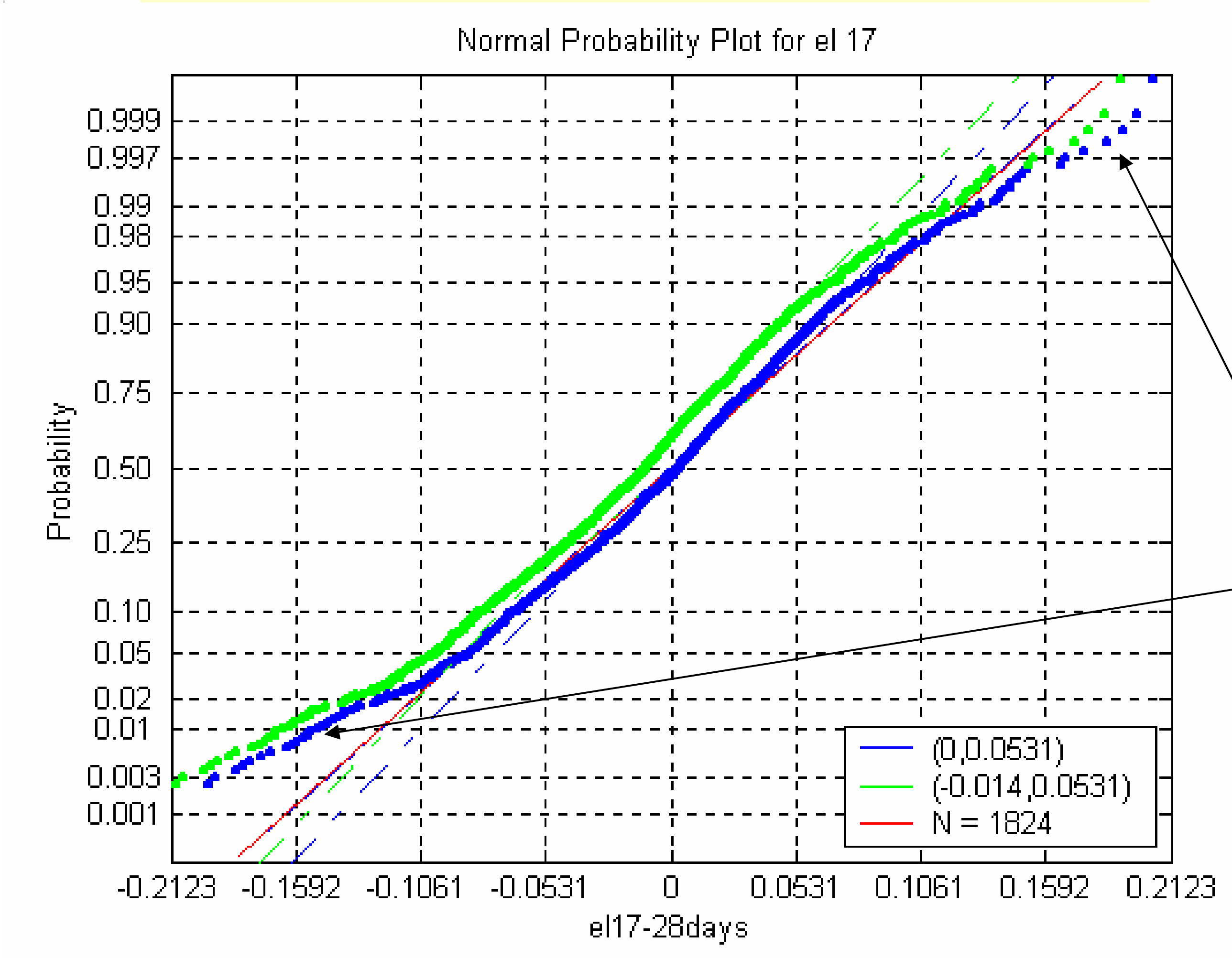


Significant tail inflation observed

***Source*: John Warburton, FAA Technical Center**

LAAS Test Prototype Error Estimates
(16.5 – 17.5 degree SV elevation angle bin)

28 days of data since June 2000
200 seconds between samples

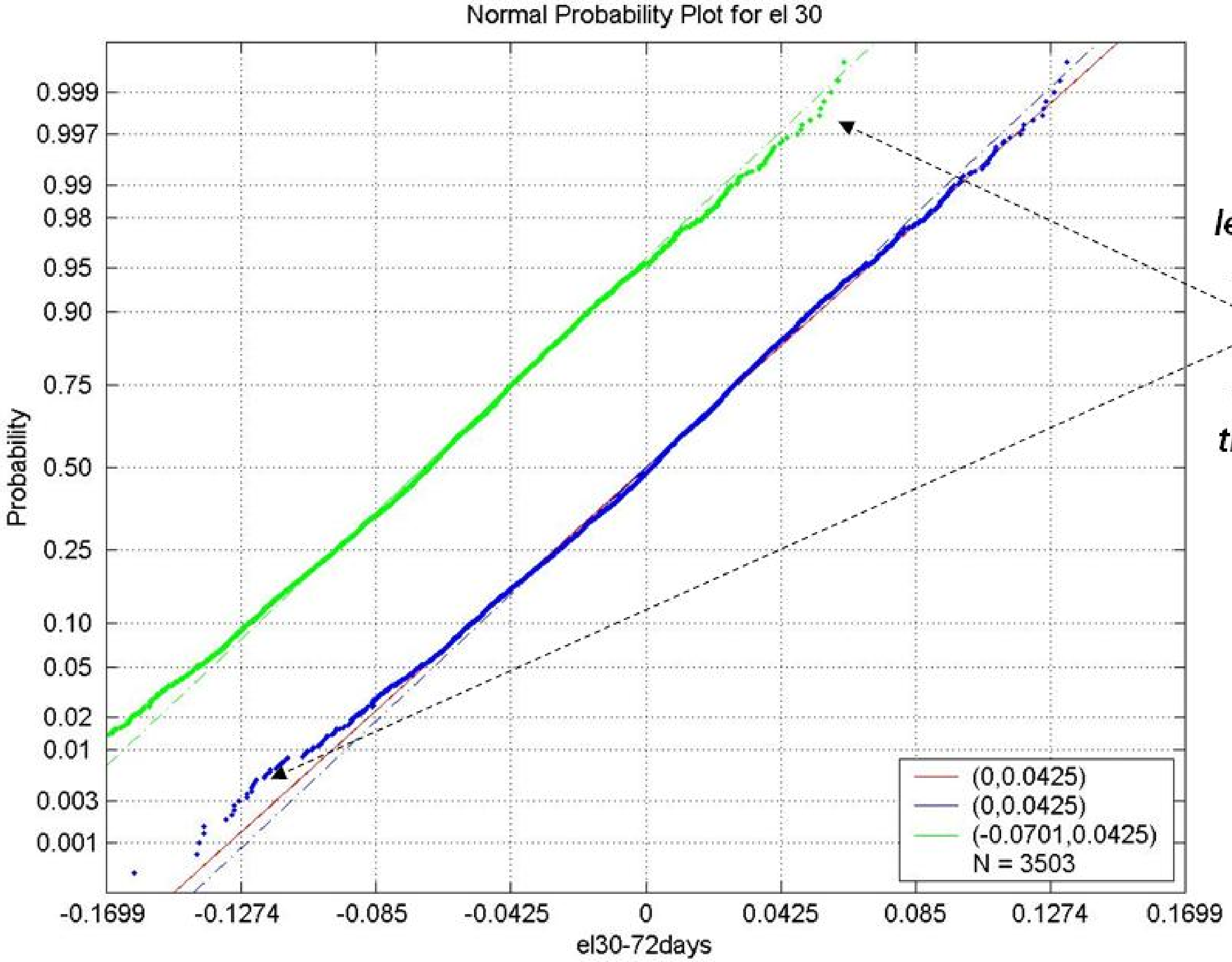


Similar tail inflation pattern – visible at both extremes

***Source*: John Warburton, FAA Technical Center**

LAAS Test Prototype Error Estimates
(29.5 – 30.5 degree SV elevation angle bin)

72 days of data: June 1999 – June 2000
200 seconds between samples



Tail inflation is less pronounced, most likely due to reduced multipath variation within this bin (i.e., less "mixing")

***Source*: John Warburton, FAA Technical Center**

Nominal Error Bounding: *Theoretical Approaches*

- ***Empirical approach*: inflate sample sigma of collected data until zero-mean Gaussian bounds tail behavior.**
  - **Insufficient due to uncertainty of behavior beyond sampled data**
- ***Error modeling approach*: attempt to bound each error source separately, arranging error sources into “deterministic,” “non-Gaussian” categories, etc., and creating a complex, non-Gaussian overall error model.**
  - **Necessary and useful, but does not address the problem of observing unpredicted fatter-than-Gaussian tails in collected data.**
- ***B. DeCleene overbounding “proof” (ION GPS 2000)*:**
  - **Requires unknown error distribution be symmetric and unimodal**
- ***J. Rife “paired” and “core” bounding***
  - **Relaxes DeCleene constraints, but still places conditions on tails**

Nominal Error Bounding: *Theoretical Approaches (2)*

- ***WAAS CNMP "moment bounding"***
  - **Relaxes constraints on non-Gaussian tails in data by selecting parameters that provide a "moment bound," meaning a bound on the moments of the collected data.**
  - **In theory, this bounds the worst distribution represented by the moments of the collected data (at the price of conservatism).**
  - **In practice, extensive extrapolation from limited collected data is required → *fundamental tail uncertainty remains*.**
- ***Bounding via Extreme Value Theory (EVT)***
  - **Under certain conditions, the tail behavior of errors could be asserted to follow distributions established by EVT.**
  - **The same problem applies: *How would you show than any particular conditions on unknown errors are met?***
- ***Bottom Line (Sam's opinion):* It is impossible to "prove" nominal error bounding at the 10^{-7} level or below.**

Nominal Error Bounding: *A Practical Addition*

- Except for simple empirical bounding, the approaches above require substantial inflation to achieve an imaginary "proof" of nominal error bounding.
  - Availability may be sacrificed for no benefit.
- Rather than relying on this, add a second step: Monte Carlo sensitivity analysis of the models for each error source.
- Specifically, run Monte Carlo simulations of the theoretical error model (inside a system simulation) in which one error source at a time is replaced by a very conservative "worst case nominal" model of that source.
- Compare results to theoretical approach to determine if the former is adequate, too conservative, or not enough.

GBAS Signal-in-Space Failure Modes

- C/A Code Signal Deformation (aka “Evil Waveforms”)
- Low Satellite Signal Power
- Satellite Code-Carrier Divergence
- Erroneous Ephemeris Data
- Excessive Range Error Acceleration

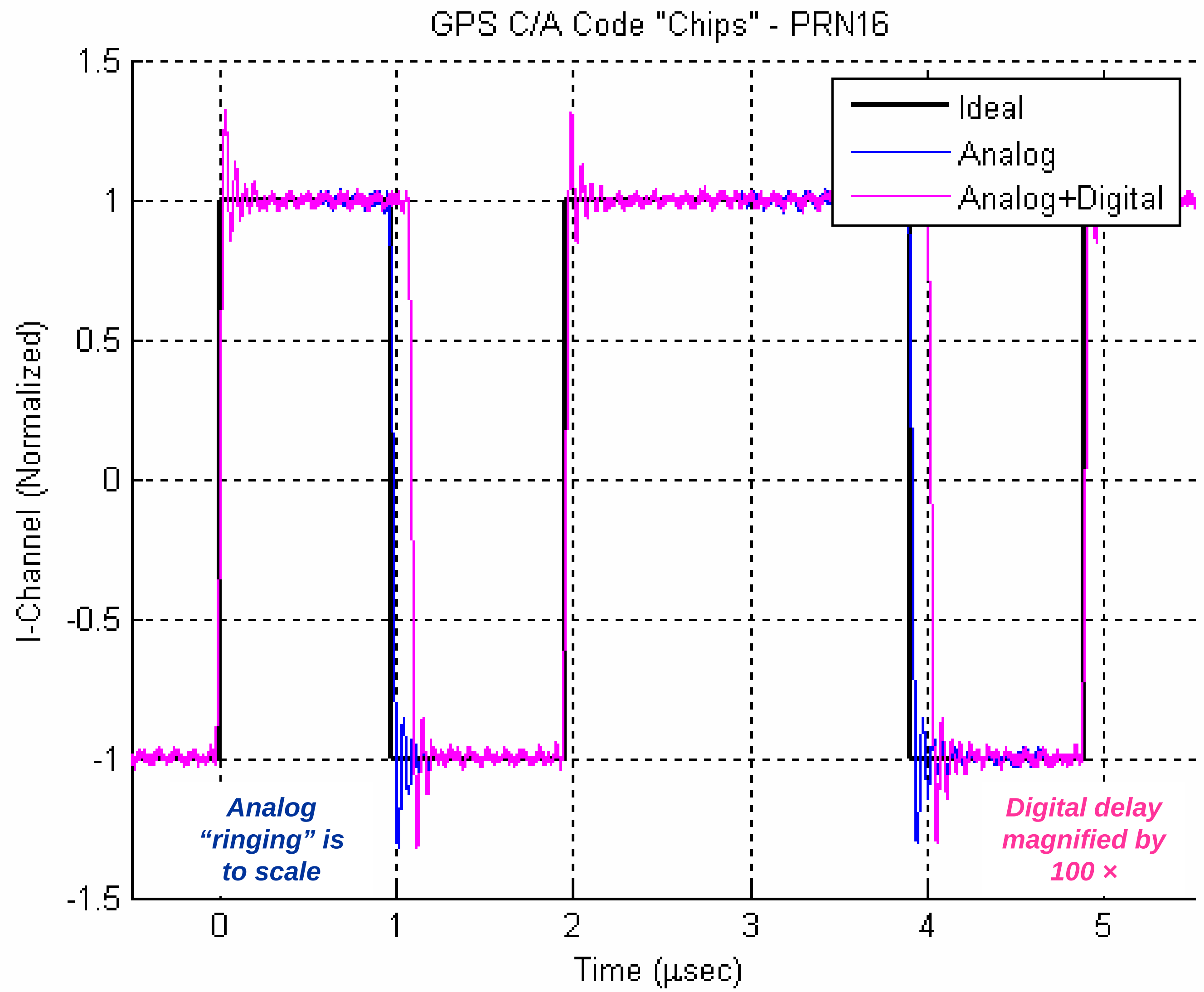
“single-SV failures” (in H2)

- Ionospheric Spatial-Gradient Anomaly
- Tropospheric Gradient Anomaly

“all other failures” (in H2)

Nominal Signals with Deformation (PRN 16 Example)

***Source*: G. Wong, *et al*, “Nominal GPS Signal Deformations, ION GNSS 2011**

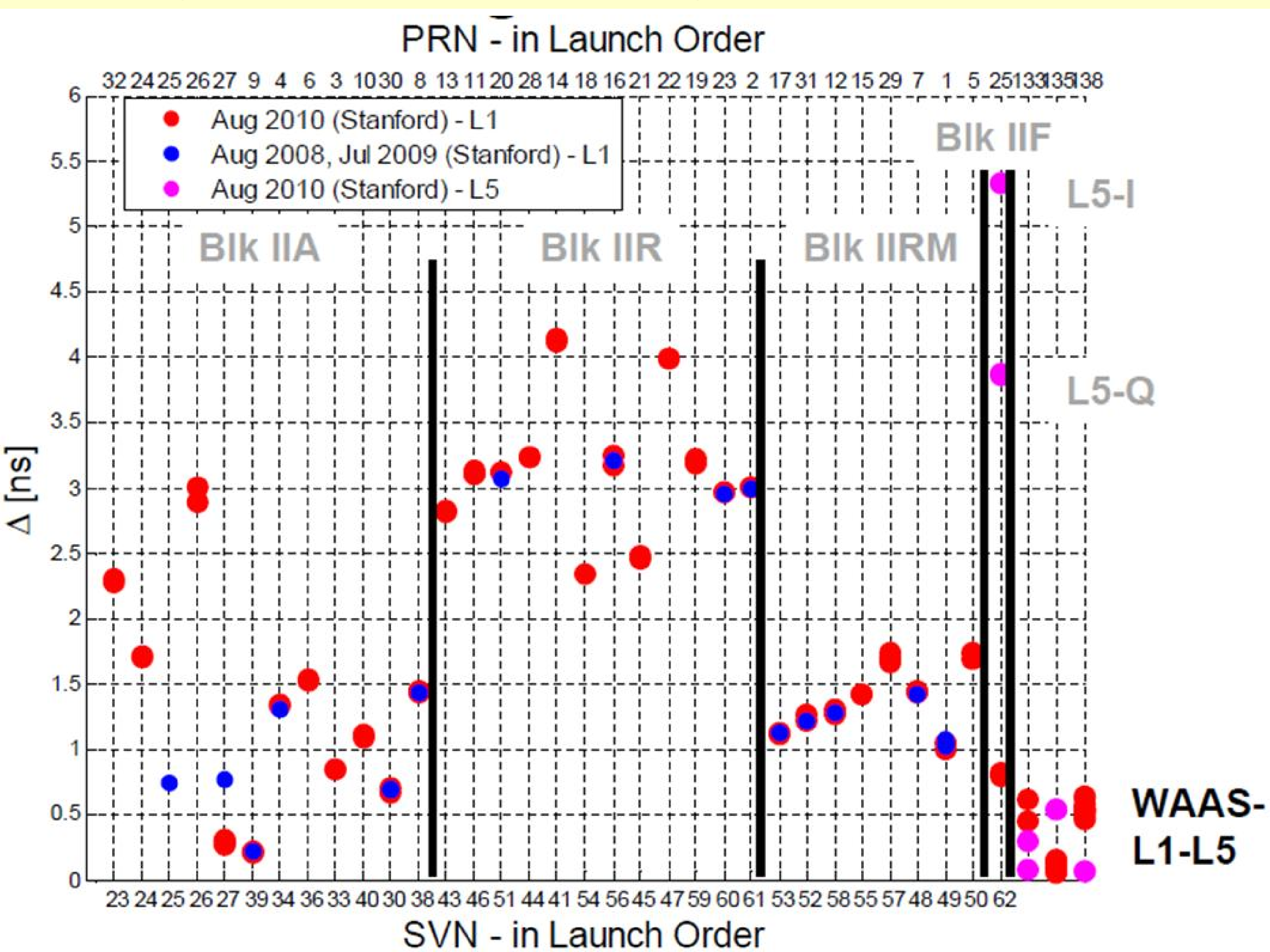


Analog “ringing” is to scale

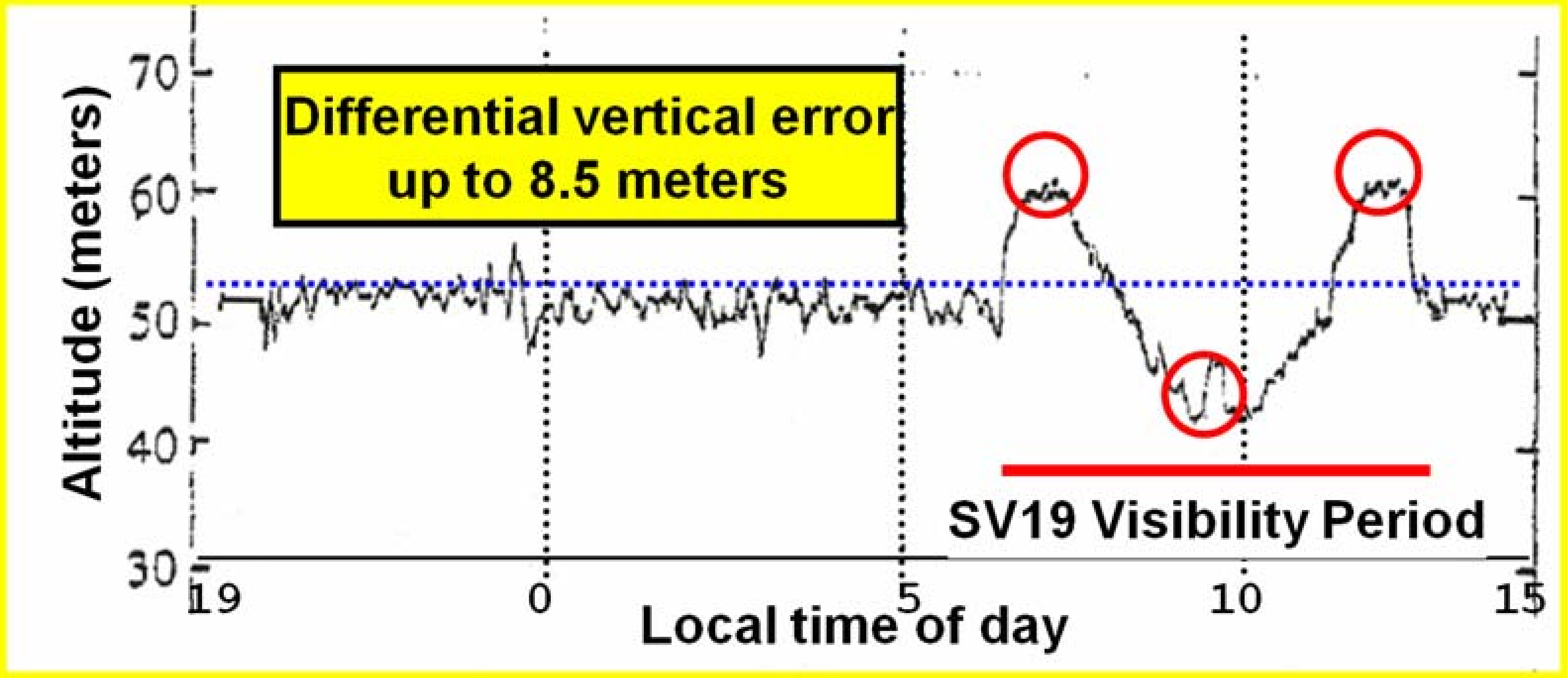
Digital delay magnified by 100 ×

Nominal Digital Distortion: Comparison Across Satellites

***Source*: G. Wong, *et al*, “Characterization of Signal Deformations,” ION GNSS 2010**



Signal Deformation (Modulation) Failure on SVN/PRN 19 in 1993

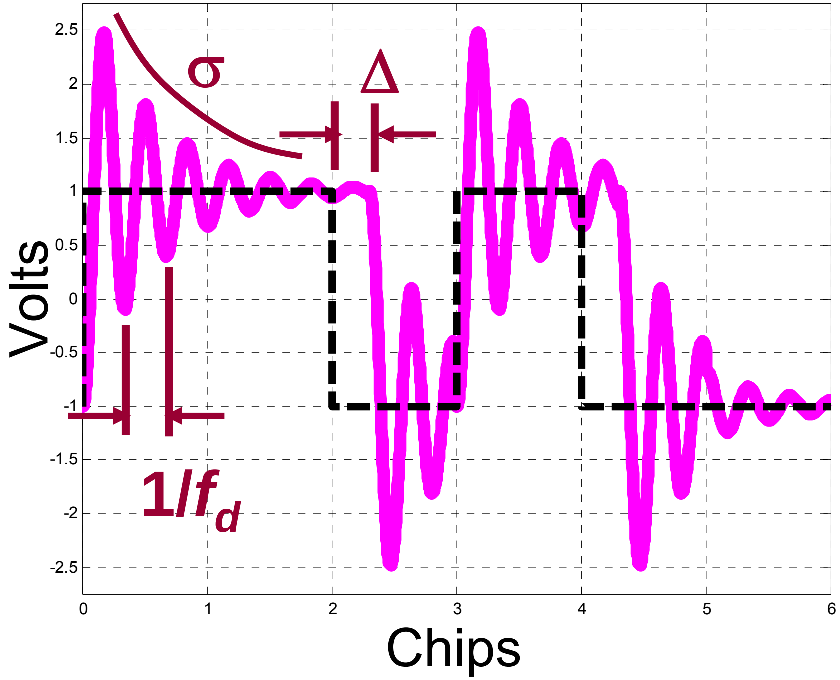


- Differential errors occur when reference and user receivers track code differently, e.g.:
  - Different RF front-end bandwidths
  - Different code correlator spacings
  - Different code tracking filter group delays

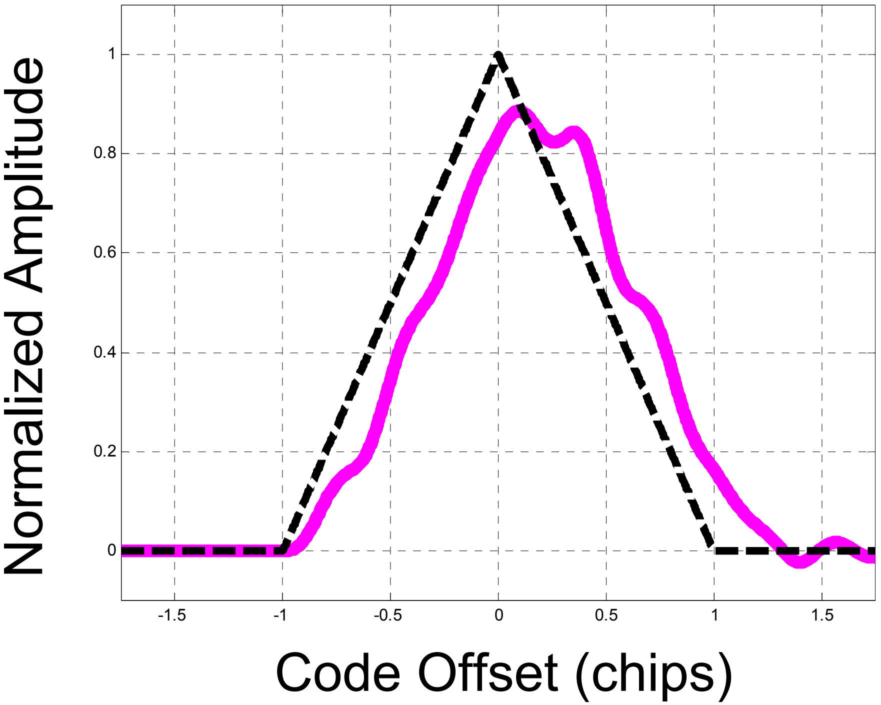
Anomalous Signal Deformation Example from "2nd-Order-Step" ICAO Threat Model

Comparison of Ideal and "Evil Waveforms" for Threat Model C

C/A PRN Codes



Correlation Peaks

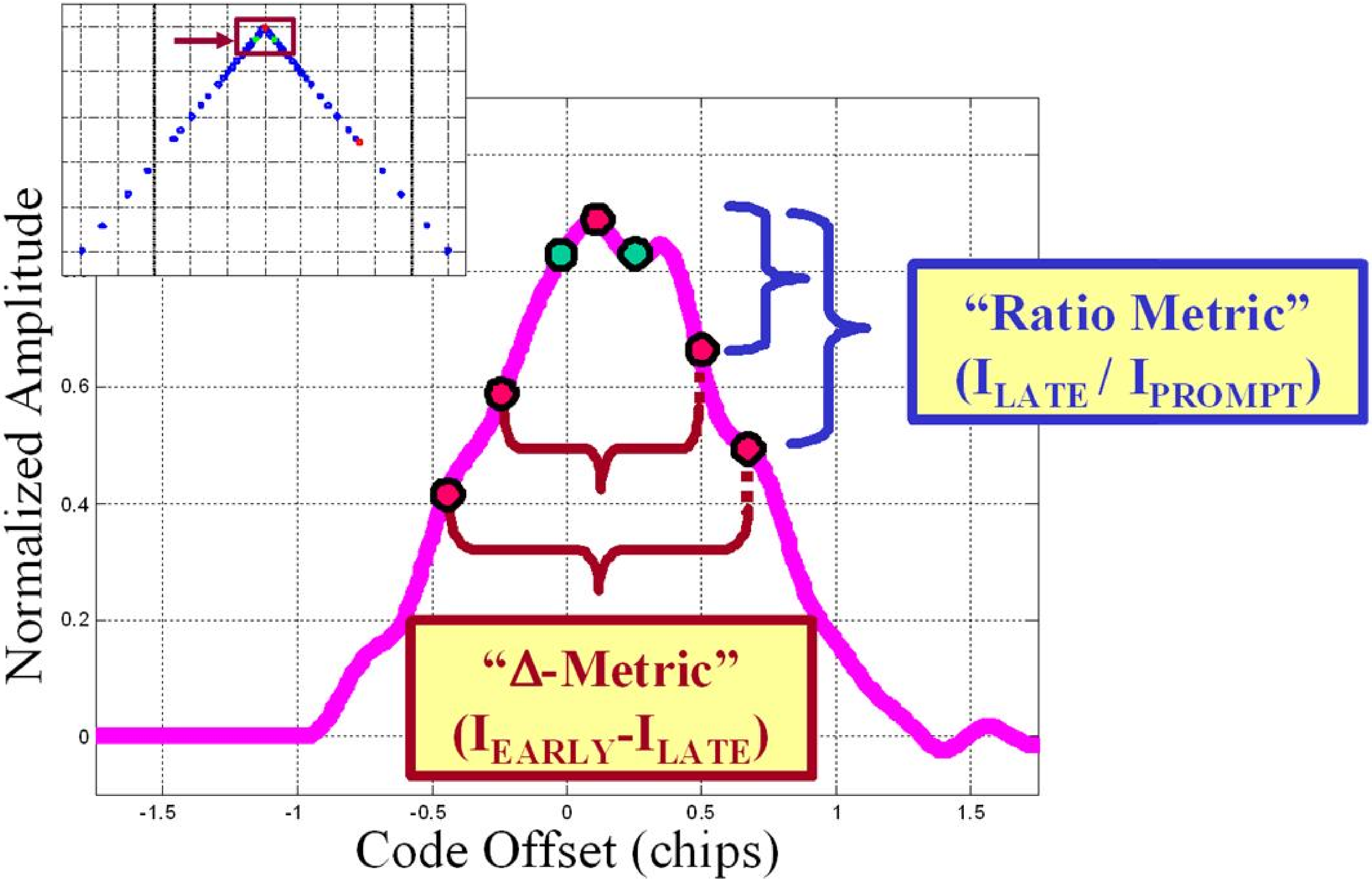


Note:

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

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

Signal Deformation Test Statistics Using Multiple-Correlator Receiver

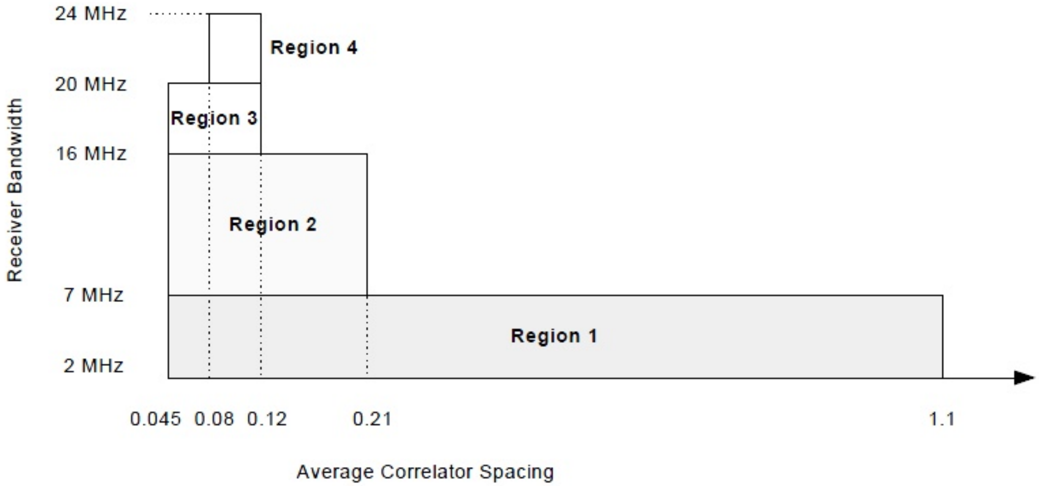


“Ratio Metric”
(I_{LATE} / I_{PROMPT})

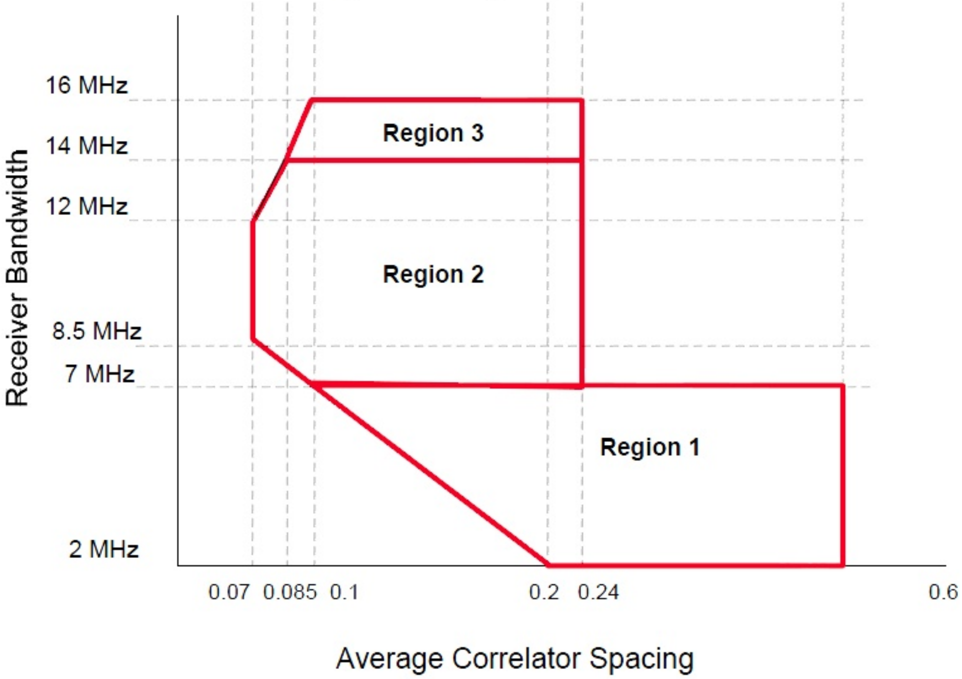
“Δ-Metric”
$(I_{EARLY} - I_{LATE})$

Allowed User Receiver Designs
(RTCA LAAS MOPS, DO-253C, 12/08)

Early-minus-Late (E-L) Receivers



Double-Delta (DD) Receivers



Ephemeris Failure Impact on GBAS Users

- **DGPS user ranging error due to satellite ephemeris error is:**

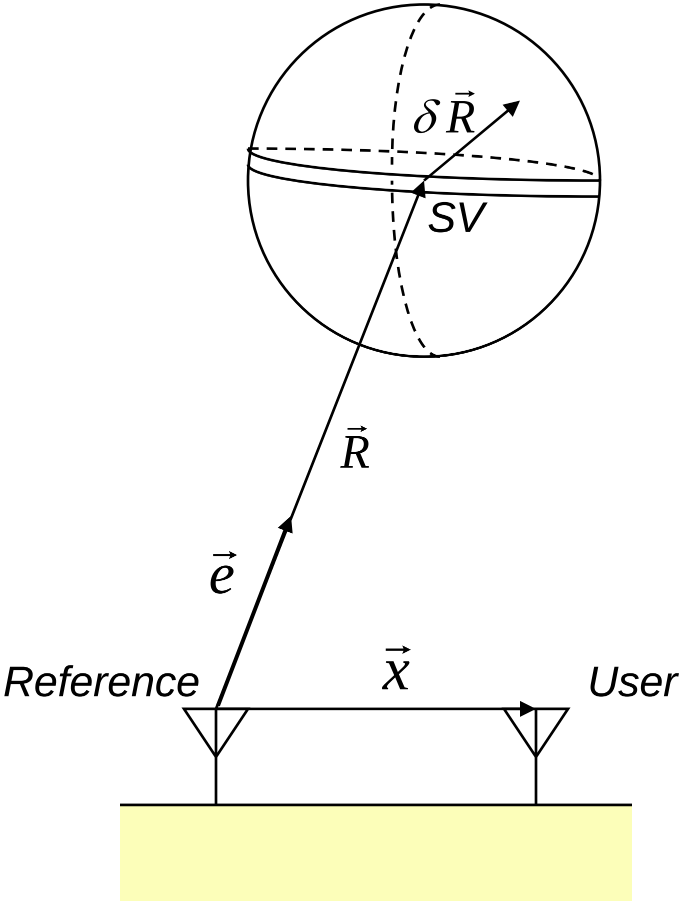
$$\delta\rho \quad = \quad \frac{\delta R^{T} \left(\boldsymbol{I} - e e^{T} \right) x}{\left| R \right|}$$

$|R|$ = Reference –> SV range

$\vec{e}$ = Reference –> SV unit vector

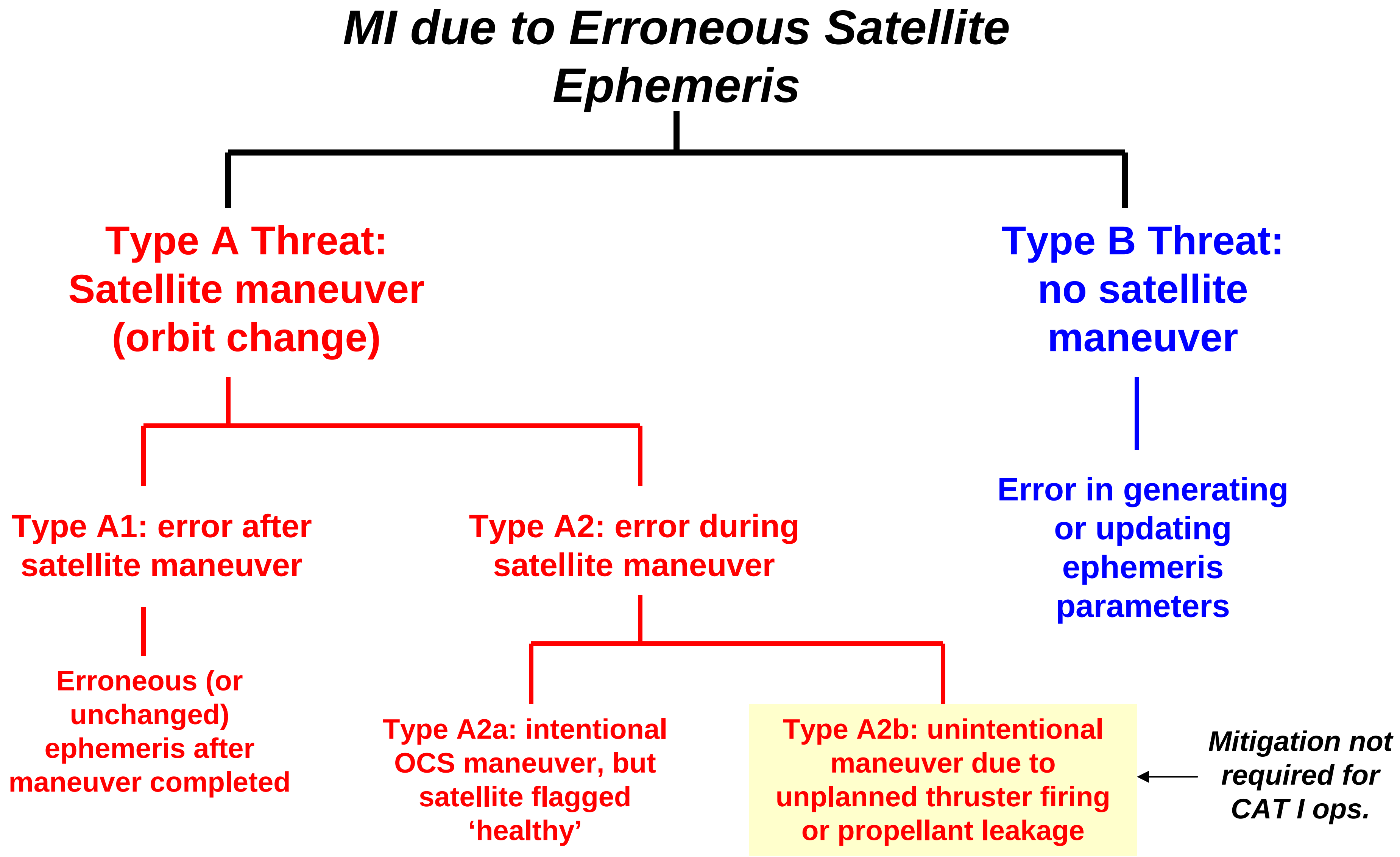
$\delta \vec{R}$ = SV ephemeris error vector

$\vec{x}$ = Reference –> user vector



- **Worst-case user error occurs when $\delta \vec{R}$ is parallel to $\vec{x}$ and when $\vec{e}$ is orthogonal to $\vec{x}$**

LAAS Ephemeris Threat Types



MI due to Erroneous Satellite Ephemeris

Type A Threat: Satellite maneuver (orbit change)

Type A1: error after satellite maneuver

Erroneous (or unchanged) ephemeris after maneuver completed

Type A2: error during satellite maneuver

Type A2a: intentional OCS maneuver, but satellite flagged 'healthy'

Type A2b: unintentional maneuver due to unplanned thruster firing or propellant leakage

Mitigation not required for CAT I ops.

Type B Threat: no satellite maneuver

Error in generating or updating ephemeris parameters

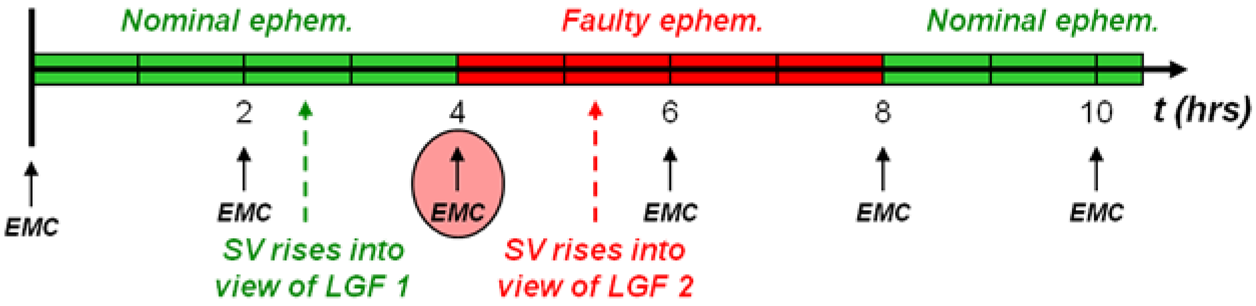
***Source*: H. Tang, et al, "Ephemeris Fault Analysis," IEEE/ION PLANS 2010**

Timelines of Potential Ephemeris Failures

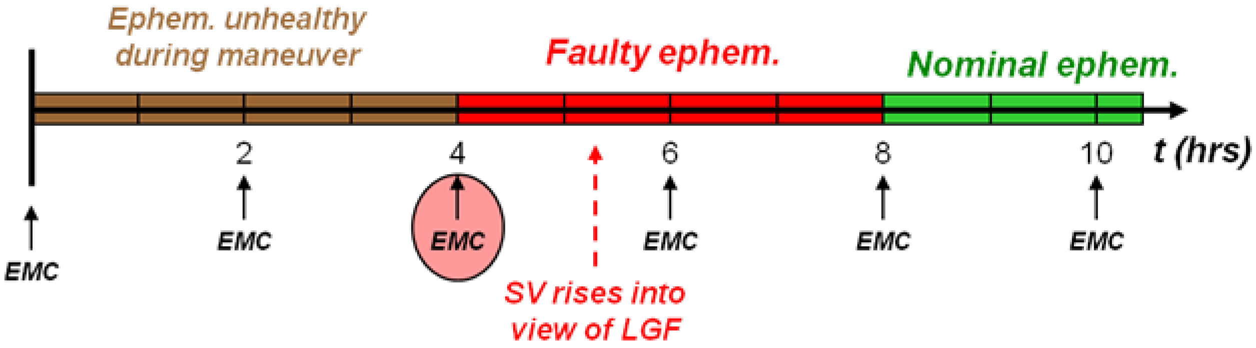
Source: **H. Tang, *et al*, “Ephemeris Fault Analysis,” IEEE/ION PLANS 2010**

EMC: ephemeris message changeover

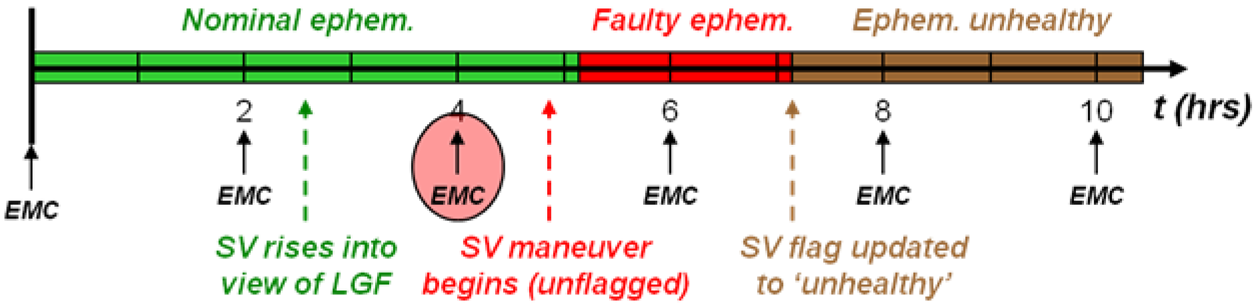
Type B Threat:
No Satellite Maneuver



Type A1 Threat:
Error After Satellite Maneuver Completed



Type A2a Threat:
Error During Satellite Maneuver (after ΔV, during drift to new orbit)



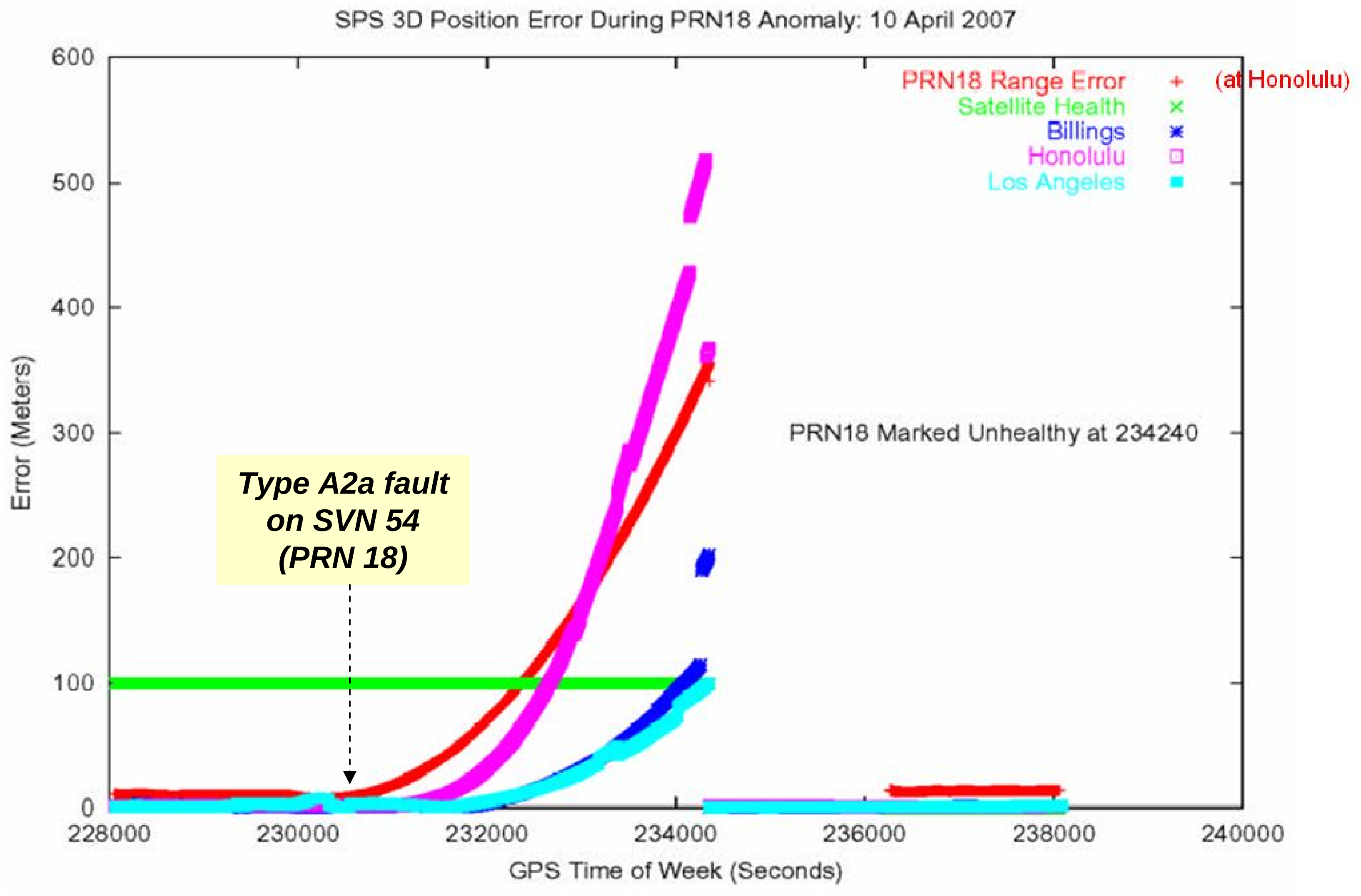
LGF Ephemeris Monitoring

- **Detection of Type B faults is based on comparison of previous (accurate) to current (possibly erroneous) ephemeris parameters.**
  - **Project previous parameters (or satellite positions) forward in time to compare with current ones.**
  - **For SV acquisition, first-order-hold (FOH) test uses two days of prior ephemerides; zero-order-hold (ZOH) uses one day.**
  - **FOH test achieves Minimum Detectable Error (MDE) of no more than 2700 meters in 3-D SV position error.**

- **No “guaranteed” means to detect Type A faults.**
  - **Instead, tight thresholds on Message Field Range Test (MFRT) confirm that pseudorange and range-rate correction magnitudes show no sign of large ephemeris errors.**
  - **Performance validation requires extensive simulation of potential worst-case scenarios.**

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

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



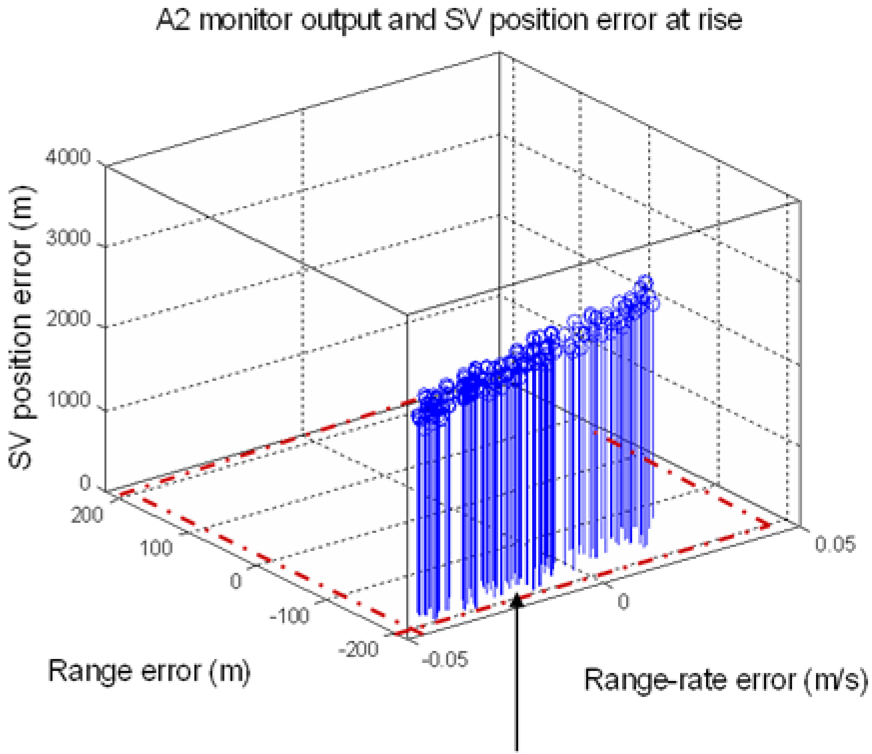
Type A2a fault on SVN 54 (PRN 18)

"Type A" Ephemeris Monitoring: Impact of 200-sec Waiting Period

Source: H. Tang, *et al*, "Ephemeris Fault Analysis," IEEE/ION PLANS 2010

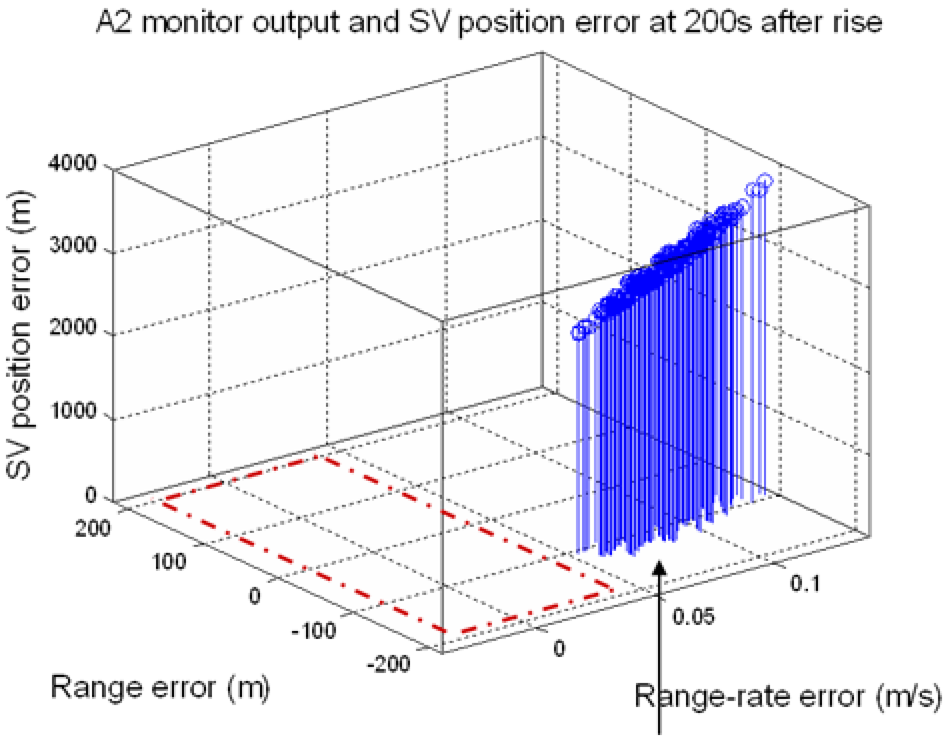
Results for 1-degree Lat/Long. Grid of Hypothetical LGF Locations

At SV Rise



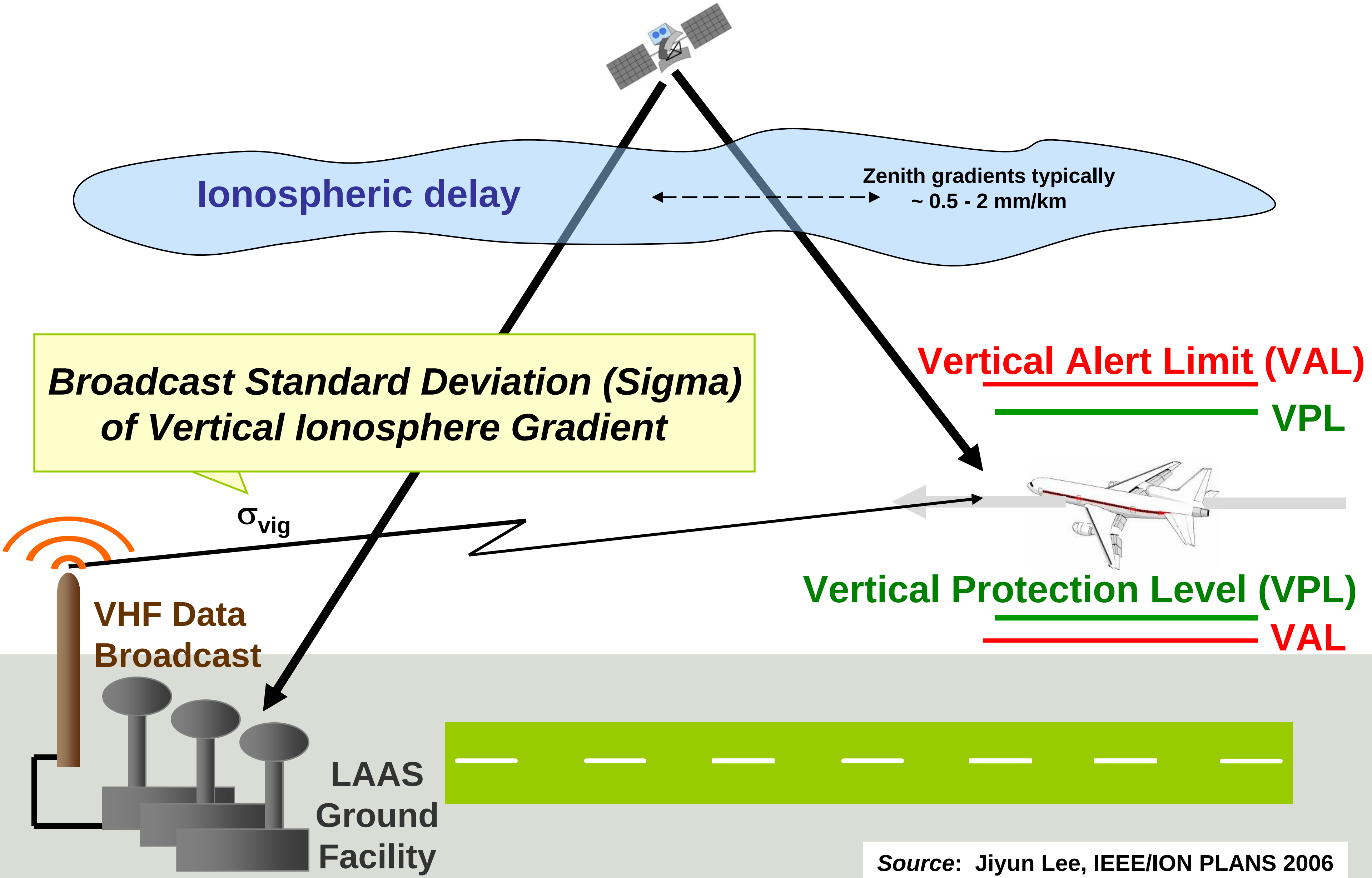
Potentially hazardous cases lie inside "undetectable" zone

200 sec After SV Rise



All large errors are beyond MDEs and are thus "detectable"

Impact of Ionospheric Decorrelation on GBAS



Ionospheric delay

Zenith gradients typically
~ 0.5 - 2 mm/km

Broadcast Standard Deviation (Sigma) of Vertical Ionosphere Gradient

σ_{vig}

Vertical Alert Limit (VAL)

VPL

Vertical Protection Level (VPL)

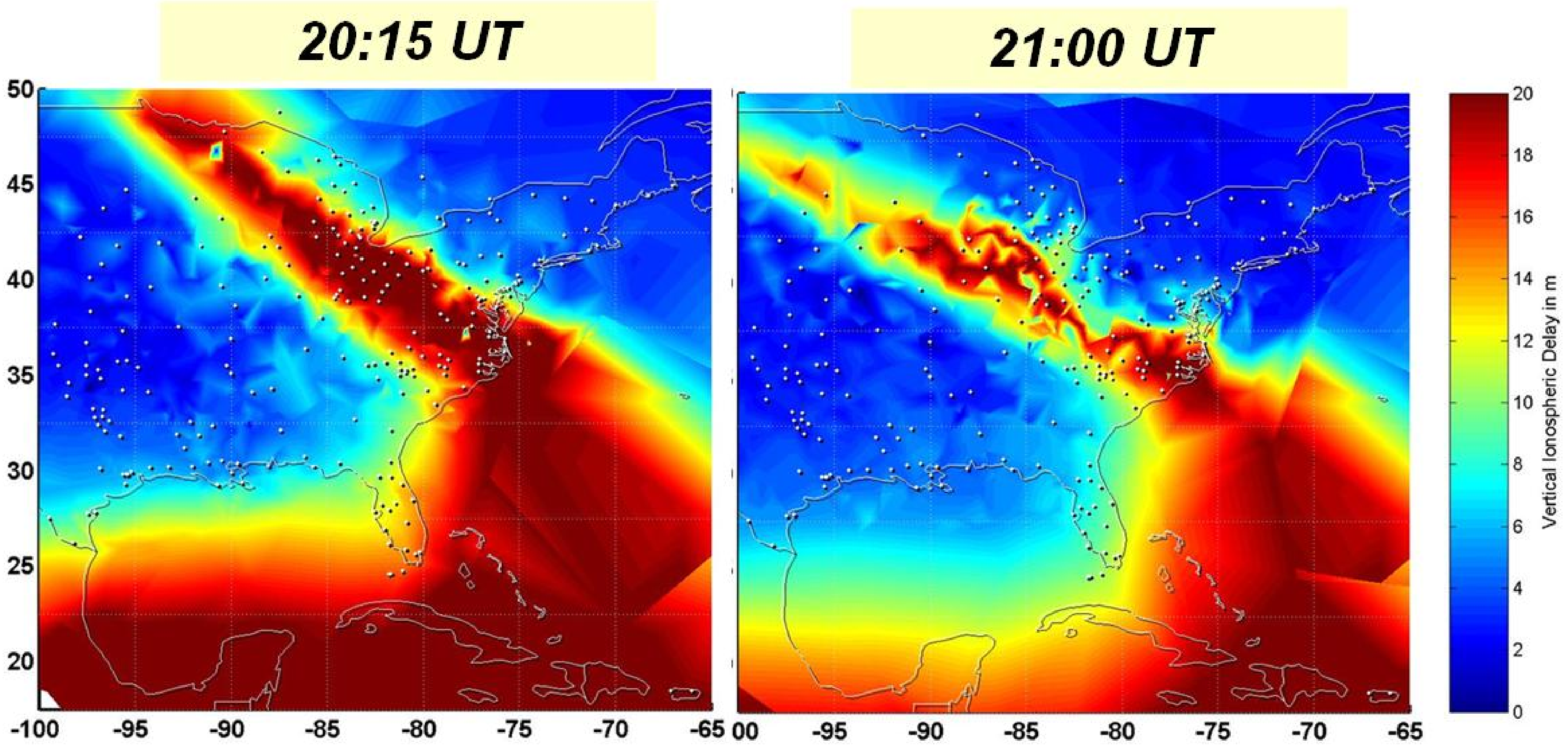
VAL

VHF Data Broadcast

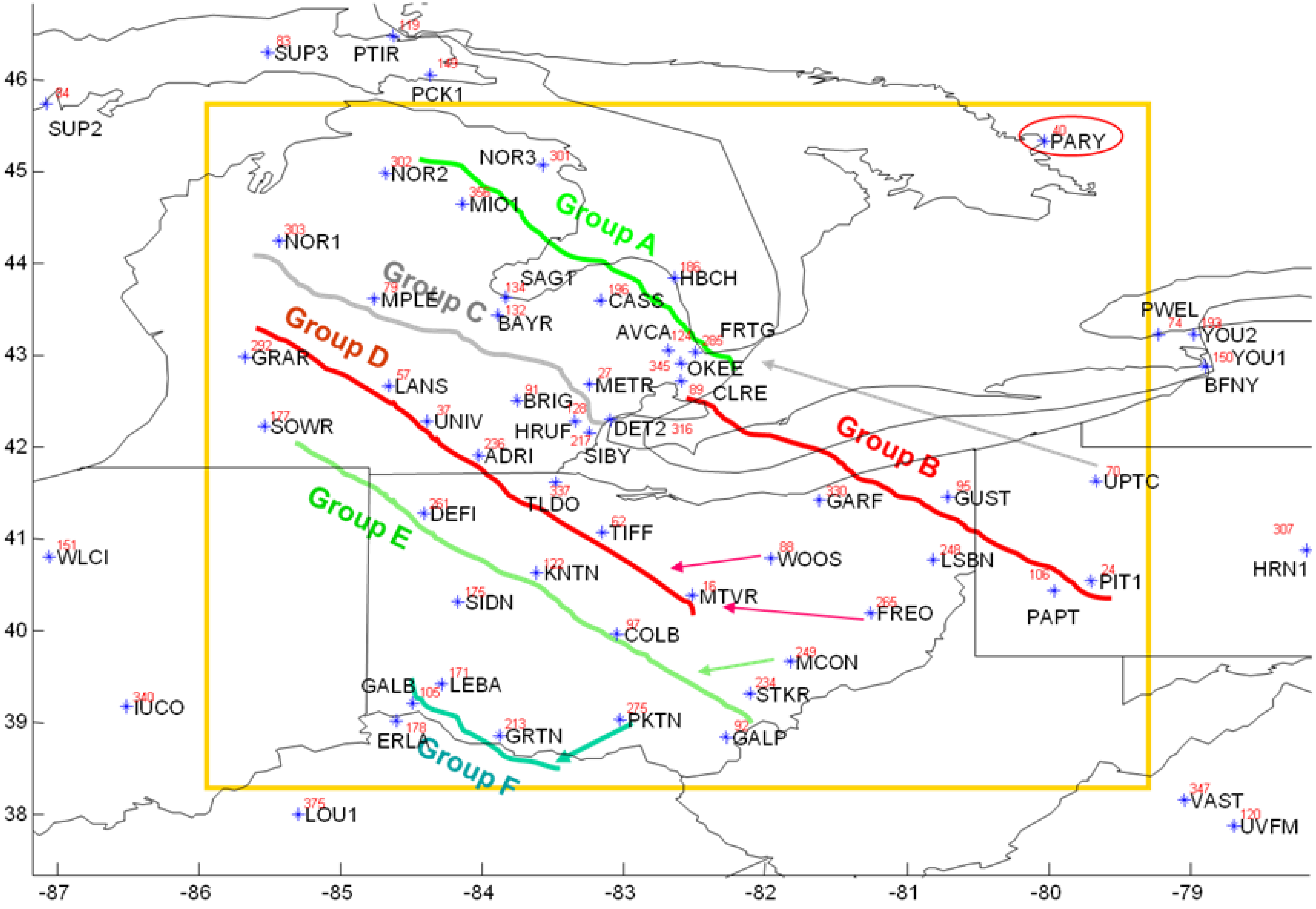
LAAS Ground Facility

Source: Jiyun Lee, IEEE/ION PLANS 2006

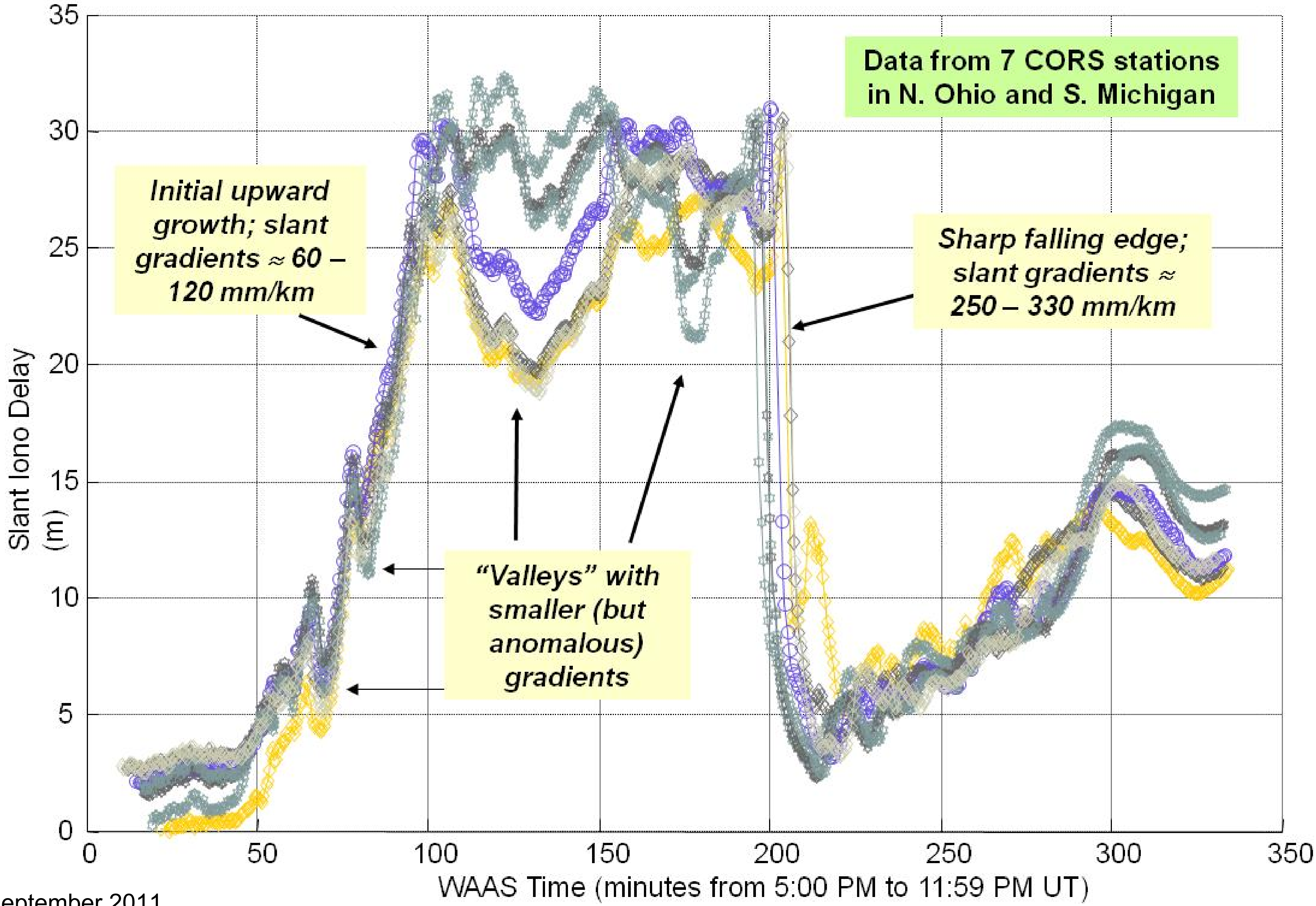
Severe Ionosphere Gradient Anomaly on 20 November 2003



Map of CORS Stations in Ohio/Michigan Region in 2003



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



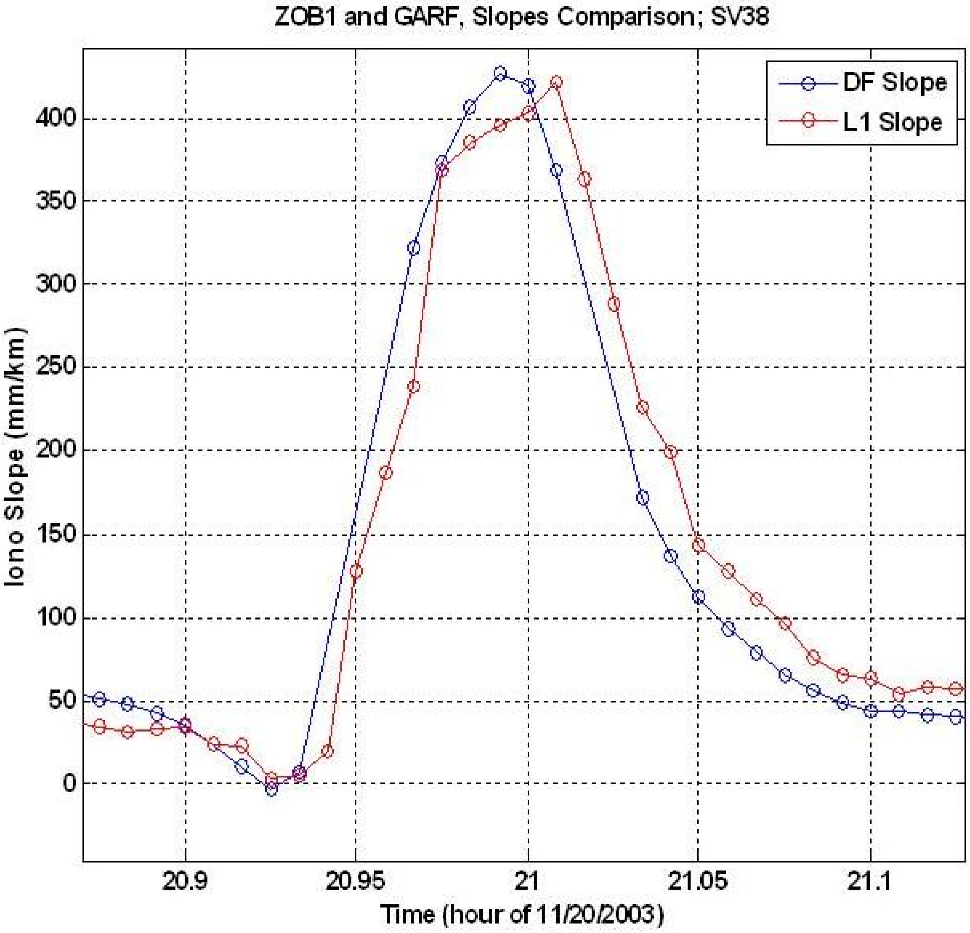
Data from 7 CORS stations in N. Ohio and S. Michigan

Initial upward growth; slant gradients ≈ 60 – 120 mm/km

Sharp falling edge; slant gradients ≈ 250 – 330 mm/km

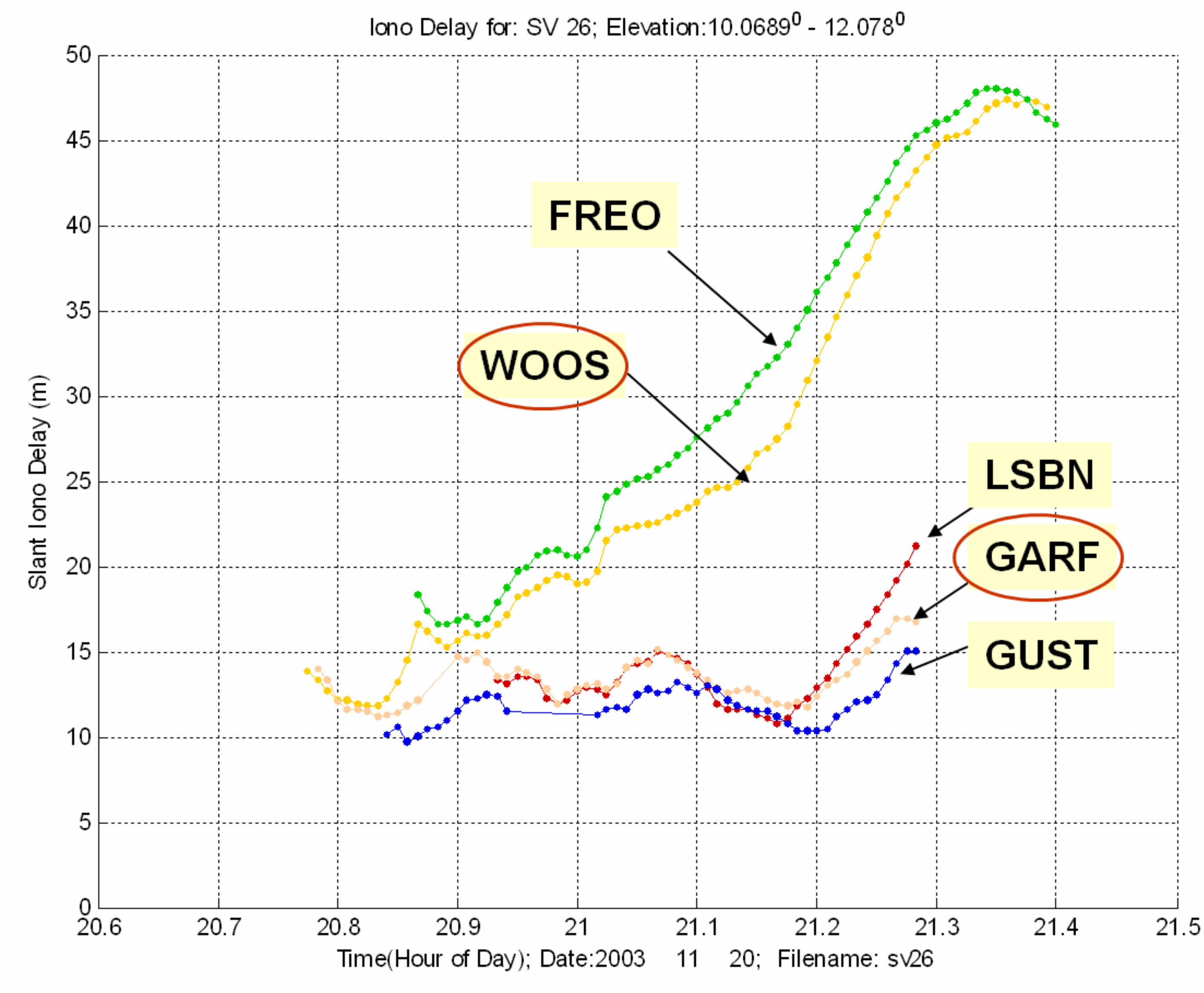
"Valleys" with smaller (but anomalous) gradients

Validation of High-Elevation Anomaly (SVN 38, ZOB1/GARF, 20/11/03)



Maximum slope from L1-only data ≅ 413 mm/km

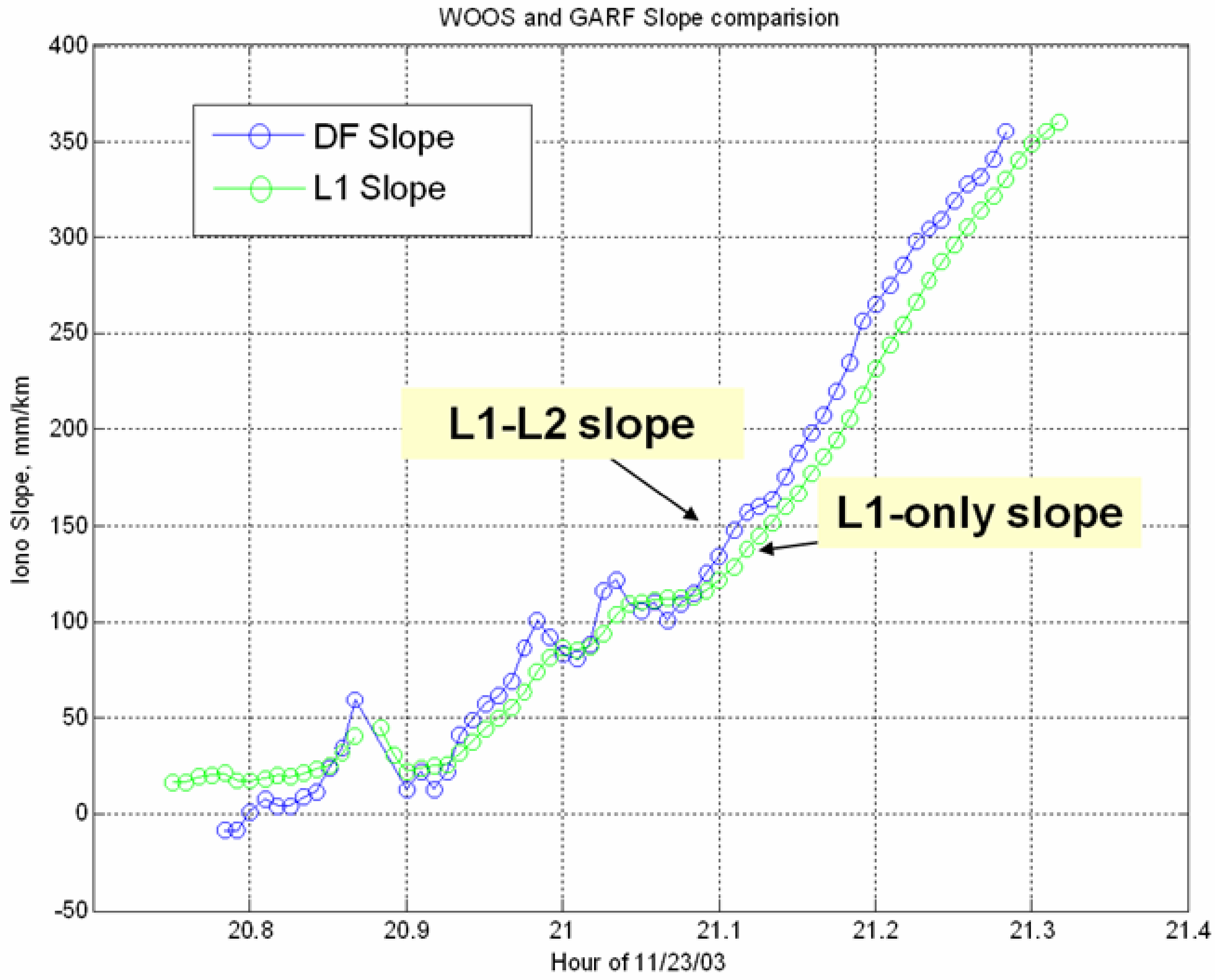
SVN 26 Slant Delays Observed at WOOS, FREO, LSBN, and GARF



- **Sufficient similarity between the two sets of ionosphere delays exists**
- **Lines-of-Sight from FREO and WOOS are within the bulk of the “enhanced” ionosphere gradient**

Severe Slope Validated with L1 Data *WOOS/GARF, SVN 26, 20 Nov. 2003*

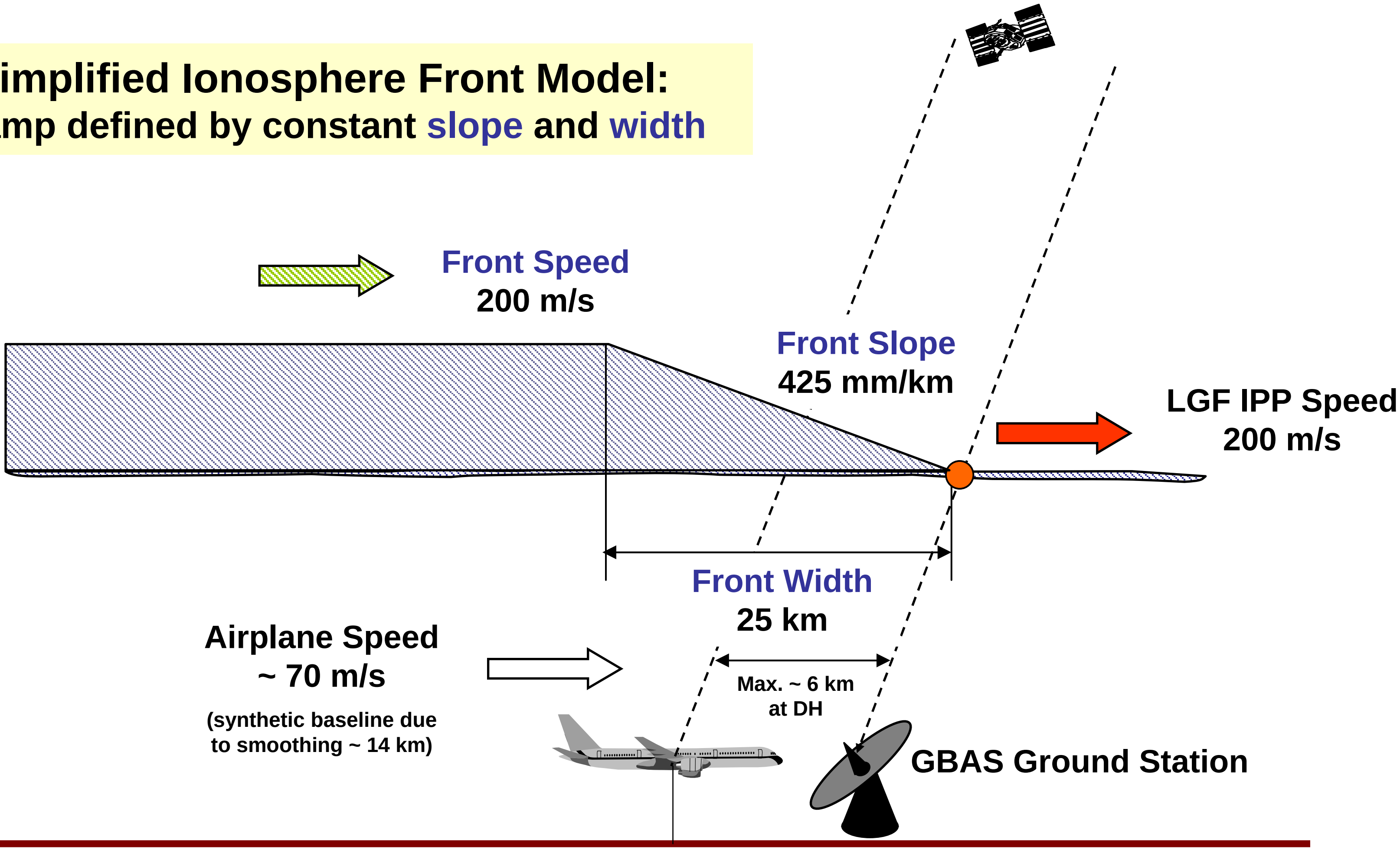
Estimated Slope using L1 Code-minus-Carrier Data



- **Maximum Validated Slope: ~ 360 mm/km**
- **This observation window is very close to the time that peak ionosphere gradients were observed on higher-elevation satellites.**

Ionosphere Anomaly Front Model:
Potential Impact on a GBAS User

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



Front Speed
200 m/s

Front Slope
425 mm/km

LGF IPP Speed
200 m/s

Front Width
25 km

Airplane Speed
~ 70 m/s

(synthetic baseline due to smoothing ~ 14 km)

Max. ~ 6 km at DH

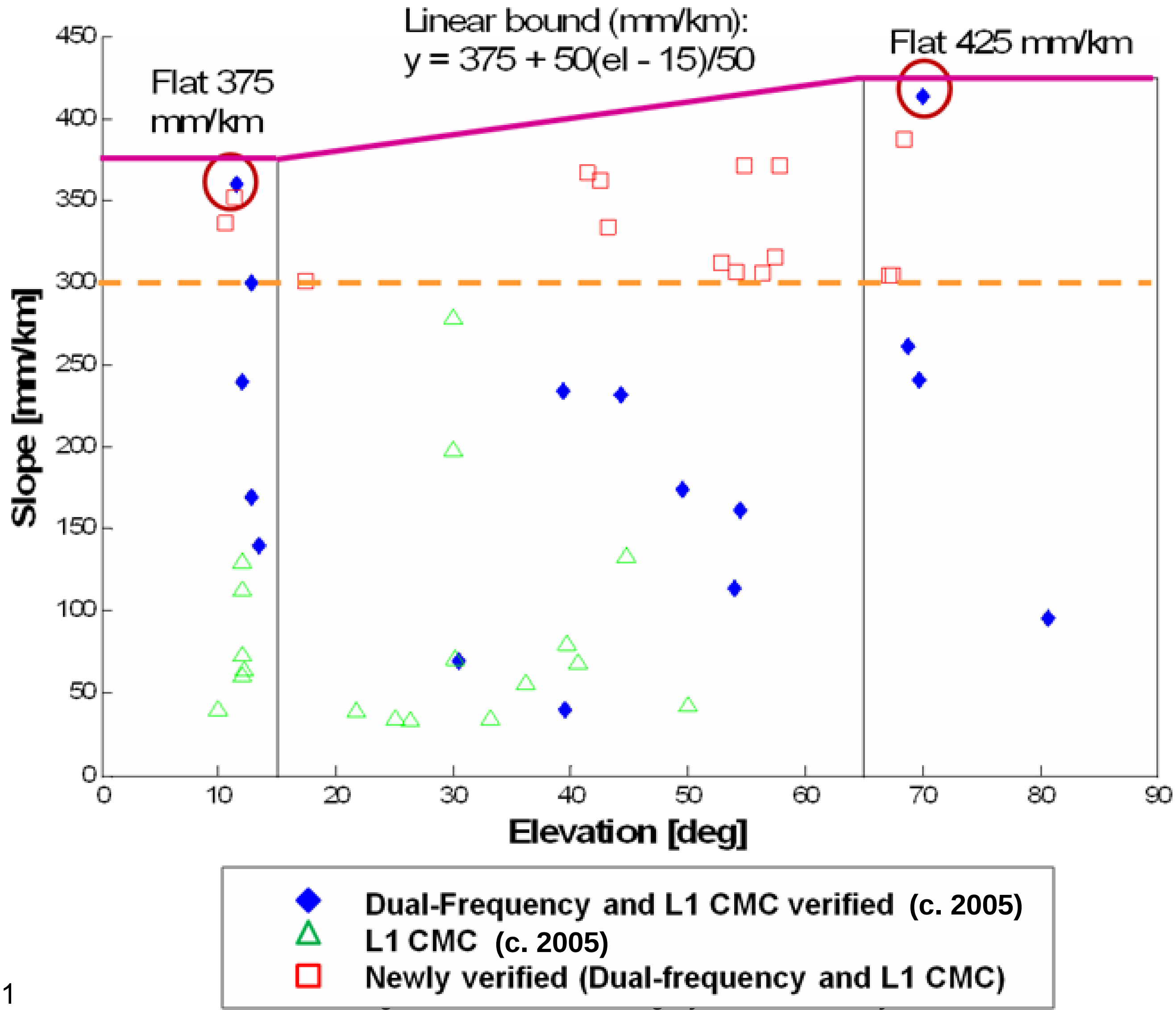
GBAS Ground Station

***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

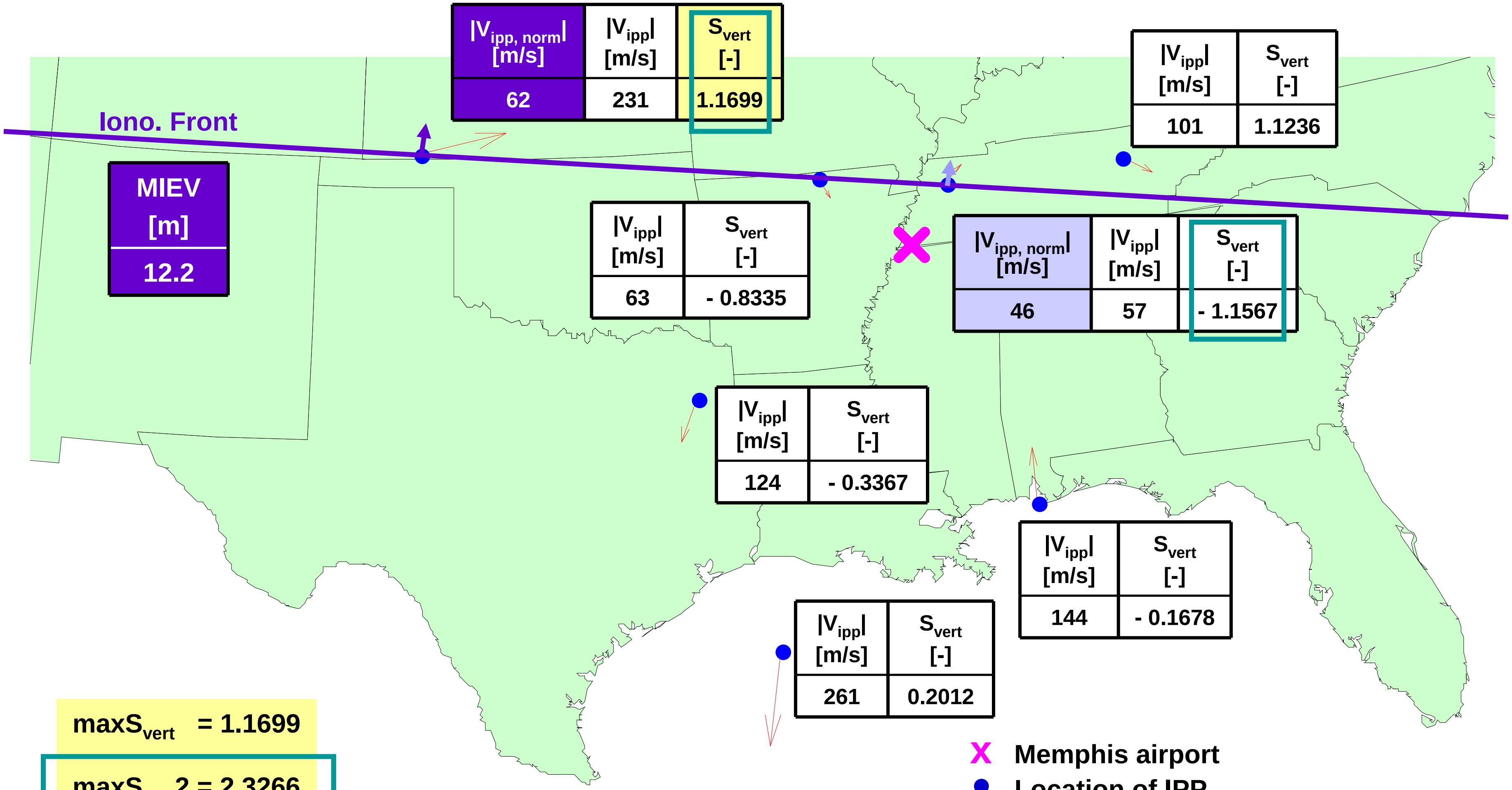
Resulting CONUS Threat Model and Validation Data

***Source*: J. Lee, “Long-Term Iono. Anomaly Monitoring,” ION ITM 2011**



"Worst-Case" Impact on GBAS User near Memphis Airport (1)

All Satellites in View at 00:08



$\lvert V_{ipp,\ norm} \rvert$ [m/s]	$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
62	231	1.1699

$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
101	1.1236

MIEV [m]
12.2

$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
63	- 0.8335

$\lvert V_{ipp,\ norm} \rvert$ [m/s]	$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
46	57	- 1.1567

$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
124	- 0.3367

$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
144	- 0.1678

$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
261	0.2012

$maxS_{vert} = 1.1699$

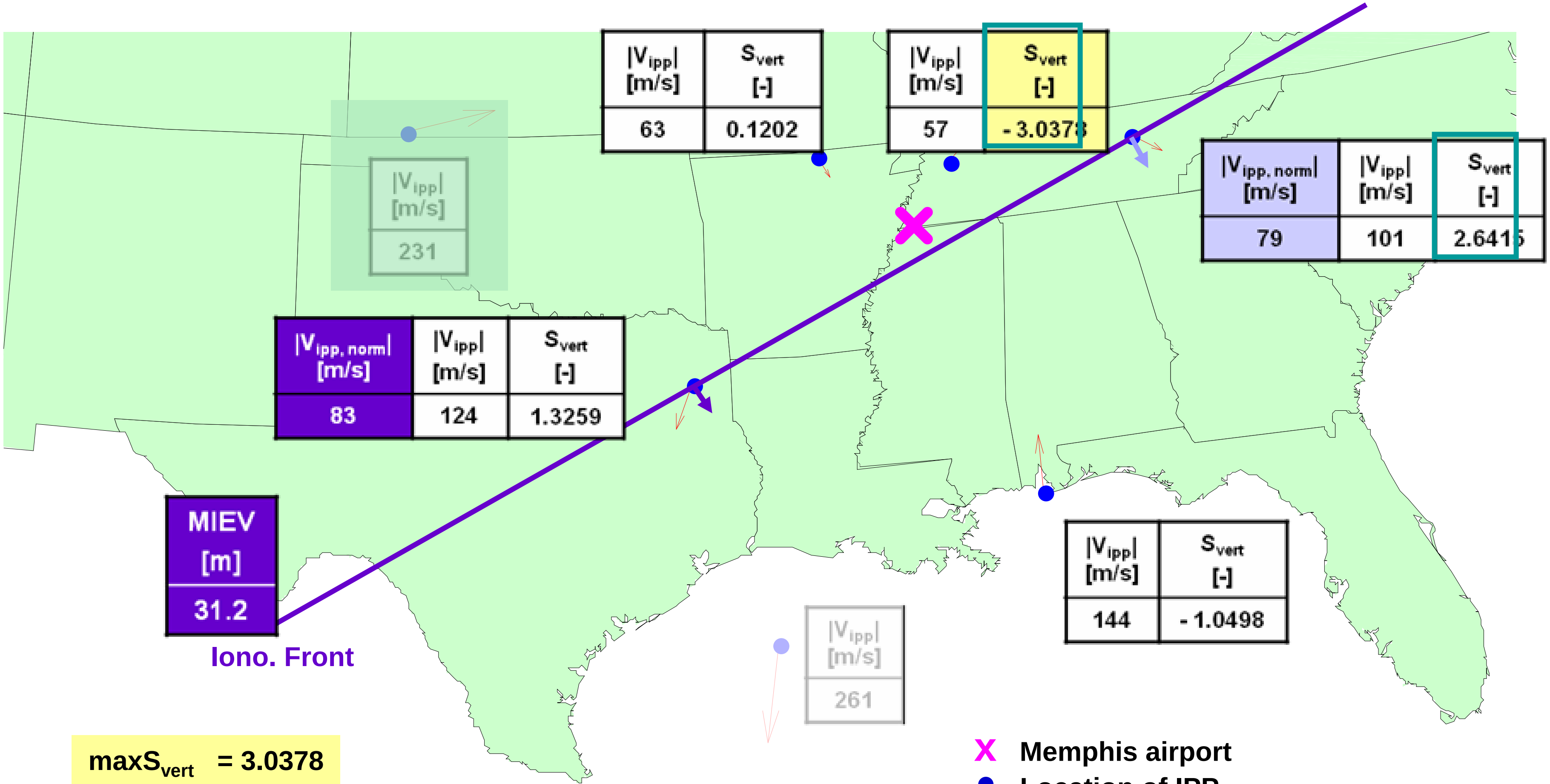
$maxS_{vert}2 = 2.3266$

- **X Memphis airport**
- **● Location of IPP**
- **↗ Velocity [m/s] and direction of IPP**

***Source*: Young Shin Park, 2009**

"Worst-Case" Impact on CAT I Approach to Memphis Airport (2)

Worst-Case 2-SV-Out Subset at 00:08



$\lvert V_{ipp} \rvert$ [m/s]
231

$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
63	0.1202

$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
57	-3.0378

$\lvert V_{ipp, norm} \rvert$ [m/s]	$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
79	101	2.6415

$\lvert V_{ipp, norm} \rvert$ [m/s]	$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
83	124	1.3259

MIEV [m]
31.2

Iono. Front

$\lvert V_{ipp} \rvert$ [m/s]	S_{vert} [-]
144	-1.0498

$\lvert V_{ipp} \rvert$ [m/s]
261

X **Memphis airport**
● **Location of IPP**
↗ **Velocity [m/s] and direction of IPP**

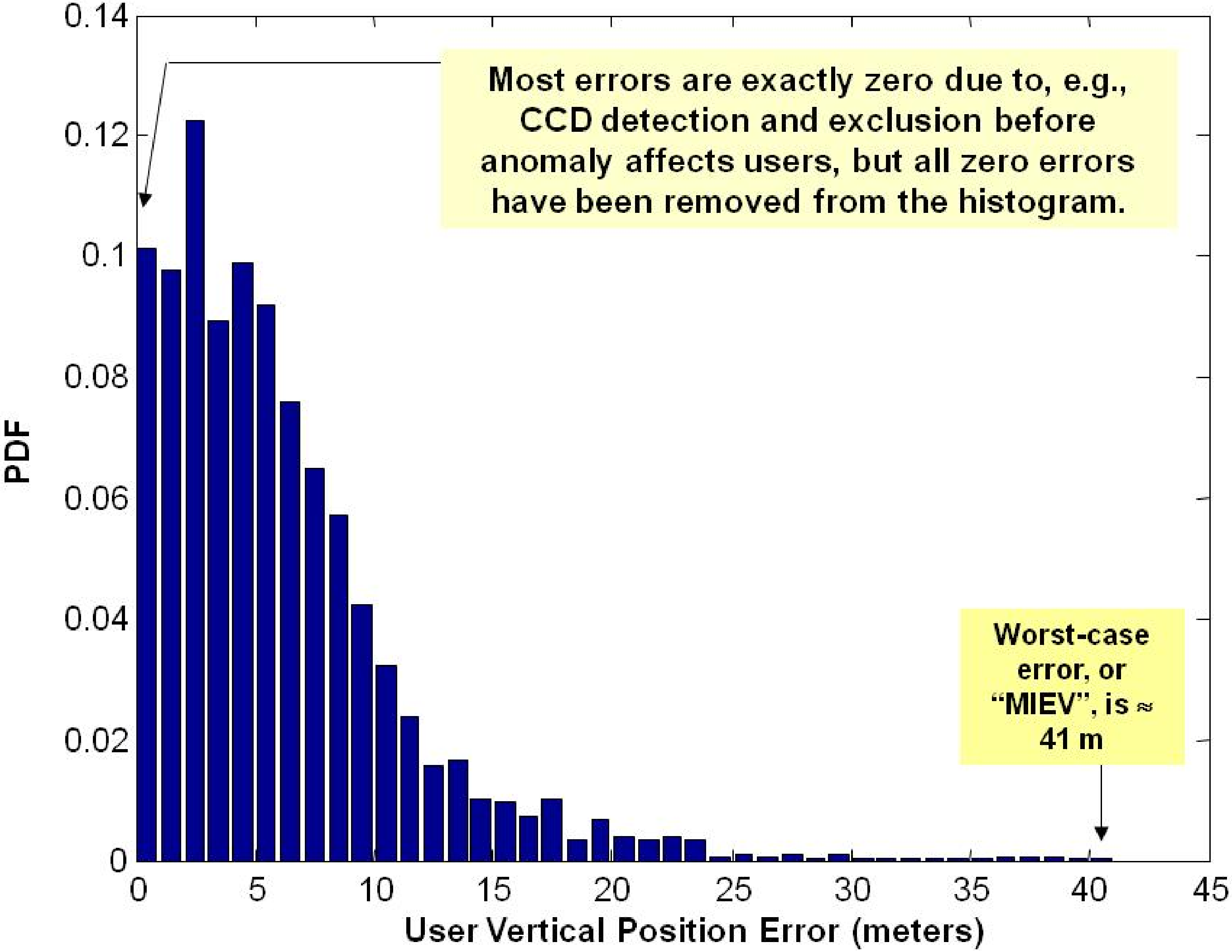
$\max S_{vert} = 3.0378$

$\max S_{vert}2 = 5.6793$

***Source*: Young Shin Park, 2009**

“Semi-random” Results for Memphis LGF at 6 km DH

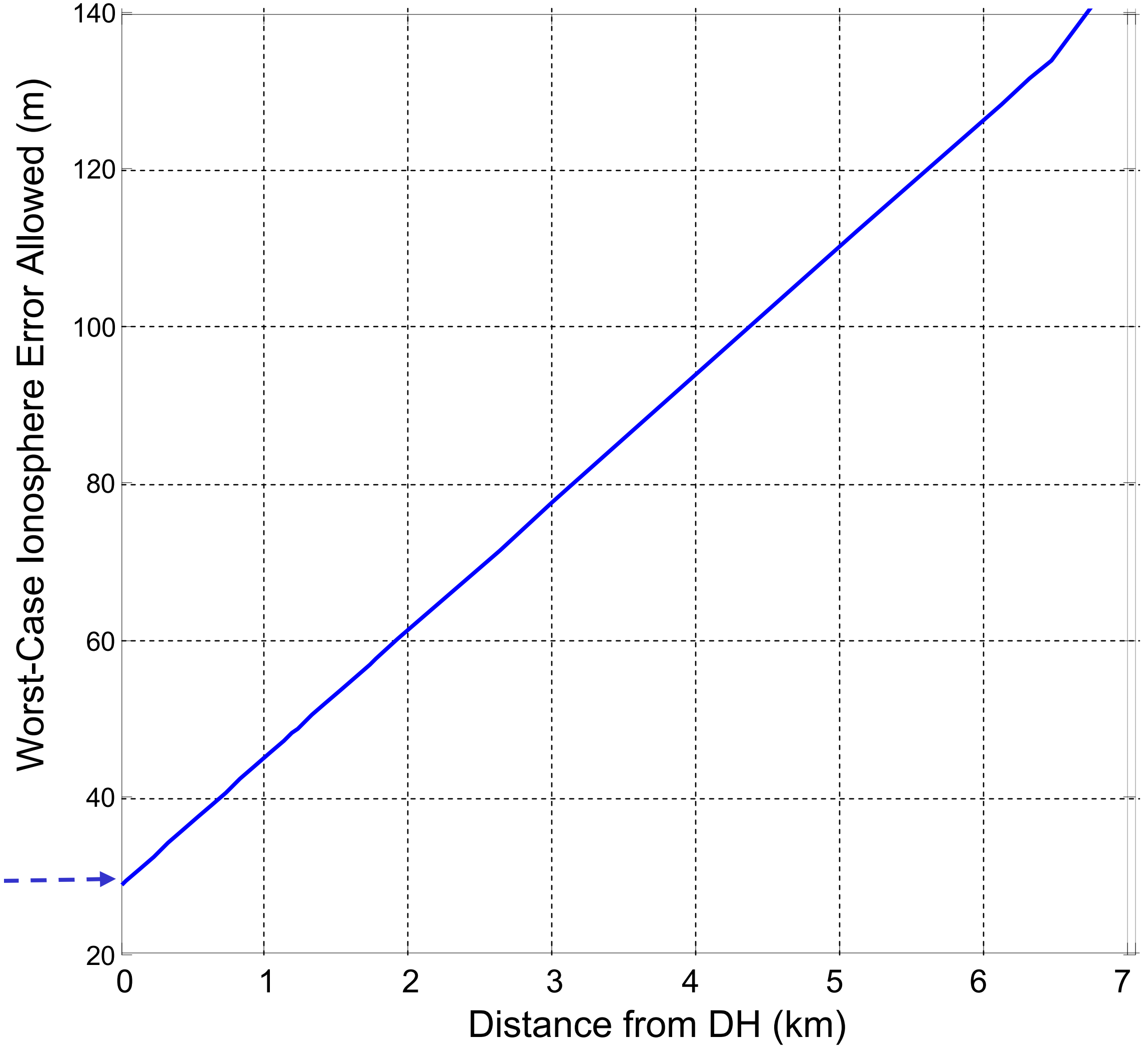
RTCA-24 Constellation; All-in-view, all 1-SV-out, and all 2-SV-out subsets included; 2 satellites impacted simultaneously by ionosphere anomaly



Most errors are exactly zero due to, e.g., CCD detection and exclusion before anomaly affects users, but all zero errors have been removed from the histogram.

Worst-case error, or “MIEV”, is ≈ 41 m

OCS-based "Tolerable Error Limit" (TEL)

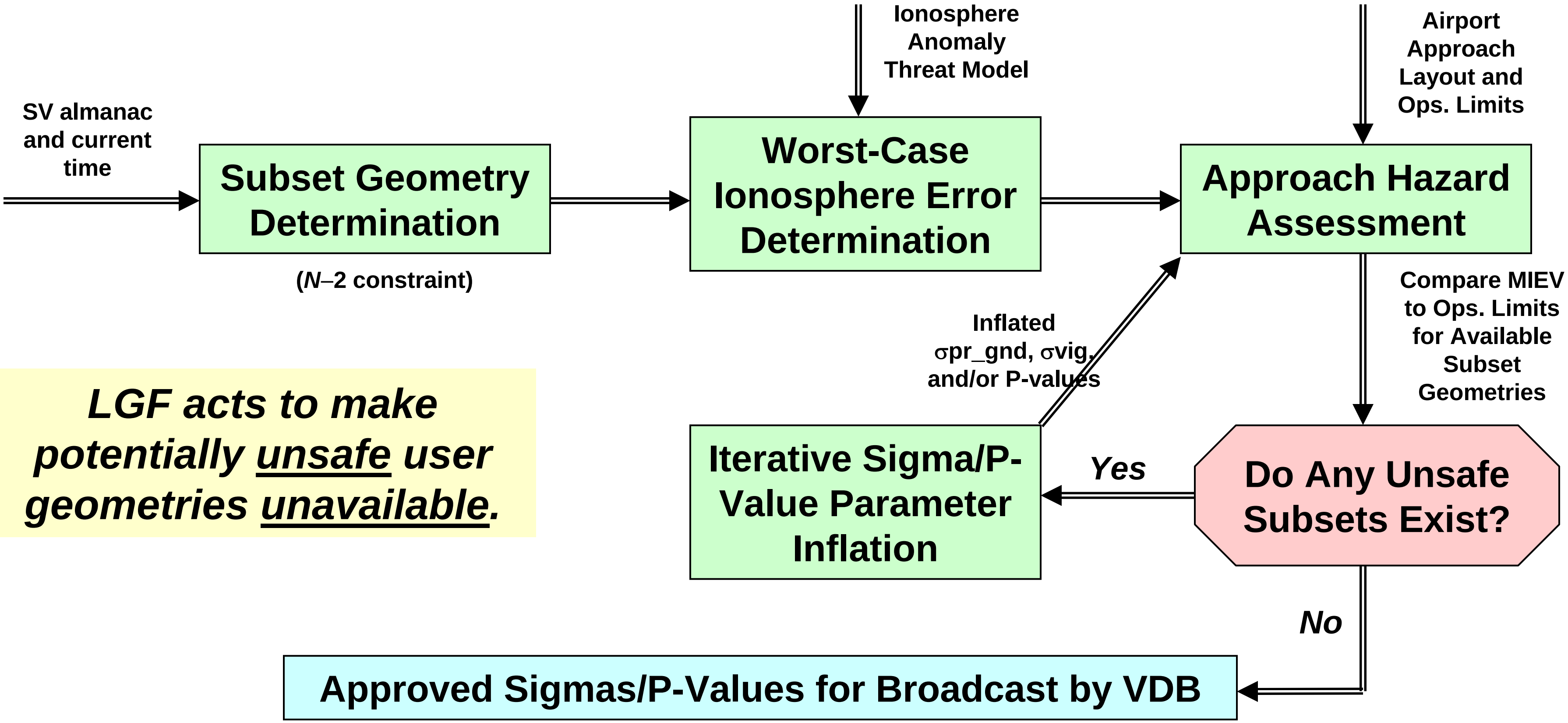


28-meter constraint at DH

- This plot shows "TEL" based on the original Obstacle Clearance Surface (OCS) requirements from which the precision approach alert limits were derived.
- Re-examination of OCS requirements (with less-conservative assumptions) led to larger "safe" error limit → *used only for worst-case iono. errors.*
- Similar analysis for WAAS justified 35-meter VAL for LPV approaches to 200 ft DH (same as CAT I LAAS).
- See ref. [8] for details.

Simplified Flow Chart for Real-Time Inflation in CAT I LGF

LAAS Ground Facility (LGF) Real-Time Geometry Screening



SV almanac and current time

Subset Geometry Determination

(*N*–2 constraint)

Ionosphere Anomaly Threat Model

Worst-Case Ionosphere Error Determination

Airport Approach Layout and Ops. Limits

Approach Hazard Assessment

Compare MIEV to Ops. Limits for Available Subset Geometries

Do Any Unsafe Subsets Exist?

Yes

Iterative Sigma/P-Value Parameter Inflation

Inflated σpr_gnd, σvig, and/or P-values

No

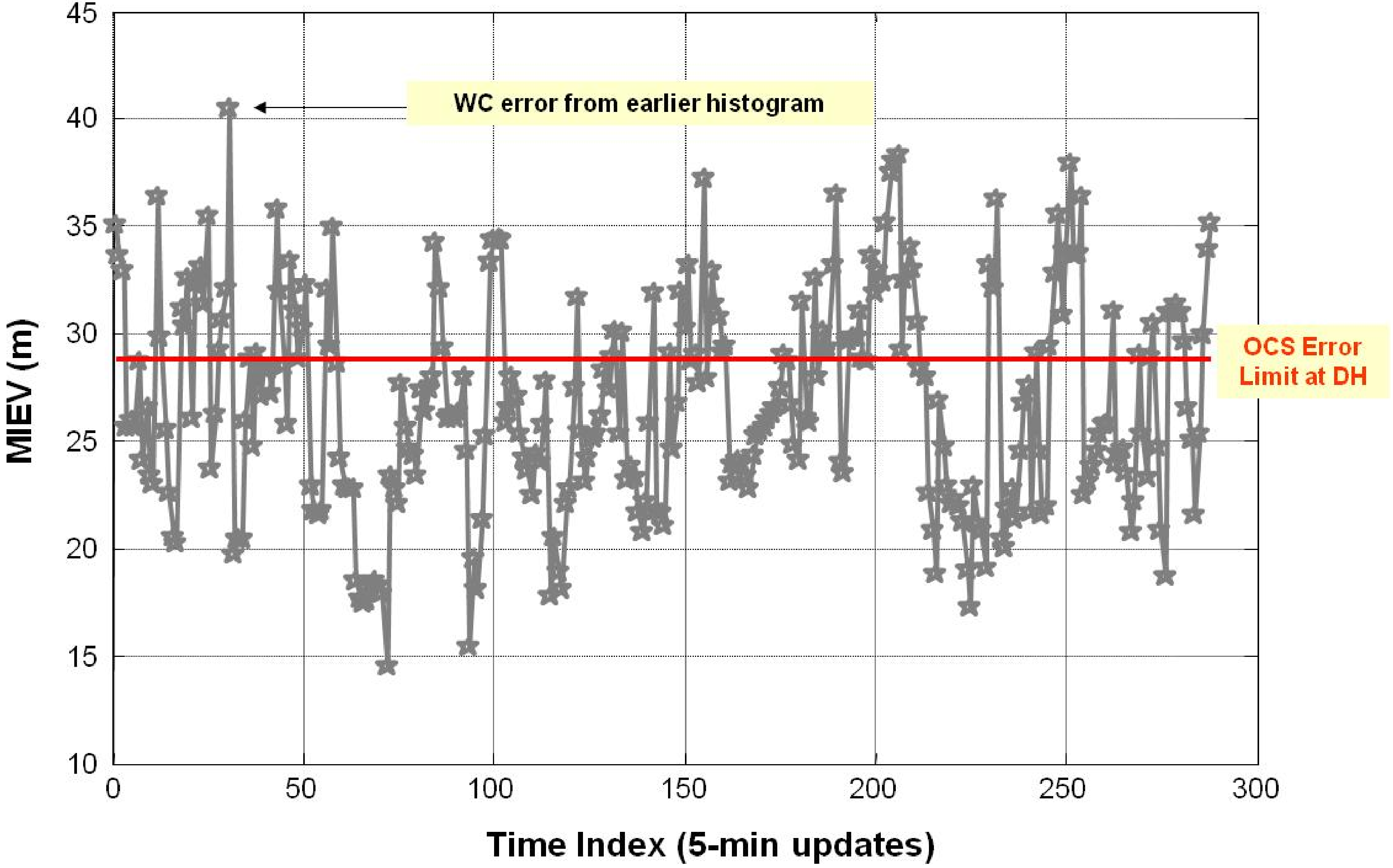
Approved Sigmas/P-Values for Broadcast by VDB

LGF acts to make potentially <u>unsafe</u> user geometries <u>unavailable</u>.

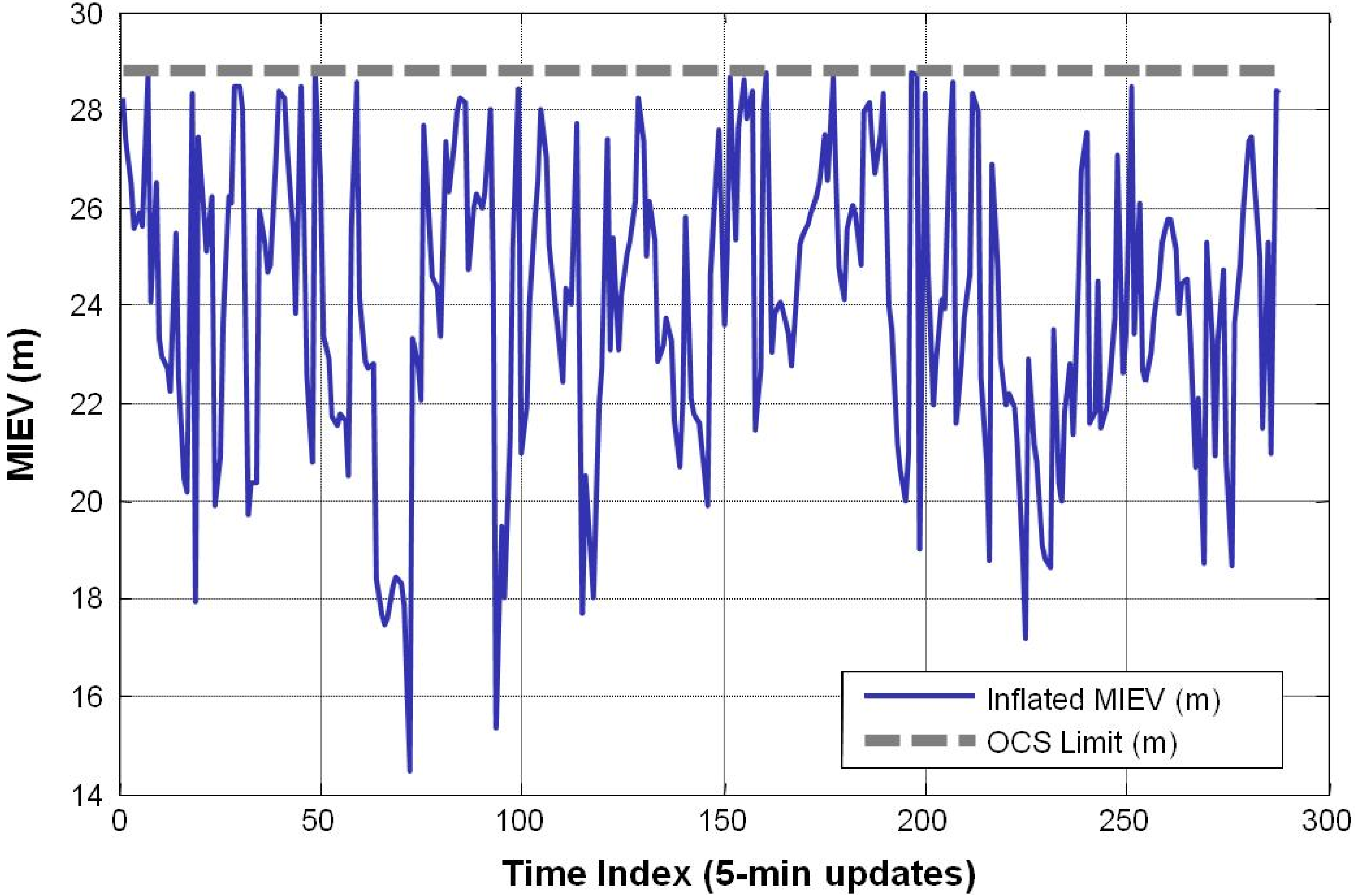
References: J. Lee, *et al., Proceedings of ION GNSS 2006*

S. Ramakrishnan, *et al., Proceedings of ION NTM 2008*

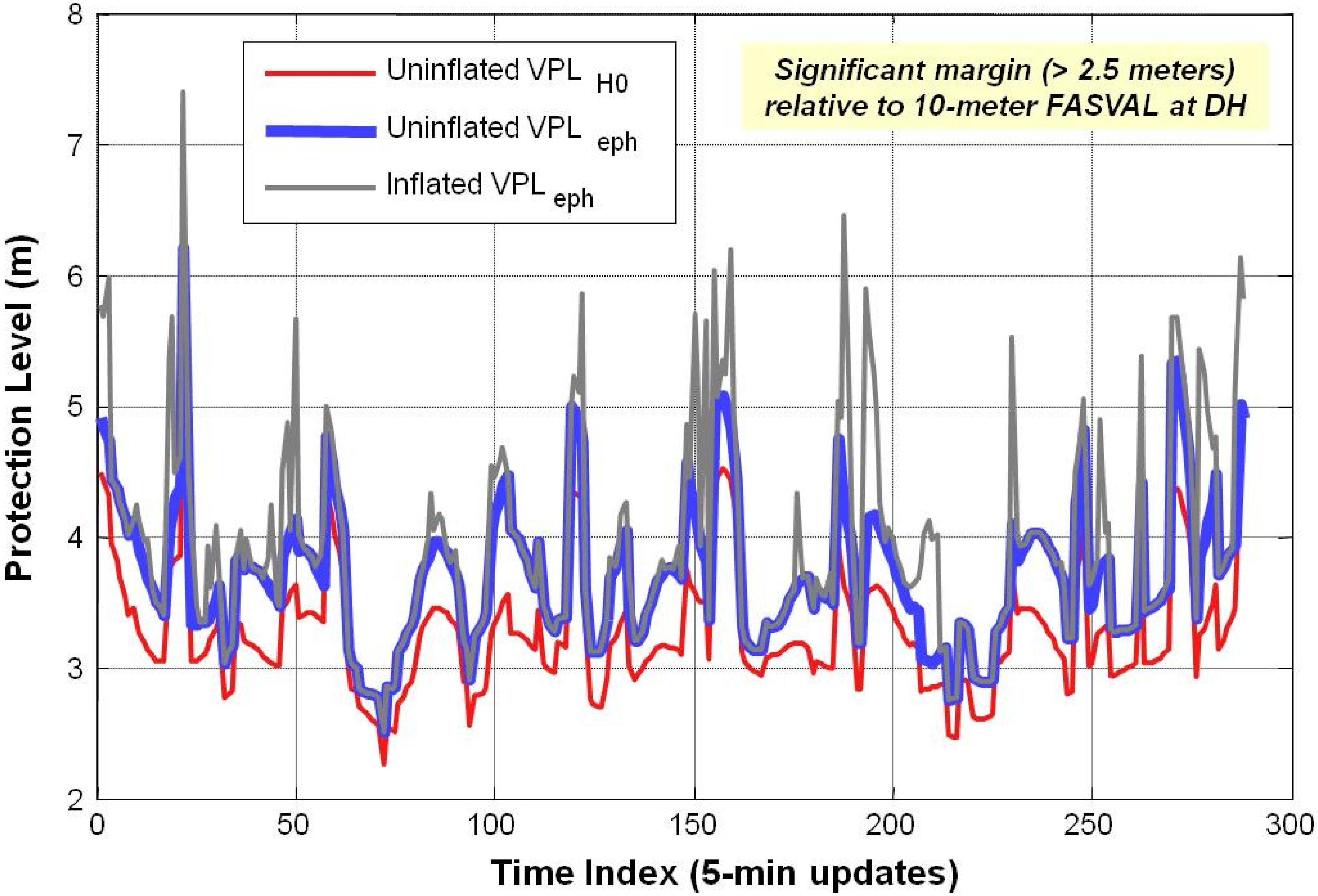
MIEV for Memphis at 6 km Prior to Inflation



MIEV for Memphis at 6 km after Inflation



Protection Levels for Memphis at 6 km from LGF



Outline

- **Augmented GNSS Terminology**
- **Introduction to GNSS and GNSS Augmentation – Differential GNSS (DGNSS)**
- **GBAS and SBAS System Architectures**
- **Aviation Applications and Requirements**
- **Principles of Integrity and Continuity**
- **Specific Examples:**
  - **Nominal Error Bounding**
  - **Signal Deformation Monitoring**
  - **Ephemeris Monitoring**
  - **Ionospheric Anomaly Mitigation**
- **Summary**

Summary and Concluding Thoughts

- **Designing integrity and continuity into GNSS and its augmentations is more difficult than it appears. It is much more than a mathematical challenge.**
  - **Requirements imperfectly represent the desired performance and safety outcomes and are hard to change.**
  - **Key parameters and physical behaviors are imperfectly known, at best.**
  - **Engineering judgment and objective use of conservatism are required.**
- **The flexibility needed to adapt to new information conflicts with the practical desire to "lock down" standards, algorithms, and certified software.**
  - **No single solution to this problem…**

Key Sources (not already listed)

1. **Misra and Enge, *Global Positioning Systems: Signals, Measurements, and Performance* (2nd Ed, 2006). www.gpstextbook.com**
2. **Parkinson and Spilker, Eds., *Global Positioning System: Theory and Applications* (AIAA, 2 Vols., 1996), esp. Vol. II, Ch. 1. www.aiaa.org**
3. **Gleason and Gebre-Egziabher, Eds., *GNSS Applications and Methods* (Artech House, 2009), esp. Chs. 4 and 10. http://www.artechhouse.com**
4. **Walter, *et al*, "Integrity Lessons from the WAAS Integrity Performance Panel (WIPP)," *Proc. ION NTM 2003*. Anaheim, CA, Jan. 22-24, 2003.**
5. **Grewal, *et al*, "Overview of the WAAS Integrity Design," *Proc. ION GPS/GNSS 2003*. Portland, OR, Sept. 9-12, 2003.**
6. **Rife, *el al*, "Core Overbounding and its Implications for LAAS Integrity," *Proc. ION GNSS 2004*, Long Beach, CA, Sept. 21-24, 2004, pp. 2810-2821.**
7. **Rife, *et al*, "Formulation of a Time-Varying Maximum Allowable Error for Ground-Based Augmentation Systems," *IEEE Trans. Aerospace and Electronic Systems*, Vol. 44, No. 2, April 2008.**
8. **Shively, *et al*, "Safety Concepts for Mitigation of Ionospheric Anomaly Errors in GBAS," *Proc. ION NTM 2008*, San Diego, CA, Jan. 28-30, 2008, pp. 367-381.**