The Use of Threat Models in Aviation Safety Assurance and an Update on Technical Challenges for Ground-Based Augmentation Systems (GBAS)

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Outline

• Anomalous Events in GNSS Safety Certification
• Threat Model Concept and Principles
• GBAS Introduction and Status
• GBAS Anomalies and Threat Model Examples
  – GPS Satellite Signal Deformation
  – GPS Satellite Ephemeris Anomaly
  – Anomalous Ionospheric Spatial Gradients
• GBAS Ionospheric Mitigation Activities
• Summary
Introduction to Safety Certification

• Certification of GNSS Services requires verification of system safety in the presence of potential hazards.
  – Loss of Integrity – unalerted hazardous conditions
  – Loss of Continuity – operation aborted due to loss of service

• Hazard conditions are mostly caused by system faults or anomalies that are not completely understood.

• Threat models are developed for significant anomaly conditions to bound potential effects and consequences.
  – Allow deterministic, worst-case calculation of safety impact
### FAA System Safety Handbook (2000), Table 3-6

<table>
<thead>
<tr>
<th>Probability (Quantitative)</th>
<th>FAR</th>
<th>JAR</th>
<th>FAR</th>
<th>JAR</th>
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<tbody>
<tr>
<td>1.0</td>
<td>Probable</td>
<td>Frequent</td>
<td>Probable</td>
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<td>10^-3</td>
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<td>Remote</td>
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<tr>
<td>10^-5</td>
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<table>
<thead>
<tr>
<th>Failure condition severity classification</th>
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<th>JAR</th>
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</thead>
<tbody>
<tr>
<td>Minor</td>
<td>Minor</td>
<td>Major</td>
</tr>
<tr>
<td>Major</td>
<td>Hazardous</td>
<td>Catastrophic</td>
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<tr>
<td>Catastrophic</td>
<td>Catastrophic</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect on aircraft occupants</th>
<th>FAR</th>
<th>JAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight decrease in safety margins</td>
<td>Nuisance</td>
<td>Operating limitations</td>
</tr>
<tr>
<td>Slight increase in crew workload</td>
<td></td>
<td>Emergency procedures</td>
</tr>
<tr>
<td>Some inconvenience to occupants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severe Cases:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce capability of airplane or crew to cope with adverse operating conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant reduction in safety margins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant increase in crew workload</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher workload or physical distress on crew - can't be relied upon to perform tasks accurately</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adverse effects on occupants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple deaths, usually with loss of aircraft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conditions which prevent continued safe flight and landing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## GBAS Requirements Table

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

<table>
<thead>
<tr>
<th>GSL</th>
<th>Accuracy</th>
<th>Integrity</th>
<th>Continuity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95% Lat. NSE</td>
<td>95% Vert. NSE</td>
<td>Pr(Loss of Integrity)</td>
</tr>
<tr>
<td>A</td>
<td>16 m</td>
<td>20 m</td>
<td>$2 \times 10^{-7} / 150$ sec</td>
</tr>
<tr>
<td>B</td>
<td>16 m</td>
<td>8 m</td>
<td>$2 \times 10^{-7} / 150$ sec</td>
</tr>
<tr>
<td>C</td>
<td>16 m</td>
<td>4 m</td>
<td>$2 \times 10^{-7} / 150$ sec</td>
</tr>
<tr>
<td>D</td>
<td>5 m</td>
<td>2.9 m</td>
<td>$10^{-9} / 30$ s (vert.); 30 s (lat.)</td>
</tr>
<tr>
<td>E</td>
<td>5 m</td>
<td>2.9 m</td>
<td>$10^{-9} / 30$ s (vert.); 30 s (lat.)</td>
</tr>
<tr>
<td>F</td>
<td>5 m</td>
<td>2.9 m</td>
<td>$10^{-9} / 30$ s (vert.); 30 s (lat.)</td>
</tr>
</tbody>
</table>
High-Level Integrity Fault Tree for CAT I (GSL C) GBAS

Loss of Integrity (LOI)

2 $\times$ 10$^{-7}$ per approach (Cat. I PA)

2.5 $\times$ 10$^{-8}$

Nominal conditions (bounded by $PL_{H0}$)

2.5 $\times$ 10$^{-8}$

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

1.5 $\times$ 10$^{-7}$

All other conditions (H2)

1.4 $\times$ 10$^{-7}$

Single-SV failures

1 $\times$ 10$^{-8}$

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

2.3 $\times$ 10$^{-8}$

Ephemeris failures (bounded by $PL_e$)

1.17 $\times$ 10$^{-7}$

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

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

Specific Threat or Anomaly Description

Bounded, multi-dimensional parameter space

Theory / Physics

Collected Data

System / User Impact Model (incl. monitoring)

Deterministic simulation

Worst-case user impact (and relevant points within threat model)
Threat Model Principles

• For deterministic fault impact analysis, threat models require bounded parameter spaces.
  – Define bounds based on best available knowledge and data
  – Parameter values outside bounds are deemed to have negligible probability (relative to fault-tree allocation).

• Within the threat model bounds, safety assessment is based on the worst-case parameter combination.
  – Worst-case: parameter combination that maximizes time to alert (as opposed to maximizing user error)
  – In other words, worst-case parameters are those where monitoring is weakest (given that MI occurs).
  – No probabilistic “averaging” among the many parameter combinations inside the threat model.
GBAS (LAAS) Architecture Pictorial

[Diagram showing GBAS (Local Area Augmentation System) architecture with pseudolites, reference antennas, processing receiver, VHF transmitter, and data broadcast.]
GBAS Architecture Overview
(supports CAT I Precision Approach)

airport boundary
(encloses GBAS Ground Facility)

Corrected carrier-smoothed
code processing
– VPL, LPL calculations

LGF Ref/Mon Rcvrs.
and Processing

VHF Data Link

GPS, L1 only

VHF Antennas

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

Differential vertical error up to 8.5 meters

• 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
Analysis of GPS SVN / PRN 19 Fault


SVN 26 rising edge

SVN 19 rising edge
Anomalous Signal Deformation from “2nd-Order-Step” ICAO Threat Model

Comparison of Ideal and “Evil Waveforms” for Threat Model C

C/A PRN Codes

Correlation Peaks

Volts

Chips

Code Offset (chips)

Note:

Threat Model A: Digital Failure Mode (Lead/Lad Only: Δ)
Threat Model B: Analog Failure Mode (“Ringing” Only: \(f_d, \sigma\))

Threat model specifies allowed ranges of these parameters.
Nominal L1 C/A Signals with Deformation (GPS PRN 16 Example)

Ephemeris Failure Impact on GBAS Users

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

\[
\delta \rho = \frac{\delta R^T (I - e e^T) x}{|R|}
\]

- Worst-case user error occurs when \( \delta \bar{R} \) is parallel to \( \bar{x} \) and when \( \bar{e} \) is orthogonal to \( \bar{x} \)

|\( |R| \) = Reference \( \rightarrow \) SV range |
|---|
|\( \bar{e} \) = Reference \( \rightarrow \) SV unit vector |
|\( \delta \bar{R} \) = SV ephemeris error vector |
|\( \bar{x} \) = Reference \( \rightarrow \) user vector |
GBAS Ephemeris Threat Classification

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

Type B Threat: no satellite maneuver

Error in generating or updating ephemeris parameters

Mitigation not required for CAT I ops.

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)
Ephemeris Threat Model Summary (for GBAS)

• For Type A1 and A2a faults (deliberate maneuvers), allowable satellite maneuvers are limited by typical maneuver characteristics.
  – Bounds on thruster force and duration of burn $\rightarrow$ bound on resulting “impulsive $\Delta V$” that begins maneuver
  – Impulsive $\Delta V$ applied in a single orbit plane

• For Type B faults (erroneous data), data errors likely to maximize user integrity risk are targeted.
  – Small errors ($< 1$ km in 3-D SV position error) are not threatening, whereas large errors ($> 5$ km) are easy to detect.

• Simulations of millions of maneuvers and faulty messages used to identify worst-case user impact.
Severe Ionosphere Gradient Anomaly on 20 November 2003

20:15 UT

21:00 UT

Vertical Ionospheric Delay in m
Moving Ionosphere Delay “Bubble” in Ohio/Michigan Region on 20 Nov. 2003

Initial upward growth; slant gradients $\approx 60 – 120$ mm/km

“Valleys” with smaller (but anomalous) gradients

Sharp falling edge; slant gradients $\approx 250 – 330$ mm/km

Data from 7 CORS stations in N. Ohio and S. Michigan
Ionospheric Anomaly “Front” Model: Potential Impact on a GBAS User

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

Front Speed 200 m/s
Front Slope 425 mm/km
Front Width 25 km
LGF IPP Speed 200 m/s
Airplane Speed ~ 70 m/s
(synthetic baseline due to smoothing ~ 14 km)

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

11 July 2014
Aviation Threat Models and GBAS Challenges
**Ionospheric Anomaly Threat Model** (for CONUS)

**Linear bound (mm/km):** \( y = 375 + 50(e - 15)/50 \)

**Flat 375 mm/km**

**Flat 425 mm/km**

**Also bounds on:**
- Front speed wrt. ground: \( \leq 750 \text{ m/s} \)
- Front width: 25 – 200 km
- Total differential delay \( \leq 50 \text{ m} \)
The Alternative: Probabilistic Risk Assessment (PRA)

General Threat or Anomaly Description

Theory / Physics

Collected Data

Expert Opinion

Unbounded, multi-dimensional probability distribution(s)

System / User Impact Model (incl. monitoring)

Monte Carlo simulation

Overall (ensemble) user impact, expressed as probability distribution(s)
(internal “worst case” may also be found if constrained by monitoring)
GBAS Status within U.S. (FAA)

- Ground and airborne system research continues under the direction of the FAA William J. Hughes Technical Center (led by John Warburton)

- For existing CAT I GBAS
  - Support new sites and ground-station siting, including Rio de Janeiro airport (equatorial ionosphere)
  - Support ground-station hardware and software improvements, e.g. “Honeywell SLS-4000 Block II”

- For future GAST-D GBAS
  - Support technical validation of current GAST-D SARPS based on Honeywell and FAA prototype testing
  - Validation expected to be completed next year
CAT I Ionospheric Mitigation

• Research continues on mid-latitude ionospheric threat models to confirm that existing (CONUS) threat model is sufficient.

• Existing CONUS threat model significantly degrades CAT I availability and makes DCPS infeasible under current requirements.

• In equatorial regions, three additional concerns exist:
  – Severe scintillation, often on multiple satellites
  – Large spatial gradients generated by “typical” ionospheric bubbles (non-rare)
  – Extreme (rare) spatial gradients potentially exceeding CONUS threat model
Prevalance of High Scintillation (S4) at Rio de Janeiro

Source: DECEA (Brazil) Update at IGWG-15 (Paris, June 2014)
Plot generated by Honeywell

Points represent day and times when S4 threshold is exceeded
Plasma Bubbles: Large vs. Extreme

- Published information on equatorial plasma bubbles (e.g., from ENRI) identifies both “extreme” and “typical” events

- “Extreme” bubble events may generate spatial gradients as large as 400 – 500 mm/km but can be treated as rare (anomalous) events.

- “Typical” bubble events generate smaller, but still large, gradients from 50 – 250 (?) mm/km and are not rare enough to be treated as anomalous.

- Data from Brazil demonstrates that these “typical” bubble gradients are both frequent and significant in magnitude.
Bounding “Typical” Plasma Bubbles

• If “typical” bubbles are not rare in equatorial locations, they should (in principle) be bounded by broadcast sigma_vig within VPL_H0.

• Since “typical” bubbles can cause gradients exceeding 100 mm/km, it is not obvious how to bound them within existing sigma_vig.

• Note that sigma_vig broadcast parameter has a maximum of 25.5 mm/km.

• Broadcasting sigma_vig at or near 25.5 mm/km leads to a dramatic loss of CAT I user availability.

• How to resolve this???
Brazil Ionospheric Study

- Contract between Brazil and MIRUS Corp. (involving FAA) to produce an independent GBAS ionospheric threat model for Brazil.
  - Concept is to apply this threat model to equatorial variant of “Block II” SLS-4000 for use in Brazil
  - Focus is on large spatial gradients (“extreme” and “typical”), but scintillation is considered as well

- Stanford, Boston College (Pat Doherty), and KAIST (Jiyun Lee) are supporting the FAATC and MIRUS
  - Use LTIAM software tool developed by KAIST
  - Identified over 100 days of interest (suspected enhanced ionospheric activity) for detailed study
Reference Station Networks in Brazil

Source: Jonas Rodrigues de Souza, INPE, Brazil

Limited number of station separations < 50 km
GAST-D Ionospheric Mitigation

• GAST-D mitigation demands introduced ground-based “Ionospheric Gradient Monitor” (IGM) into draft SARPS.
  – Several versions of IGM algorithm have been developed (e.g., Honeywell, IIT, DLR, ENRI)
  – Issues remain with requirement definition and allowance for prior probability credit

• Recently, Honeywell discovered large gradients over very short separations that are non-threatening and appear to be caused by tropospheric irregularities
  – Events are correlated with hot, clear weather and appear to move with local wind
  – Under these conditions, IGM alerts would be too frequent.
Iono. Gradient Monitor (IGM) Concept (1)

- Use double-difference (DD) carrier-phase measurements across ground antennas to detect large iono. gradients:

  \[ \lambda \Delta^2 \phi = \Delta e \cdot b + \lambda \Delta^2 n + \alpha b + \Delta^2 v \]

- Baseline vectors are known, but cannot separate cycle ambiguities from iono. gradient at SV acquisition.
  - Ambiguity estimation by integer ‘rounding’ potentially hides threatening gradients
Honeywell IGM Data at Houston (IAH) (22 June 2013)


Frequent IGM alerts during daylight hours
Sky Plot of IGM Data at Newark (EWR) (16 July 2013)


- Newark (EWR) skyplot for July 16, 2013
  - Yellow denotes satellite tracks
  - Red denotes normalized test statistic from 4 to 6.5
  - Blue denotes normalized test statistic > 6.5

- Events observed at:
  - All azimuths
  - Elevations up to 55°
Zoom In on IGM Data at Newark (EWR) (16 July 2013)

“Tropospheric” Gradient Features

• “Tropospheric” spatial gradients can reach magnitudes similar to extreme ionospheric gradients (> 200 – 300 mm/km)

• However, observed “tropospheric” gradients are not hazardous to GBAS because they persist only briefly.
  – Duration of gradients observed over baselines of several hundred meters is tens of seconds to ~ 100 seconds
  – Gradient width appears to be < 1 km
  – Propagation speed appears to correspond to local wind speed (e.g., 5 – 15 m/s)

• Full characterization (i.e., “tropospheric gradient threat model”) is TBD.
Masking Out “Tropo” Gradients in IGM

- Assuming that “tropo” gradients are not hazardous, their rate of occurrence requires that they be separated from (potentially hazardous) ionospheric gradients in IGM to maintain adequate continuity.

- Basic approach is to exploit different behavior of ionospheric and “tropospheric” gradients.
  - Brief duration of “tropo” gradients vs. lengthy evolution of threatening iono. gradients (min. 25 km width)
  - Exploiting this requires allowance for “waiting time” after IGM threshold is first violated
  - How much waiting time is allowable before iono. threat becomes intolerable (now under study)?
    - Initial results in ICAO NSP CSG WP-32 (May 2014)
Summary

• Threat models are used to demonstrate integrity compliance as part of aviation system certification.
  – Evaluate the worst possible consequences of specific system fault modes or anomalies.
  – Deterministic constraints on threat behavior parameters must be derived from limited knowledge and data.
  – Worst-case parameter set within defined “threat space” is used to quantify safety performance.

• GBAS research supported by FAA is pursuing both upgrades to CAT I ground system and technical validation of GAST-D SARPS.
  – Maximize performance under equatorial ionospheric behavior
  – Maintain tight monitoring of ionospheric gradients without alerting non-hazardous “tropospheric” gradients
• Backup slides follow…
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

- **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

- **Catastrophic**: failure conditions which would prevent continued safe flight and landing (with probability $\rightarrow 1$)

* 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  

<table>
<thead>
<tr>
<th>Consequence</th>
<th>Prob. Of Occurance</th>
<th>Catastrophic</th>
<th>Hazardous</th>
<th>Major</th>
<th>Minor</th>
<th>No Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Catastrophic</td>
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<td>Hazardous</td>
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<td></td>
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<tr>
<td>Major</td>
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<td></td>
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<tr>
<td>Minor</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Effect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frequent (&gt;10^-2)</strong></td>
<td></td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>Reasonably Probable (10^-2 to 10^-5)</td>
<td></td>
<td>2</td>
<td>5</td>
<td>9</td>
<td>14</td>
<td>22</td>
</tr>
<tr>
<td>Remote (10^-5 to 10^-7)</td>
<td></td>
<td>4</td>
<td>8</td>
<td>13</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>Extremely Remote (10^-7 to 10^-9)</td>
<td></td>
<td>7</td>
<td>12</td>
<td>16</td>
<td>19</td>
<td>24</td>
</tr>
<tr>
<td>Extremely Improbable (&lt;10^-9)</td>
<td></td>
<td>11</td>
<td>15</td>
<td>18</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

**Cat. III ILS case**

<table>
<thead>
<tr>
<th>Hazard Risk Index</th>
<th>Acceptance Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-6</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>7-10</td>
<td>Undesirable</td>
</tr>
<tr>
<td>11-18</td>
<td>Acceptable, but FAA review required</td>
</tr>
<tr>
<td>19-25</td>
<td>Acceptable</td>
</tr>
</tbody>
</table>

**Cat. I ILS case**

- 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  
# Summary of CAT III Airworthiness Requirements

<table>
<thead>
<tr>
<th>Condition</th>
<th>Airworthiness Requirements Model</th>
<th>Related Success Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AC 120-28D Nominal Performance – App. 3, Section 6.3.1</td>
<td>Demonstrate equivalent or better performance under nominal conditions. (All variables varying across entire range). Meet $10^{-6}$ box</td>
</tr>
<tr>
<td>2</td>
<td>AC 120-28D Performance with <em>Malfunction</em> – App. 3, Section 6.4.1</td>
<td>For all failures with probability $&gt; 10^{-9}$ demonstrate safe landing $\rightarrow$ Land in box (with probability 1), given environment and other variables ‘nominal’.</td>
</tr>
<tr>
<td>3</td>
<td>JAR AWO Subpart 1 – Performance Demonstration <em>Limit-case</em> conditions</td>
<td>Demonstrate performance when one of the variables is at its most critical value while the others vary in their expected manner – Land in defined box with $10^{-5}$ $\rightarrow$ <em>Conditional probability approach</em></td>
</tr>
</tbody>
</table>

Tim Murphy’s presentation and paper are inside RTCA SC-159 WG-4 Archive File: [http://sc159.tc.faa.gov/wg4/060706/Jun072006.htm](http://sc159.tc.faa.gov/wg4/060706/Jun072006.htm)
Approach and Landing Minima


- **GPS (SPS)**: 400 – 600 ft MDA
- **SBAS**: 350 – 400 ft DA
- **SBAS**: 200 – 300 ft DA
- **GBAS**: 200 – 0 ft, Cat II/III

Diagram showing the approach and landing minima for GPS (SPS), SBAS, and GBAS systems.
Anomalous Impacts on GBAS Integrity Risk

<table>
<thead>
<tr>
<th>Cause</th>
<th>Fault/Anomaly Mode</th>
<th>Design Impact</th>
<th>Integrity Risk Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>Signal Deformation</td>
<td>Much work needed to protect worst case</td>
<td>Small</td>
</tr>
<tr>
<td></td>
<td>Low Signal Power</td>
<td>Easy to monitor</td>
<td>Very Small</td>
</tr>
<tr>
<td></td>
<td>Excess Acceleration</td>
<td>Easy to monitor</td>
<td>Small</td>
</tr>
<tr>
<td></td>
<td>Code-Carrier Divergence</td>
<td>Monitoring supports ionospheric mitigation</td>
<td>Very Small</td>
</tr>
<tr>
<td></td>
<td>Ephemeris</td>
<td>Many threat scenarios to defend against</td>
<td>Moderate</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>Ionosphere</td>
<td>Worst-case mitigation sacrifices availability</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Troposphere</td>
<td>Worst-case gradient bound has limited impact</td>
<td>Small</td>
</tr>
<tr>
<td>Local</td>
<td>Multipath</td>
<td>Siting restricted; Long-term monitoring needed</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>RF Interference</td>
<td>Siting restricted; Complex monitor interactions</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Nominal Digital Distortion: GPS Satellite Comparison

Semi-Random, Near-Worst-Case Iono. Anomaly Impact at Memphis (DH 6 km from LGF Centroid)

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.

Safety limit derived from OCS $\approx 28$ m

Worst-case error, or “MIEV”, is $\approx 41$ m
Simplified Flow Chart for Real-Time LGF Parameter Inflation ("Geometry Screening")

LGF acts to make potentially unsafe user geometries unavailable.

Inflate broadcast parameters as needed to eliminate (make unavailable) all subset geometries with MIEV > OCS-based safety limit.

This makes many safe (MIEV < limit) geometries unavailable as well and thus significantly reduces system availability.

Approved Sigmas/P-Values for Broadcast by VDB
### Use of SBAS (WAAS) GIVE
*(Original Stanford Concept)*

<table>
<thead>
<tr>
<th>GIVE Value</th>
<th>GIVE Integer(s)</th>
<th>LAAS Class</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \leq 6.0 \text{ m} )</td>
<td>0 – 12</td>
<td>Good</td>
<td>WAAS verifies that no threat is present here.</td>
</tr>
<tr>
<td>15.0 m</td>
<td>13</td>
<td>Not Observed</td>
<td>WAAS observations are too limited to confirm that no threat exists.</td>
</tr>
<tr>
<td>45.0 m</td>
<td>14</td>
<td>Bad</td>
<td>WAAS detects a nearby ionosphere storm – possible threat.</td>
</tr>
<tr>
<td>Not Monitored</td>
<td>15</td>
<td>Not Observed</td>
<td>WAAS observations are too limited to provide any iono. assurance.</td>
</tr>
</tbody>
</table>
GBAS IPP and Surrounding WAAS IGPs

IGP 1 (GIVE\(_1\))

IGP 2 (GIVE\(_2\))

IGP 3 (GIVE\(_3\))

IGP 4 (GIVE\(_4\))

LGF IPP for SV \(j\)

\[ \text{Lat}_1 + 5^\circ \]

\[ \text{Long}_1 \]

\[ \text{Long}_1 + 5^\circ \]
### Use of SBAS (WAAS) UDRE
*(Original Stanford Concept)*

<table>
<thead>
<tr>
<th>UDRE Value</th>
<th>UDRE Integer</th>
<th>GBAS Class.</th>
<th>Ephemeris MDE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 50.0 m</td>
<td>0 – 12</td>
<td>Good</td>
<td>500</td>
</tr>
<tr>
<td>150.0 m</td>
<td>13</td>
<td>Adequate</td>
<td>1500</td>
</tr>
<tr>
<td>Not Monitored</td>
<td>14</td>
<td>Neutral</td>
<td>GBAS value (~ 3500 m)</td>
</tr>
<tr>
<td>Do Not Use</td>
<td>15</td>
<td>Do Not Use</td>
<td>Exclude from Use</td>
</tr>
</tbody>
</table>
IGM SARPS Requirements Issue (1)

- Current SARPS requirement for IGM (Section B.3.6.7.3.4) reads as follows:

3.6.7.3.4. Ionospheric Gradient Monitoring,

A ground subsystem classified as FAST D shall within 1.5 seconds mark the differential corrections for affected satellites as invalid in MT11 (σ_{pr,0} D bit pattern “1111 1111” ), if the probability that there is an undetected spatial ionospheric delay gradient with a magnitude greater than 1.5m/D in the direction of any approach supporting GAST D is greater than 1x10^9. D is the distance between the reference point of the FAST D ground subsystem and the threshold. The direction of the approach is defined by the runway heading.

Note - The total probability of an undetected delay gradient includes the prior probability of the gradient and the monitor probability of missed detection. For example, if the distance to the threshold is 5 km then the magnitude of the gradient that needs to be detected is 1.5 m/5 km = 300 mm/km. The magnitude of the undetected ionospheric spatial delay gradient as observed over a baseline parallel to runway being served must not exceed 300 mm/km with a total probability of greater than 1x10^9.

- This requires detection of an ionospheric gradient magnitude within 1.5 seconds without allowing for limited ground station observability.
IGM SARPS Requirements Issue (2)

• Honeywell has proposed reformulating the IGM requirement in the range domain (i.e., detect range error > X meters rather than gradient > G mm/km).
  – Allows for “waiting time” until defined differential range error is exceeded before IGM action is required
  – Allows more room for “trading off” reduced threat space vs. increased maximum ground-airborne separation (D)

• Alternatively, within the current gradient-based requirement, define the threat subspaces and waiting times for which the ground station is responsible.
Iono. Gradient Monitor (IGM) Concept (2)

- Detection not guaranteed if, for any integer $n$,

$$\lambda n - (k_{ffd} + k_{md})\sigma_\phi < \alpha b < \lambda n + (k_{ffd} + k_{md})\sigma_\phi$$