

# GPS III Signal Integrity and Aviation Applications

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# GPS III Integrity Topics

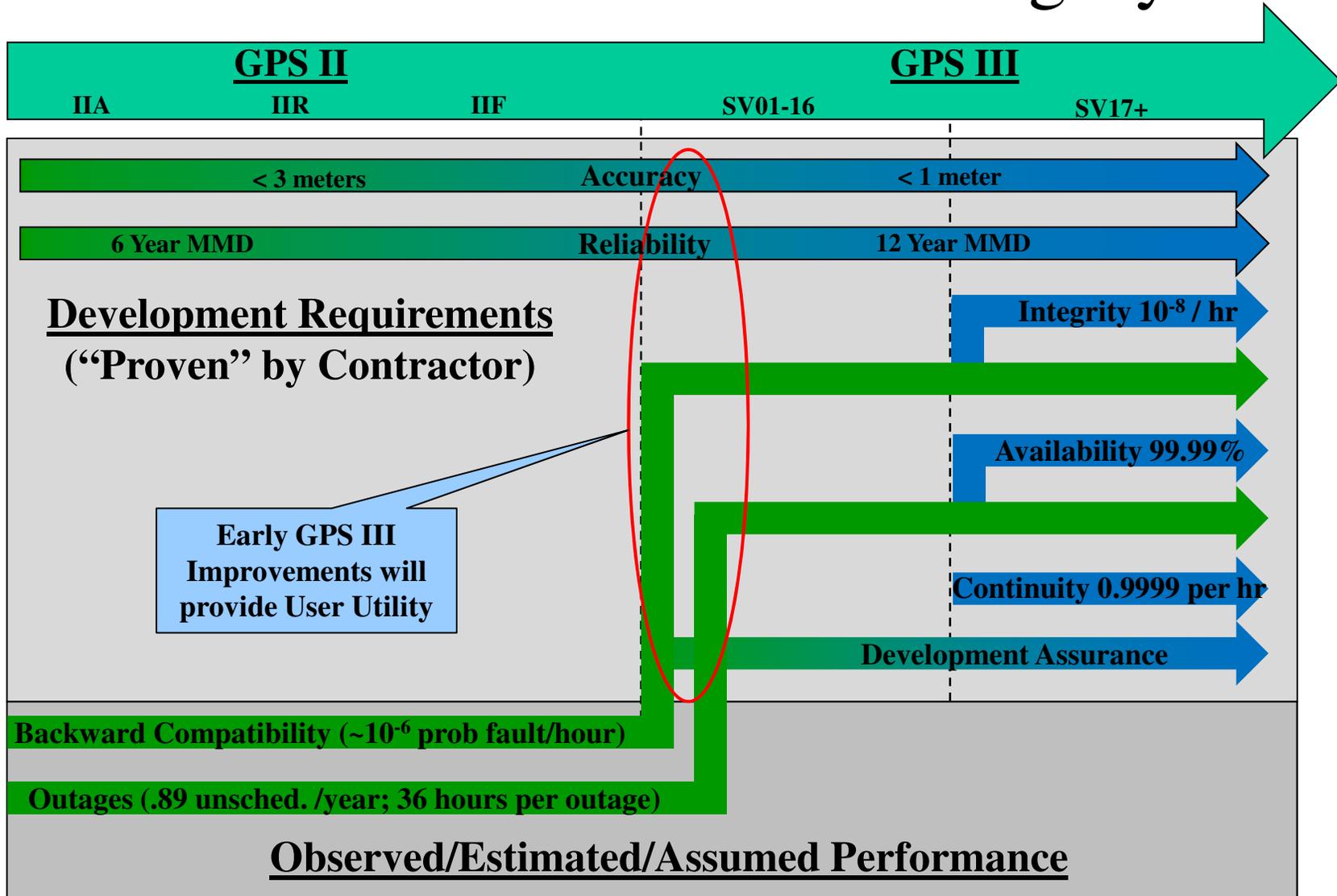
- GPS III Space Vehicle (SV) design complies with enhanced requirements for Signal Integrity, Continuity and Availability
- Improvements in GPS III signal will result in improved performance for any Safety-of-Life users
- Presentation describes GPSIII integrity attributes and an example of how this could improve availability of LPV Precision Approach

# Signal Integrity and Continuity Assurance

- Design attributes and development assurance standards to limit risk of GPS III signal failures that are potentially hazardous to navigation users
- Design attributes and performance requirements to limit the occurrence of
  - Erroneous signals that would result in user navigation errors
  - Unexpected loss of GPS signals
  - Extended periods of GPS signal outage
- Development assurance standards to assure GPS III SS design, development and test activities result in a system that has limited risk of defects
- New set of processes and analysis approaches for GPS III
  - Approaches are based on standards defined by FAA for aircraft and navigation systems
    - RTCA DO-254 (for complex hardware) and RTCA DO-278 (for software development)
    - Society of Automotive Engineers Aerospace Recommended Practice (SAE ARP 4754) for systems engineering and analysis
- Integrity and continuity assurance is evolutionary to achieve objective (i.e., future) GPS III performance
  - Processes applied early in GPS III development to reduce impacts for future GPS III
  - GPS III activities define additional capabilities required for future GPS III performance

***Early Application of Assurance Processes Provides High Confidence for Navigation Users***

# Evolution of GPS III Integrity



**GPS III Requirements Ensure Continued Performance & Improve Future Performance**

# Key Space Segment Integrity & Continuity Requirements

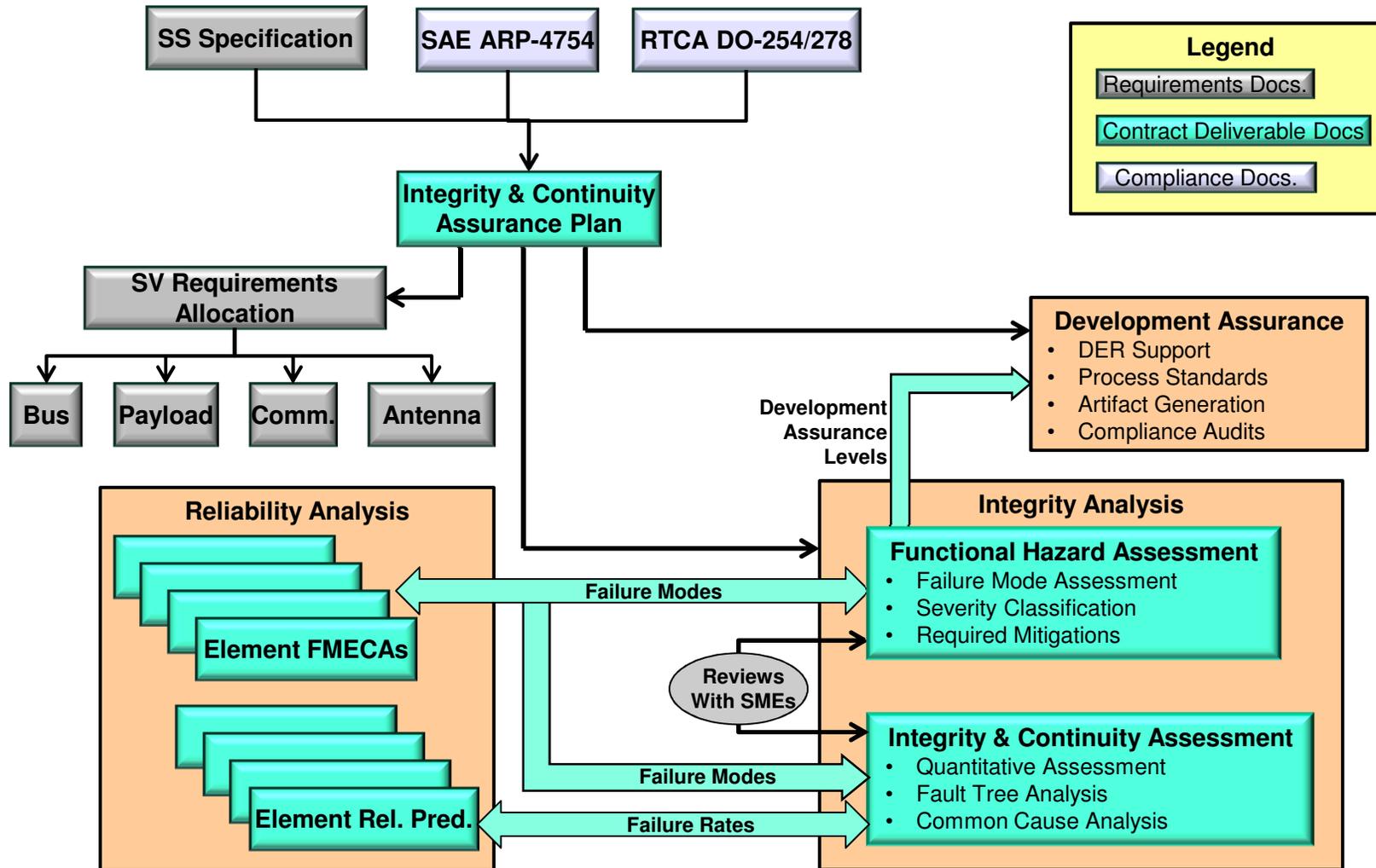
Anomaly Type	Magnitude	Probability of Occurrence
Large URE	URE > 7 meters	<5E-6 per hour
Unbounded URE	URE > 4.42 * URA	<5E-6 per hour
	URE > 5.73 * URA*	<1E-8 per hour*
Large URA	URA > 2.5 * 24-hour RMS URE	<1% over year
Scheduled Outage	<12 hours per outage	< 1.3 outages per year
Unscheduled Outage	<36 hours per outage	< 0.89 outages per year
Major Service Failure	URE > 4.42 * URA or URE > 30 m	< 1.3E-5 per hour
Phase step error	>3.6 m & <300 m	< 9E-5 per hour
Pseudo-Range Velocity Error	>0.01 m/s & <0.05 m/s	< 9E-7 per hour
Pseudo-Range Acceleration Error	>0.019 m/s <sup>2</sup>	< 9E-5 per hour
Signal Deformation	Lead, lag ≥ 10 ns Ring ≥ 7.3 MHz	< 1E-4 per hour
Development Assurance* per SAE ARP-4754, RTCA DO-254, RTCA DO-278		
*Note: Requirements in red denote future GPS III requirements		

# GPS III Development Assurance

- Development assurance is a future GPS III requirement (along with an enhanced level of integrity)
  - GPS III inherent signal integrity was viewed as an enabling capability for future safety-of-life systems
  - Allows for reduced reliance on augmentation systems
- Compliance with development assurance standards requires generation of compliance artifacts during design, development & test activities
  - Provides objective evidence for compliance
- LM elected to apply development assurance standards in initial SV development to minimize impact of achieving end-state integrity
  - Allows for re-use of development artifacts
  - Ensures early agreement on compliance basis and analytical methods to demonstrate compliance
- Development assurance per FAA standards has never been applied to satellite development

***GPS III is Being Developed in Accordance with FAA Standards NOW***

# Development Assurance Process



**Comprehensive Analysis & Development Assurance Process**



# Hazard Severity Classification for GPS

## Hazard Severity Defined in Future Requirement Effectivity

Failure Class	Hazard Consequence	Development Assurance Level		
		SAE ARP 4754	S/W DO-278	H/W DO-254
One or more SVs transmitting a SIS with a URE that is greater or equal to 5.73 times the integrity-assured URA that persists for more than 5.2 seconds when the Integrity Status flag is "on".	Hazardous/ Severe Major	B	2	B
Unscheduled outage of a navigation signal (or signals) concurrently from two or more SVs.	Major	C	3	C
One or more SVs transmitting a SIS with a URE that is greater or equal to 4.42 times the Nominal URA when the Integrity Status flag is "off", or Unscheduled outage of a navigation signal (or signals) from a single SV	Major/Minor	D	4	D
Scheduled outage of a navigation signal (or signals) from one or more SVs	Minor	D	5	D

**Government Defined Hazard Severities Used to Establish Process Rigor**



# Development Assurance Levels

## Development Assurance Levels Derived for SV01 based on initial FHA

SV Element	S/W DAL RTCA DO-278	H/W DAL RTCA DO-254	Rationale
Navigation Payload Element	3	C	<ul style="list-style-type: none"> <li>• Signal generation functions can directly contribute to signal error or unscheduled outage</li> <li>• Mitigated by future Integrity Monitor</li> </ul>
SV Bus Element	4	D	<ul style="list-style-type: none"> <li>• Bus functions indirectly contribute to signal errors, directly contribute to unscheduled outages</li> <li>• Mitigated by future Integrity Monitor</li> </ul>
Network Communication Element	4	D	<ul style="list-style-type: none"> <li>• Comm. functions indirectly contribute to signal errors, directly contribute to unscheduled outages</li> <li>• Mitigated by future Integrity Monitor</li> </ul>
Antenna Element	N/A	N/A	Contains no S/W or Complex Electronic Hardware per DO-254
Integrity Monitor Element*	2	B	Primary mitigation for hazardous signal errors in future effectivity

\*Note: Integrity Monitor Element Planned for Future Effectivity

**Development Assurance Levels Have Been Defined for Initial SV01+**

# GPS III Fault Detection Capability

- Clock Monitoring
  - Based on comparison between long-term Atomic Frequency Standard (AFS) and short-term Voltage Controlled Crystal Oscillator (VCXO)
    - Significant faults in either AFS or VCXO will cause detectable short-term (20 seconds) drift
  - Switch to Non-Standard Code (NSC)
- Payload fault detection
  - Internal anomalies result in switch to NSC
    - Phase lock loop detector, communication errors, etc.
- Bus
  - Detects attitude (2 deg), thruster, power, thermal anomalies
  - Sends flag to payload resulting in switch to NSC
- Loss of communication between Bus and Payload processor results in switch to NSC

***Significantly Enhanced GPS III On-board Monitoring, Fault Detection and Fail-Safe Response***



# Key Requirement Performance Summary

**Analysis reflects conservative assumptions and data obtained from CDR reliability analysis, FMECA and element level performance analyses**

Requirement	Value	Predicted Performance	Remarks
Prob (URE > 7 m) Prob (URE > 4.42 * URA)	<5e-6 per hour	7.6e-7	Driven by SV mass leaks
Number of Scheduled Outages	<1.3 per year	1	Station-keeping maneuvers
Duration of Scheduled Outages	<12 hours	7.3	
Number of Unscheduled Outages	<0.89 per year	0.55	Includes H/W, S/W, SEE
Duration of Unscheduled Outages	<36 hours	17	Average outage duration, reflects recovery time for each major component
Prob (Signal Deformation)	<1e-4 per hour	0	No signal deformation failure modes identified in FMECA
Prob (Major Service Failure)	<1.3e-5 per hour	7.6e-7	Equivalent to signal error
Prob (Step Error >300 meters)	<9e-7 per hour	7.9e-8	Excludes SV mass leaks
Prob (PR Velocity Error >0.01 m/sec)	<9e-7 per hour	7.6e-7	Most constraining requirement
Prob (PR Acc. Error >0.019 m/sec <sup>2</sup> )	<9e-5 per hour	1.7e-6	Not detectable on-board, driven by AFS clock history data

***Comprehensive Analysis of GPS III Design Shows Compliance With Requirements***



# Analysis Results Summary

Analysis	Summary
Functional Hazard Analysis	<ul style="list-style-type: none"> <li>• Systematic evaluation of functional failure modes to determine severity</li> <li>• Used to assign development assurance level</li> </ul>
Fault Tree Analysis	<ul style="list-style-type: none"> <li>• Systematic decomposition of top-level failures into constituent causative events</li> <li>• Fault trees developed for both signal error and unscheduled outage</li> </ul>
Failure Mode Effects and Criticality Assessment	<ul style="list-style-type: none"> <li>• Bottoms-up assessment of component failure modes and end-level effects</li> <li>• Used in conjunction with reliability predictions to determine signal fault probabilities</li> </ul>
Reliability Analysis	<ul style="list-style-type: none"> <li>• Predicts component failure probability</li> <li>• Typically based on component operating failure history data</li> <li>• Includes software reliability predictions</li> </ul>
Common Cause Analysis	<ul style="list-style-type: none"> <li>• Identify failures with potential to propagate more than one pathway (e.g. electrical short) or systematic faults common to multiple components (e.g., common design)</li> <li>• Used to validate independence claims for fault detection and correction</li> </ul>
Impact of Attitude Error or Antenna Element Failures	<ul style="list-style-type: none"> <li>• Potential for signal error due to antenna pointing error or single element failures</li> <li>• Results show both have the potential to induce group delay errors</li> </ul>
Command Corruption Analysis	<ul style="list-style-type: none"> <li>• Determine probability that bit errors on communication links (CS to SV or SV internal) can cause signal error</li> <li>• Also, assess which SV commands have potential to cause signal errors if executed incorrectly or at the wrong time</li> </ul>
Mass Leaks	<ul style="list-style-type: none"> <li>• Determine probability that mass leaks from SV cause ephemeris errors while the SV is radiating a valid signal</li> </ul>
Clock Monitoring	<ul style="list-style-type: none"> <li>• Determine probability of missed detection and false alarm for SV clock monitoring</li> </ul>

***Extensive Analysis Applied to GPS III Design***

**How can these improvements benefit Safety-of-Life users?**



# Motivation

- **Examine ARAIM performance and availability for LPV precision approach with GPS only**
  - Military users (L1 – L2 P/Y code)
  - Future civil users (L1 – L5)
- **Since availability for a single GNSS constellation is limited, examine benefits of GPS modernization**
- **Focus here on GPS satellite improvement over time: transition from (today's) Block II to Block III satellites (in development)**
  - Improved accuracy → lower bounds on SIS User Range Accuracy (URA)
  - Improved integrity → lower satellite failure probability
- **Examine two ARAIM concepts**
  - Use of independent Integrity Status Message (ISM)
    - Provides most accurate URA for local region
  - Use of GPS broadcast User Range Accuracy (URA)
    - Provides conservative URA for entire SV footprint and includes quantization errors due to Nav message formatting

# Constellation Scenarios

Constellation Option	# of SVs	Type of SVs	(Possible) Date	Notes
Baseline 26	26	IIA / IIR / IIRM / IIF	May 2013	26 SVs in "Primary" Slots (B5 slot empty)
Baseline 27	27	IIA / IIR / IIRM / IIF	May 2013	27 SVs in "Primary" Slots (B5 slot filled)
II-Max-27	27	IIR / IIRM / IIF	2020	Last of Original 12 IIF
III-All-27	27	III	2030	All IIIs

Source: "The Impact of GPS Modernization on Standalone User Performance and Integrity with ARAIM", Sam Pullen, et al, ION GNSS 2013



# ISM-Based Error Model (Local ISM)

SV Type	URA	URA bias	URE
(1) Block IIA	1.25 m	1.00 m	0.90 m
(2) Block IIR	0.80 m	1.00 m	0.60 m
(3) Block IIRM	0.80 m	0.70 m	0.60 m
(4) Block IIF	0.80 m	0.80 m	0.60 m
(5) Block III	0.50 m	0.40 m	0.38 m

## Failure Probabilities

SV Type	SV Fault Rate	Constellation Fault Rate
Block II	$10^{-5}$ / SV / hour	$10^{-8}$ / hour
Block III	$10^{-6}$ / SV / hour	$10^{-9}$ / hour

*Difference is irrelevant for LPV ops.*

Source: "The Impact of GPS Modernization on Standalone User Performance and Integrity with ARAIM", Sam Pullen, et al, ION GNSS 2013

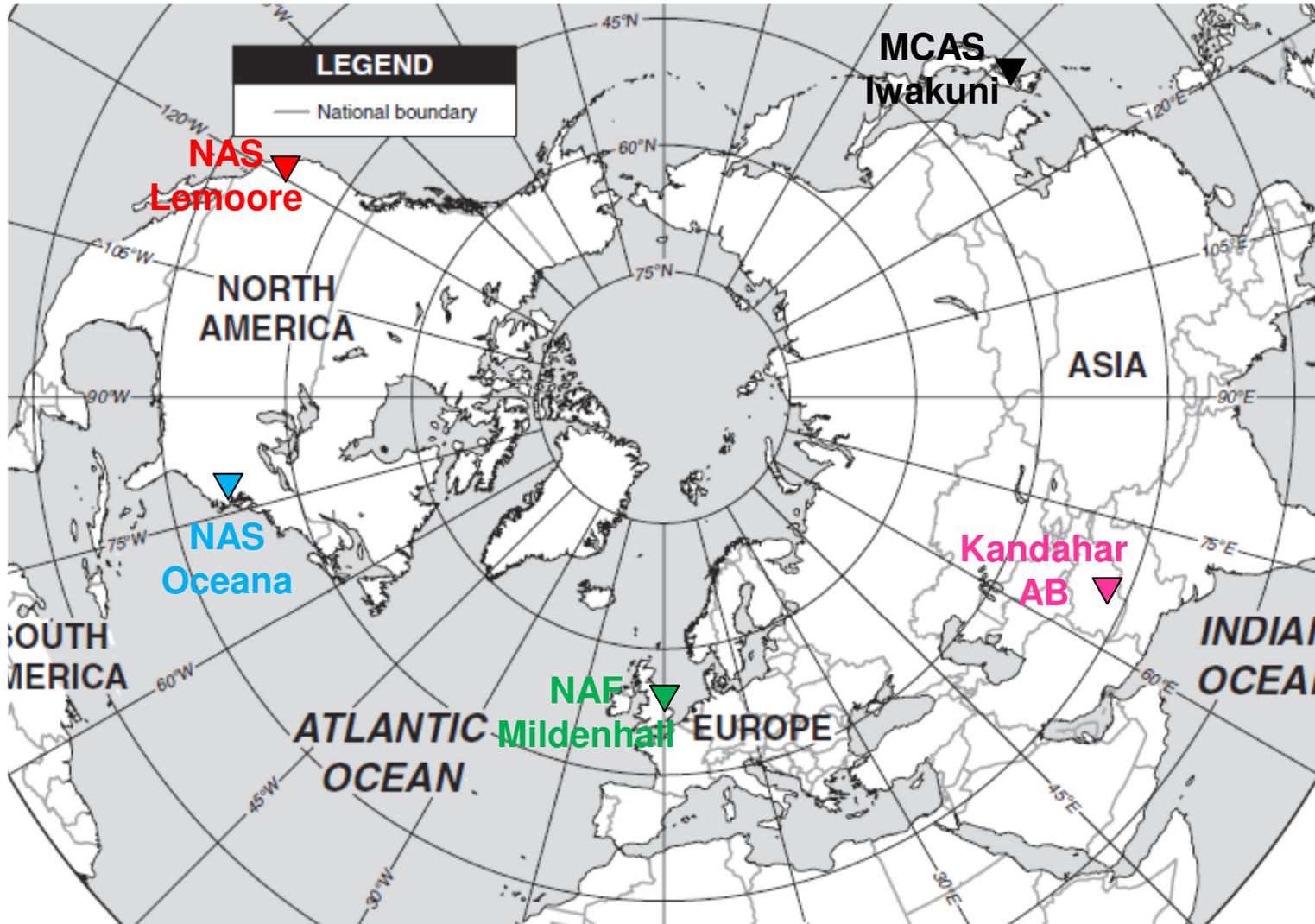
# URA Error Model (global or no ISM)

SV Type	URA	URA bias	URE
<b>(1) Block IIA</b>	<b>1.57 m</b>	<b>1.00 m</b>	<b>0.90 m</b>
<b>(2) Block IIR</b>	<b>1.05 m</b>	<b>1.00 m</b>	<b>0.60 m</b>
<b>(3) Block IIRM</b>	<b>1.05 m</b> (NED = 1.038 m; ED = 0.136 m)	<b>0.70 m</b>	<b>0.60 m</b>
<b>(4) Block IIF</b>	<b>1.05 m</b> (same as IIRM)	<b>0.80 m</b>	<b>0.60 m</b>
<b>(5) Block III</b>	<b>0.66 m</b> (NED = 0.658 m; ED = 0.086 m)	<b>0.40 m</b>	<b>0.38 m</b>

- URA based on re-scaled MITRE covariance matrix for Block IIR-M PRN 31 prior to broadcast message quantization
- URA bias the same as in ideal model
- UREs unchanged from ideal values (same “nominal” errors)
- Note: SV’s only broadcast URA (incl. NED and ED) → bias and URE are either fixed or come from global ISM

Source: “The Impact of GPS Modernization on Standalone User Performance and Integrity with ARAIM”, Sam Pullen, et al, ION GNSS 2013

# Five User Locations Simulated



Map source: [http://www.eduplace.com/ss/maps/pdf/n\\_hemis.pdf](http://www.eduplace.com/ss/maps/pdf/n_hemis.pdf)



# Summary of Results

Scenario	90 <sup>th</sup> Pct VPL* (m)	99 <sup>th</sup> Pct VPL (m)	LPV-200 Avail.	LPV-250 Avail.
<i>ISM-based Error Model</i>				
Baseline 26	27.0	64.8	95.9 %	98.2 %
Baseline 27	22.9	34.4	99.1 %	99.9 %
Block II Maximum 27	21.1	30.8	99.5 %	99.9 %
Block III All 27: Prob. Only	17.8	26.1	99.7 %	99.9 %
Block III All 27: Prob. & URA	13.2	19.0	100 %	100 %
<i>URA-based Error Model; K = 1.0</i>				
Baseline 26	35.8	80.6	87.9%	94.6 %
Baseline 27	31.2	45.7	93.9 %	98.8 %
Block II Maximum 27	27.2	39.3	97.7 %	99.6 %
Block III All 27: Prob. Only	19.6	28.2	99.6 %	99.9 %
Block III All 27: Prob. & URA	14.4	20.6	100 %	100 %
*Note: Vertical Protection Limit = “buffer zone”, outside of which, users’ safety meets established safety criteria				

Source: “The Impact of GPS Modernization on Standalone User Performance and Integrity with ARAIM”, Sam Pullen, et al, ION GNSS 2013

# Summary

- Next generation of GPS SVs designed with explicit requirements for signal integrity and continuity
- Resulted in design features to enhance inherent integrity of the signal and reduce the rate of occurrence of anomalies
  - More robust fault monitoring and fail-safe response via NSC
  - More robust set of analyses to assess performance
- Application of safety standards to ensure GPS III adheres to safety criteria used for commercial aviation
- Improvements in accuracy and fault probability are expected to enhance Civil and Military aviation operations