Supporting
European
Aviation

EUROCONTROL

Advanced RAIM

Foundation for robust DFMC GNSS

Gerhard Berz
ICAO Navigation Systems Panel, ARAIM SARPs ad-hoc group Rapporteur
February 2024
gerhard.berz@eurocontrol.int
With contributions from Stanford University, FAA and EU Space Program Agency

FOUNDING MEMBER SESAR JOINT UNDERTAKING

NETWORK MANAGER

Starting Point: ABAS / RAIM (GPS L1)

3.7.3.3 *Aircraft-based augmentation system (ABAS)*

3.7.3.3.1 *Performance*. The ABAS function combined with one or more of the other GNSS elements and both a fault-free GNSS receiver and fault-free aircraft system used for the ABAS function shall meet the requirements for accuracy, integrity, continuity and availability as stated in 3.7.2.4.

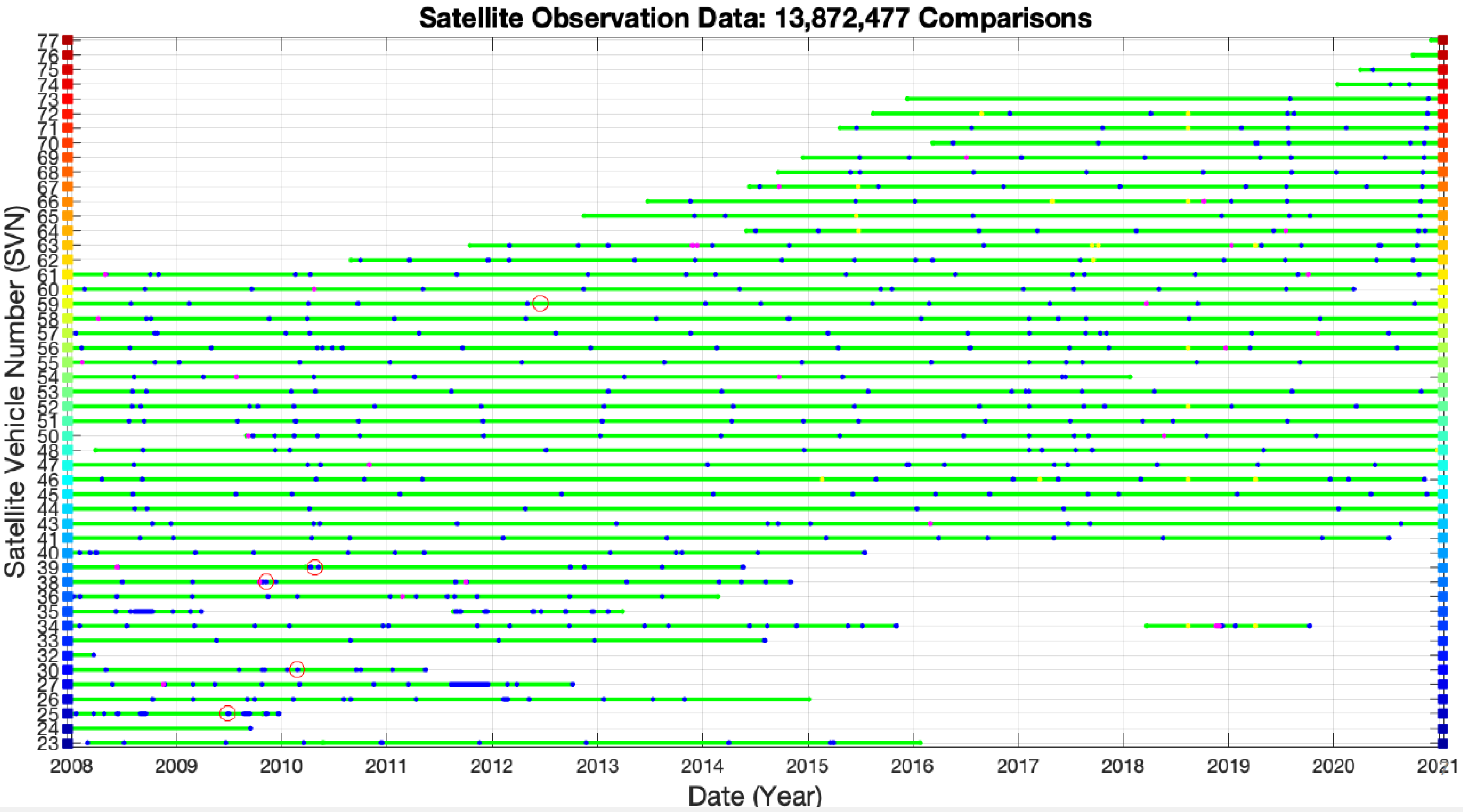
Table 3.7.2.4-1 Signal-in-space performance requirements

Typical operation	Accuracy horizontal 95% (Notes 1 and 3)	Accuracy vertical 95% (Notes 1 and 3)	Integrity (Note 2)	Time-to-alert (Note 3)	Continuity (Note 4)	Availability (Note 5)
En-route	3.7 km (2.0 NM)	N/A	$1 - 1 \times 10^{-7}$/h	5 min	$1 - 1 \times 10^{-4}$/h to $1 - 1 \times 10^{-8}$/h	0.99 to 0.99999
En-route, Terminal	0.74 km (0.4 NM)	N/A	$1 - 1 \times 10^{-7}$/h	15 s	$1 - 1 \times 10^{-4}$/h to $1 - 1 \times 10^{-8}$/h	0.99 to 0.99999
Initial approach, Intermediate approach, Non-precision approach (NPA), Departure	220 m (720 ft)	N/A	$1 - 1 \times 10^{-7}$/h	10 s	$1 - 1 \times 10^{-4}$/h to $1 - 1 \times 10^{-8}$/h	0.99 to 0.99999

- Simplest version of ABAS is GPS RAIM based on FAA TSO C129A (RTCA DO-208)
  - Essential component of majority of Air Transport operations today
  - Drawbacks: Dependence, Vulnerabilities, Lack of Clarity / Transparency

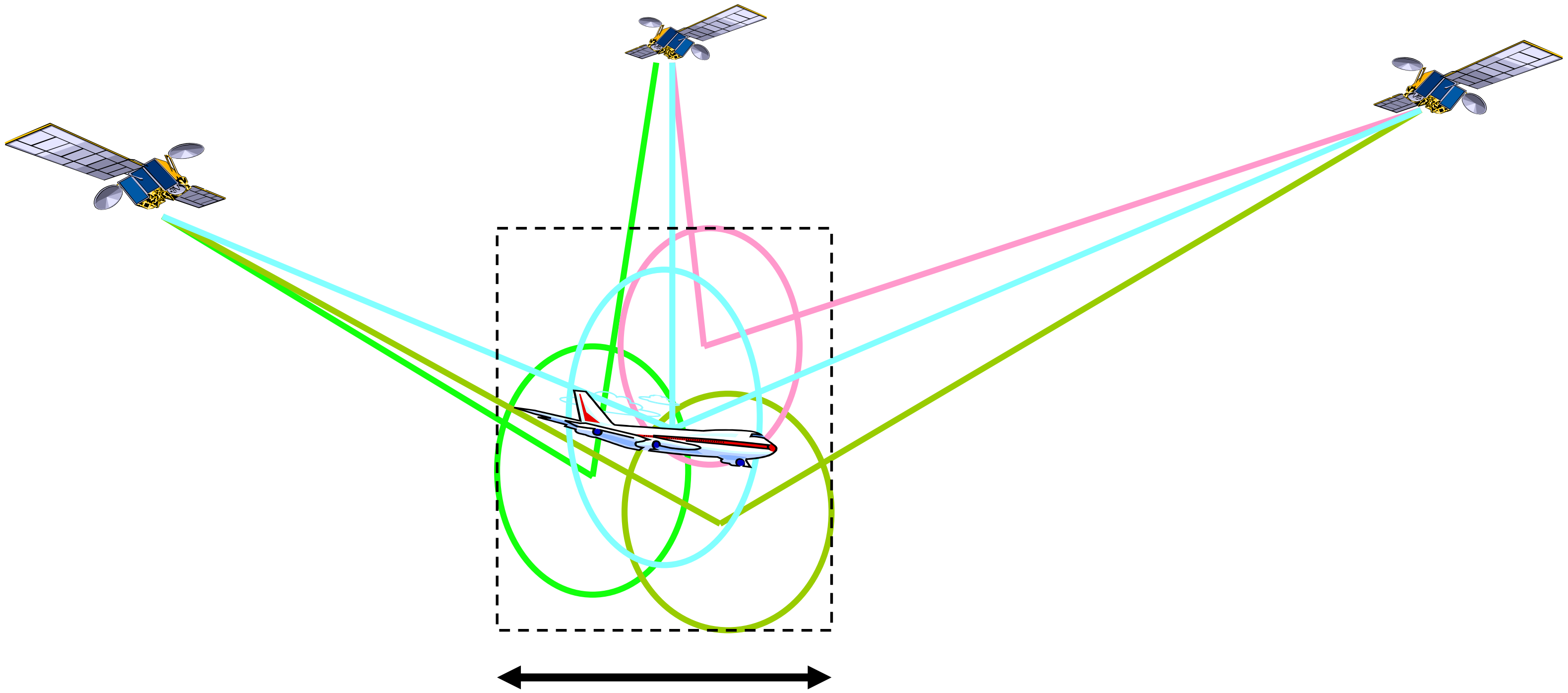
Impressive Service Quality for Many Years!

GPS Performance Summary



What is Receiver Autonomous Integrity Monitoring?

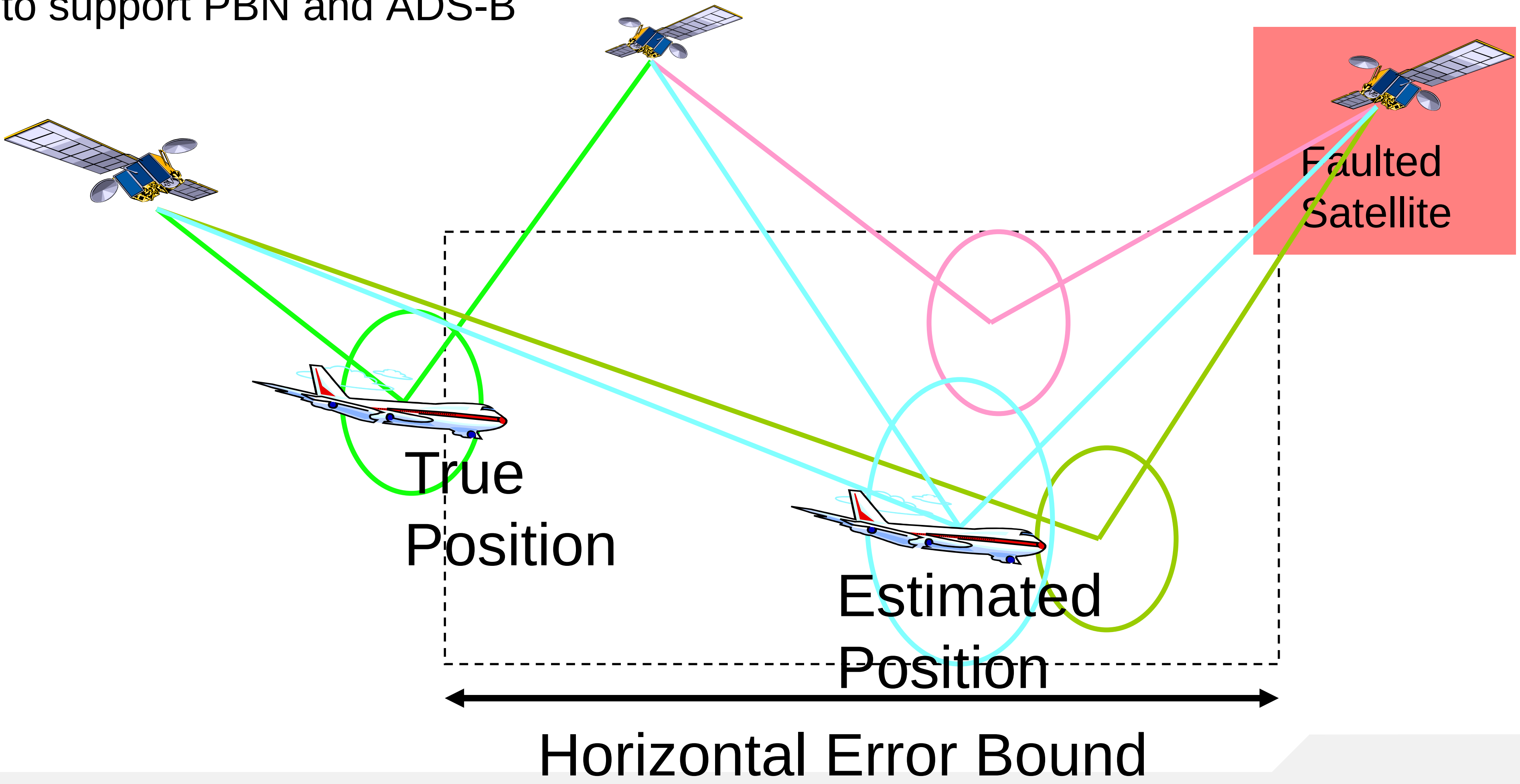
- An algorithm internal to the GNSS receiver
- It takes advantage of the fact that more satellites are received than necessary to compute a position ➔ enables cross-checking of sub-solutions against each other



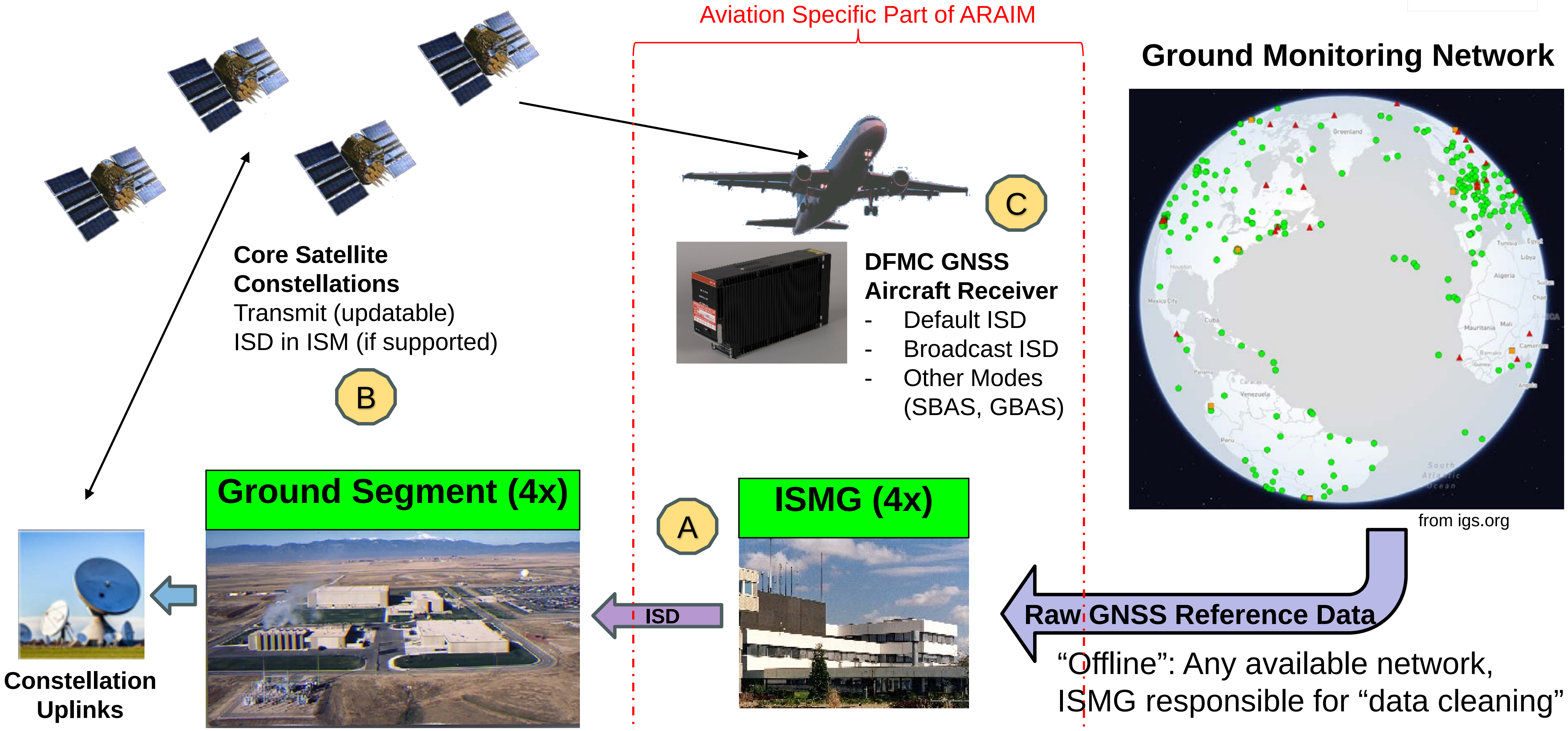
Horizontal Error Bound

What is RAIM?

- Provides WGS-84 Position plus a bound of the horizontal position error
- Can detect and [exclude] individual satellite faults (Fault Detection and Exclusion, FDE)
- Necessary to support PBN and ADS-B



Overview of the ARAIM System



ARAIM Benefits Roadmap

- ARAIM likely to be only future GNSS Augmentation with redundant modes (single frequency or single constellation)
- Incremental Development
  - Current H-ARAIM, Service Type A with default ISM supports performance data collection to build up to:
  - V-ARAIM, Service Type B, enabler for AR37-11 globally

	GPS	GPS + GNSS 2	GPS + GNSS 2 + GNSS 3
Single frequency L1	Good coverage of RNP0.3 with RAIM	Robust worldwide coverage of RNP0.1 with ARAIM	Robust worldwide coverage of RNP0.1 with ARAIM
Dual frequency L1+L5	Good coverage of RNP0.1 with RAIM	Worldwide coverage of LPV 200 with ARAIM	Robust Worldwide coverage of LPV 200 with ARAIM

Note: RNP 0.1 is not a currently defined PBN Navigation Specification per Doc 9613, PBN Manual

ARAIM Development by EU/US WG-C: Milestone Reports

SBAS Polar Coverage, MS3 Report

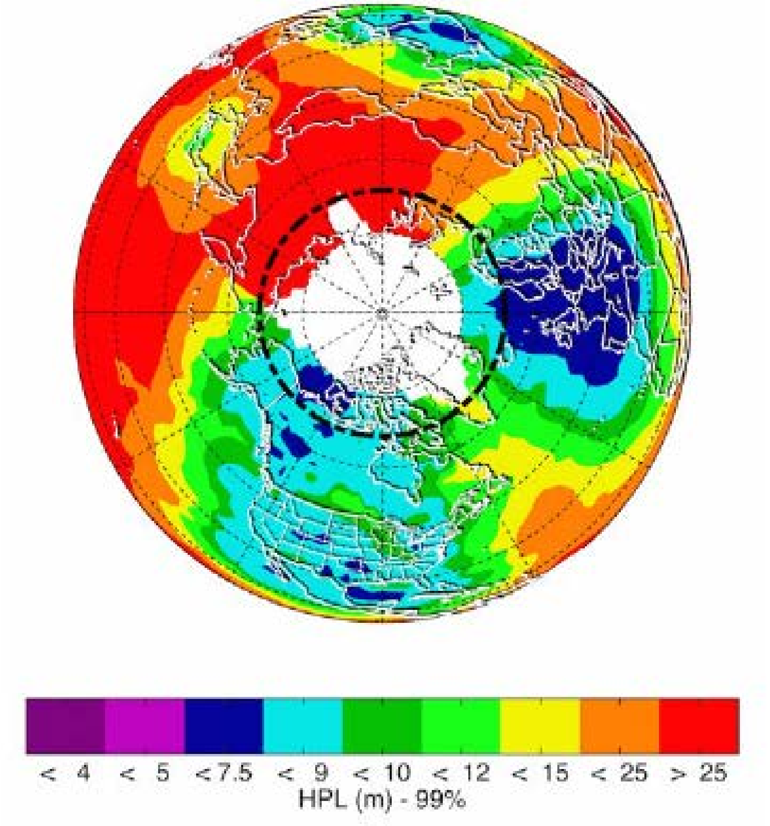


Figure 8: HPL for the Arctic Region Based on Dual Frequency GPS Augmented by WAAS + EGNOS MSAS

ARAIM Polar Coverage, MS3 Report

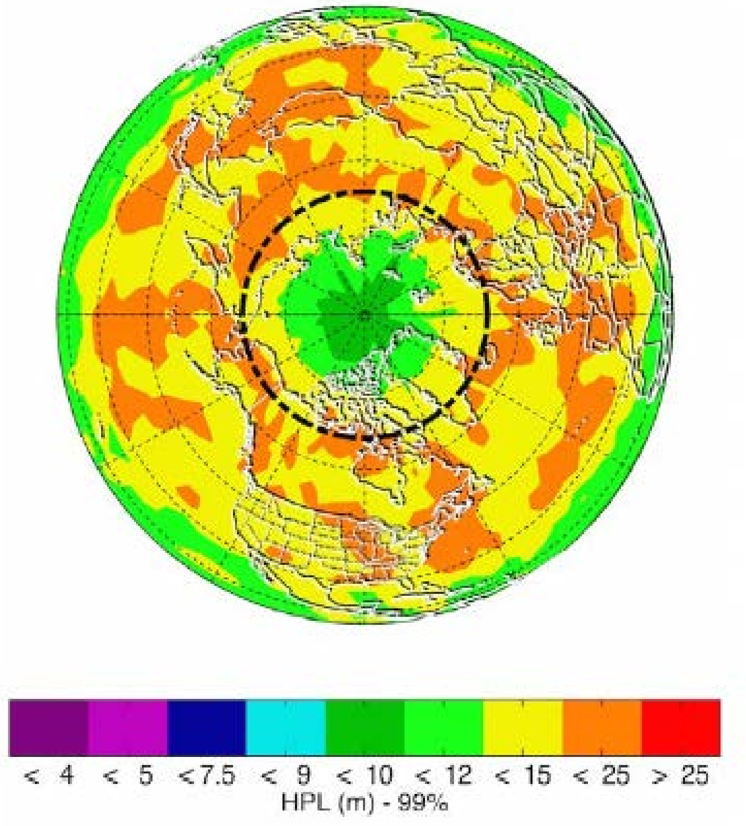
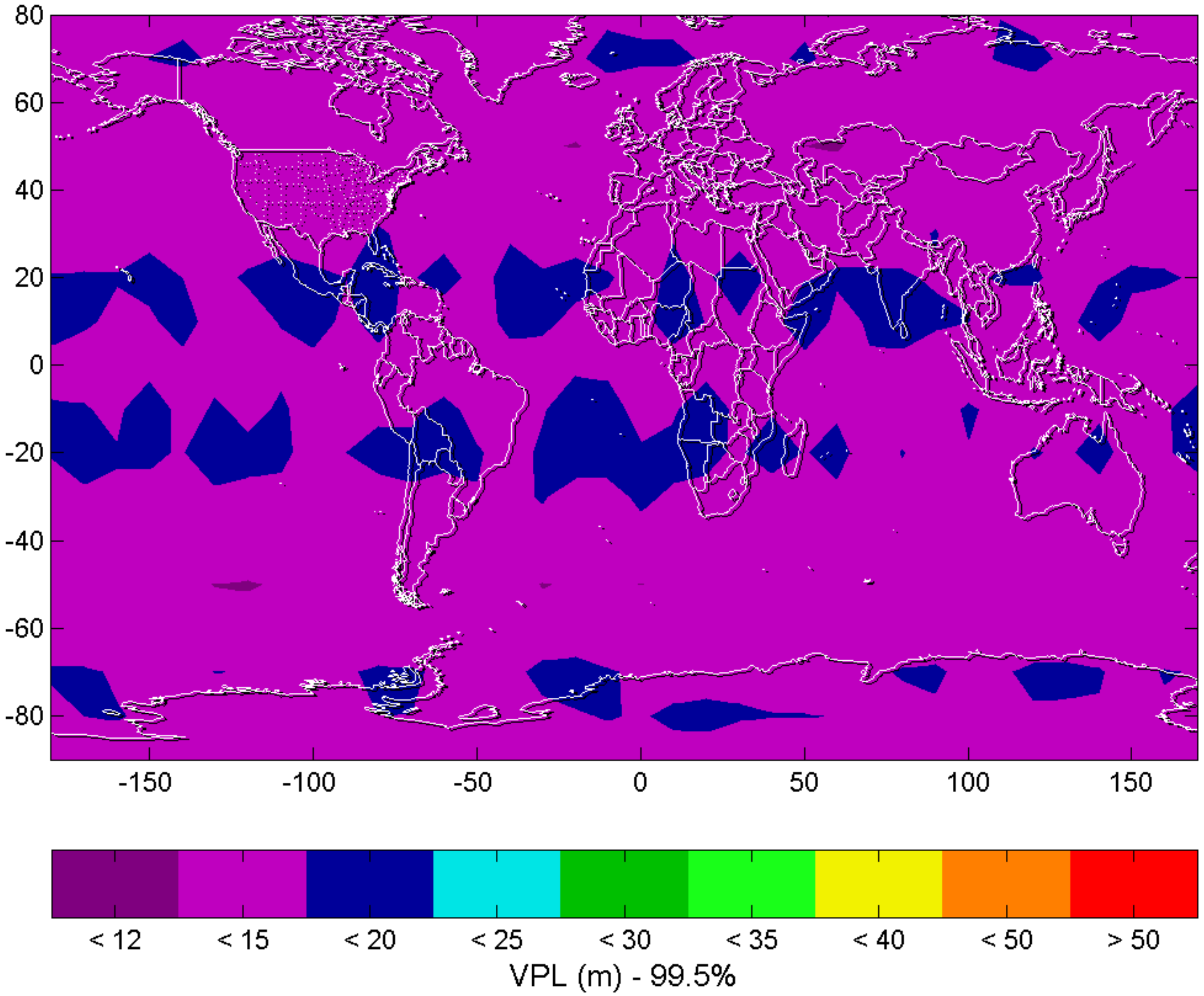


Figure 9: HPL for the Arctic Based on ARAIM with Dual Frequency GPS + Galileo

ARAIM Vertical Protection Level Map:
Three constellations (Galileo 27 + GPS 24 + GLONASS 24)



$P_{const} = 10^{-4}$
$P_{sat} = 10^{-5}$

URA = .75 m
Bias = .75 m

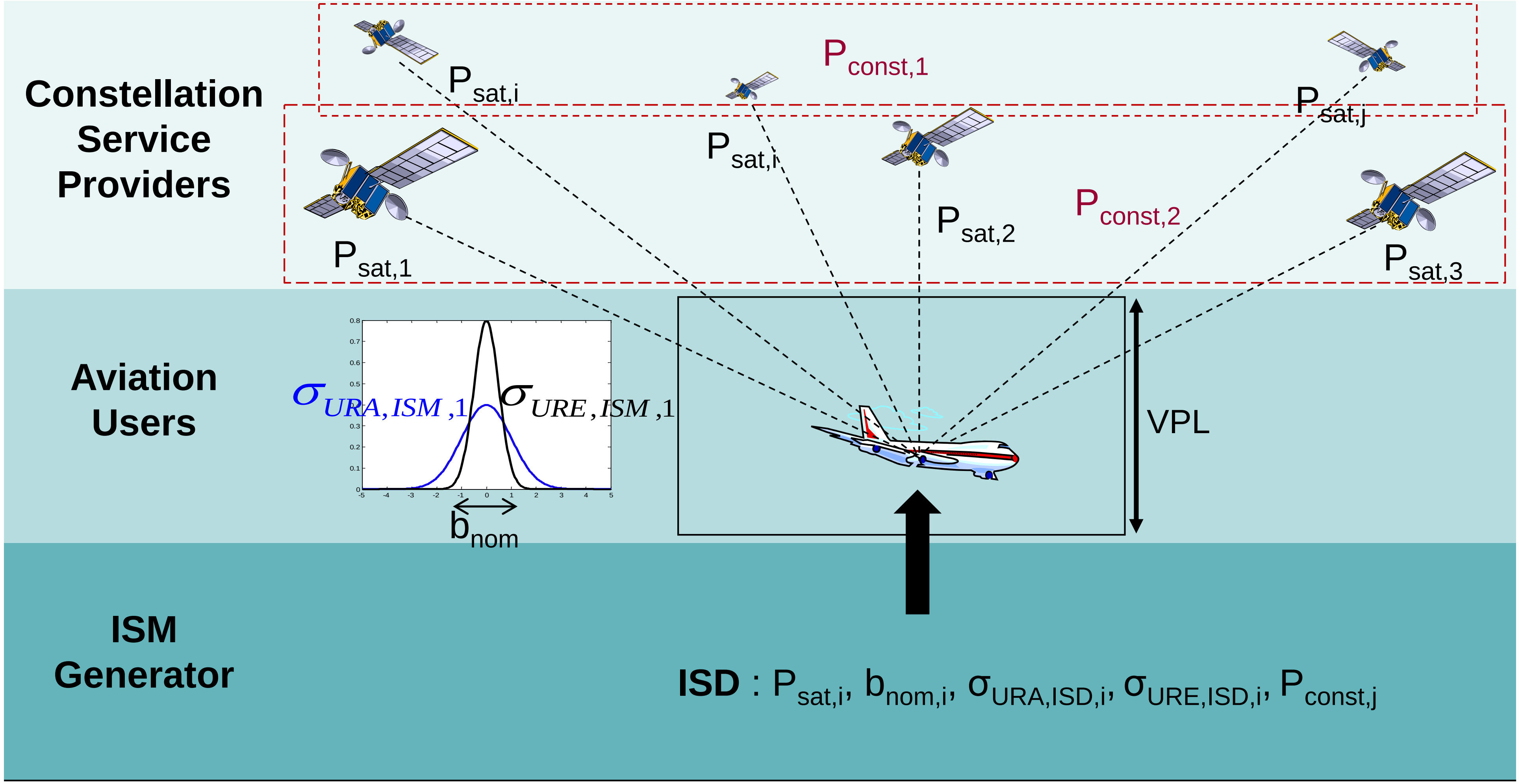
code available at
waas.stanford.edu

Integrity Approach

Constellation Service Providers	Service history	Service Performance Commitments	Communication between CSP and ISMG
Aviation Users	Receiver safeguards (beyond residual check: spacing ephemeris updates)		Margin in error models
ISM Generator	Offline monitoring (30 days)		Margin in ISM

Blanch, J., Walter, T., Enge, P., Wallner, S., Fernandez, F., Dellago, R., Ioannides, R., Pervan, B., Hernandez, I., Belabbas, B., Spletter, A., and Rippl, M., "Critical Elements for Multi-Constellation Advanced RAIM for Vertical Guidance," *NAVIGATION*, Vol. 60, No. 1, Spring 2013, pp. 53-69.

Integrity Support Message



Blanch, J., Walter, T., Enge, P., Wallner, S., Fernandez, F., Dellago, R., Ioannides, R., Pervan, B., Hernandez, I., Belabbas, B., Spletter, A., and Rippl, M., "Critical Elements for Multi-Constellation Advanced RAIM for Vertical Guidance," *NAVIGATION*, Vol. 60, No. 1, Spring 2013, pp. 53-69.

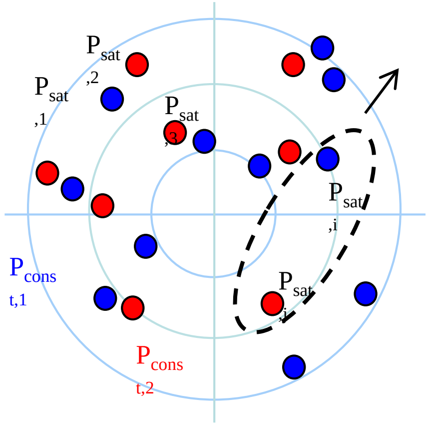
Positioning Threats

ISD

	Nominal	Narrow fault	Wide fault
1-Clock and Ephemeris	Orbit/clock estimation and prediction and broadcast limits	Includes clock runoffs, bad ephemeris, unflagged manoeuvres	Erroneous EOPP, inadequate manned ops, ground-inherent failures
2-Signal Deformation	Nominal differences in signals due to RF components, filters, and antennas waveform distortion $\sigma_{URA,i}$	Failures in satellite payload signal generation components. Faulted signal model as described in ICAO	N/A
3-Code-Carrier Incoherence	e.g. incoherence observed in IIF L5 signal or GEO L1 signals $b_{nom,i}$	e.g. incoherence observed in IIF L5 signal or GEO L1 signals $P_{sat,i}$	N/A $P_{const,j}$
4-IFB	Delay differences in satellite payload signal paths	Delay differences in satellite payload signal paths TBC	N/A
5-Satellite Antenna Bias	Look-angle dependent biases caused at satellite antennas	Look-angle dependent biases caused at satellite antennas	N/A
6-Ionosphere	N/A	Scintillation	Multiple scintillations at solar storms
7-Troposphere	Nominal troposphere error (after applying SBAS MOPS model for tropo correction) $\sigma_{tropo,i}$	N/A	N/A
8-Receiver Noise and Multipath	Nominal noise and multipath terms in airborne model (TBC Gailleo BOC(1,1) and L5/E5a) $\sigma_{airborne,i}$	e.g.: receiver tracking failure or multipath from onboard reflector. TBC	e.g.: receiver tracking multiple failure or multipath from onboard reflector. TBC

From: Working Group C, ARAIM Technical Subgroup, Interim Report, Issue 1.0, December 19, 2012
http://ec.europa.eu/enterprise/newsroom/cf/_getdocument.cfm?doc_id=7793
http://www.gps.gov/policy/cooperation/europe/2013/working-group-c/ARAIM-report-1.0.pdf

Baseline ARAIM Airborne Algorithm



ISM → Real time determination of faults to be monitored ← Geometry

↓

Consistency check and Protection Level Equation

$$\sum_j Q\left(\frac{VPL - T_j}{\sigma_j}\right) P_{fault,j} = \text{Integrity risk}$$

↓

Exclusion function

Baseline Algorithm likely to be included in DFMC GNSS Receiver Standard or other publicly available document

- ➔ *Manufacturers have complete freedom to implement and certify equivalent or better algorithms*
- ➔ *ARAIM can be combined with other ABAS elements such as INS, Baro, etc.*

ARAIM Milestone 1 Report

Blanch, J., Walter, T., Enge, P., Lee,Y., Pervan, B., Rippl, M., Spletter, A. "**Advanced RAIM User Algorithm Description: Integrity Support Message Processing, Fault Detection, Exclusion, and Protection Level Calculation**," *ION GNSS 2012, Nashville, September 2012*

Summary / Conclusions

- It is not possible / not correct to use new constellations & signals with “old RAIM”
- ARAIM improves transparency in constellation service provision
  - Globally harmonized set of parameters to characterize error distribution
  - Expect further harmonization and coordination between the 4 ISM Generator entities
  - Service monitoring is integrated and can easily be relied upon by States which do not operate a core satellite constellation
  - CSP / ISMG separation allows aviation oversight of ISMG, consistent with ANSP principles
- ISD / ISM will be broadcast by CSP: An aviation specific service message will be provided!
  - ARAIM ISD may / likely to also serve other user communities
- Service Type A SARPs pave the way for Service Type B
  - Global vertical instrument approach guidance (LPV200 / Cat I)
- ARAIM enables the use of DFMC GNSS while providing redundant modes for robustness
- Ensures interoperability while retaining flexibility / performance-based approach for both service providers and avionics manufacturers

Supporting
European
Aviation

EUROCONTROL

Thank you for your attention!

Questions ?

Advanced RAIM Development Path

Initial Service Type A: ca. 2025
Initial Service Type B: ca. 2030

1. Deploy initial ARAIM capability using Default ISD based on core satellite constellation commitments in SARPs
   - Provides redundant modes for DFMC SBAS
2. Build updateable, broadcast ISD for Service Type A
   - Data collection networks already widely available, reference data being stored
3. Implement DFMC GNSS Receivers
   - Validate ISM interfaces with on orbit ISM
   - Collect H-ARAIM Performance Data, including vertical performance
   - Validate Draft V-ARAIM Performance Requirements
4. Update SARPs and MOPS for ARAIM Service Type B
   - Expected to require broadcast ISD
   - May require more frequent update rates of ISD

ARAIM Development Plan

	2023				2024				2025				2026				2027				2028				2029			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Standardisation activity																												
ICAO SARPs	State letter process																											
ARAIM ConOps																												
GNSS manual (TBC)																												
EUROCAE MOPS																												
RevA (DFMC SBAS)																												
RevB (ARAIM + Institutional scenario)																												
ARAIM receiver development and certification									3 years optimistic scenario based on TSO/eTSO from ED-259B																			
ARAIM service milestones																												
Galileo																												
ISM ICD (date TBC)																												
Default ISD operations												Default ISD operation based on ARAIM SARPs																
ISM on broadcast (TBD)																												
Other milestone (TBD)																												
GPS																												
ISM ICD																												
Default ISD operations												Default ISD operation based on ARAIM SARPs																
ISM on broadcast (TBD)																												
Other milestone (TBD)																												
SESG activities on ARAIM																												
Support to H-ARAIM SARPs publication																												
Support to ARAIM MOPS publication																												
Exchange on ARAIM for other sectors																												
Coordination on ISMG development and operations																												
Coordination on ARAIM service declaration																												
Exchange on V-ARAIM complementary studies																												
Support to V-ARAIM standardisation																												

ARAIM Path from Default ISD to Broadcast ISD (ca. 2025)

A. **ISM Generator (one per constellation)**
   - Develop offline GNSS Recording and Analysis Network
   - Generate ISD (ISD ADD, Algorithm Description Document)
   - Transmit ISD to Core Satellite Constellation
   - Develop and agree aviation oversight process

B. **Core Satellite Constellation (GPS. GLONASS, Galileo, BDS)**
   - Update ground and space segment to enable ISM data message
   - Receive ISD from ISMG, Package and Uplink ISM
   - Continue providing ISD not in ISM
   - Publish Interface Control Documents for ISD / ISM

Under development for GPS by US and Galileo by EU

C. **Aircraft DFMC GNSS Receiver**
   - Include ARAIM in DFMC GNSS Rx: RTCA/EUROCAE MOPS Standard
   - Obtain certification and integrate in aircraft avionics architecture
   - Receive, decode and apply ISD

Under development by RTCA SC159 / EUROCAE WG62 and avionics / aircraft OEM

ARAIM Path from Service Type A to B (V-ARAIM, ca. 2030)

A. **ISM Generator (one per constellation)**
   - Develop offline GNSS Recording and Analysis Network
   - Generate ISD (ISD ADD, Algorithm Description Document)
   - Transmit ISD to Core Satellite Constellation
   - Develop and agree aviation oversight process

B. **Core Satellite Constellation (GPS. GLONASS, Galileo, BDS)**
   - Update ground and space segment to enable ISM data message
   - Receive ISD from ISMG, Package and Uplink ISM
   - Continue providing ISD not in ISM
   - Publish Interface Control Documents for ISD / ISM

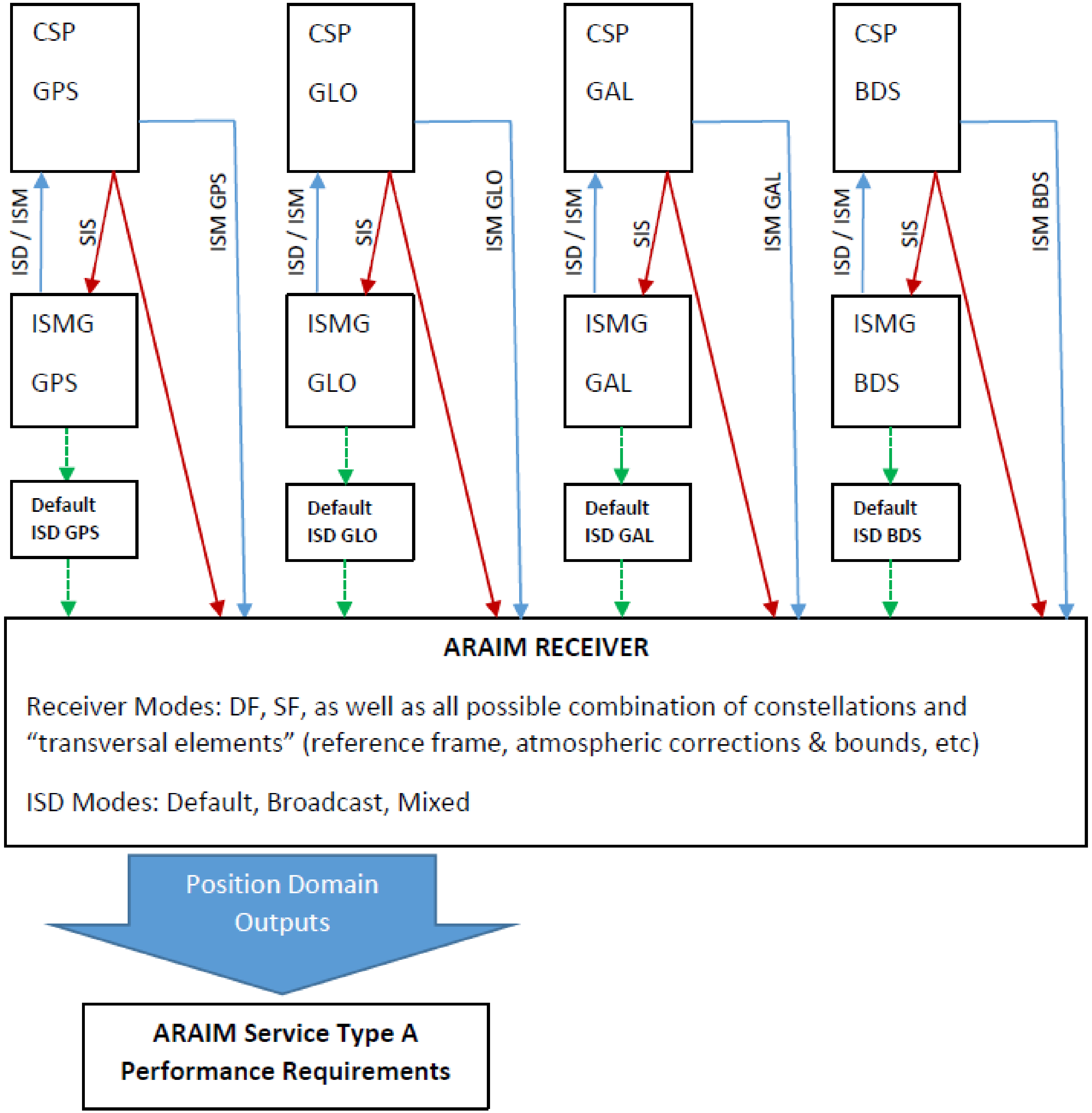
Update algorithms and processes for ST-B, Interfaces remain the same

C. **Aircraft DFMC GNSS Receiver**
   - Include ARAIM in DFMC GNSS Rx: RTCA/EUROCAE MOPS Standard
   - Obtain certification and integrate in aircraft avionics architecture
   - Receive, decode and apply ISD

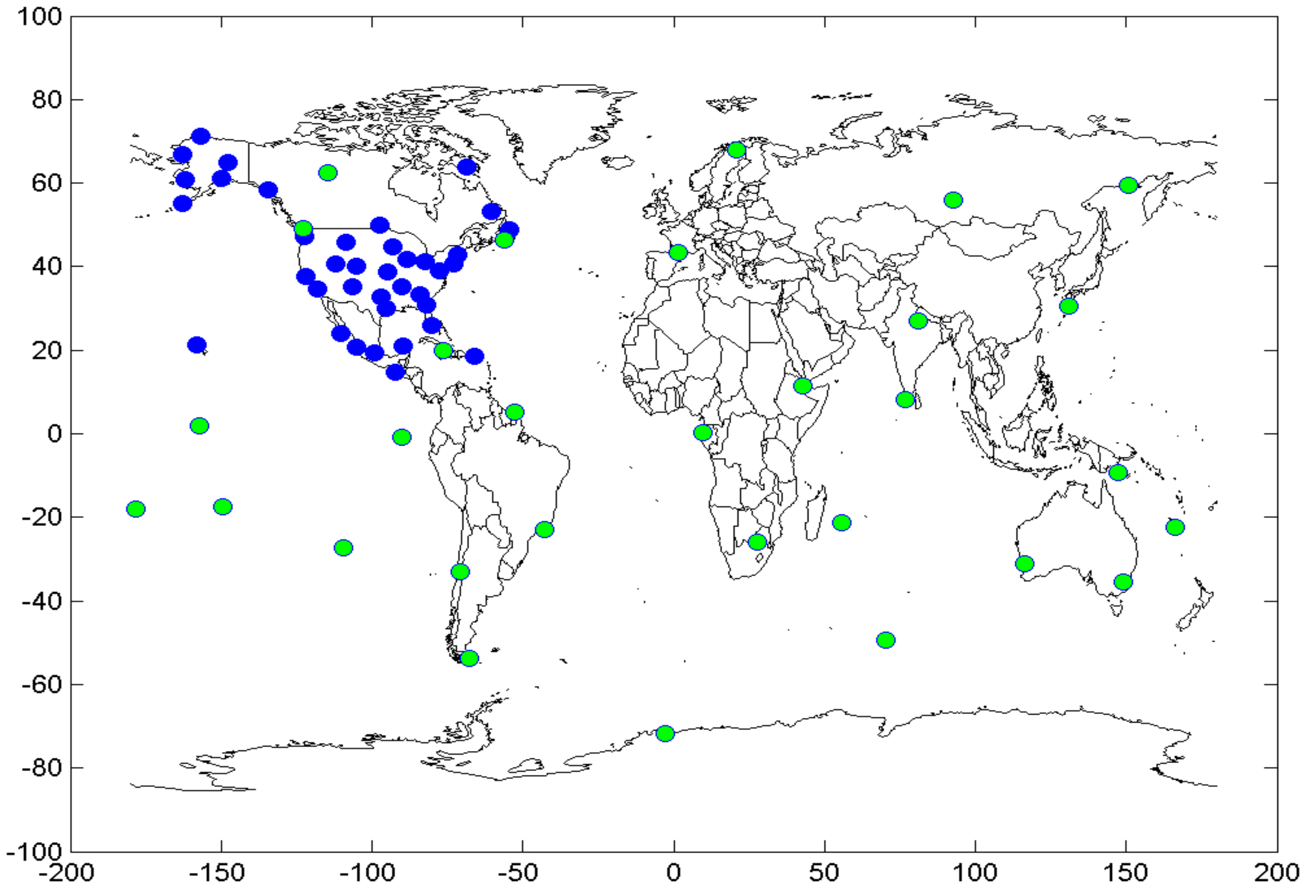
Update algorithms and processes for ST-B, Interfaces remain the same

ARAIM Architecture

- Dynamic Integrity Support Data (ISD)
  - Allows to adapt algorithm performance to core satellite constellation performance
- Initial start of H-ARAIM with Default ISM linked to constellation provider minimum commitments in Annex 10
  - ISD can only improve
- ISD mostly contained in Dedicated Integrity Support Message (ISM) provided by ISM Generator
  - ISMG is a limited ANSP function
  - ISD provided to receiver through constellation navigation messages: no new aircraft interface!



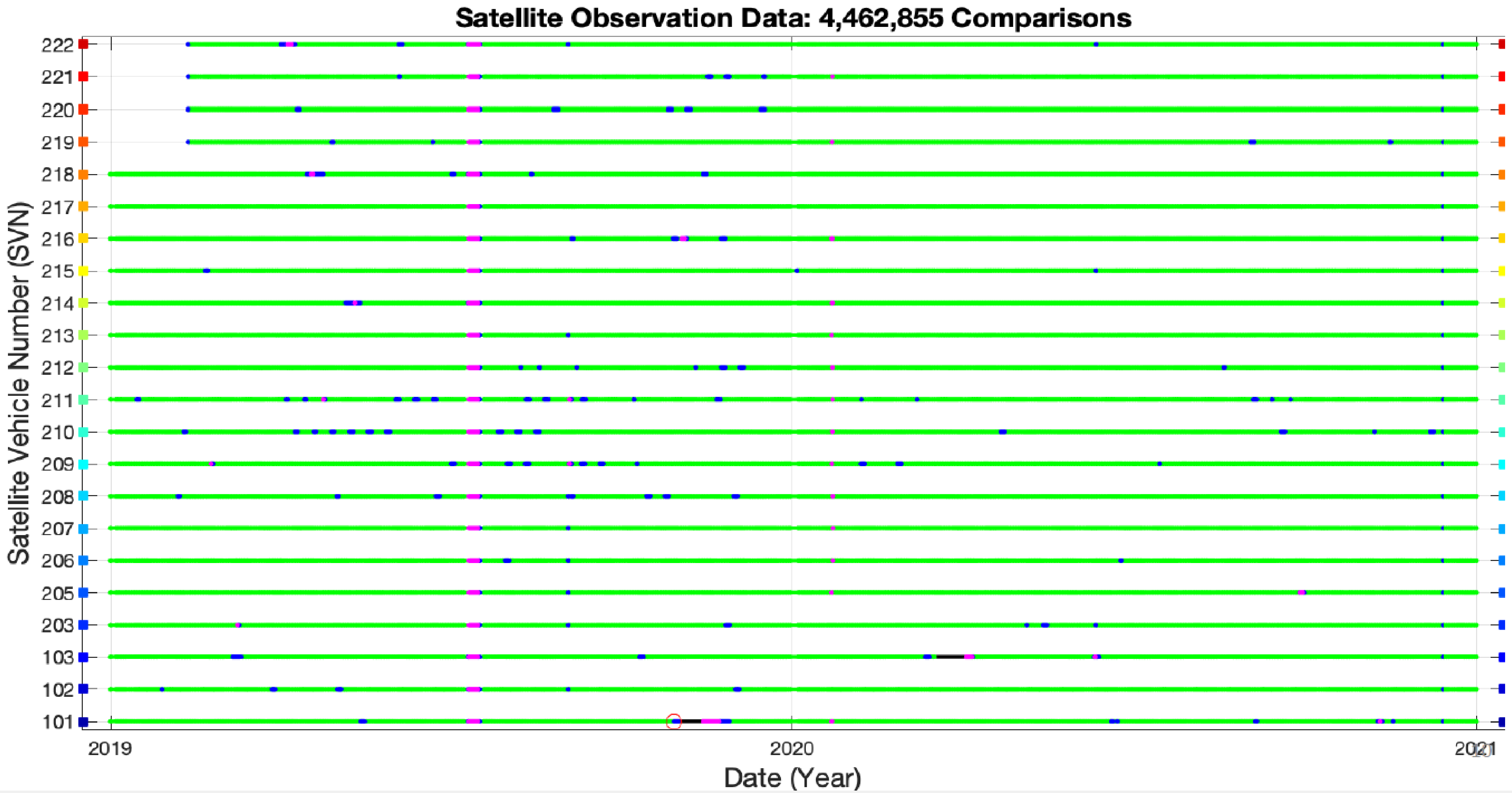
Offline Monitoring to generate ISD



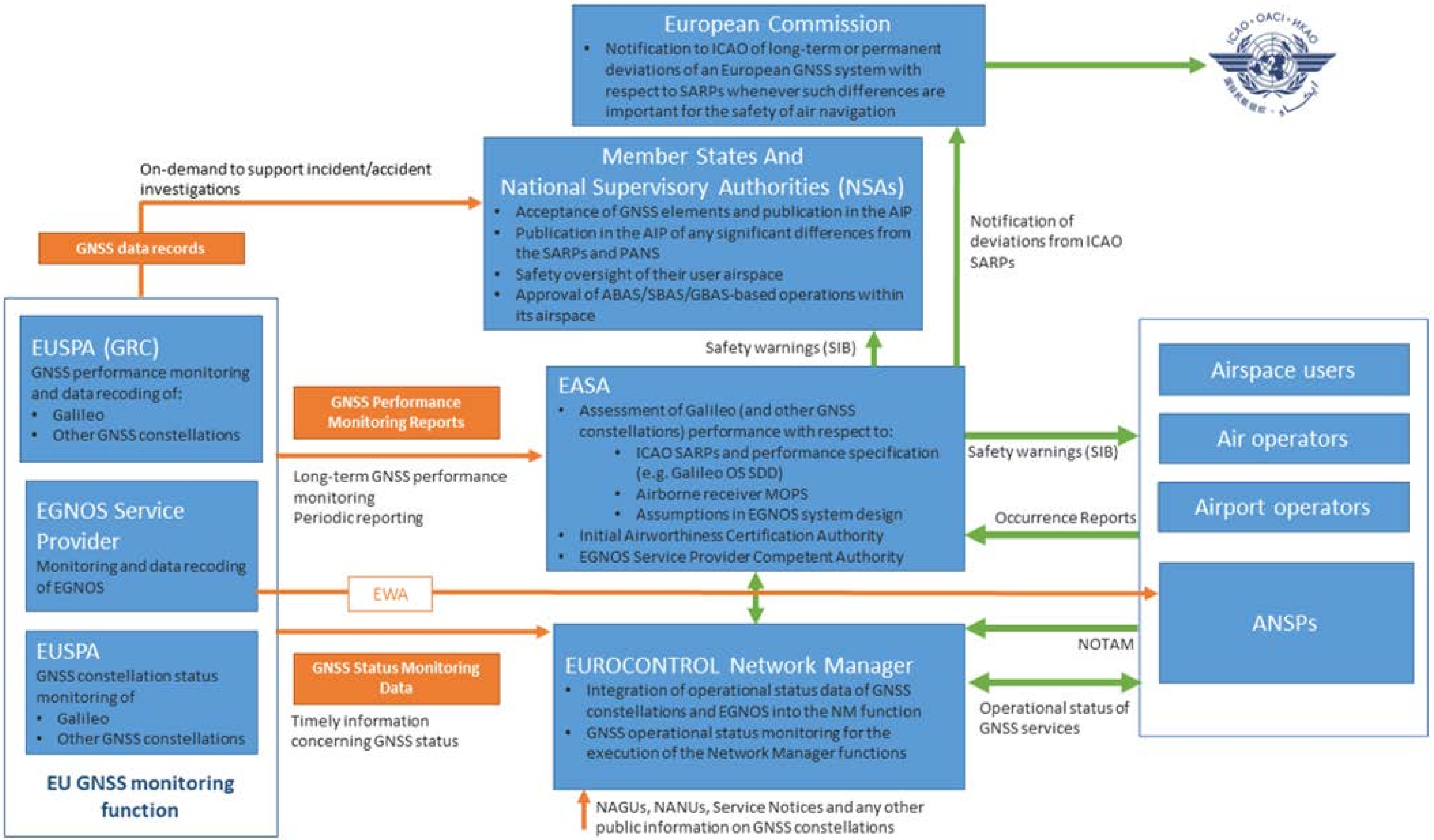
- Based on global sparse network for offline monitoring
  - global, not dedicated
  - reference stations: sufficient to calculate precise orbits
  - subset of network for Signal Deformation and other specialized receiver statistics

- ISM update performed monthly. Analysis similar to:
  - Offline monitoring for WAAS: Gordon, S., Sherrell, C., Potter, B.J., "WAAS Offline Monitoring," *Proceedings of the 23rd International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2010)*, Portland, OR, September 2010, pp. 2021-2030.
  - Performance Assessment Report (WAAS and GPS) by the FAA: Global Positioning System (GPS) Standard Positioning Service (SPS) Performance Analysis Report available at http://www.nstb.tc.faa.gov/reports/PAN82_0713.pdf

Galileo Performance Summary

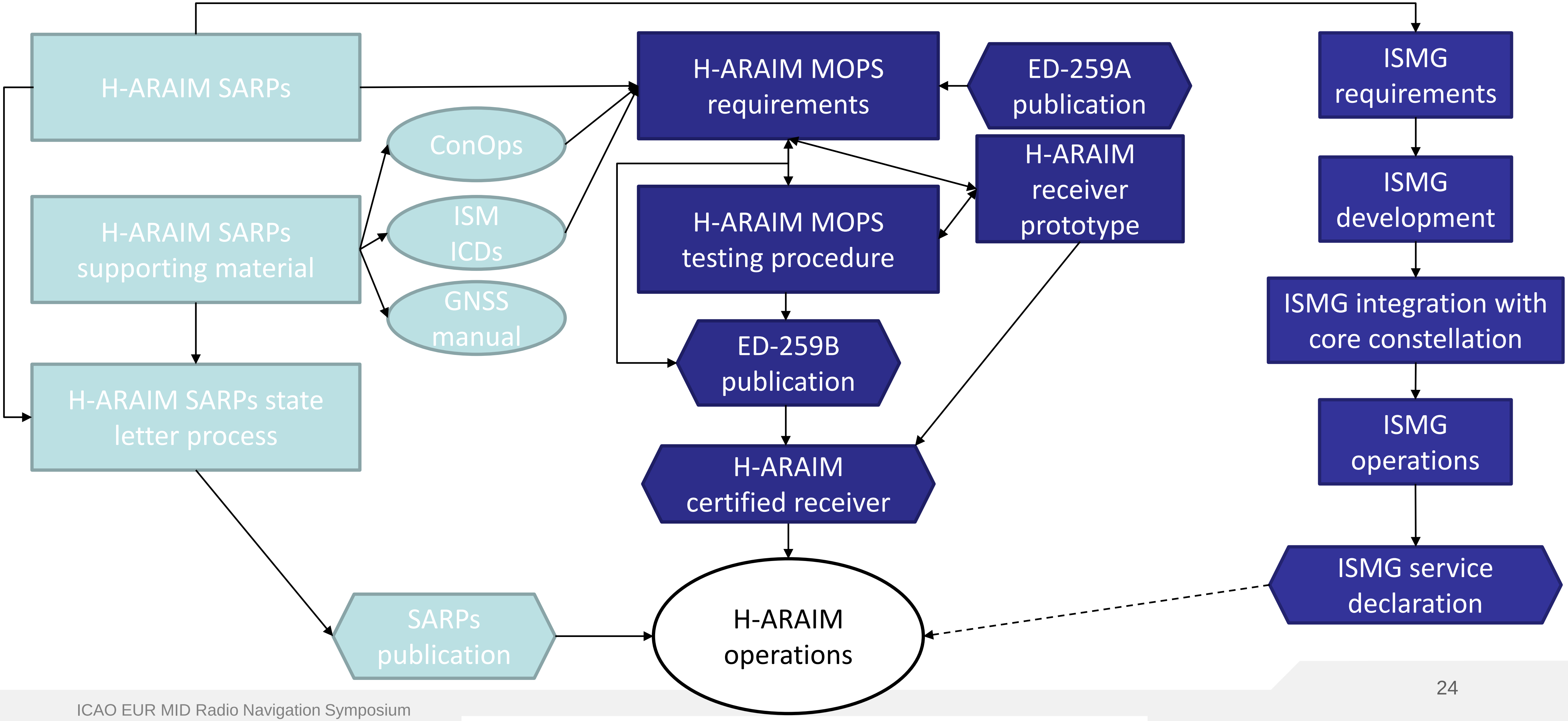


EU GNSS Monitoring CONOPS (Under Development)



Provides continuous evidence of compliance with ICAO Annex 10 GNSS Core Constellation Provider Requirements!

Towards H-ARAIM Operations



Key Concepts for ARAIM SARPs

- ARAIM SARPs have a non-aircraft element
  - Patterned after SBAS SARPs structure
  - Makes use of “transversal” GNSS components (reference frame, atmospheric elements)
- Most ISD will be in ISM, but there are exceptions
  - GPS $SIGMA_{URA}$ in current GPS Navigation Data Messages
  - ➔ Requires distinction between ISD and ISM
  - ➔ Requires consistency between ISD in ISM and ISD not in ISM
- Offering Dynamic ISD is optional, minimum are defaults linked to core constellation SARPs
  - ➔ Requires distinction between ISD contained in core constellation SARPs versus ISD used by ARAIM
  - Plans for GLONASS and BDS still under development
  - GPS and GALILEO are building ISMG and developing ISM data message ISD which will be part of future satellite upgrades
    - Expect formal publication of GPS and GALILEO Interface Control Documents (ICD) for ISM during State Letter process
  - ISD may be tailored to different generations of satellites to better characterize and improve performance

H-ARAIM versus Service Type A

- Service Type A was chosen in order not to exclude the use of vertical height output for applications other than approach guidance
  - Or, vertical approach guidance could be achieved by combining H-ARAIM with other ABAS elements???

- Service Type Description in line with well-established GNSS Signal in Space Performance Table
  - Nominally, H-ARAIM linked to hazard category “major”, V-ARAIM linked to hazard category “hazardous”
  - Expect that V-ARAIM will require broadcast ISD
  - Hazard level link can’t be made in SARPs in order to give integration flexibility to manufacturers

Signal Quality Monitoring (SQM) Requirements in ARAIM

EUROCONTROL

- SQM requirements were developed for Differential GNSS (GBAS, SBAS)
  - These requirements may be more constraining than necessary for a non-differential system
  - No GNSS receiver manufacturer currently has any plans to develop an “ARAIM only” DFMC GNSS Receiver (SBAS and/or GBAS will be included as well)
  - Significant work would be necessary to re-derive SQM requirements for non-differential systems

- Consequently, SQM requirements were moved over to ISMG
  - ISD will be derived assuming a GNSS receiver which meets the Differential SQM constraints
  - If a GNSS receiver manufacturer would develop an ARAIM-only DFMC receiver which does not meet the Differential SQM constraints, some ISD may need to be adjusted (b_{nom})
  - Determining how to do this will be the burden of the GNSS receiver manufacturer

Data Integrity

- An interface will exist between the ISMG and the Core Satellite Constellation Provider
  - Handing over ISD for transmission by CSP
  - CSP will become a “bent pipe” similar to SBAS GEO

- Most likely mechanism used for preventing data errors during transmission will be Cyclic Redundancy Check
  - CRC is well established in GNSS – if CRC used, must be done the GNSS-way
    - Polynomial length not specified
  - Different possibilities exist for CRC-wrapping and packaging navigation data messages
  - ARAIM SARPs leave flexibility to ISMG and CSP, close cooperation between the two entities is expected

- Safety Analysis conducted in US and EU indicates that the required assurance level and detailed design can be figured out without too much difficulty
  - All that matters to the user is how data is coded in navigation data message, not necessary to specify “internal interfaces”

ISD Update Concepts

- Need to distinguish between message broadcast rate and update rate
  - Broadcast or repeat rate is how quickly ISD is sent and repeated
  - Relevant for receiver cold start to get a complete set of ISD
  - Initial startup always enabled by default ISD

- ISD Update is about sending a new ISD set
  - Could be the same ISD with a new validity or actually updated values due to improvement of constellation performance (or reduction, but while still meeting minimum commitment)

- SARPs allows two options: with or without validity end time
  - Galileo: With end time. New message will need to be sent before current message expires
  - GPS: Without end time: New message will need to be sent before current message becomes invalid

New ISD Elements

- Constellation Fault Probability
  - GPS RAIM with fixed ISD assumed P_{const} to be negligible (smaller than 10^{-7})
  - This has been met by GPS but is difficult to ensure in large complex systems
- Fault Rates versus Probabilities
  - GPS Satellite Fault Probability of 10^{-5} (or 10^{-4} for a position solution with 10 satellites) sets the requirement for the Probability of Missed Detection P_{MD} used in RAIM algorithms
  - This was really a fault rate rather than a state probability
  - The two numbers happened to be the same since Mean Fault Duration in GPS is 1 hour
  - ARAIM improves the clarity in the relation between P, R and MFD
- B_{NOM}
  - Common assumption in many systems is that all errors are zero-mean Gaussian
  - This is not really true, however, errors can still be over-bound like this
    - To accommodate bias, sigma needs to be inflated, which increases tails
  - Introducing a bias term can optimize protection level performance
    - Initially, everyone will set b_{nom} to zero, continuing traditional approach

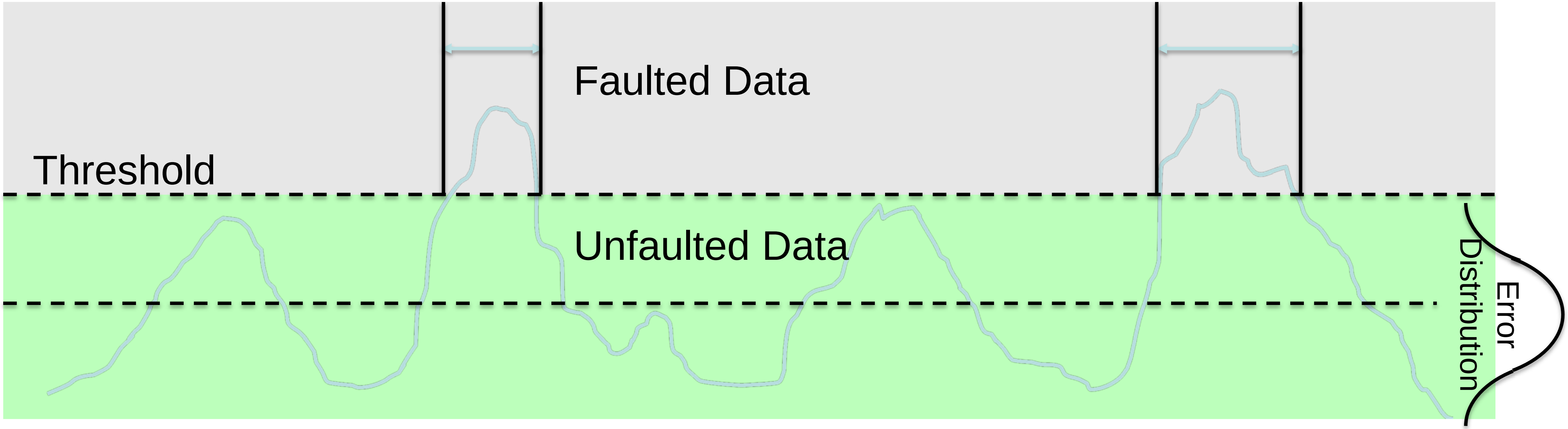
Fault Probabilities

- The satellite fault probabilities can be bounded by two fault probability bounds: P_{sat} and P_{const}:
  - P_{sat} is the probability that an individual satellite is faulted at any time
    - May be different for each satellite or all satellites may use the same numerical upper bound
  - P_{const} is the probability that any single cause leads to simultaneous faults on more than one satellite
    - May only affect 2 satellites or may affect the whole constellation
    - One single upper bound is used to cover all possible fault cases
- These two numbers may be used to bound the likelihood of all possible fault modes

Fault Rates and Fault Probabilities

- There are two related concepts: fault rate and fault probability
  - Fault rate is the number of expected times that a fault is expected to initiate in a given time – it has units of faults per hour
  - Fault probability is the likelihood of experiencing a fault right now
- They ask two related questions:
  - Fault rate asks: How many times will the error change from below the fault threshold to above it in any given length of time
  - Fault probability asks: If I measure the error right now, how likely is it to be above the fault threshold
- These are related by the Mean Fault Durations (MFD)
  - $P_{sat} = MFD_{sat} \times R_{sat}$
  - $P_{const} = MFD_{const} \times R_{const}$

Rsat, Psat and MFD



R_{sat} counts the number of upward crossings of the threshold in a given time period

MFD is used to indicate the mean fault duration and is the total length of time that the errors are above the threshold divided by the number of upward crossings

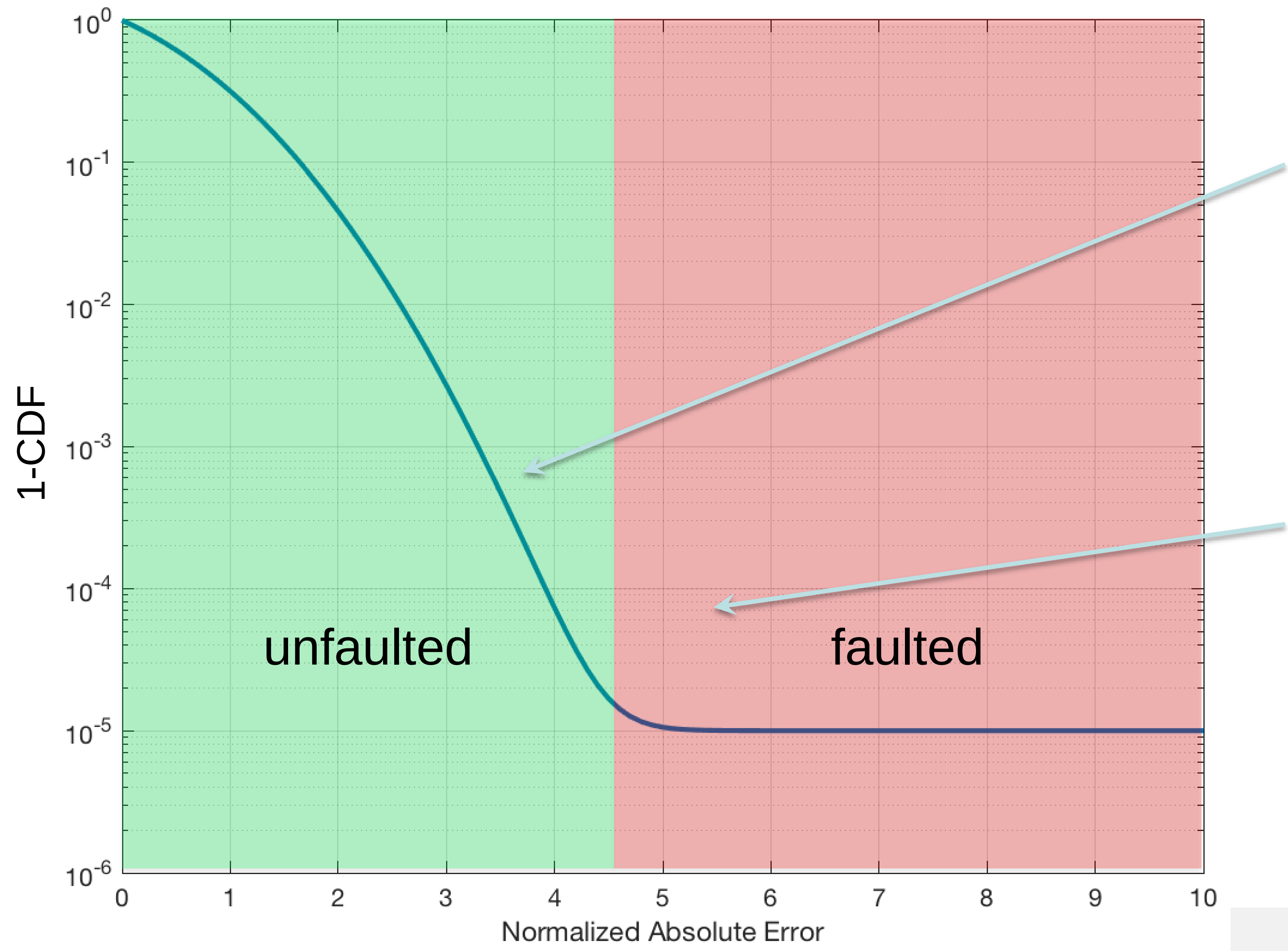
P_{sat} is the fraction of time spent above the threshold and equals R_{sat} x MFD

Rsat, Psat and MFD

- Faults can end in two ways:
  - Satellite is flagged as unhealthy
    - If problem persists, satellite can be removed from ARAIM use with ARAIM satellite mask
  - Problem disappears or is removed by corrective action
  - Depends on satellite and control segment monitor architecture

- Some CSP use Mean Time to Notify
  - SARPs considers the terms to be equivalent
  - Fault removal makes notification unnecessary

Signal-In-Space Error Distribution



Nominal Gaussian Error Model (Characterized by $SIGMA_{URA}$, $SIGMA_{URE}$, B_{NOM})

Boundary Characterized by $P_{SAT / CONST}$, $R_{SAT / CONST}$, $MFD_{SAT / CONST}$

SARPs Allow Flexibility in Over-bounding Concepts

- Core Satellite Providers have different designs for their constellations and subsequently different assurance processes for characterizing performance

- Examples: Galileo chooses not to specify MFD and does not want receiver processing to assume an MFD
  - Baseline ARAIM Algorithm was updated to clarify that receiver processing is possible using only Fault Probability and Rate

- Example: GLONASS uses a fixed boundary between faulted and non-faulted errors, while GPS links boundary to broadcast URA (User Range Accuracy)

- These differences will need to be taken into account in the DFMC GNSS Receiver Standards and specified in ISM ICD's

- Error Over-bounding is well understood and established in GNSS Community