EU-U.S. Cooperation on Satellite Navigation

Working Group C - ARAIM Technical Subgroup

Milestone 3 Report

Final Version

February 25th, 2016

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Executive Summary

Objectives of this Report: The U.S.-EU Agreement on GPS/Galileo Cooperation signed in 2004 established the principles for the cooperation activities between the United States of America and the European Union in the field of satellite navigation. The Agreement foresaw *a working group to promote cooperation on the design and development of the next generation of civil satellite-based navigation and timing systems*. This work became the focus of Working Group C (WG-C).

One of the objectives of WG-C is to develop GPS-Galileo based applications for Safety-of-Life services. To this end, WG-C established the ARAIM Technical Subgroup (ARAIM TSG) on July 1, 2010. The objective of the ARAIM TSG is to investigate ARAIM (Advanced Receiver Autonomous Integrity Monitoring) on a bilateral basis. The further goal is to establish whether ARAIM can be the basis for a multi-constellation concept to support air navigation worldwide. Specifically, ARAIM should support en route and terminal area flight; it should also support lateral and vertical guidance during airport approach operations.

Amongst these operations, global approach guidance for aviation is the most ambitious goal. These aircraft operations are identified as localizer precision (LP) for horizontal navigation and localizer precision vertical (LPV) for vertical navigation. LPV-200 indicates that this guidance should support approach operations down to a 200-foot height (above runway threshold). The ARAIM TSG focuses on ARAIM architectures to support LPV-200 or LPV-250 globally.

This document concludes the third phase in a three-phased effort.

After Milestone 1, the TSG produced a first report (dated December 19, 2012), which described the progress made on the analysis of the relevant performance requirements, the definition of an ARAIM reference user algorithm[1], a first evaluation of the achievable performance, as well as the identification and first characterization of ARAIM threats.

A second report was produced after Milestone 2 (dated February 11, 2015) with the main focus on the description of the architectures for the implementation of the ARAIM service (ground infrastructure, ARAIM threat allocation and mitigation, Integrity Support Message contents, and potential ISM broadcast means and risks). The descriptions covered Horizontal ARAIM as well as two options for Vertical ARAIM: the Offline and Online architectures. Furthermore, the Milestone 2 Report extended the ARAIM availability results by considering a wider range of ranging accuracy errors (URE/SISE) as well as additional scenarios for the GPS and Galileo operational constellations.

After the second report, the TSG gathered feedback from stakeholders that they considered fundamental to the treatment of the open points identified in the Milestone 2 report [RD-74]. Collection of feedback from the aviation community (avionics manufacturers and integrators, Air Navigation Service Providers, standardization bodies) on the general concepts, results, as

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[1] The reference algorithm was used as the basis for the assessment of ARAIM performance by the ARAIM TSG; other user algorithms may be used for as long as they demonstrate a level of performance equal or better than the reference.

well as on the implementation options was organized. The ARAIM TSG has incorporated elements of this feedback in the Milestone 3 Report, in the sections on

- ARAIM Roadmap; and,

- Message Types for ARAIM: Modes and Messages for Horizontal ARAIM (H-ARAIM), Messages for Vertical Offline, and Messages for Vertical Online ARAIM.

The Milestone 3 Report also includes the proposed Implementation Roadmap for ARAIM Services, the consideration of institutional issues and their discussion, as well as the elaborated view of ARAIM complementing the services provided by SBAS systems.

Furthermore, the ARAIM TSG complemented the availability results provided in the previous reports with the results for H-ARAIM under various scenarios. Results are obtained for a global grid of users with improvements thanks to the optimization of the reference user algorithm, whose latest version is described in Annex A.

This report was prepared by the ARAIM TSG members from the U.S. Federal Aviation Administration (FAA), Stanford University (SU), The MITRE Corporation, Illinois Institute of Technology (IIT), the German Aerospace Center (DLR), University FAF Munich (UniBW), the European Space Agency (ESA), the European Commission (EC), Centre National d’Etudes Spatiales (CNES), Ecole Nationale d’Aviation Civile (ENAC), and EUROCONTROL.

ARAIM Roadmap: The ARAIM TSG concluded that ARAIM services should be implemented incrementally.

ARAIM should begin with a horizontal only service, H-ARAIM, to support near-term, proposed multi-constellation (MC) applications.

A global vertical service, V-ARAIM, can be implemented subsequently once sufficient data is collected and experience gained to demonstrate safe operations. Similarly, analysis and experience with observed data will determine whether additional monitoring capabilities may need to be implemented for V-ARAIM. Alternatively, stakeholders may examine additional criteria and safety cases to extend vertical services to cover other, more stringent operations beyond LPV-200.

Currently, standards development plans focus on dual-frequency, multi-constellation (DFMC) SBAS MOPS. It is anticipated ARAIM could support horizontal navigation (H-ARAIM) in cases where SBAS services are unavailable while providing superior performance of traditional RAIM. It is the view of the group that H-ARAIM should be incorporated into DFMC SBAS standards anticipated for development in EUROCAE and RTCA.

DFMC SBAS vertical services are expected to support vertical requirements with low risk to avionics manufacturers and SBAS providers. We expect DFMC SBAS to dominate vertical guidance for an extended period of time (e.g., 20 years) after their initial service provision - within the SBAS service areas. Testing and evaluation of V-ARAIM services will proceed in the meantime and could be implemented based on user needs and the presence of sufficient evidence supporting its safety case.

Figure E-1 illustrates the proposed ARAIM Roadmap. In light of the remaining uncertainties in the longer term, the roadmap at this stage provides firm dates for H-ARAIM. Notwithstanding, it includes defined milestones – namely Feasibility Checkpoints and Readiness Keypoints for both H- and V-ARAIM – which are established to guide industry, government, and standards coordination in the path towards service provisions for civil aviation.

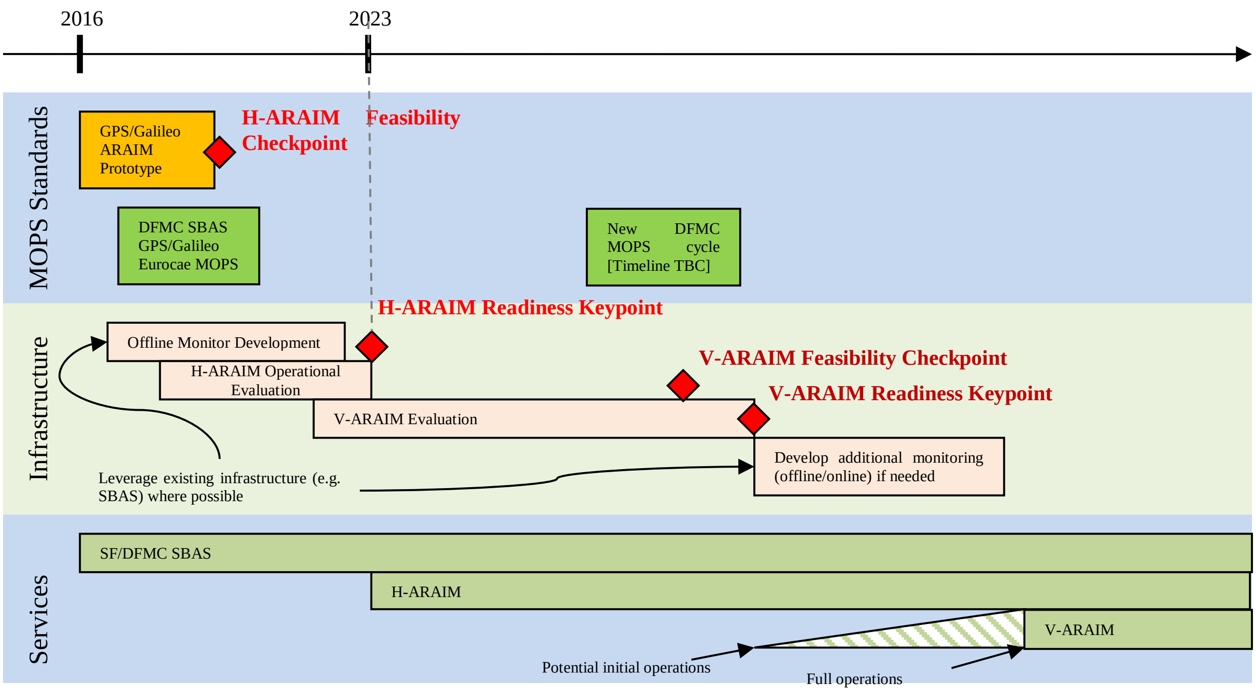

Figure E-1: Aviation Long-term Timeline

It is believed that H-ARAIM with a static ISM can be implemented with offline monitoring at moderate risk, so initial efforts will focus on requirements development and validation for offline monitoring. Alternative ISM dissemination solutions are identified (including hard-coded ISM at the avionics level or the use of geo-fenced databases housed in the navigation receiver) and could be included in the standards to the extent practical.

After an evaluation period, interested Air Navigation Service Providers (ANSPs) and users may seek operational approval for vertical guidance based on the performance targets set by a dedicated safety case. ANSPs and regulators will need to verify offline monitoring and Constellation Service Provider (CSP) performance against these safety targets and the commitments documented in the standards.

These approvals may be possible without any modification to the H-ARAIM software or interfaces. However, additional offline and/or online monitoring fidelity maybe required to achieve more demanding vertical guidance operations, and the H-ARAIM standards will likely need to be updated to reflect the V-ARAIM services.

Thus, the timeline for V-ARAIM operational introduction may be gradual in terms of the performance capabilities achieved depending on the architectural concept employed. This growth in capabilities is depicted at the bottom of the figure above. The SF/DF SBAS Service is also depicted as continuous in order to reflect on one hand the plans of SBAS service providers and, on the other hand, the expected complementarity with ARAIM.

Institutional Issues: The introduction of ARAIM services based on multi-constellation and with worldwide coverage poses a number of questions in the institutional arena which have been identified and initially addressed by the ARAIM TSG.

Current GPS L1-based RAIM established a precedent based on a hard-coded ISM, setting the probability of constellation failure as negligible and the probability of an individual satellite failure at 10^{-5} per hour. Evidence that supports these assumptions as valid based on historical observation was not available when these assumptions were implicitly accepted. Initial concerns over legal and institutional issues were dealt with by the International Civil Aviation Organization (ICAO, a United Nations body) and led to the agreement of a "Charter on the Rights and Obligations of States relating to GNSS Services," Assembly resolution 32-19, 1998 [RD-88].

On the other hand, the ARAIM concept adds characteristics which require at least some consideration. At a minimum, multi-constellation implies a necessity to further clarify and formalize current arrangements to ensure international acceptance, as well as safety and interoperability.

It is with this perspective that the ARAIM TSG conducted an overall analysis of the current ICAO principles and practices. Main findings note that under the ICAO Convention provision of radio services is a sovereign responsibility. There are no restrictions on how a contracting State provides these services, e.g., whether through a State agency, a privatized ANSP, or even a commercial or foreign entity. However, the responsibility to provide such services rests with the State. For example, if the State delegates this sovereign obligation or an element thereof, it implies that the State should oversee the service.

With regards to PNT based on GNSS, Annex 10 to the ICAO Convention defines application-specific integrity monitoring as an integral component of the service. In this respect, the GNSS Charter defines the core constellation service (e.g., navigation signals emanating directly from satellites not under aviation control) not as an air navigation service per se, but only an ingredient thereof, a definition that respects the sovereign role of States.

The GNSS Charter addresses sovereignty and it also clearly establishes that safety is the responsibility of all actors involved.

The sovereign obligation of States to provide air navigation services (ANS) primarily results in States having the right to authorize, or not, the use of a particular constellation and augmentation service. Nevertheless, many States have not made these determinations, nor is there a mechanism in avionics or pilot training that forces the enabling or disabling of a particular GNSS element or elements when crossing a State boundary.

The GNSS Charter is silent on the topic of liability. While the need (and chance of success) for a global liability framework for aviation use of GNSS is debatable, this missing element can be mitigated by ensuring that no such negligence exists.

The ARAIM TSG asserts that the principles of safety and interoperability should drive the institutional arrangements necessary to satisfy the demands of sovereignty and liability for

ARAIM services. Consequently, the TSG proposes that the demands of sovereignty and liability be translated into the following practical and realizable requirements for GNSS-based air navigation service provision:

- Sufficiently detailed information available from constellation service providers to expert standardization groups to enable the development of suitable standards for aircraft avionics and augmentation system ground equipment (none in the case of ABAS/RAIM – however, ARAIM will require some type of ground monitoring network);
- Transparent set of verifiable constellation performance assumptions that ensure the integrity of the service (ISM content);
- Provision of constellation performance and status information to support service predictions (Aeronautical Information Services); and,
- Definition of a GNSS service provision framework which clearly defines the roles and responsibilities of all actors consistent with the GNSS charter.

Finally, in view of the implications to safety and interoperability with regards to the key question of single versus multiple ISMs, the ARAIM TSG concluded that the most practical and easiest technical option is the generation and provision of a single, globally harmonized ISM, generated through a transparent and standardized methodology building on the already existing processes and frameworks.

Nevertheless, the TSG recognizes that individual States may want to generate their own ISM – for various reasons, not necessarily technical. One way to achieve this would be to have geographically separate, State ISMs using a geo-fencing database. These databases would be updated on the 28 day Aeronautical Information Regulation and Control (AIRAC) cycle and could carry the ISM for each individual State. This approach may lead to a significant additional operational burden.

In any case, any entity charged with ISM generation must do so following a standardized methodology and must be able to satisfy the regulatory requirements of all contracting ICAO States, which may include the need for individual contractual agreements.

ARAIM complements SBAS: It is the view of the TSG that ARAIM services offer important capabilities that complement SBAS services. Table E-1 lists these applications in a rough chronological order. Other applications may arise and be more important than the ones we anticipate today.

Table E-1: ARAIM Applications that Complement SBAS

Horizontal ARAIM in the Near Term Based on One Frequency: ARAIM may find near-term application before dual frequency GPS and dual frequency Galileo are operational. Specifically, ARAIM could enable dual or multiple constellation navigation based on one frequency. After all, single frequency GPS is already operational; single frequency GLONASS is already operational; and single frequency Galileo will be operational in 2020. ARAIM would enable the integration of these early constellations even if they differ sharply in P_{sat} and P_{const}. In the near term, ARAIM could store the ISM in the receiver's non-volatile memory or disseminate the ISM via an existing communications link or database. In the same manner, when operating in dual frequency, dual constellation, the single frequency mode would become a backup mode in case of lost measurements at the other frequency. In this sense, results in chapter 5 show that single frequency L5/E5a H-ARAIM mode provides robust RNP 0.3 service.
ARAIM to Support Arctic Navigation: The Arctic Ocean requires navigation with integrity for energy exploration, eco-tourism, and shipping. Importantly, ARAIM could enable the ship to travel in existing ice cracks or tracks from previous ships. Thus guided, the ship could double its speed. ARAIM supplants SBAS in the Arctic, because the needed ISM could be broadcast by the GNSS satellites or through the use of databases, while SBAS GEOs do not cover the Arctic.
Vertical ARAIM Worldwide Without Needing Geostationary Satellites: In time, ARAIM could obviate or reduce the need for geostationary satellites used by SBAS, and it can operate with a network of fewer ground stations than that of SBAS. As such, it would reduce a significant part of the SBAS operational budget. At the same time, ARAIM could reuse the SBAS reference stations, and so SBAS could be used to accelerate the deployment of ARAIM at lower cost.
ARAIM to Provide GNSS Resilience: As mentioned above, ARAIM does not need the SBAS geostationary satellites. The needed ISM will be broadcast over the GNSS satellites, stored in the receivers or disseminated through aviation databases. As such, ARAIM does not suffer from the signal outages associated with geostationary satellites that frequently appear low in the sky. These outages can be due to blockage by terrain or buildings, or they can be due to intentional or non-intentional radio frequency interference.

Availability of ARAIM for Horizontal Navigation: The ARAIM TSG continued the evaluation of availability for ARAIM, and in particular for horizontal navigation. In addition to the previous analysis on availability for two levels of service (RNP 0.1, RNP 0.3) the robustness of H-ARAIM service with regard to signal in space error (URA/SISA) was evaluated, with a view to find the boundary conditions for an H-ARAIM service. For this purpose, the URAs/SISAs chosen for the parametric availability simulations start at 2.5 m and increase to more conservative values.

It must however be mentioned that the availability analyses conducted rely on assumptions that have not been fully addressed, in particular the masking angle (5 degrees, consistent with observations from airborne receivers), the effect of ionospheric scintillation in high latitudes and equatorial latitudes, and the fact that faults had a negligible impact on the loss of continuity. These aspects will need to be addressed in future ARAIM related work.

The same reference algorithm used for H-ARAIM is applicable to offline V-ARAIM [RD-54]. The H-ARAIM user algorithm allocates the full integrity budget to the horizontal mode (see Annex A). The availability criteria for RNP 0.1 and RNP 0.3 used in this report are that the HPL must be below an HAL of 185 m and 556 m, respectively (Annex A).

The results show that the primary mode of H-ARAIM (DF L1-L5) provides the highest performance, as expected. As shown in Table E-2 below, RNP 0.1 is always available when both frequencies (L1 and L5) are available and two constellations are tracked, even for theoretically high values of URA.

Table E-2: Estimated global level of service for DFMC (Pconst = 10^{-4})

Constellation/URA	2.5m	...	20m
<Depleted>	RNP 0.1 (100%)	URA < 9m (89.6%)	RNP 0.3 (97.7%)
<Baseline>	RNP 0.1 (100%)	URA ≤ 15m (91.2%)	RNP 0.3 (100%)
<Optimistic>	RNP 0.1 (100%)	URA ≤ 16m (90.7%)	RNP 0.3 (100%)

Results further show that H-ARAIM with a single baseline constellation (GPS or Galileo) also supports RNP 0.1 capabilities[2].

For the single frequency mode, which uses ionospheric corrections included in the CSP navigation message, it was found that RNP 0.1 can be achieved in both the Baseline and Optimistic constellation scenarios, while RNP 0.3 can be achieved either in the depleted constellation scenario and even in the Baseline and Optimistic scenarios with only a single constellation (GPS or Galileo).

Given the current levels of URA for GPS and the expected SISA for Galileo, there is a low risk that the ranging accuracy necessary for H-ARAIM target service availability may not be provided by the SPCs. Even if the new constellations did not achieve the performance of the current L1 GPS service, the results show that single frequency multi-constellation H-ARAIM would provide improved availability and robustness compared to single constellation.

In the case of lost measurements at the L1/E1 frequency, the airborne receiver can utilize an L5/E5a only H-ARAIM mode. Single frequency L5/E5a H-ARAIM mode provides robust RNP 0.3 service assuming that a sufficient number of satellites broadcast signals on the L5/E5a frequency, thus providing robustness.

Message Types for ARAIM: The concept of Message Types for ARAIM was expanded to take into account feedback received from the aviation community following the Milestone 2 Report. The ARAIM TSG is proposing modes and messages for Horizontal ARAIM (H-

[2] For each constellation, the table indicates the most capable level of service for which a 90% coverage of 99.5% availability is achieved and illustrates robustness of H-ARAIM as a function of URA/SISA bounds. The table window is coloured based on RNP 0.1/0.3 capability, where the label "Low" indicates a global coverage between 80% and 90%.

ARAIM), Messages for Vertical Offline ARAIM, and Messages for Vertical Online ARAIM as follows below. In all cases, ISM dissemination requires only a very modest data rate which could be accommodated easily within the GPS CNAV and GAL I/NAV capacities, or in the future SBAS SIS ICD. On the other hand, it should be noted that the latency needed for Online V-ARAIM is more stringent than any current or planned capability of GPS."

Messages for Horizontal ARAIM and Offline Vertical ARAIM

The Horizontal ARAIM architecture is an extension of today's RAIM architecture. As stressed before, the ARAIM concept adds four main elements: multiple constellations, dual-frequency, a deeper threat analysis, and the possibility to update the ISM.

The ISM parameters are based upon CSP commitments and observational history. For H-ARAIM it is believed that a static ISM with offline monitoring can be implemented. Alternatively, an updatable ISM allows the performance to adapt to the changing GNSS environment. In particular, it will allow ANSPs to include new constellations as they become available, and to improve the ISM parameters as they establish a history of good performance.

The ISM elements for H-ARAIM have been defined such that they are common to the V-ARAIM offline architecture so as to permit a smooth transition from H-ARAIM-only operation to the inclusion of V-ARAIM. The ISM parameters are the same for both although the specific parameter values will likely change due to the higher criticality of the impact of loss of integrity for vertically guided operations. The message contents are synthesized in the tables below (note that all ISM values are preliminary). The header contains a specific bit to indicate whether the message is intended to support horizontal-only or horizontal and vertical operations.

The reference algorithm described in Annex A is also common for H-ARAIM and offline V-ARAIM, with the simplification that for H-ARAIM only the HPL needs to be computed and there is, correspondingly, a different allocation of the overall integrity budget between horizontal and vertical modes.

Two message types are foreseen: one where all of the ISM content is contained in a single message (Type 1A), and another where each message contains only the ISM content for a single constellation (Type 1B). The former is more compact and requires lower bandwidth. The latter provides more flexibility if there is a need to have different values apply to different satellites within each constellation.

These two data formats can easily be broadcast through GPS CNAV messages. CNAV messages are 300 bits each and have 238 bits of usable data for the ISM. Alternatively, they would also allow for a specific SBAS message type for ARAIM (the SBAS message has either 212 data bits available for L1 or 214 available for L5).

Table E-3: Offline ISM Parameters for Single Message – ARAIM ISM Type 1A

	Parameter	Description	Value	Size (bits)
Data Header	ISM_WN	ISM Week Number	[0, 1, … 1023]	10
	ISM_TOW	ISM Time of Week (hours)	[0, 1, … 167]	8
	ANSP ID	Service Provider Identification	[0, 1, … 255]	8
	Criticality	Usable for Precise/Vertical?	[0, 1]	1
	Total Header = 27 bits			
Per Constellation Parameters	$Mask_i$	32 bits indicating whether an SV is valid for ARAIM (1) or not (0)	[m_1, m_2, … m_{32}]	32
	$P_{const,i}$	Probability of constellation fault at a given time	[10^{-8}, 10^{-5}, 10^{-4}, 10^{-3}]	2
	$P_{sat,j}$	Probability of satellite fault at a given time	[10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}]	2
	$\alpha_{URA,j}$	Multiplier of the URA for integrity	[1, 1.25, 1.5, 2, 2.5, 3, 5, 10]	3
	$\alpha_{URE,j}$	Multiplier of the URA for continuity & accuracy	[0.25, 0.5, 0.75, 1, 1.25, 1.5, 2, 4]	3
	$b_{nom,j}$	Nominal bias term in meters	[0.0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 3, 4, 5, 7.5, 10]	4
	Total Core = 46 bits x 4 Constellations = 184 bits			

Table E-4: Offline ISM Parameters for one SBAS Message per Constellation – ARAIM ISM Type 1B

	Parameter	Description	Value	Size (bits)
Data Header	ISM_WN	ISM Week Number	[0, 1, … 1023]	10
	ISM_TOW	ISM Time of Week (hours)	[0, 1, … 167]	8
	ANSP ID	Service Provider Identification	[0, 1, … 255]	8
	Criticality	Usable for Precise/Vertical?	[0, 1]	1
	Constellation	Specify constellation described	[GPS, GLONASS, Galileo, Beidou]	2
	$Mask_i$	3 bits for each of 32 SVs indicating SV grouping (0 is do not use, otherwise m_i provides the group number that the SV belongs to)	[m_1, m_2, … m_{32}]	3 x 32
	Total Header = 125 bits			
Per Satellite Group Parameters	$P_{const,i}$	Probability of constellation fault at a given time	[10^{-8}, 10^{-5}, 10^{-4}, 10^{-3}]	2
	$P_{sat,j}$	Probability of satellite fault at a given time	[10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}]	2
	$\alpha_{URA,j}$	Multiplier of the URA for integrity	[1, 1.25, 1.5, 2, 2.5, 3, 5, 10]	3
	$\alpha_{URE,j}$	Multiplier of the URA for continuity & accuracy	[0.25, 0.5, 0.75, 1, 1.25, 1.5, 2, 4]	3
	$b_{nom,j}$	Nominal bias term in meters	[0.0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 3, 4, 5, 7.5, 10]	4
	Total Core = 14 bits x 6 Groups = 84 bits			

Messages for Online V-ARAIM

For the Online Vertical ARAIM the proposed principle follows SBAS precedent, which provides correction data to the broadcast GNSS navigation message. The ARAIM ground segment derives independent navigation messages, containing more accurate on-board clock state and the orbital positions, but only the correction with respect to the broadcast GNSS navigation messages data is disseminated by the ISM.

The proposed ISM (Type 2) shown in the table below takes that into account, as well as the provision of absolute error bounds for integrity and continuity and the integrity data individualized per satellite rather than per group of satellites. P_{const} is not included in this proposed Online V-ARAIM Message Type 2, as it is assumed that it would be reduced by design to 10^{-8} or lower.

Table E-5: Possible Default Message for Online V-ARAIM – ARAIM ISM Type 2

DATA	BITS	SCALING FACTOR	MAXIMUM RANGE
Satellite ID	6	N/A	[0 … 63]
Navigation message IOD	10	N/A	[0 … 1023]
ISM SOA (SOA: Start Of Applicability)	11	60 sec	[0 … 1 day]
Constellation	2	N/A	[0, 1, 2, 3]
SUBTOTAL	**29**		
Psat{sat}	3	N/A [Index=Value]	[0=3.00; 1=3.50; 2=4.00; 3=4.50; 4=5.00; 5=5.50; 6=6.00; 7=6.50; 8=DON'T USE] Note 1: Negative exponent of 10.
Sigma_int {sat}	3	N/A [Index=Value]	[0=0.30; 1=0.40; 2=0.50; 3=0.60; 4=0.70; 5=0.90; 6=1.10; 7=1.50] meter.
Sigma_cont {sat}	3	N/A [Index=Value]	[0=0.20; 1=0.25; 2=0.35; 3=0.40; 4=0.50; 5=0.60; 6=0.75; 7=1.00] meter.
Bias_int {sat}	3	N/A [Index=Value]	[0=0.00; 1=0.10; 2=0.20; 3=0.30; 4=0.40; 5=0.50; 6=0.75; 7=1.00; 8=1.25] meter.
SUBTOTAL	**12**		
Along Track Error (at SOA)	09	0.2496 meter	[-63.8976, +63.6480] meter
Across Track Error (at SOA)	08	0.2496 meter	[-31.9488, +31.6992] meter
Common Error (at SOA)	12	0.0312 meter	[-63.8976, +63.8664] meter
Distance Error (at SOA)	5	0.0312 meter	[-00.4992, +00.4680] meter
Along Track Error Rate (at SOA)	06	0.000346666 meter/second	[-0.011093333, +0.010746666] meter/second
Across Track Error Rate (at SOA)	05	0.000346666 meter/second	[-0.011093333, +0.010746666] meter/second
Common Error Rate (at SOA)	11	0.000043333 meter/second	[-0.044373333, +0.044333333] meter/second

Distance Error Rate (at SOA)	03	0.000043333 meter/second	[-0.000173333, +0.000130000] meter/second
SUBTOTAL	**59**		
TOTAL	**100**		

The ARAIM ISM Message Type 2 could easily fit into a Galileo I/NAV.

Finally, different options are possible for ISM dissemination through the GNSS constellations. In this respect, it is important to notice that this Type 2 is expected to be updated every 12-15 minutes for each satellite. Table E-6Table E-6 is an example of how the Galileo Signal-In-Space I/NAV can be used to disseminate Message Types 1A and 2 for both Galileo and GPS satellites.

Table E-6: ISM Dissemination of Type 1A (for two constellations) and Type 2 for Galileo and GPS

TIME (seconds)	Galileo Signal In Space WORD 16
00:00:29 --- 00:00:30	Message Type 2 (for the conveying Galileo SV)
00:00:59 --- 00:01:00	Message Type 1A (for the Galileo and GPS constellation)
00:01:29 --- 00:01:30	Message Type 2 (for selected GPS SV; based on proximity)
00:01:59 --- 00:02:00	Message Type 1A (for the Galileo and GPS constellation)
00:02:29 --- 00:02:30	Message Type 2 (for the conveying Galileo SV)
00:02:59 --- 00:03:00	Message Type 1A (for the Galileo and GPS constellation)
00:03:29 --- 00:03:30	Message Type 2 (for selected GPS SV; based on proximity)
00:03:59 --- 00:04:00	Message Type 1A (for the Galileo and GPS constellation)
…	…

Way Forward: In light of the proposed ARAIM Roadmap, the ARAIM TSG has identified three main areas of work in which WG-C can continue to contribute for the period 2016-2018:

- Contributions to Standards Development,
- Prototype development and testing for ground and airborne algorithms, and
- Constellation Service Providers requirements development and compatibility coordination.

WG-C envisions an interactive process where proposed standards are coordinated with the relevant industry, public, government and other and State stakeholders at regular intervals. Prototyping activities will inform the standards development process and the requirements process of service providers (e.g., Constellation Service Providers, Air Navigation Service Providers, etc.).

In terms of priorities in the medium term, the main focus will be to enable the H-ARAIM Feasibility Checkpoint, the first milestone identified in the Roadmap, to take place around mid-2018.

Continuation of the current R&D activities carried out by the ARAIM TSG, and especially those regarding Vertical ARAIM, will be a second objective examined in parallel with the H-ARAIM development and implementation.

Finally, R&D work related to the extension of the ARAIM concept to other user communities (e.g., maritime and rail) is expected to be initiated.

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1 INTRODUCTION AND PURPOSE

This report provides the results of the studies and analyses by the ARAIM Technical Subgroup (ARAIM TSG) Phase 1 through 3 milestones as established in its Terms of Reference [RD-01]. The ARAIM TSG was created on July 1, 2010, with its parent group being the Working Group C, which stemmed from the U.S.-EU Agreement on GPS/Galileo Cooperation signed in 2004.

The mandate of the ARAIM TSG is to investigate ARAIM (Advanced Receiver Autonomous Integrity Monitoring) on a bilateral basis with the objective of defining a reference multi-constellation ARAIM concept allowing global horizontal and vertical guidance.

After Milestone 1, the TSG produced a first report (dated December 19, 2012), which described the progress made on the analysis of the relevant performance requirements, the definition of an ARAIM reference user algorithm[3], a first evaluation of the achievable performance, as well as the identification and first characterization of ARAIM threats.

A second report was produced after Milestone 2 (dated February 11, 2015) with the main focus on the description of the architectures for the implementation of the ARAIM service (ground infrastructure, ARAIM threat allocation and mitigation, Integrity Support Message contents, and potential ISM broadcast means and risks). The descriptions covered Horizontal ARAIM as well as two options for Vertical ARAIM: the Offline and Online architectures. Furthermore, the Milestone 2 Report extended the ARAIM availability results by considering a wider range of ranging accuracy errors (URE/SISE) as well as additional scenarios for the GPS and Galileo operational constellations.

It was the intention of the ARAIM TSG to use the Milestone 2 Report to gather feedback from the aviation community (avionics manufacturers and integrators, Air Navigation Service Providers, standardization bodies) on the general concepts, results, and implementation options. The TSG considered it fundamental to assess such feedback so as to come up with adequate guidance in relation to the open points identified within the report.

Taking into account feedback following the Milestone 2 Report, the ARAIM TSG has now expanded upon the Message Types for ARAIM: Modes and Messages for Horizontal ARAIM (H-ARAIM), Messages for Vertical Offline, and Messages for Vertical Online ARAIM.

Importantly, the Milestone 3 Report proposes an Implementation Roadmap and includes discussions on the institutional issues that need to be considered for the provision of the service and on the ARAIM relationship to SBAS.

Further, ARAIM availability results are provided, showing the results obtained on a global grid of users and the improvements thanks to an optimization of the reference user algorithm, which is described in Annex A.

[3] The reference algorithm has been taken as the basis for the assessment of the ARAIM performance by the ARAIM TSG; other user algorithms may be used for as long as they demonstrate a level of performance equal or better than the reference.

2 ARAIM ROADMAP

This section outlines a potential path for implementation of the ARAIM concept for horizontal and vertical guidance described in this and previous reports developed by WG-C. It includes key milestones and decision points identified by the U.S. and EU and is intended to guide industry, government, and standards coordination on the concept described in this Milestone 3 Report.

Where possible, this section will describe near-term activities and tasks which the ARAIM TSG believes will aid in future decision points. Longer term tasks are also discussed at a high level to provide context to the roadmap and illustrate how ARAIM may be phased into operational service over time and how existing infrastructure (e.g., SBAS) may evolve to support these services.

The ARAIM TSG has concluded ARAIM services should be implemented incrementally. Beginning with a horizontal only service, H-ARAIM, it is to support near-term, proposed multi-constellation (MC) applications. EUROCAE currently has plans to publish MOPS for GPS/Galileo applications that will require a RAIM service in support of horizontal navigation and surveillance requirements. ARAIM provides a safe and efficient means for integrating MC signals. The ISM provides a means to communicate constellation data in a safe manner without affecting the aircraft certification and avoiding overly conservative assumptions during initial fielding when data from new constellations may be limited. Additionally, the ISM allows for these assumptions to be adjusted if a constellation's performance changes over time as the constellations evolve. In this respect, different dynamics of the ISM data can be envisaged, as identified later in this report.[4]

A global vertical service, V-ARAIM, can be implemented once sufficient data is collected and experience gained to establish safe operations. Analysis and experience with observed data will determine whether additional monitoring capabilities may need to be implemented. The ARAIM TSG has assessed the level of performance for precision approach down to 200 ft decision height (LPV-200) [RD-74] and used performance requirements established under the WAAS LPV-200 program. This criterion has been used to demonstrate one acceptable means for achieving such operations with WAAS; however, this criterion will need to be reviewed in the context of the ARAIM concept and the specific safety hazard applicable to the target operations (e.g., the ARAIM specific safety case for LPV 200 or for CAT I approach operations). See Section 2.2 for next steps identified for validation of V-ARAIM service and operational approvals. Additionally, the ARAIM TSG and stakeholders may examine additional criteria and safety cases to extend vertical services to cover other, more stringent operations.

Currently, standards development plans focus on DFMC SBAS MOPS. It is anticipated ARAIM could support horizontal navigation (H-ARAIM) in cases where SBAS services are unavailable while providing superior performance of traditional RAIM. It is the view of the group that H-ARAIM services should be incorporated into DFMC SBAS standards anticipated for development in EUROCAE and RTCA. DFMC SBAS vertical services are expected to support vertical requirements with low risk to avionics manufacturers and SBAS

[4] Note that for H-ARAIM, a static solution is considered technically feasible.

providers. We expect DFMC SBAS to dominate vertical guidance for an extended period of time (e.g., 20 years) after initial service provision – within the SBAS service areas. Testing and evaluation of V-ARAIM services will proceed in the meantime and could be implemented based on user needs and the presence of sufficient evidence supporting its safety case.

2.1 **Implementation Timeline**

A number of users identified the need for near-term RAIM services that can safely handle MC signals. While standard RAIM algorithms could be adapted to support MC, it is asserted that ARAIM – adding a layer of monitoring on the ground – provides a more effective and safe approach for MC implementation enabling the use of less conservative constellation performance assumptions. This approach will lead to higher availability, reliability and user confidence in un-augmented GNSS services. The following are example implementations that could utilize H-ARAIM services prior to 2025:

- EUROCAE is starting to develop a GPS/Galileo MOPS with the DFMC SBAS services including H-ARAIM. H-ARAIM will provide safe and effective means for using GPS and Galileo in conjunction with each other.

- The EC plans to conduct prototype development of an ARAIM airborne receiver. This receiver can be used to validate preliminary requirements and provide a path to a receiver which can be certified for operational use.

- Maritime and rail have an increasing need for robust, accurate GNSS horizontal guidance. H-ARAIM will provide additional means for increased safety in utilising MC signals for horizontal guidance for user communities beyond civil aviation[5].

These applications are expected to be the first opportunities for H-ARAIM implementation. V-ARAIM test and evaluation for these or other applications will come only after sufficient data is collected and the necessary safety case is developed and approved by at least by one State.

Figure 1 illustrates how ARAIM could be incrementally implemented. Initially, the concept of ARAIM would be fielded to support H-ARAIM services only.

The H-ARAIM standards as an integral element of the DFMC Standards are expected to be completed by 2020 at EUROCAE. The user algorithm can be V-ARAIM forward compatible to the extent possible and with the ISM interfaces[6] needed to support V-ARAIM (e.g., reserve sufficient communication link data bandwidth to support potential, future features for V-ARAIM). The main objective would be to gain the immediate benefits of H-ARAIM to support multi-constellation signals while gaining data and experience which could be used in the future evaluation of ARAIM for V-ARAIM. However, V-ARAIM forward compatibility must not put at risk the completion of the MOPS on time as identified above.

[5] Specific integrity requirements for user communities beyond civil aviation will need to be assessed.

[6] This does not require a bit-level definition of ISM for V-ARAIM.

It is believed that H-ARAIM with a static ISM can be implemented with offline monitoring at very low risk, so initial efforts will focus on requirements development and validation for offline. Alternative ISM dissemination solutions are identified (including hard-coded ISM at the avionics level) and could be included in the standards to the extent possible.

H-ARAIM implementation will require ANSPs and CSPs to reach agreement on new performance commitments and offline monitoring processes. It is expected the new commitments and offline monitoring can be implemented by the respective parties at moderate risk. Generation (if not static) and monitoring of the H-ARAIM ISM by an entity in compliance with those defined processes and approved by corresponding certification authorities could eventually accelerate the provision of the H-ARAIM service. Similar challenges exist in terms of liability and sovereignty as for current classical RAIM, and will need to be addressed.

Once H-ARAIM services have been implemented and GPS/Galileo achieves FOC, each with 24 operational satellites with dual frequency capabilities (circa 2024) and performance commitments from the core constellations for dual frequency services are published, it will be possible to assess ARAIM with offline monitoring and its ability to support V-ARAIM services.

After an evaluation period, interested ANSPs and users may seek operational approval for vertical guidance based on the performance targets set by a dedicated safety case. ANSPs and regulators will need to verify offline monitoring and CSP performance against these safety targets and the commitments documented in the standards.

This approval for vertical guidance may be possible without any modification to the H-ARAIM software or interfaces. However, additional offline and/or online monitoring fidelity maybe required to achieve more demanding vertical guidance operations and H-ARAIM standards will likely need to be updated to reflect the V-ARAIM services.

In light of the remaining uncertainties, the ARAIM roadmap can only provide at this stage firm dates for H-ARAIM. In addition, the ARAIM TSG has identified milestones along the path to full ARAIM implementation, for which firm dates are not yet available. These milestones will aid coordination of activities among stakeholders toward common goals. Note, it is possible for different stakeholders to reach different conclusions at each milestone and take different actions, so this possibility should be accounted for in each stakeholder's plans based on their own independent investment analysis.

- H-ARAIM Feasibility Checkpoint – This MS 3 Report includes the necessary detail to start H-ARAIM prototyping of airborne equipment and offline monitoring functions for H-ARAIM. This prototyping should aid in the development of detailed, validated standards. At the Feasibility Checkpoint, stakeholders will determine if the concept is sufficiently defined to continue formal development and validation of standards for H-ARAIM service. This Feasibility Checkpoint will likely require the development of a detailed concept paper, draft standards (MOPS and SARPs), concept of operations (CONOPS), preliminary safety case, and validation evidence to support them. It is expected that CSP commitments and other minimum requirements necessary to support H-ARAIM services will be clearly identified at this checkpoint. A preliminary safety case shall be available for the H-ARAIM Feasibility Checkpoint. In addition, if the ISM data are to be provided through a communication link, the corresponding ICD will be required.

- H-ARAIM Readiness Keypoint – All necessary standards for the H-ARAIM Service provision will have been developed, validated, and approved at this Readiness Keypoint by the respective standards bodies. Similarly, avionics and offline monitoring supporting the H-ARAIM service will have been developed. An evaluation period before the Readiness Keypoint will be required to verify the CSP performance against published commitments for operational use and to identify initial H-ARAIM ISM quantities. The period of time and methods used for this evaluation period are highly dependent on the type of commitments and transparency of CSPs into their compliance with these commitments. The corresponding criteria will need to be derived for this Readiness Keypoint based on the specific approval situation (e.g., air carrier applicant using specific H-ARAIM MOPS, supporting offline monitoring services, and specific ISM source). Finally, the H-ARAIM service safety case must be available at this point, supported by sufficient validation evidence.

- V-ARAIM Feasibility Checkpoint – After some period of H-ARAIM service being successfully fielded, it is anticipated users and ANSPs will want to maximize their investment. Some ANSPs and users may evaluate existing designs for use in vertical approach operations (V-ARAIM). An additional evaluation period will likely be required for these efforts. A V-ARAIM Feasibility Checkpoint before the V-ARAIM Readiness Keypoint is needed to ensure the feasibility of vertical guidance based on ARAIM concepts following initial performance assessments. It is expected this milestone will meet similar objectives and produce similar products as the H-ARAIM Feasibility Checkpoint.

  It is anticipated that V-ARAIM will require addition statistic confidence from analysis and data collection, more stringent CSP commitments, high fidelity monitoring in support of ISM assurance, and potentially other factors. Again, it is expected that CSP commitments and other minimum requirements necessary to support V-ARAIM services will be clearly identified at this checkpoint.

- V-ARAIM Readiness Keypoint – As for the H-ARAIM case, all necessary standards for the V-ARAIM service provision will have been developed, validated and approved at this Readiness Keypoint by the respective standards bodies. The corresponding criteria to verify the CSP performance against published commitments for operational use and to verify the V-ARAIM ISM parameters will need to be derived for this Readiness Keypoint, based on the specific approval situation. The safety case specific for the V-ARAIM service must be available at this point, supported by sufficient validation evidence.

  As an outcome of the V-ARAIM Readiness Keypoint, the achievable level of performance and the coverage of the service will have been evaluated. Several options can be foreseen at that point. Providing that at the time of the V-ARAIM Readiness Keypoint it is determined either that the existing monitoring would not provide a high level of availability for a V-ARAIM service worldwide, or that in any case it would be worth improving the achievable level of service performance, then additional offline/online monitoring would be implemented (assuming the cost-benefits analysis is positive). In that case, a second V-ARAIM Readiness Keypoint may be envisaged to evaluate the achievable level of service once those additional offline/online monitoring capabilities have been implemented.

The timeline for V-ARAIM operational introduction may be gradual in terms of performance capabilities depending on the architectural concept. This gradual increase in capabilities is depicted at the bottom of Figure 1 below.

Also to be pointed out is the fact that the SF/DF SBAS service is depicted as continuous in the figure in order to reflect on one hand the plans of SBAS Service providers and, on the other hand, the expected complementarity with ARAIM (later discussed in Section 4 of this report).

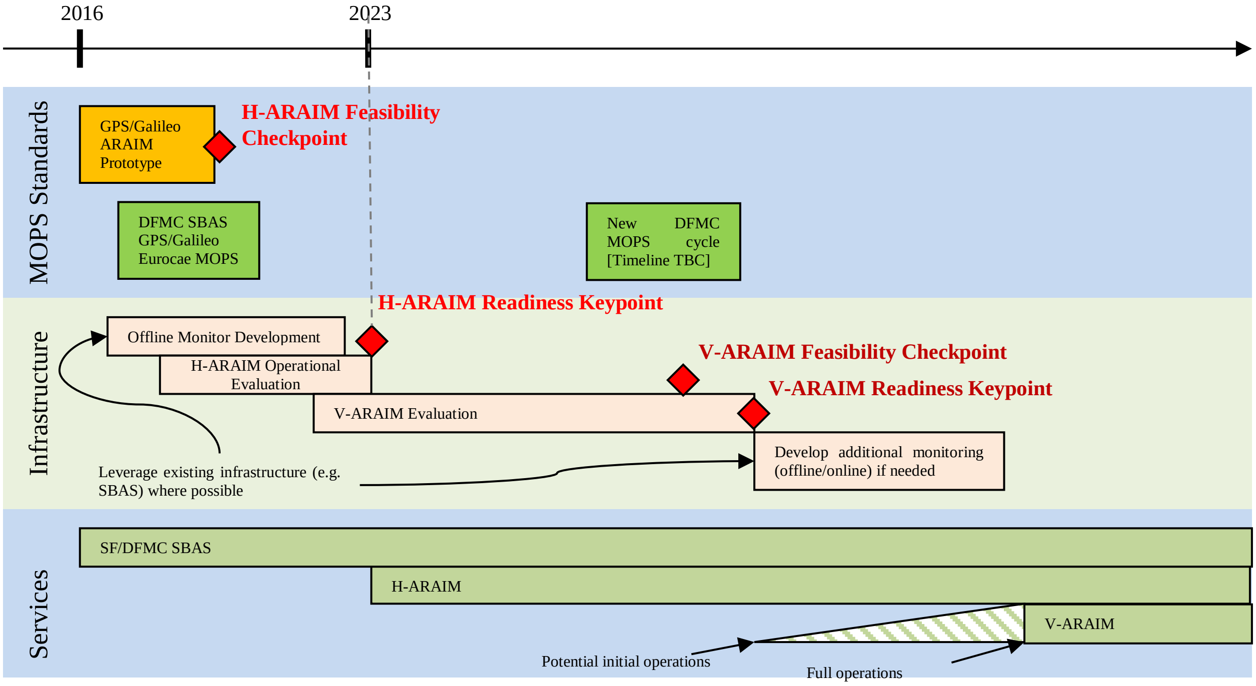


Figure 1: Aviation Long-term Timeline

Figure 2 provides a more detailed look at the ARAIM development and evaluation activities. It also shows how these proposed activities potentially align with the current development plans of standards bodies, CSPs, and SBAS providers. ARAIM development and validation will require coordination among these stakeholders to ensure timely introduction of services.

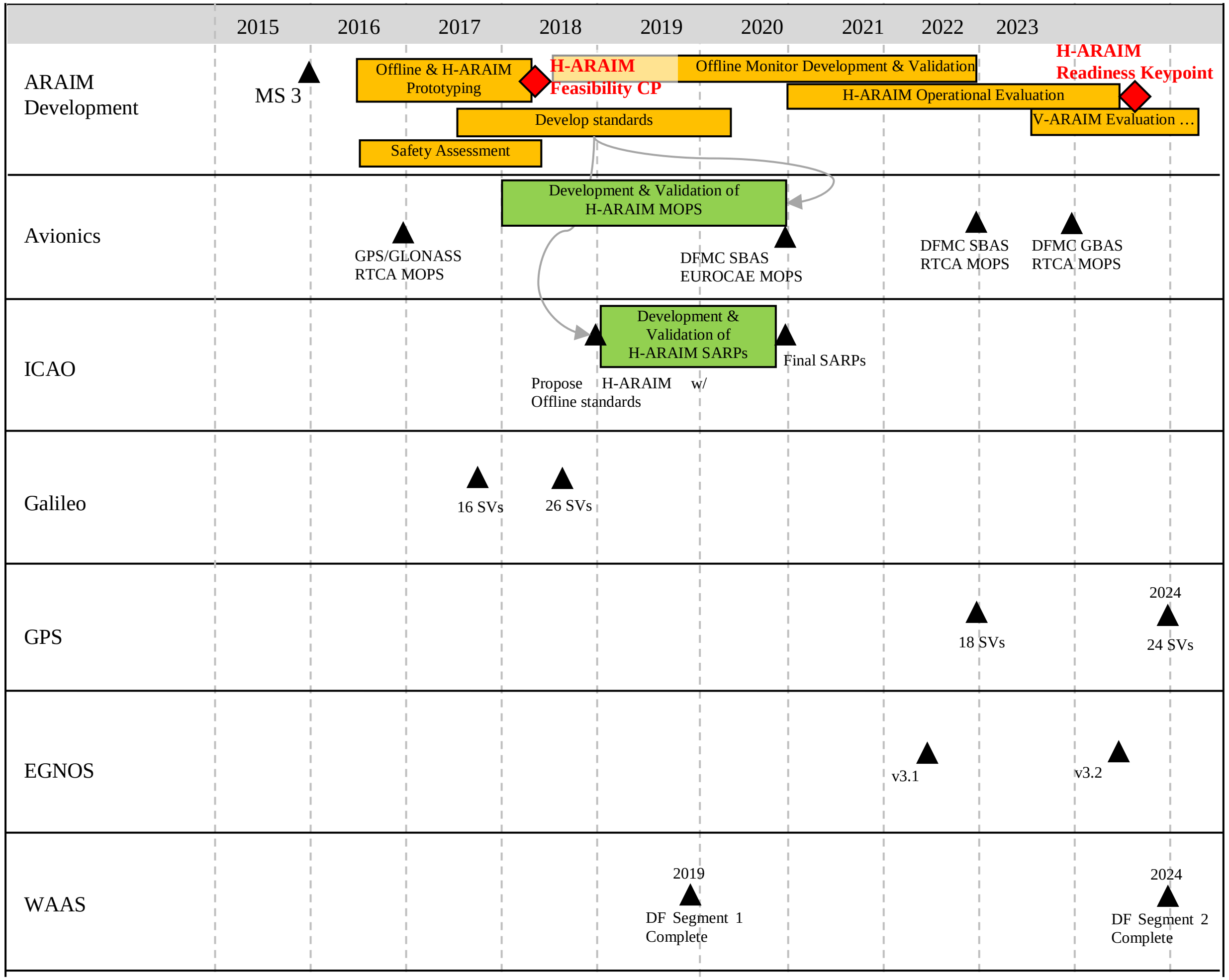


Figure 2: Aviation Near-Term Development Schedule until 2023

2.2 Challenges and Future Validation Work

The roadmap presented above, and in particular the identified milestones require that a number of tasks are completed in order to have the necessary material ready.

For the items concerning H-ARAIM, the ARAIM TSG expects that the development and implementation can be completed in the medium term (prior to 2024).

The first relevant point is the H-ARAIM Feasibility Checkpoint for which the following elements will be needed:

- Detailed concept paper,
- Standards: MOPS and SARPs, through contribution to the relevant standards (DFMC SBAS MOPS),
- Concept of Operations (CONOPS) for H-ARAIM, and
- Preliminary Safety Case.

In order to consolidate these elements, a number of challenges need to be tackled (not necessarily at the technical level), such as Global ISM approval, sovereignty, and liability. Those issues are discussed in Section 3 of this report.

The second milestone is the H-ARAIM Readiness Keypoint for which emphasis will be on validation, following the period of evaluation. A relevant part of the work will be devoted to measuring the actual performance of the constellations in order to validate their level of compliance with respect to the corresponding Constellation Service Performance Commitments. In this respect, criteria should be developed to quantify the amount and type of data that needs to be collected and any special collection guidance. The criteria should be traceable to the H-ARAIM safety case. The Final Safety Case specific for the H-ARAIM service must be available at this point, supported by sufficient validation evidence

For the V-ARAIM, similar elements will be needed for the corresponding milestones. Taking into account that the level of performance to be provided is higher, additional R&D, prototype, and evaluation work will be required.

Similar to the H-ARAIM, at the time of the V-ARAIM Feasibility Checkpoint the following elements will be needed:

- Detailed concept paper,
- Standards: Preliminary standards for V-ARAIM,
- Concept of Operations (CONOPS) for V-ARAIM, and a
- Preliminary Safety Case.

Similar to the H-ARAIM, at the time of the V-ARAIM Readiness Keypoint the following elements will be needed, in addition to those from the Feasibility Checkpoint:

- Standards including the relevant parts for the V-ARAIM service: MOPS and SARPs,

- Evaluation of the actual performance of the constellations from the perspective of V-ARAIM,

- Validation of the level of compliance with respect to the corresponding Constellation Service Performance Commitments, and a

- Final Safety Case specific to the V-ARAIM service, supported by sufficient validation evidence.

3 INSTITUTIONAL ISSUES

3.1 Motivation

Currently, GPS L1-based RAIM is widely used in aviation globally. Consequently, there is significant precedent on the use of signals from a constellation of navigation satellites operated by an entity that is not under direct aviation oversight and, with the exception of the United States, a foreign State. In view of the current ARAIM developments, traditional RAIM has established the use of a widely accepted, hard-coded ISM, setting the probability of constellation failure as negligible and the probability of an individual satellite failure at 10^{-5} per hour. Evidence that supports these assumptions as valid based on historical observation was not available when these assumptions were implicitly accepted. Initial concerns over legal and institutional issues were dealt with by the International Civil Aviation Organization (ICAO, a United Nations body) and led to the agreement of a "Charter on the Rights and Obligations of States relating to GNSS Services" (Assembly resolution 32-19, 1998 [RD-88]). It was also agreed that aviation use of GNSS should be free of direct user charges.

Given the precedent described above, what is different for ARAIM that would require the resolution of further legal and institutional issues? The following differences are impacting ARAIM:

- GPS L1-based operations were introduced as a "supplemental means." Most procedures required the "overlay" of conventional navigation procedures, and many operational safety cases rely on significant redundancy provided by other CNS systems. Now, ARAIM is intended to support "primary means," operations similar to SBAS, where an extensive near real-time monitoring infrastructure is required.

- The GPS L1 RAIM supported navigation applications range from en route to "non-precision approach." ARAIM is intended to support applications that include vertical guidance, e.g., with a higher hazard level. Meanwhile, the use of GNSS for other aviation functions (ADS-B, EGPWS) is increasing. Thus, the number of applications and equipped users, and in particular their associated hazard classifications continues to increase significantly.

- While established practice based on GPS L1 RAIM has served aviation well, that is all it is: established practice. With the increase in constellation service providers, it is necessary to further clarify and formalize current arrangements to ensure international acceptance, as well as safety and interoperability. This formalization will ensure that constellation service providers understand what is required in order to provide an aviation service based on "open signals" (e.g., the civil standard positioning service in the case of GPS).

The aim of this section is to both review current established practice in the framework of ICAO principles, as well as propose how this practice could be extended to apply to aviation ARAIM services in the future. It is expected that this extension will also serve the needs of other transport modes and/or safety critical applications at least in principle.

3.2 Current GNSS Service Provision based on ICAO Principles

The Chicago convention [RD-77] makes the provision of radio services a sovereign responsibility as per its Article 28:

Air navigation facilities and standard systems

Each contracting State undertakes, so far as it may find practicable, **to**:

a) **Provide, *in its territory***, airports, **radio services**, meteorological services and other air navigation facilities **to facilitate international air navigation**, in accordance with the standards and practices recommended or established from time to time, pursuant to this Convention;

An ANS includes communication, navigation, and surveillance services, but also air traffic, aeronautical information, and meteorological services [RD-87]. Positioning as provided by GNSS is consequently only a small part of an ANS. There are no restrictions on how a contracting State provides these services, e.g., whether through a State agency, a privatized air navigation service provider (ANSP) or even a commercial or foreign entity. However, the responsibility to provide such services rests with the State. For example, if the State delegates this sovereign obligation or an element thereof, it implies that the State should oversee the service. While the free-of-direct-user-charge provision of GNSS signals is thus a welcome assistance in the provision of signals to facilitate international air navigation, the State retains an oversight responsibility [RD-86].

In Annex 10 [RD-06] to the ICAO Convention, the definition of GNSS makes application-specific integrity monitoring an integral component: *"A worldwide position and time determination system that includes one or more satellite constellations, aircraft receivers **and system integrity monitoring**, augmented as necessary to support the required navigation performance for the intended operation."* ICAO then defines Ground Based, Space Based, and Aircraft Based Augmentation as the possible augmentations to provide such integrity monitoring. In other words, aviation always requires an additional layer of monitoring that complements the service to qualify it as an air navigation service. While it would be possible for constellation service providers to provide such services directly, so far the direct provision of integrity services by a constellation service provider has been considered to be either cost-prohibitive or impractical for a variety of reasons.

The GNSS Charter defines that the core constellation service (e.g., navigation signals emanating directly from satellites not under aviation control) is not an Air Navigation Service as defined by ICAO, but only an ingredient thereof. This definition respects the sovereign role of States. GNSS constellation service providers therefore "provide navigation aid signals for use in aircraft positioning" [RD-88], which by themselves are "only" an essential ingredient of the end-user's navigation service. The air navigation service provided to aircraft operators using GNSS always includes additional integrity monitoring specific to the requirements of the application.

The Single European Sky Regulations require that ANS providers are certified. Similar requirements exist in all regions of the world. In the case of GNSS augmentation services, the SBAS and GBAS providers are certified. Part of the certification is that the operators need to verify the suitability of the core constellation to provide the required safety and quality of service, e.g., the oversight responsibility can be delegated to the ANS provider. In the case of ABAS or RAIM however, the only thing that can be and is certified is the avionics. Because several European States have struggled to authorize services based on GNSS/ABAS, work is underway to ensure the oversight of core constellation performance to ensure that assumptions made in certified avionics that are critical to the safety of the operation are correct. These assumptions are defined in the ISM, which are hard coded into the avionics receivers in the case of current RAIM. The absence of a tangible organizational entity providing the augmentation service for ABAS has caused some States to struggle more in approving ABAS than SBAS or GBAS.

3.3 **Sovereignty and Liability in View of Current Practices**

The ICAO GNSS Charter addresses sovereignty explicitly, but is silent on the topic of liability. However, the charter clearly establishes that safety is the responsibility of all actors involved. The Chicago convention was established in 1944, and could thus not possibly foresee the complexities of service provision based on satellite navigation. The sovereign obligation of States to provide ANS primarily results in States having the right to authorize or not the use of a particular constellation and augmentation service [RD-89]. Despite existing provisions in Annex 15, many States have not made these determinations, nor is there a mechanism in avionics or pilot training that forces the enabling or disabling of a particular GNSS element when crossing a State boundary. Due to both the additional complexities of such a scheme and the positive service record of GPS, it can also be said that it would not be reasonable or even unsafe to withhold from aircraft operators a fully suitable global air navigation service. The principles of safety and interoperability should consequently drive the institutional arrangements necessary to satisfy the demands of sovereignty and liability.

Liability provides accountability in the case of damages caused by negligence, especially in the case of accidents with loss of life. A recent review has concluded that no suitable legal mechanisms exist today if ever an accident would occur where the primary cause could be attributed to negligence by a satellite navigation constellation operator [RD-90]. While the need (and chance for success) for a liability framework for aviation use of GNSS is debatable, this need can be mitigated by ensuring that no such negligence exists. For example, if the provision of GNSS is based on a suitable set of ICAO standards written by a team of qualified experts, and compliance with those standards is continuously verified, the chances can be maximized that there will never be a need for such a framework. Given the excellent safety record of navigation systems so far, this seems to be a justifiable position.

Consequently, it is proposed that the demands of sovereignty and liability can be translated into the following practical and realizable requirements for a GNSS-based air navigation service provision:

- Sufficiently detailed information available from constellation service providers to expert standardization groups to enable the development of suitable standards for aircraft avionics and ground equipment (augmentation systems, none in the case of ABAS/RAIM – but will include some type of monitoring network for ARAIM),

- Transparent set of verifiable constellation performance assumptions that ensure the integrity of the service (ISM content),

- Provision of constellation performance and status information to support service predictions (Aeronautical Information Service), and

- Definition of a GNSS service provision framework which clearly defines the roles and responsibilities of all actors in line with the GNSS charter.

GPS has set a good precedent to satisfy these requirements through a letter of commitment to ICAO, standardization of key system aspects in Annex 10, the availability of interface control and service performance documents (ICD and SPS), avionics equipment standards (RTCA), and a user support center. The work of this group has provided further clarity on inherent assumptions for current RAIM-based services through the definition of the ISM and by doing so has provided the basic understanding on what parameters require oversight to verify the safety of the service.

3.4 **Extending ANS Provision Principles to ARAIM**

Multi-constellation GNSS provides additional complexities and opportunities. It is considered paramount to preserve the following principles established with GPS-based RAIM:

- Safety – given the global nature of satellite navigation, a globally uniform level of safety is provided by RAIM. ARAIM should not introduce any national or regional differences in the achieved safety level; and,

- Interoperability – Operation of RAIM is seamless globally, without any (technical) mode switching requirements. No undue complexity should be introduced by ARAIM.

Both of these principles strongly suggest that the ISM for a given system should be valid globally. This approach ensures that the same safety level is achieved globally and that only a single ISM is needed instead of State or region specific ISM’s. Some States may choose not to authorize the use of all constellations within their airspace. Nevertheless, the ISM parameters describing fault probabilities and confidence values should be chosen to be applicable everywhere throughout the globe. The same values for these parameters should be used by all States that choose to authorize each specific constellation. It is expected that not all States will approve all constellations for use, since there is an associated oversight burden. This leads to the consideration of needing to distinguish differing service levels. For example, if ARAIM supports en route and terminal area procedures as is done today with GPS-based RAIM, it would be highly desirable if no constellation-specific switching logic would be needed. While this opens up the possibility that an aircraft operator could use a non-authorized constellation at their own risk, as shown in [RD-90] this risk is already carried by the aircraft operator, regardless of the GNSS authorization/approval status.

With the use of ARAIM for vertical guidance, the need for an increased control over the combination of signals used by the ANSP is understandable and also has significant established precedent. The use of a particular system for approach operations is determined by the instrument approach chart title. For example, the ANSP can specify what navigation system is suited to perform an approach. Again, it should be possible to introduce ARAIM services in line with established practice.

3.5 **Institutional Implications of a Global ISM**

The ISM drives how a constellation is weighted by the ARAIM algorithm. It provides a clear and tangible benchmark of how a given constellation is assumed to perform. The word “assumed” is used here because especially during early service introduction, a constellation may be performing better than suggested by the ISM but not yet have sufficient historical evidence to justify the update of the ISM values. The question that needs to be answered is who would actually determine the ISM values? Of course a State (or group of States) operating a GNSS constellation will want to determine their ISM values. This situation may create a conflict of interest for other States. The determination of ISM values, based on the explanations above, is considered to be an Air Navigation Service duty. This view would need further discussion and agreement. The transmission of the ISM through a GNSS core constellation operator could be seen as only a means of broadcast. As long as it can be assured that the values provided to the satellite operator will not be changed, the ISM provider can thus be a separate entity. Using the example of the United States, the FAA could become the ISM provider and then furnish the ISM values for GPS to not only the GPS system operator but also the Galileo operator (assuming that both systems will broadcast values for both constellations). In Europe, a suitable organization similar to the ESSP (European Satellite Services Provider) could be created and would be able to satisfy the relevant European regulations.

It is considered advisable that an organization with close ties to the GNSS constellation operator would become the ISM provider. However, to ensure that the ISM values can be accepted globally, a sufficient level of transparency needs to be ensured. This need for transparency suggests that the methods to determine ISM values should be standardized. Furthermore, if another State disagreed with published ISM values based on observation or analysis, some type of an appeal procedure would need to be in place. Following the example of EGNOS in Europe, and given the requirements stipulated in Section 3.3, individual States should be able to have contractually binding "Working Agreements" with the entities that determine ISM values. Conversely, a global intermediary such as ICAO could take over this role, as long as sufficiently clear and acceptable treaty obligations exist for all participants.

In summary, in view of the implications on safety and interoperability, the goal of a globally harmonized and accepted ISM for supporting ARAIM operations should be pursued. If individual States choose to disallow the use of specific constellations or insist on determining their own ISM values, significant additional operational functionality will be required, which will negatively impact the feasibility and benefits that can be obtained through multi-constellation GNSS. Such a global ISM must be generated and maintained using a transparent and standardized methodology, building on the already existing processes and frameworks. The entity or entities charged with ISM generation must be able to satisfy the regulatory requirements of all contracting ICAO States, which may include the need for individual contractual agreements.

4 ARAIM Complements Satellite Based Augmentation Systems

4.1 Introduction

Today, the Satellite Based Augmentation Systems (SBAS) are serving an increasing number of aircraft. Figure 3 shows the coverage of SBAS in 2015; it shows four separate SBAS. The Wide Area Augmentation System (WAAS) covers North America, providing approach guidance to over 3,000 runways with avionics carried by more than 100,000 aircraft. The European Geostationary Navigation Overlay Service (EGNOS) covers Europe; the GPS-Aided Geo-Augmented Navigation (GAGAN) system serves India, and the MTSAT Satellite Augmented System (MSAS) is used over the Japanese Islands.

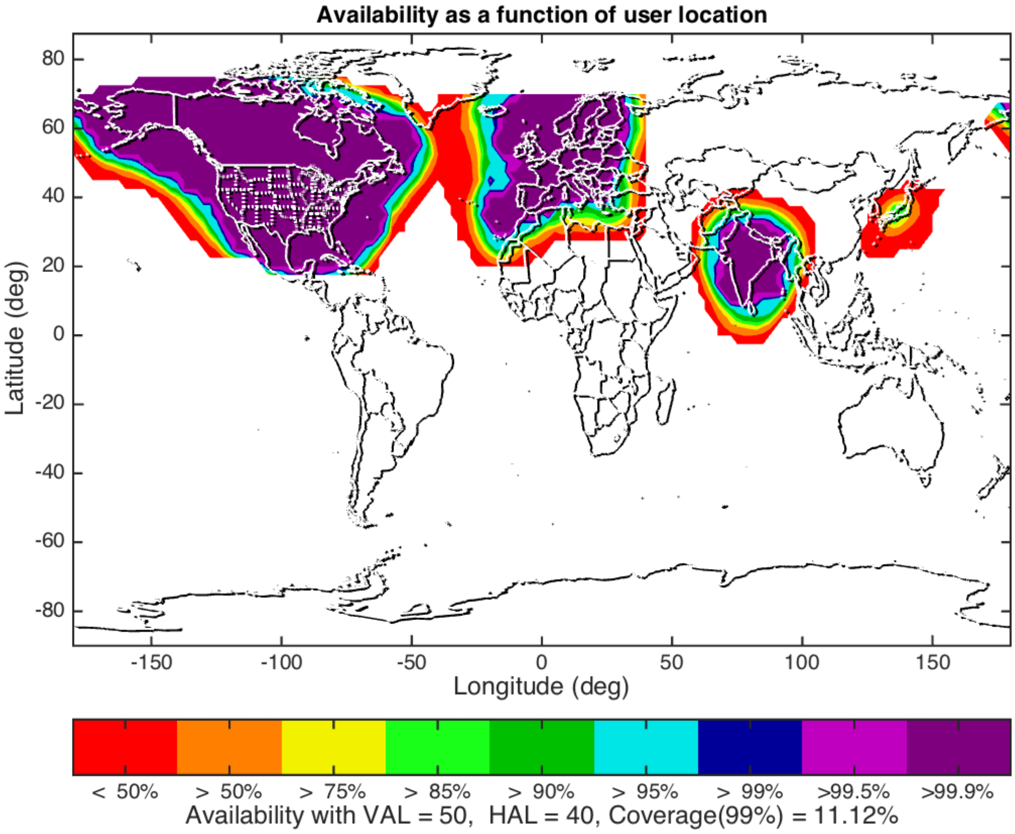


Figure 3: SBAS Coverage for LPV-200 in 2015

Figure 3 coverage assumes that the aircraft carries SBAS receivers that only use the GPS civil signal at the L1 frequency of 1575.42 MHz. In other words, the Figure 3 coverage is for single-frequency single-constellation (SFSC) operation of SBAS. The simulation shown uses the GPS almanac broadcast on May 15, 2015 containing 31 healthy satellites. Figure 4 shows foreseen coverage by 2026 and is based on air receivers that process signals at 1575.42 MHz and 1176.45 MHz. These are dual-frequency (DF) systems, and the DF operation eliminates troublesome ionospheric error.

WAAS will continue to serve avionics that use the L1 frequency alone, but it will also support SBAS avionics that process the GPS signals at 1575.42 and 1176.45 MHz. As such, WAAS will become a dual-frequency single constellation (DFSC) system. EGNOS will expand to support GPS and Galileo at these two frequencies. With dual frequencies, SBAS coverage will expand from Figure 3 to Figure 4, because the airborne receivers will eliminate the ionospheric error that is the largest error source for single-frequency operation.

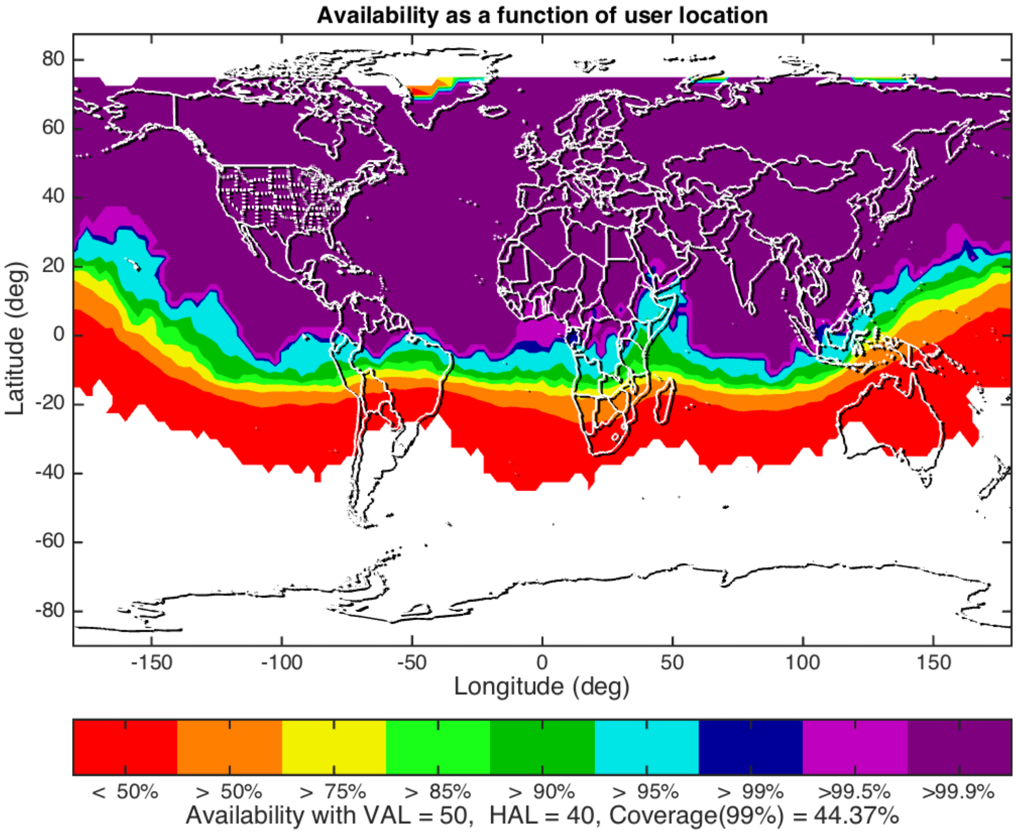


Figure 4: SBAS Coverage for LPV-200 in 2026

The DF coverage of SBAS shown in Figure 4 will support approach operations down to an altitude of 200 feet for all of the airports within the coverage area. The simulation uses the standard 24 satellite GPS constellation for all SBASs, and in addition to that EGNOS and SDCM also use the standard 24 satellite Galileo constellation. This DF SBAS capability has some important advantages. Specifically:

- DF operation can be based on a single healthy constellation (e.g., GPS or Galileo only), and the capability will become available when the GPS L5 and Galileo E5A signals are operational.
- The DF ground systems will be able to reuse much of the single-frequency software.
- A strong cadre of existing SBAS receiver manufacturers will be able to readily make the step from single-frequency to dual-frequency avionics. Thus, the technical risk associated with the new receivers should be reasonably low.
- No dramatically new safety proofs are needed to support DF operation. Unlike ARAIM, SBAS supports the time-to-alert from the ground system directly. Thus, the safety proof does not need to address the short term effect of GNSS faults that are not detected by ARAIM.
- LPV-200 approach operations can be approved based on the now familiar error distribution associated with SBAS, while ARAIM will present a new error distribution.

- Sovereign control of SBAS seems feasible on a regional basis.

Even so, ARAIM offers important capabilities that complement SBAS, and Table 1 lists these applications in a rough chronological order. Please know that these applications are the ones foreseen by ATSG in line with the Roadmap presented in section 2. Other applications may arise and be more important than the ones we anticipate today.

The remainder of this section discusses the table entries in turn.

Table 1: ARAIM Applications that Complement SBAS

Horizontal ARAIM in the Near Term Based on One Frequency: ARAIM may find near-term application before dual frequency GPS and dual frequency Galileo are operational. Specifically, ARAIM could enable dual or multiple constellation navigation based on one frequency. After all, single frequency GPS is already operational; single frequency GLONASS is already operational; and single frequency Galileo will be operational in 2020. ARAIM would enable the integration of these early constellations even if they differ sharply in P_{sat} and P_{const}. In the near term, ARAIM could store the ISM in the receiver's non-volatile memory or disseminate the ISM via an existing communications link or database. In the same manner, when operating in dual frequency, dual constellation, the single frequency mode would become a backup mode in case of lost measurements at the other frequency. In this sense, results in chapter 5 show that single frequency L5/E5a H-ARAIM mode provides robust RNP 0.3 service.
ARAIM to Support Arctic Navigation: The Arctic Ocean requires navigation with integrity for energy exploration, eco-tourism and shipping. Importantly, ARAIM could enable the ship to travel in existing ice cracks or tracks from previous ships. Thus guided, the ship could double its speed. ARAIM supplants SBAS in the Arctic, because the needed ISM could be broadcast by the GNSS satellites or through the use of databases, while SBAS GEOs do not cover the Arctic.
Vertical ARAIM Worldwide Without Needing Geostationary Satellites: In time, ARAIM could obviate or reduce the need for geostationary satellites used by SBAS, and it can operate with a network of fewer ground stations than that of SBAS. As such, it would reduce a significant part of the SBAS operational budget. At the same time, ARAIM could reuse the SBAS reference stations, and so SBAS could be used to accelerate the deployment of ARAIM at lower cost.
ARAIM to Provide GNSS Resilience: As mentioned above, ARAIM does not need the SBAS geostationary satellites. The needed ISM will be broadcast over the GNSS satellites, stored in the receivers or disseminated through aviation databases. As such, ARAIM does not suffer from the signal outages associated with geostationary satellites that frequently appear low in the sky. These outages can be due to blockage by terrain or buildings, or they can be due to intentional or non-intentional radio frequency interference.

4.2 Horizontal ARAIM in the Near Term Based on One Frequency

As described earlier, ARAIM generally assumes two or more constellations (nominally GPS and Galileo) and two signaling frequencies (e.g., L1/E1 and L5/E5a). However, ARAIM concepts may also be helpful to multi-constellation receivers that only use one frequency.

This capability may provide early utility from ARAIM. After all, dual frequency operation of both GPS and Galileo is not expected until 2024; and dual frequency SBAS is not expected until after 2024. Yet multiple single frequency constellations will be operational before that date. Specifically, single frequency GPS and GLONASS are already operational in 2015. Beidou is scheduled to be available before dual frequency GPS and Galileo is scheduled to be operational by 2020 (having both single and dual frequency capabilities).

Information describing $\{P_{sat}, P_{const}\}$ may be particularly helpful for early single frequency operations with multiple constellations. Recall that $\{P_{sat}, P_{const}\}$ approximate the *a priori* risk of a satellite fault and the *a priori* risk of a constellation failure, respectively. The avionics uses this information to determine how many sets of potentially failed satellites must be considered. This information may be of immediate interest to avionics that are using the already operational satellites.

GPS plus GLONASS is of current interest because Russia has mandated GLONASS use by Russian flag carriers in their airspace, and several receiver manufacturers are planning a GPS/GLONASS product for the resulting market. The standards activity has already commenced at RTCA. However, it faces an appreciable technical challenge.

To date, the reliability record for GLONASS does not demonstrate the maturity necessary to assure safety when bounded by conventional RAIM. Additionally, the CSP has not published a performance standard identifying national commitments for reliability and integrity of services. Specifically, GLONASS suffered a constellation fault of large magnitude on April 1, 2014. The navigation message for most of the satellites indicated a rotation of the constellation by approximately 10 kilometers. This fault persisted for ten hours. Traditional RAIM would not necessarily detect a rotation of this sort because the test metrics rely on satellite-to-satellite consistency, and such consistency was sustained for one hour out of this ten-hour integrity event.

Horizontal ARAIM (H-ARAIM) for aviation is shown in

Figure 5. As shown, safe values for $\{P_{sat}, P_{const}\}$ are conveyed to the aircraft, and these values may well be different from constellation to constellation, and they will vary over time as the individual constellations mature (and are eventually retired). H-ARAIM does not need URA updates because lateral air operations could be well supported with constant URA values chosen today. However, the same may not be true for $\{P_{sat}, P_{const}\}$ and a reasonable mechanism to support soft-coding of $\{P_{sat}, P_{const}\}$ is needed.

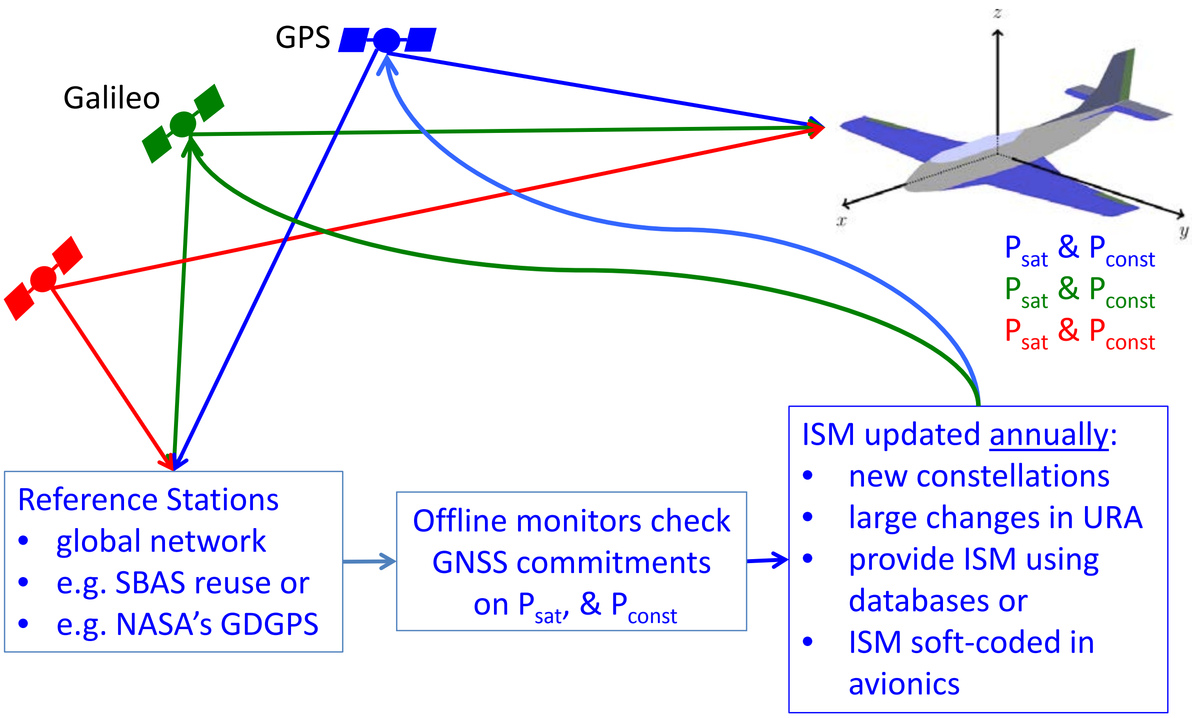


Figure 5: Horizontal ARAIM

Table 2 shows that misbalanced values of $\{P_{sat}, P_{const}\}$ do not eviscerate the availability benefit of two constellations over one. Table 2 uses the following notation $\{P_{sat}, P_{const}\}$ = $\{10^{-5}, 10^{-8}\}$, which means that $P_{sat} = 10^{-5}$ and $P_{const} = 10^{-8}$. Table 2 is also based on L1/E1 use only. It assumes a mask angle of 5^{o} and a URA/SISA of 2.5 meters. It gives the coverage of 99.5% availability. As shown, the time availability of RNP 0.1 and RNP 0.3 operations is weak when only GPS is used and the GPS constellation is either depleted or baseline. These availabilities climb to 100% when GPS and Galileo are used together, and these strong results hold whether P_{const} for Galileo is 10^{-8} or 10^{-4}. Thus, H-ARAIM benefits from dual constellation when one of the constellations is already strong. This implies that early adoption of H-ARAIM could come even in the case where the initial performance commitments are conservative for Galileo.

Table 2: Coverage of 99.5% Available RNP 0.1 and RNP 0.3 Support from Horizontal ARAIM

Operation	Constellation $\{P_{sat}, P_{const}\}$	GPS Only $\{10^{-5}, 10^{-8}\}$	Balanced GPS + Galileo Both: $\{10^{-5}, 10^{-8}\}$	Unbalanced GPS: $\{10^{-5}, 10^{-8}\}$ Galileo: $\{10^{-5}, 10^{-4}\}$
RNP 0.1	Depleted: 23 SVs	1.0%	100%	100%
	Baseline: 24 SVs	29.4%	100%	100%
	Optimistic: 27 SVs	65.8%	100%	100%
RNP 0.3	Depleted: 23 SVs	57%	100%	100%
	Baseline: 24 SVs	94.4%	100%	100%
	Optimistic: 27 SVs	100%	100%	100%

4.3 Dual Frequency ARAIM for Arctic Navigation

As the northern ice retreats, transportation in the Arctic grows to serve energy exploration, shorter shipping routes (especially in the summer), and tourism. This increase requires significant improvements in ice navigation. Figure 6 is an ice image and shows a current challenge to Arctic transportation. The field of view is dominated by one-year ice, and shows two possible ship tracks through this ice field. The top track takes advantage of a crack in the ice that is either natural or created by an icebreaker or previous ship. So advantaged, the ship can make the indicated journey of 60 nautical miles (nm) in 5 hours. The bottom track shows the journey of a ship without such benefit, and this ship requires 10 hours to travel the same distance.

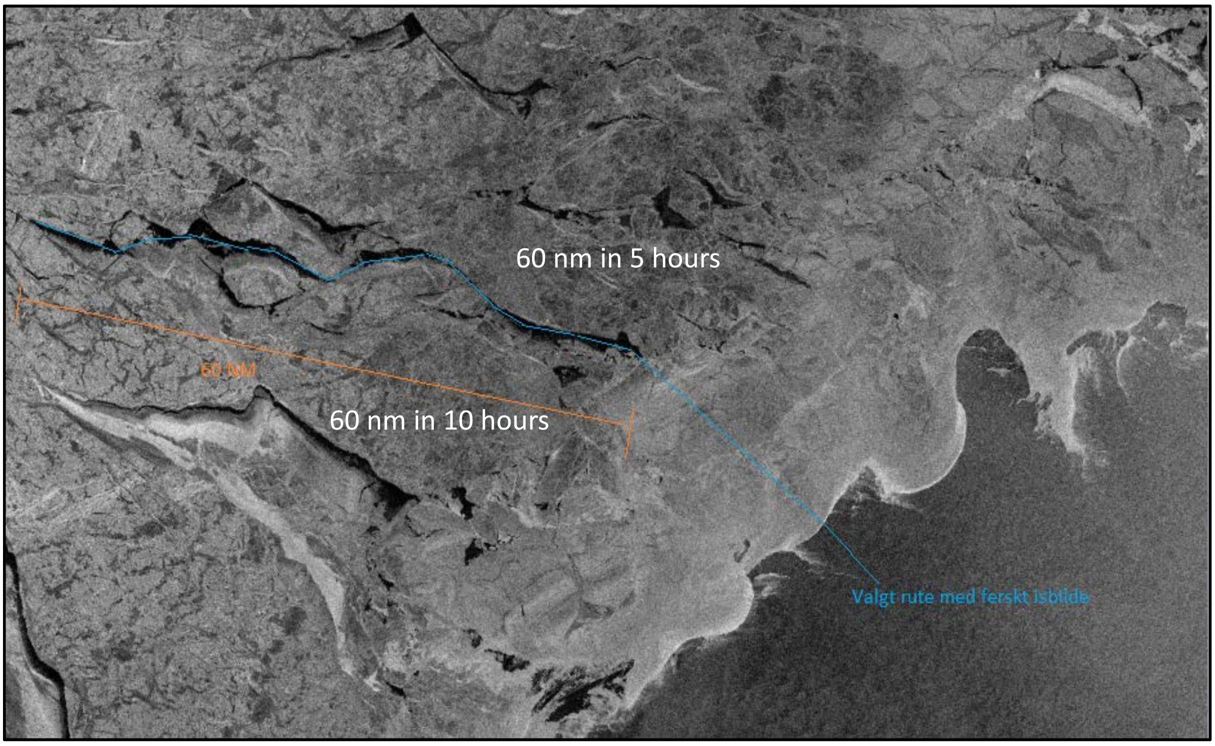


Figure 6: An Example of Ice Navigation

High integrity navigation is required to find the above-described routes or conduct other critical operations, especially at night or in foul weather. The reader is referred to [RD-79] for a broad description of the increasing criticality of Arctic navigation and a sharp description of SBAS shortcomings in this regard.

Unfortunately, SBAS does not reach the Arctic because geostationary satellites appear below the ship's horizon and any one SBAS does not monitor all of the satellites in view of an Arctic ship. Professor Kjerstad [RD-79] reports that the EGNOS geostationary signal is often lost when crossing the Barents Sea and is certainly lost in the Kara Sea. In fact, Figure 7 is a polar map that shows the joint coverage of single frequency WAAS, EGNOS, and MSAS. As shown, little SBAS coverage exists above the Arctic Circle. In fact, the horizontal protection levels (HPLs) offered in the Arctic are poor; greater than 25 m. Figure 8 shows the joint coverage from these three if dual frequency is used. As shown, coverage improves, but is still limited by the coverage footprint of geostationary satellites.

Figure 9 predicts the coverage that would be provided by dual frequency ARAIM when the underlying constellations are GPS and Galileo. This analysis also assumes 24 GPS satellites and 30 Galileo satellites. As shown, coverage improves dramatically relative to

Figures 6 and 7 because ARAIM does not need the geostationary satellites given that the ISM is provided by the core constellations themselves. In addition, ARAIM enjoys excellent geometry for horizontal navigation at the poles, especially when GPS and Galileo are used together.

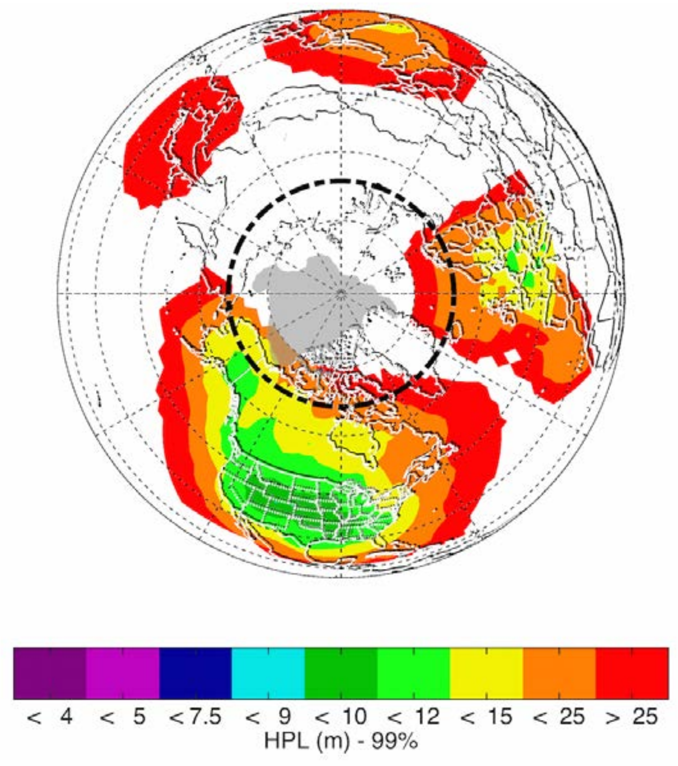


Figure 7: HPL for the Arctic Region Based on GPS L1 Augmented by WAAS + EGNOS + MSAS

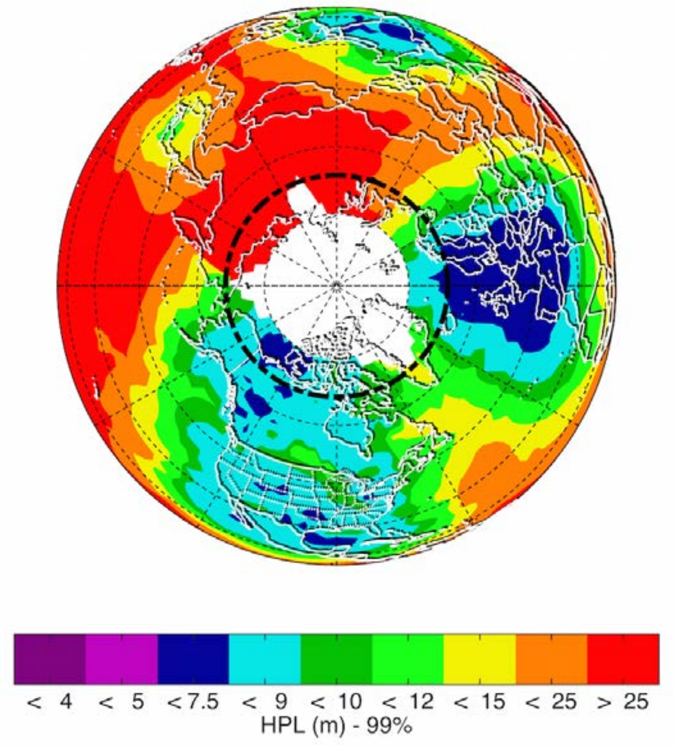


Figure 8: HPL for the Arctic Region Based on Dual Frequency GPS Augmented by WAAS + EGNOS + MSAS

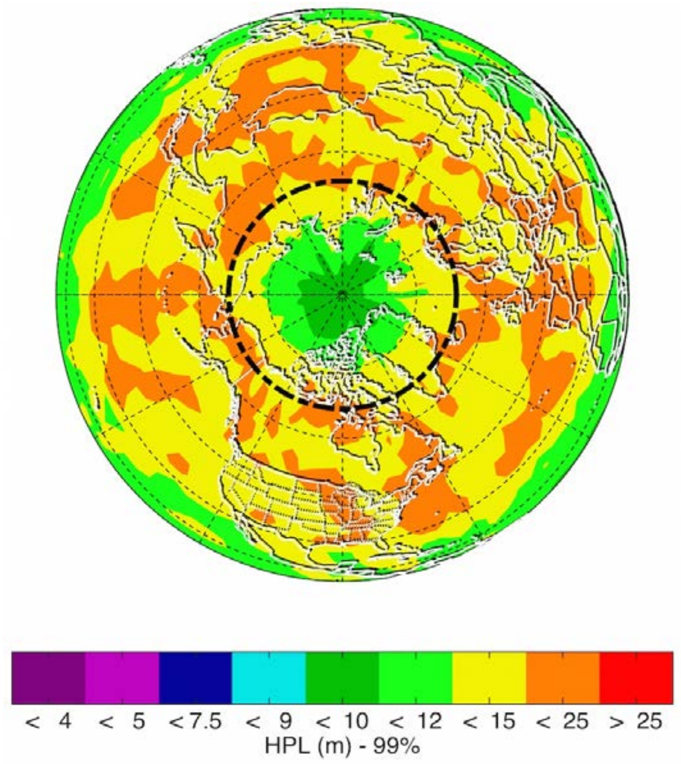


Figure 9: HPL for the Arctic Based on ARAIM with Dual Frequency GPS + Galileo

4.4 Vertical ARAIM to Support Airport Approach Guidance Worldwide Without Geostationary Satellites

The primary goal of the ARAIM Technical Subgroup (ATSG) is to develop an ARAIM system that combines GPS and Galileo to support vertical guidance during airport approach. This vertical ARAIM (V-ARAIM) capability would be worldwide, but would not require any infrastructure at the individual airports. V-ARAIM would bring the safety benefits provided by precision approach relative to non-precision approach (i.e., drive and dive). It would help with the elimination of controlled flight into terrain (CFIT), and this life-saving improvement would be available to all airports worldwide.

To support vertical navigation worldwide, the ATSG has developed two architectures with the hope that one will follow the other to support increasingly low decision heights. Importantly, neither of these architectures requires any geostationary satellites to broadcast the integrity data. ARAIM would also need fewer reference stations for its ground network than SBAS. Moreover, the ARAIM reference stations could be chosen from the set developed to support SBAS. For all of these reasons, ARAIM could significantly reduce a large portion of the SBAS operational budget.

Figure 10 shows the offline phase of V-ARAIM and Figure 11 shows the online phase of V-ARAIM. These two architectures are described in depth in the Milestone 2 Report; hence, no lengthy prose is required here. Rather, we simply summarize the main features of the two phases. Both endeavor to deliver vital support information to the ARAIM algorithm within the avionics. In relation to the online V-ARAIM concept published in the earlier report, an important reduction of the data bandwidth has recently been achieved by the group, opening the possibility to reduce the connectivity risk assigned to this architectural concept. The details on the message can be found in Section 6.3 of this report.

Both figures show the data delivered to the aircraft in the upper right. As shown, Offline V-ARAIM delivers {URA[7], P_{sat}, P_{const}} for each core constellation. Online V-ARAIM supports an additional message type to deliver ephemeris and clock data {ECD} for each constellation so that the total ISM message has {ECD, URA, P_{sat}, P_{const}} for each constellation. Within the core data, URA estimates the quality of the individual pseudo-range measurements; P_{sat} is the *a priori* probability of an individual satellite failure, and P_{const} is the probability of a common mechanism that may cause multiple satellite faults within a constellation. Online V-ARAIM replaces the ephemeris and clock data broadcast by the core constellations. As such, it is more complicated than Offline V-ARAIM. However, it reduces sensitivity to the key constellation parameters {URA, P_{sat}, P_{const}}, and may provide access to lower decision heights. Indeed, Online V-ARAIM may be able to support Category II procedures that have 100-foot decision heights, and this goal is an active research topic.

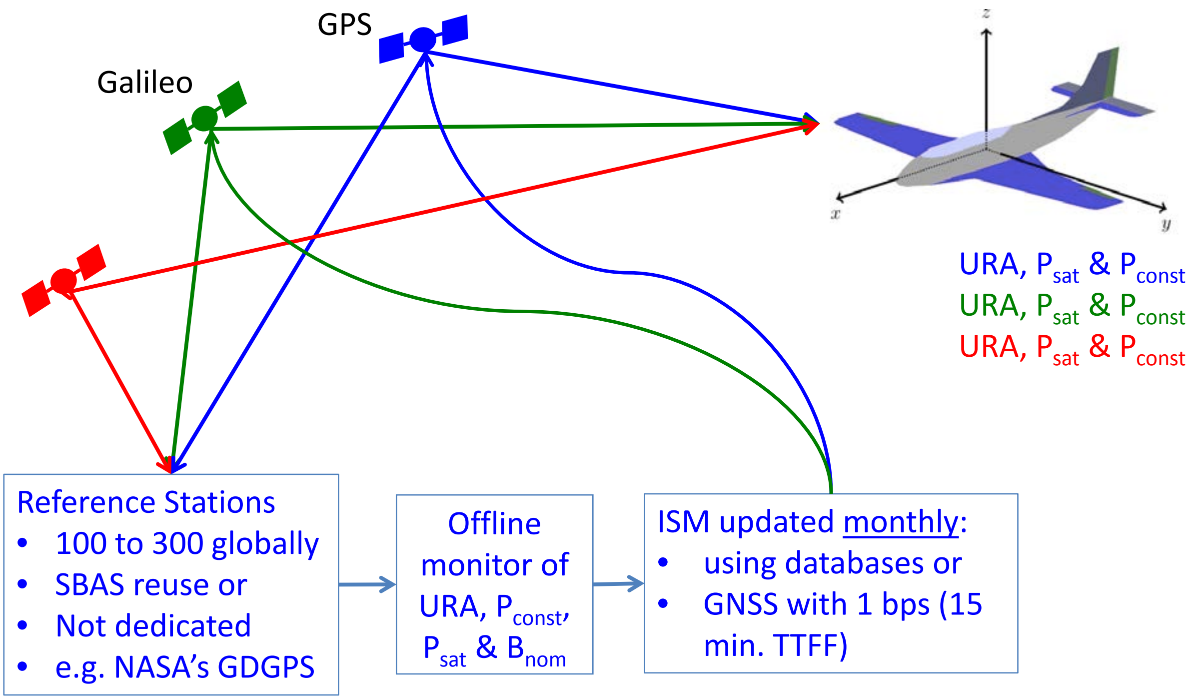


Figure 10: Offline V-ARAIM is based on the Ephemeris & Clock Data (ECD) Broadcast by the Core Constellations

[7] Referred to as Signal in Space Accuracy (SISA) in Galileo

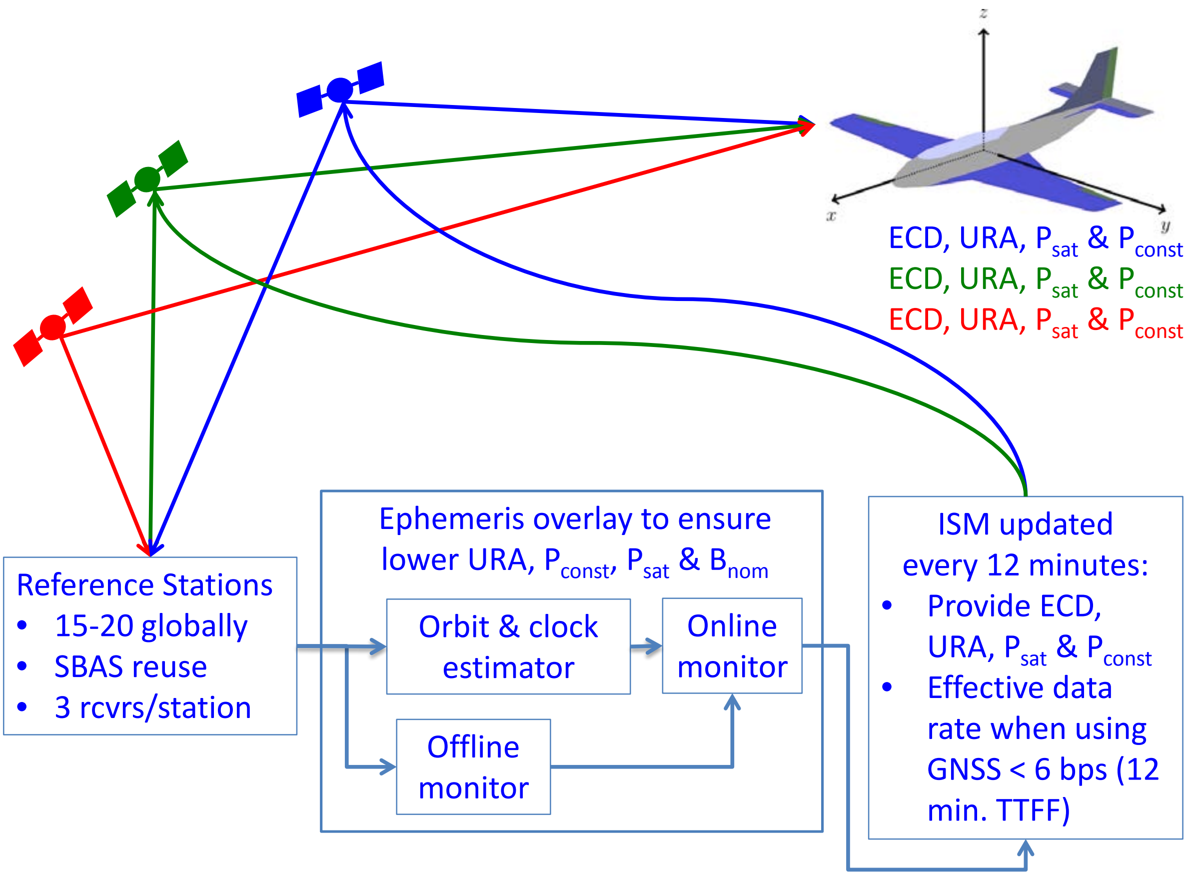


Figure 11: Online V-ARAIM replaces the Ephemeris & Clock (ECD) Generated by the Core Constellations

4.5 ARAIM to Toughen GNSS Receivers

Since many GNSS applications include safety critical applications/infrastructure (i.e., safety-of-life operations, communications, commerce, and finance), the prospect of bad actors increases. These ill-intentioned people would like to deny the GPS service or inject false location information. They include jammers that would deny GNSS service by sending a radio signal that is much more powerful than the weak GNSS signals from medium Earth orbit (MEO). They also include spoofers that send counterfeit GNSS signals that cause the user location to suffer potentially hazardous errors without warning or detection. Today, GNSS jammers are plentiful and GNSS spoofers are increasingly available. These spoofers are often based on repeaters and replay devices that induce erroneous information.

ARAIM may be able to toughen GNSS receivers against jamming and spoofing. Indeed, the GNSS literature contains a variety of applicable techniques (e.g., [RD-91]). Some of these toughening techniques use aircraft antennas that attenuate signals from below the aircraft or near the radio horizon (e.g., [RD-92]). These antennas attenuate the jamming (or spoofing) signals from below the aircraft at the price of attenuating some of the low-lying satellite signals including the SBAS geostationary signals. ARAIM enables this protective shift because it operates with multiple constellations that will populate the higher elevation angles and thus tolerate the loss of satellites on the horizon. In addition, ARAIM does not need to receive the SBAS geostationary satellite signals that will also come from the horizon for aircraft in moderate to high latitudes.

Table 3 shows the impact of toughened antennas on the worldwide coverage of RNP 0.3 based on ARAIM. The table is based on the availability/coverage tool used in Section 5. It is based on the combined use of L1/E1 and L5/E5a, and URA/SISA=2.5 m. Like Table 2, it uses $\{P_{sat}, P_{const}\}=\{10^{-5},10^{-8}\}$ for GPS and $\{10^{-5},10^{-4}\}$ for Galileo. However, Table 4 provides data for two mask angles. Five degrees is the nominal mask angle where the antenna offers no additional attenuation of signals from below the fuselage. Fifteen degrees is the mask angle of an antenna that attenuates signals from below the aircraft by 10 dB or more. With GPS only, the coverage drops from 99.1% to 2.30% for the depleted 23-satellite constellation. It drops from 100% to 2.3% and 19.0% for the baseline 24-satellite constellation and the optimistic 27-satellite constellation, respectively. With GPS plus Galileo, the coverage drops from 100% to 69.3% for the depleted constellations. The coverage does not drop for the baseline and optimistic constellations. All of the coverage percentages mentioned above and captured in the table are for 99% time availability. Of course, these results are speculative and not tied to any specific operational benefits, but they suggest that air navigation based on ARAIM may enjoy some toughening against bad actors. The rationale to choose the criterion of 90% coverage of 99.5% availability is that, in most cases, the maps showed good availability everywhere except in a few isolated points where the availability, while not reaching 99.5%, was still high (there is no strict requirement for coverage: even 10% coverage might be good if a region of interest is inside the area of availability).

Table 3: Worldwide Coverage of RNP0.3 Based on ARAIM and Two Antenna Mask Angles

Constellation(s) state	GPS only Mask = 5°	GPS only Mask = 15°	GPS+Galileo Mask = 5°	GPS+Galileo Mask = 15°
Depleted with 23 satellites	99.1%	0%	100%	69.3%
Baseline with 24 satellites	100.0%	2.3%	100%	100%
Optimistic with 27 satellites	100.0%	19.0%	100%	100%

5 AVAILABILITY RESULTS

The availability of horizontal navigation from ARAIM for the two levels of service (RNP 0.1, RNP 0.3) with the satellite ranging integrity bounds set to 2.5 m was evaluated in [RD-74]. Here, we evaluate the robustness of H-ARAIM service with regard to signal-in-space error (URA). In particular, we wish to find the boundary conditions for an H-ARAIM service. For this purpose, the URAs chosen for the availability simulations go from 2.5 m to a conservative upper bound of 10 m.

The availability analyses conducted here and in [RD-54] rely on assumptions that have not been fully addressed. These include assumptions on the constellation configurations for GPS and Galileo and ISM content quality. In addition, we assumed:

- a mask angle of 5 degrees for signals in both L1 and L5, which is in line with observations from airborne receivers;
- that the effect of ionospheric scintillation in high latitudes and equatorial latitudes was negligible; and,
- that faults had a negligible impact on the loss of continuity. This assumption, and more generally the analysis of continuity, will need to be revisited [RD-75] and refined in future analyses.

These aspects, in addition to the validation of the assumptions made here, (e.g., LPV 200 interpretation, $\sigma_{continuity}$ /$\sigma_{integrity}$) and detailed in [RD-54], will need to be addressed in future ARAIM related work.

5.1 ISM Parameter Settings

In H-ARAIM the ISM parameters shall be set to values that are expected to be safe for use for the foreseeable future. The range of parameters chosen here is meant to be a very conservative estimate of both the expected CSP commitments and the actual performance. Below, we describe each ISM parameter setting [RD-74].

5.1.1 Nominal User Pseudorange Errors

For each pseudorange, the nominal error has two characterizations: a conservative one used for integrity purposes and a less conservative one used for accuracy and continuity purposes [RD-54]. Each of those is described by a Gaussian distribution and a maximum bias. The nominal pseudorange error includes the effect of the residual tropospheric error, code noise and multipath, and the effect of the nominal signal-in-space error (which includes the nominal clock/ephemeris error and the nominal signal deformation). For the single frequency case, it also includes the effect of the ionospheric delay error. All details on error models for the single and dual frequency measurements are described in [RD-74].

The signal-in-space error (σ_{URE}) is characterized by the URA (SISA for Galileo) and the URE (SISE for Galileo) [RD-54]. The URA/SISA is used for integrity purposes.

The maximum value for URA/SISA was set to 10 m.

The URE/SISE, which is used for accuracy and continuity purposes, was set to be two thirds of the URA/SISA. The URE/SISE is not safety critical, therefore it will require a less conservative value than the URA/SISA. The choice of two thirds, while arbitrary, is representative of what can be expected [RD-54].

The maximum nominal bias for integrity purposes (b_{nom}) was kept at 0.75 m, and at 0 for accuracy purposes.

5.1.1 Satellite Fault and Constellation Fault Probabilities (P_{sat} and P_{const})

The probability of a satellite being in a faulted state at a given time, P_{sat}, was set at 10^{-5}. This is the value that is currently assumed by GPS RAIM receivers (which provide the same levels of service that H-ARAIM targets). It is also supported by GPS service history [RD-54] and partially supported by the GPS performance commitments [RD-70]. These commitments specify a fault rate of 10^{-5} per hour per satellite and faults are typically resolved within 15 minutes. For newer constellations, P_{sat} might need to be set higher. However, previous simulation studies have found that it did not change availability results substantially whether we use 10^{-5} or 10^{-4} for either narrow or wide faults [RD-54].

The probability that there are two or more faulted satellites in view of the user from one constellation (P_{const}) was set at 0 for the single constellation results (Annex B). This is the value that is currently being assumed in GPS RAIM. As for P_{sat}, this value cannot be automatically extended to newer constellations. For the dual constellation results, P_{const} was set at 0 for GPS and 10^{-4} for Galileo (see Annex B) to account for this uncertainty.

Small values for P_{sat} and P_{const} require years of observation. When establishing both failure probabilities, the statistics should not aggregate data over intervals when there were major system level upgrades, in particular at the Ground Segment level (that are possibly transparent to the user), took place. Considering limited observability, data logging is fully necessary but not sufficient by itself: both need to rely as well on performance commitments. Therefore, at the beginning of dual frequency multi-constellation (DFMC) H-ARAIM, P_{sat} and P_{const} might initially be large.

The values for P_{sat} and P_{const} discussed in this paragraph are for H-ARAIM only. The values for V-ARAIM may need to be set higher (especially P_{const}) than for H-ARAIM.

5.2 Constellation Configuration

Three constellation scenarios were considered (Table 4). They are meant to represent three situations: a baseline configuration, a depleted configuration, and an optimistic configuration. The ‘baseline’ uses a reference almanac for each constellation. For GPS, it is the 24-slot nominal constellation described in [RD-70]. For Galileo, it is a Walker 24/3/1 [RD-59]. In the ‘depleted’ configuration, one arbitrarily chosen satellite has been removed from the baseline in each constellation. For the ‘optimistic’ configuration, both constellations have 27 satellites. The ‘optimistic’ GPS constellation was obtained by removing three satellites from an actual almanac (with 30 satellites flagged healthy) so that the expandable slots are filled. The ‘optimistic’ Galileo constellation takes into account the planned replenishment strategy (which is meant to ensure that the 24 main slots are filled with healthy satellites) [RD-59]. It represents a hypothetical case where three in orbit spares would be transmitting from optimal positions, one in each three orbital plane. While the optimistic GPS constellation is well within what is expected for GPS (as service history shows), the optimistic Galileo constellation might be less probable.

Table 4: Constellation Configurations

Constellation	Dual Constellation	Single Constellation	
		GPS	**Galileo**
Depleted	GPS 24-1, Galileo 24-1	GPS 24-1	Galileo 24-1
Baseline	GPS 24, Galileo 24	GPS 24	Galileo 24
Optimistic	GPS 24+3, Galileo 24+3	GPS 24+3	Galileo 24+3

The almanacs can be downloaded from [RD-61]. A user elevation masking angle of 5 degrees was applied to both constellations.

5.3 User Algorithm – Nominal and Availability Criteria

The same reference algorithm used for H-ARAIM is applicable to Offline V-ARAIM [RD-54]. The H-ARAIM user algorithm allocates the full integrity budget to the horizontal mode (see Annex A). The availability criteria for RNP 0.1, and RNP 0.3 used in this report are that the HPL must be below an HAL of 185 m and 556 m, respectively (Annex A).

5.4 Results

Users were simulated on a 5 by 5 degree grid, for a period of 10 sidereal days – the repetition rate of the Galileo constellation – with a time step of 600 s. Then, for each user, the availability (defined as the percentage of time that the availability criteria are met) was computed. Figure 12 shows a map of the availability of RNP 0.1 for the DFMC configuration $P_{const,GAL} = 10^{-4}$, $P_{const,GPS} = 0$, $P_{sat} = 10^{-5}$, and $\sigma_{URA} = 2.5$ m.

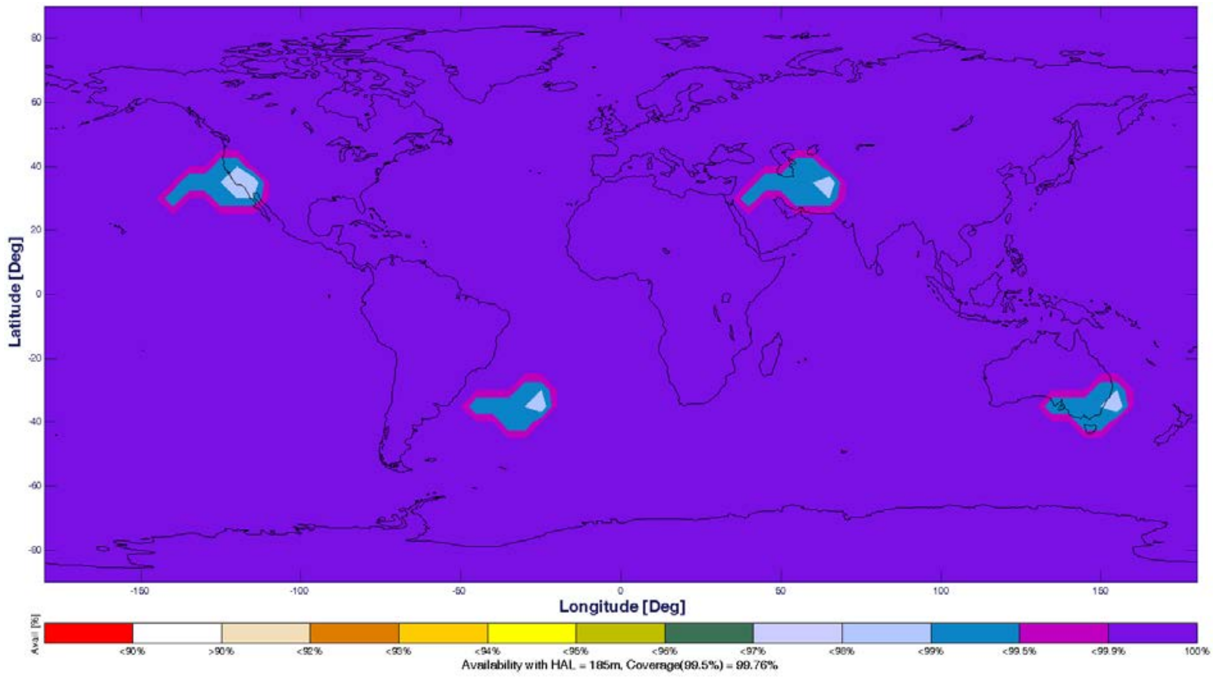


Figure 12: Availability map for the depleted constellation configuration and DFMC H-ARAIM, $P_{const,GAL} = 10^{-4}$, $P_{const,GPS} = 0$, $P_{sat} = 10^{-5}$ and σURA = 2.5 m

The results for all scenarios are summarized as a function of the constellation configuration.

Each of the following tables shows the worldwide coverage of 99.5% availability of RNP 0.1 or RNP 0.3. Here, the coverage is defined as the fraction of the users that have an availability above 99.5%. (Because we use a rectangular grid, each user is weighted by the cosine of the latitude to account for the relative area they represent). Each entry indicates the most stringent level of service and maximum URA/SISA value for which a coverage value shown in brackets of 99.5% availability is achieved.

Notice that in this section a Pconst equal to zero has been used for the Galileo only cases for H-ARAIM (Table 6, Table 9 and Table 12). To be coherent with Assertion 2 (Annex B), those scenarios represent the situation where already operational experience with the Galileo constellation has been gained, so as to apply the ‘similarity’ argument as done for GPS Pconst.

The primary mode of H-ARAIM is L1-L5 as it provides the highest performance. Table 5, Table 6, and Table 7 show the boundary conditions for signal-in-space error for dual frequency (DF) H-ARAIM service. As shown in Table 5, RNP 0.1 is always available when both signaling frequencies (L1 and L5) are available and the two constellations are tracked. Moreover, H-ARAIM with a single baseline constellation (GPS or Galileo) supports RNP 0.1 capabilities. Each entry indicates the highest URA for which a 90% coverage of 99.5% availability of the indicated level of service is achieved and illustrates robustness of H-ARAIM as a function of URA/SISA bounds.

Table 5: Estimated maximum URA required to achieve RNP 0.1 and 0.3 for DFMC ($P_{const,GAL} = 10^{-4}$, $P_{const,GPS} = 0$, $P_{sat} = 10^{-5}$)

Constellation/ Required URA	RNP 0.1	RNP 0.3
<Depleted>	9 m	>10 m
<Baseline>	>10 m	>10 m
<Optimistic>	>10 m	>10 m

Table 6: Estimated maximum URA required to achieve RNP 0.1 and 0.3 for DF single constellation (Galileo)

Constellation/ Required URA	RNP 0.1	RNP 0.3
<Depleted>	N/A	N/A
<Baseline>	>10 m	>10 m
<Optimistic>	>10 m	>10 m

Table 7: Estimated maximum URA required to achieve RNP 0.1 and 0.3 for DF single constellation (GPS)

Constellation/ Required URA	RNP 0.1	RNP 0.3
<Depleted>	N/A	4 m
<Baseline>	6 m	>10 m
<Optimistic>	9 m	>10 m

As expected DFMC H-ARAIM provides higher coverage values even for larger values of URA than single constellation DF.

Before the CSPs establish dual frequency service and publish a performance standard, H-ARAIM could be used in single frequency (L1) mode instead of L1-L5. This mode uses ionospheric corrections included in the CSP navigation message. Table 8, Table 9, and Table 10 show the boundary condition for the signal-in-space error for single frequency (L1) H-ARAIM service.

Table 8: Estimated maximum URA required to achieve RNP 0.1 and 0.3 for single frequency (L1) multi-constellation ($P_{const,GAL} = 10^{-4}$, $P_{const,GPS} = 0$, $P_{sat} = 10^{-5}$)

Constellation/ Required URA	RNP 0.1	RNP 0.3
<Depleted>	N/A	>10 m
<Baseline>	>10 m	>10 m
<Optimistic>	>10 m	>10 m

Table 9: Estimated maximum URA required to achieve RNP 0.1 and 0.3 for single frequency (L1) single constellation (Galileo)

Constellation/ Required URA	RNP 0.1	RNP 0.3
<Depleted>	N/A	N/A
<Baseline>	N/A	>10 m
<Optimistic>	N/A	>10 m

Table 10: Estimated maximum URA required to achieve RNP 0.1 and 0.3 for single frequency (L1) single constellation (GPS)

Constellation/ Required URA	RNP 0.1	RNP 0.3
<Depleted>	N/A	N/A
<Baseline>	N/A	>10 m
<Optimistic>	N/A	>10 m

Given the current levels of URA for GPS and the expected SISA for Galileo, there is a low risk that the ranging accuracy required for H-ARAIM target service availability may not be guaranteed by the SPCs. Even if the new constellations did not achieve the performance of the current L1 GPS service, these results show that single frequency multi-constellation H-ARAIM would provide improved availability and robustness compared to single constellation. In the case of Table 8, we do note that with the current GPS constellation (almanac from November 6, 2015) the simulations predict a 97.9% coverage of 99.5% RNP 0.1 availability, which is consistent with current RAIM predictions [RD-76].

In the case of lost measurements at the L1 frequency, the airborne receiver can utilize only L5 H-ARAIM mode. The ionospheric delay error on L5 must be scaled appropriately with respect to errors estimated for L1 single frequency observations [RD-54]. Table 11, Table 12, and Table 13 show the boundary conditions for signal-in-space error and single frequency (L5) H-ARAIM service. Single frequency L5 H-ARAIM mode provides robust RNP 0.3 service assuming that a sufficient number of satellites broadcast signals on the L5 frequency.

Table 11: Estimated maximum URA required to achieve RNP 0.1 and 0.3 for single frequency (L5) multi-constellation ($P_{const} = 10^{-4}$)

Constellation/ Required URA	RNP 0.1	RNP 0.3
<Depleted>	N/A	>10 m
<Baseline>	N/A	>10 m
<Optimistic>	N/A	>10 m

Table 12: Estimated maximum URA required to achieve RNP 0.1 and 0.3 for single frequency (L5) single constellation (Galileo)

Constellation/ Required URA	RNP 0.1	RNP 0.3

<Depleted>	N/A	N/A
<Baseline>	N/A	>10 m
<Optimistic>	N/A	>10 m

Table 13: Estimated maximum URA required to achieve RNP 0.1 and 0.3 for single frequency (L5) single constellation (GPS)

Constellation/ Required URA	RNP 0.1	RNP 0.3
<Depleted>	N/A	N/A
<Baseline>	N/A	2.5 m
<Optimistic>	N/A	>10 m

These results (Table 11 to Table 13) show the robustness of H-ARAIM service. H-ARAIM supports RNP 0.1 under all normal conditions and reverts to RNP 0.3 when the L1 signal has been lost. Figure 13 provides an overview for the averaged HPL values and baseline constellation configuration.

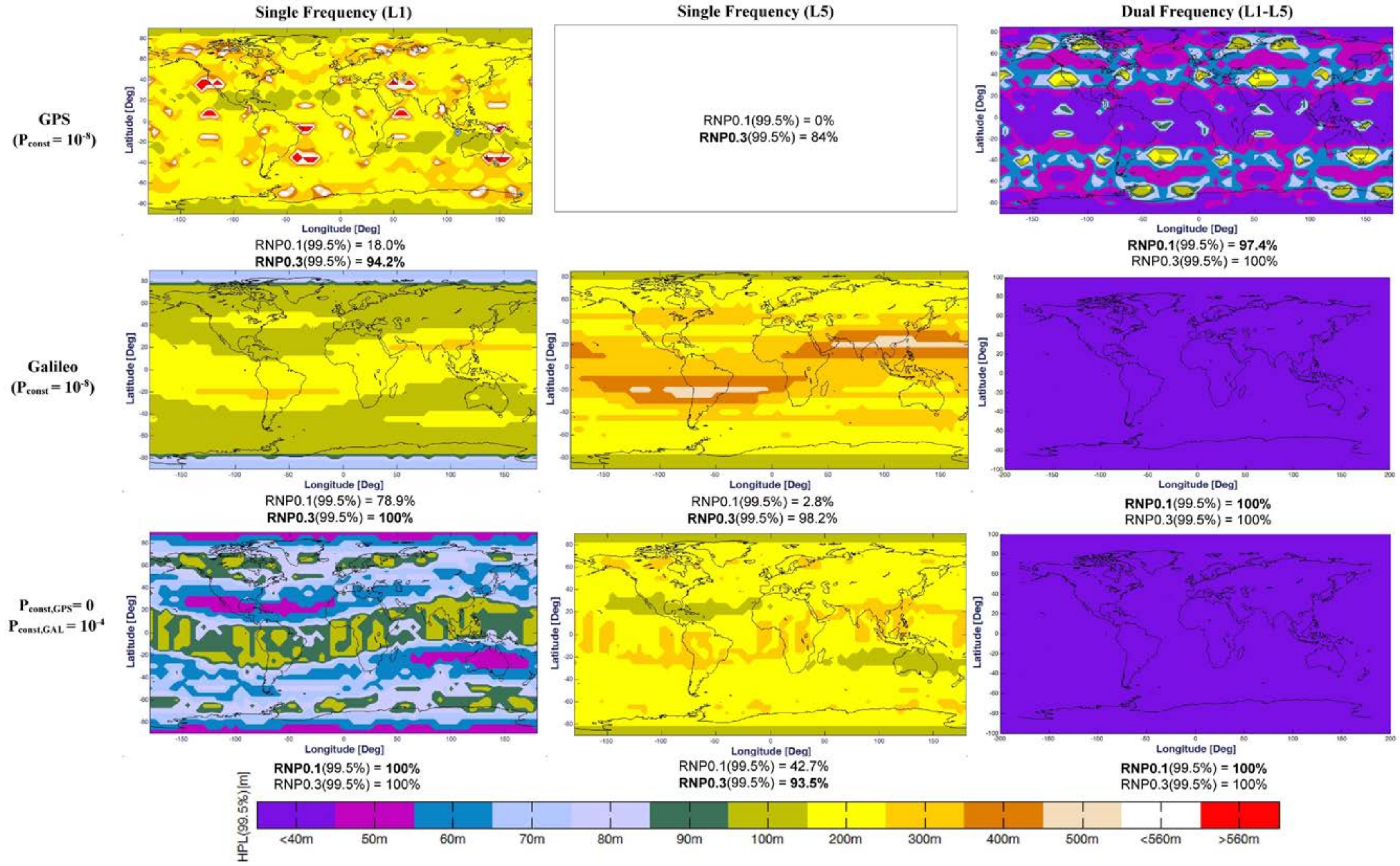


Figure 13: HPL(m)-99.5% map for the baseline constellation configuration with $P_{sat} = 10^{-5}$,$b_{nom} = 0.75$ m and $\sigma_{URA} = 2.5$ m

6 MESSAGE TYPES FOR ARAIM

6.1 Modes and Messages for Horizontal ARAIM

6.1.1 Introduction

The horizontal ARAIM architecture is an extension of today's RAIM architecture [RD-46], [RD-70]. It adds four elements: Multiple constellations, dual-frequency, a deeper threat analysis, and the possibility to update the ISM. The ISM parameters are based upon CSP commitments and observational history. An updatable ISM allows the performance to adapt to the changing GNSS environment. In particular, it will allow ANSPs to include new constellations as they become available, and to improve the ISM parameters as they establish a history of good performance.

6.1.2 Horizontal ARAIM ISM Content

The ISM elements described in this section are common to both the horizontal-only architecture and to the offline vertical architecture.

6.1.2.1 Horizontal ISM Header Content

Satellite mask: The satellite mask is similar in format to the SBAS Message Type 1 satellite mask [RD-10], but updated to include all constellations. Each bit corresponds to a specific PRN number in a specific constellation. Setting a bit to 1 indicates that the satellite will have parameters included in the core of the ISM message. If a bit is set to 0, then there is no information provided for that satellite and it should not be used for ARAIM in that ANSP's airspace.

Time of applicability: The time of applicability includes a week number and a time of week. This value indicates a start time for when the information may be used. It will likely be set to the approximate time of creation for the ISM or for the time that the data was disseminated. Later time tags should preempt any earlier information, and any earlier ISM data should be discarded. A variant that may be considered is that ISM data could have a finite window of effectiveness and that any data older than a certain threshold can also be discarded. This would ensure that the user maintains the most current information.

ANSP ID: There is an identification number for the specific ANSP, which may be national, regional, or global. This number could be matched to the air-route or approach and gives the ANSP the ability to decide which ISM is used in its airspace.

Criticality: This flag indicates whether these parameters may be used for more precise or vertical guidance. If this bit is set to 0 then the parameters may only be used to support horizontal guidance. If the bit is set to 1 then the data may be used to support either horizontal-only guidance or horizontal and vertical guidance. Because there is a difference in the risk level for these operations, it is possible that horizontal-only operations may be supported with somewhat less conservative ISM parameters. It is still to be decided whether ARAIM should support simultaneous but separate horizontal and vertical ISMs or whether a single ISM with criticality set to 1 is sufficient for all operations.

6.1.2.2 Horizontal ISM Core Content

The core horizontal ISM data contains parameters specific to each constellation and satellite.

P_{const}: For each constellation included in the satellite mask, there is a parameter specifying the value for P_{const}.

P_{sat} : For each satellite included in the satellite mask, there is a parameter specifying the value for P_{sat}.

α_{URA}: This value multiplies the broadcast *URA/SISA* value from the satellite to determine the overbounding integrity sigma to be input to the user algorithm. α_{URA} allows the ANSP to increase the overbounding sigma term used in the protection level computation, σ_{URA}.

α_{URE}: This value multiplies the broadcast *URA/SISA* value from the satellite to determine the accuracy/continuity sigma to be input to the user algorithm. α_{URE} allows the ANSP to set the sigma term used to describe the expected accuracy of the ranging signal, σ_{URE}.

b_{nom}: allows the ANSP to specify the overbounding nominal bias term used in the protection level computation.

6.1.3 Legacy RAIM ISM Values

Legacy RAIM provides default ISM values for GPS. These are the values that RAIM assumes currently for GPS, and that are expected to be valid in the future (Table 14).

Table 14: Default Message Content

Criticality	$P_{const,GPS}$	$P_{sat,GPS}$	$\alpha_{URA,GPS}$	$\alpha_{URE,GPS}$	$b_{nom,GPS}$
0	0	10^{-5}	1	1	0

Other constellations have yet to publish performance commitments and establish a similar history of operation. It is anticipated that, at least initially, larger values may be needed for at least P_{const}, P_{sat}, and α.

6.1.4 Optimized ISM for Offline ARAIM

This section presents two offline approaches: one where all of the ISM content is contained in a single message, and another where each message contains only the ISM content for one constellation. The former is more compact and requires lower bandwidth. The latter provides more flexibility if there is a need to have different values apply to different satellites within each constellation.

All ISM content values are preliminary. Only GPS has been well characterized so the range of values needed for the other constellations may not be well represented by the tentative values proposed here. The specific values may need to be updated, but the overall message format should still be valid.

6.1.4.1 Offline ARAIM ISM in a Single Message (ARAIM Message Type 1A)

First we look at putting all ISM values in a single 250-300 bit message (ARAIM Message Type 1A; see Table 15). For example, an SBAS message has either 212 data bits available for L1 or 214 available for L5. Our proposed message requires 211 data bits. A specific SBAS message type could be designated for the ARAIM ISM. This message would then use 27 header bytes to specify the time the message was either created or should start being used. Users should then use the latest version that is before the current time. There is also information to specify the specific ANSP. Each country would have its own unique ID number and there could be numbers to specify regions or the entire globe. Finally, the header includes a criticality indicator, which would let the user know if the values may be used for horizontal guidance only (0) or may be used for both horizontal and vertical guidance (1). An ANSP may send two ISMs one optimized for horizontal only and one optimized for vertical (but that would also support horizontal). The user can elect which one to use when not in a precision flight mode.

The rest of the message contains specific values for each of four constellations. The ISM parameters are contained in a set of 46 bits specific to each constellation. The first set of 46 bits is for GPS, the next set for GLONASS, then Galileo, and finally for Beidou. Within the constellation specific set is a mask used to indicate whether a satellite may be used (1) or not (0). The mask contains 32 bits and may therefore indicate usage of up to 32 satellites per constellation. If an ANSP does not wish aircraft to use a specific constellation, all mask bits for that constellation would be set to zero.

The remaining 12 bits are used to indicate the values for P_{const}, P_{sat}, α_{URA}, α_{URE}, and b_{nom} for the constellation. The same set of values applies to all allowed satellites within a constellation. However, different values may be used for different constellations.

Table 15: Offline ISM Parameters for Single Message – ARAIM ISM Type 1A

	Parameter	Description	Value	Size (bits)
Data Header	ISM_WN	ISM Week Number	[0, 1, … 1023]	10
	ISM_TOW	ISM Time of Week (hours)	[0, 1, … 167]	8
	ANSP ID	Service Provider Identification	[0, 1, … 255]	8
	Criticality	Usable for Precise/Vertical?	[0, 1]	1
	Total Header = 27 bits			
Per Constellation Parameters	$Mask_i$	32 bits indicating whether an SV is valid for ARAIM (1) or not (0)	$[m_1, m_2, \dots m_{32}]$	32
	$P_{const,i}$	Probability of constellation fault at a given time	$[10^{-8}, 10^{-5}, 10^{-4}, 10^{-3}]$	2
	$P_{sat,j}$	Probability of satellite fault at a given time	$[10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}]$	2
	$\alpha_{URA,j}$	Multiplier of the URA for integrity	[1, 1.25, 1.5, 2, 2.5, 3, 5, 10]	3
	$\alpha_{URE,j}$	Multiplier of the URA for continuity & accuracy	[0.25, 0.5, 0.75, 1, 1.25, 1.5, 2, 4]	3
	$b_{nom,j}$	Nominal bias term in meters	[0.0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 3, 4, 5, 7.5, 10]	4
	Total Core = 46 bits x 4 Constellations = 184 bits			

6.1.4.2 Offline ARAIM ISM in One Message per Constellation (ARAIM Message Type 1B)

Instead of trying to describe all satellites within a single constellation by the same set of parameters, satellites may be grouped and different sets of parameters would apply to different sets of satellites within a constellation (Message Type 1B; see Table 16). For example, satellites could be grouped by block, by age, by clock type, or by some combination of all of those characteristics. This message allows up to six different groupings to be defined. These are specified by a three-bit grouping indicator with values between 0 and 6 (0 indicates not to use the satellite at all).

Table 16: Offline ISM Parameters for one SBAS Message per Constellation – ARAIM ISM Type 1B

	Parameter	Description	Value	Size (bits)
Data Header	ISM_WN	ISM Week Number	[0, 1, … 1023]	10
	ISM_TOW	ISM Time of Week (hours)	[0, 1, … 167]	8
	ANSP ID	Service Provider Identification	[0, 1, … 255]	8
	Criticality	Usable for Precise/Vertical?	[0, 1]	1
	Constellation	Specify constellation described	[GPS, GLONASS, Galileo, Beidou]	2
	$Mask_i$	3 bits for each of 32 SVs indicating SV grouping (0 is do not use, otherwise m_i provides the group number that the SV belongs to)	[m_1, m_2, … m_{32}]	3 x 32
	Total Header = 125 bits			
Per Satellite Group Parameters	$P_{const,i}$	Probability of constellation fault at a given time	[10^{-8}, 10^{-5}, 10^{-4}, 10^{-3}]	2
	$P_{sat,j}$	Probability of satellite fault at a given time	[10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}]	2
	$\alpha_{URA,j}$	Multiplier of the URA for integrity	[1, 1.25, 1.5, 2, 2.5, 3, 5, 10]	3
	$\alpha_{URE,j}$	Multiplier of the URA for continuity & accuracy	[0.25, 0.5, 0.75, 1, 1.25, 1.5, 2, 4]	3
	$b_{nom,j}$	Nominal bias term in meters	[0.0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 3, 4, 5, 7.5, 10]	4
	Total Core = 14 bits x 6 Groups = 84 bits			

The following example, using GPS, details the implementation of the *Mask* field of the data header described above:

Currently GPS consists of IIR, IIR-M and IIF satellites; it previously contained IIA satellites and will soon include Block III satellites. Let us imagine that we have decided to assign IIR to group 1, IIR-M to group 2, IIF RB to group 3 and IIF CS to group 4. Using the Table 17 below, taken from the Navigation Center website [RD-93], PRNs 1,3,6, etc are IIF RBs, PRN 2 is a IIR, PRN4 is not active, PRN 5 is a IIR-M etc. so the mask numbers would be 3, 1, 3, 0, 2, 3, …

Anything with a mask value of 1 will be described by the parameters in the first group; anything with a 2 in the second group, etc. Anything with a 0 is not described as it does not exist or should not be used.

Table 17: Example for mask groups using GPS constellation from [RD-93]

Plane	Slot	SVN	PRN	Block-Type	Clock
D	2	63	1	IIF	RB
D	1	61	2	IIR	RB
E	1	69	3	IIF	RB
E	3	50	5	IIR-M	RB
D	4	67	6	IIF	RB
A	4	48	7	IIR-M	RB
C	3	72	8	IIF	CS
F	3	68	9	IIF	RB
E	6	73	10	IIF	RB
D	5	46	11	IIR	RB
B	4	58	12	IIR-M	RB
F	6	43	13	IIR	RB
F	1	41	14	IIR	RB
F	2	55	15	IIR-M	RB
B	1	56	16	IIR	RB
C	4	53	17	IIR-M	RB
E	4	54	18	IIR	RB
C	5	59	19	IIR	RB
B	6	51	20	IIR	RB
D	3	45	21	IIR	RB
E	2	47	22	IIR	RB
F	4	60	23	IIR	RB
A	1	65	24	IIF	CS
B	2	62	25	IIF	RB

B	5	71	26	IIF	RB
C	2	66	27	IIF	RB
B	3	44	28	IIR	RB
C	1	57	29	IIR-M	RB
A	3	64	30	IIF	RB
A	2	52	31	IIR-M	RB
F	5	70	32	IIF	RB

6.1.4.3 GPS CNAV messages

These data formats can easily also be broadcast through GPS CNAV messages. CNAV messages are 300 bits each and have 238 bits of usable data for the ISM. The addition 26 bits could be put to use to expand the range of some of the described variables or they could be left as reserved to keep the formats identical to other data channels.

6.2 Messages for Offline V-ARAIM

The V-ARAIM message structure is deliberately kept identical to the H-ARAIM message structure. This approach is designed to permit a smooth transition from H-ARAIM-only operation to the inclusion of V-ARAIM. The user algorithm and ISM parameters are the same for both although the specific parameter values will likely change due to the higher criticality of the impact of loss of integrity for vertically guided operations. The message contents have already been described above. The header contains a specific bit to indicate whether the message is intended to support horizontal-only or horizontal and vertical operations. The same format should be used for V-ARAIM to ensure consistency on how the required parameters are transmitted to the user.

6.2.1 Default Message

Unlike H-ARAIM, it is not yet possible to specify any default values for the V-ARAIM parameter values. Extensive evaluation of the iono-free ranging performance of the two constellations needs to take place. Further, the civil aviation authorities need to determine acceptable methodologies for determining and setting these parameters. Larger values for α, P_{sat}, and P_{const} are possible or even likely.

6.2.2 User Algorithm

The reference algorithm described in Annex A can be used for H-ARAIM and offline V-ARAIM (although in H-ARAIM, only the HPL needs to be computed). There are some differences in the allocation of the integrity budget between horizontal and vertical modes, but otherwise the same algorithms may be used for each.

6.3 Messages for Online V-ARAIM

The work presented in this chapter regarding efficient formatting of Online V-ARAIM ISM data and possible dissemination means through core constellations is the result of R&D

level work and does not preclude any implementation decisions regarding the ARAIM concept, nor does it address wider system relevant aspects.

The proposed principle follows that of the established SBAS, which provides correction data to the broadcast GNSS navigation message. The ARAIM Ground Segment derives the on-board clock state and orbital positions independently with respect to the broadcast GNSS navigation messages, but only the correction data is disseminated by the ISM.

It is to be noted that the following conceptual differences apply to the Online V-ARAIM case compared to H-ARAIM or Offline V-ARAIM, making it necessary to specify a dedicated Online V-ARAIM message type.

- *Dissemination of correction data* to be applied to the nominal broadcast ephemeris and clock data provided by the core constellation. Dedicated fields are foreseen for these message elements. The dissemination of correction data allows for
    - Lower narrow fault probability (P_{sat}) and lower wide fault probability (P_{const})
    - Lower error bounds (σ_{URE} , σ_{URA}) and lower biases bound (b_{nom})
- *Provision of absolute error bounds for integrity and continuity* rather than scaling factors to be applied to the core constellation URA/SISA values. The advantages include establishing core-constellation independent and lower error bounds with optimized formatting for integrity and continuity leading finally to guaranteed availability
- *Individualized integrity data per satellite* rather than global integrity data per group of satellites or per constellation thus allowing for
    - Lower narrow fault probability (P_{sat})
    - Lower error bounds (σ_{URE} , σ_{URA}) and lower biases bound (b_{nom})

6.3.1 Online V-ARAIM Message Type

The following table presents a possible default Message Type for Online V-ARAIM. Justification aspects for the parameter selection, their range and identified granularity are provided in Annex C. The message is expected to be updated every 12-15 minutes and refreshed within this time in order to ensure sufficiently lower Time-to-First-Operations (compared to the 12-15 min update rate). Its detailed content is explained in Table 17:

Table 18: Possible default Message Type for Online V-ARAIM

DATA	BITS	SCALING FACTOR	MAXIMUM RANGE
Satellite ID	6	N/A	[0 … 63]
Navigation message IOD	10	N/A	[0 … 1023]
ISM SOA (SOA: Start Of Applicability)	11	60 [s]	[0 … 1 day]

Constellation	2	N/A	[0, 1, 2, 3]
SUBTOTAL	**29**		
Psat{sat}	3	N/A [Index=Value]	[0=3.00; 1=3.50; 2=4.00; 3=4.50; 4=5.00; 5=5.50; 6=6.00; 7=6.50; 8=DON'T USE] Note 1: Negative exponent of 10.
Sigma_int {sat}	3	N/A [Index=Value]	[0=0.30; 1=0.40; 2=0.50; 3=0.60; 4=0.70; 5=0.90; 6=1.10; 7=1.50] [m].
Sigma_cont {sat}	3	N/A [Index=Value]	[0=0.20; 1=0.25; 2=0.35; 3=0.40; 4=0.50; 5=0.60; 6=0.75; 7=1.00] [m].
Bias_int {sat}	3	N/A [Index=Value]	[0=0.00; 1=0.10; 2=0.20; 3=0.30; 4=0.40; 5=0.50; 6=0.75; 7=1.00; 8=1.25] [m].
SUBTOTAL	**12**		
Along Track Error (at SOA)	09	0.2496 [m]	[-63.8976, +63.6480] [m]
Across Track Error (at SOA)	08	0.2496 [m]	[-31.9488, +31.6992] [m]
Common Error (at SOA)	12	0.0312 [m]	[-63.8976, +63.8664] [m]
Distance Error (at SOA)	5	0.0312 [m]	[-00.4992, +00.4680] [m]
Along Track Error Rate (at SOA)	06	0.000346666 [m/s]	[-0.011093333, +0.010746666] [m/s]
Across Track Error Rate (at SOA)	05	0.000346666 [m/s]	[-0.011093333, +0.010746666] [m/s]
Common Error Rate (at SOA)	11	0.000043333 [m/s]	[-0.044373333, +0.044333333] [m/s]
Distance Error Rate (at SOA)	03	0.000043333 [m/s]	[-0.000173333, +0.000130000] [m/s]
SUBTOTAL	**59**		
TOTAL	**100**		

Notes:

1. P_{const} is not required within the Online V-ARAIM Message Type as it can be reduced by design to 10^{-8}.
2. The worst range quantization error due to Message Type 2 format is 4 cm (worst projection on the satellite coverage area at any time between nominal updates).

Table 18 shows how the ARAIM ISM data of Type 2 could fit into a Galileo I/NAV word type.

Table 19: Word Type 16: ARAIM ISM Type 2 - Satellite Specific Data for Online V-ARAIM

Type=16	ISM Header				ISM Core				Eph/Clock Correction (at SoA)				Eph/Clock Correction Rate (at SoA)				Total [bits]
	SAT-ID	Message IOD	ISM SoA	Const-ID	P_sat	Sigma_int	Sigma_cont	Bias_int	Along Track	Across Track	Common Error	Distance Error	Along Track Error	Across track Error	Common Error	Distance Error	
6	6	10	11	2	3	3	3	3	9	8	12	5	6	5	11	3	100

6.3.2 Dissemination Strategy

The ISM is reconstructed on the user side by aggregating all applicable ARAIM Message Types received through the GNSS core constellation signals. A GNSS core constellation provider may disseminate information only for its own constellation or alternatively for its own constellation plus others constellations. Furthermore, each GNSS core constellation provider may decide to broadcast both Message Types 1A/1B and Message Type 2, or just Message Types 1A/1B. Recall that Type 1A/1B are both for H-ARAIM and V-ARAIM; Type 1A has all of the ISM content contained in a single message and Type 1B contains only the ISM content for one constellation. Other dissemination means different than the GNSS core constellation signals are certainly possible (e.g., GEO broadcast).

The following three tables (Table 20 to Table 22) are examples on how the Galileo Signal-In-Space (I/NAV Message, Word 16 on E1-B Signal) could be used for ISM dissemination. In the first example, the Galileo Signal-In-Space is used to disseminate Message Type 1A (for two constellations only) and Message Type 2 for solely Galileo satellites. In the second example, the Galileo Signal-In-Space I/NAV is used to disseminate Message Type 1A and Message Type 2 for both Galileo and GPS satellites. In the third example, the Galileo Signal-In-Space is used to disseminate only Message Type 2 for Galileo and GPS satellites.

Again, please note that Message Type 1A contains ARAIM ISM information allowing for horizontal and/or offline V-ARAIM applications, while Message Type 2 allows for online V-ARAIM applications.

Table 20: ISM dissemination of Type 1A (for two constellations) and Type 2 for Galileo only

TIME (seconds)	Galileo Signal In Space WORD 16
00:00:29 --- 00:00:30	Message Type 2 (for the conveying Galileo SV)
00:00:59 --- 00:01:00	Message Type 1A (for the Galileo and GPS constellation)
00:01:29 --- 00:01:30	Message Type 2 (for the conveying Galileo SV)
00:01:59 --- 00:02:00	Message Type 1A (for the Galileo and GPS constellation)
…	…

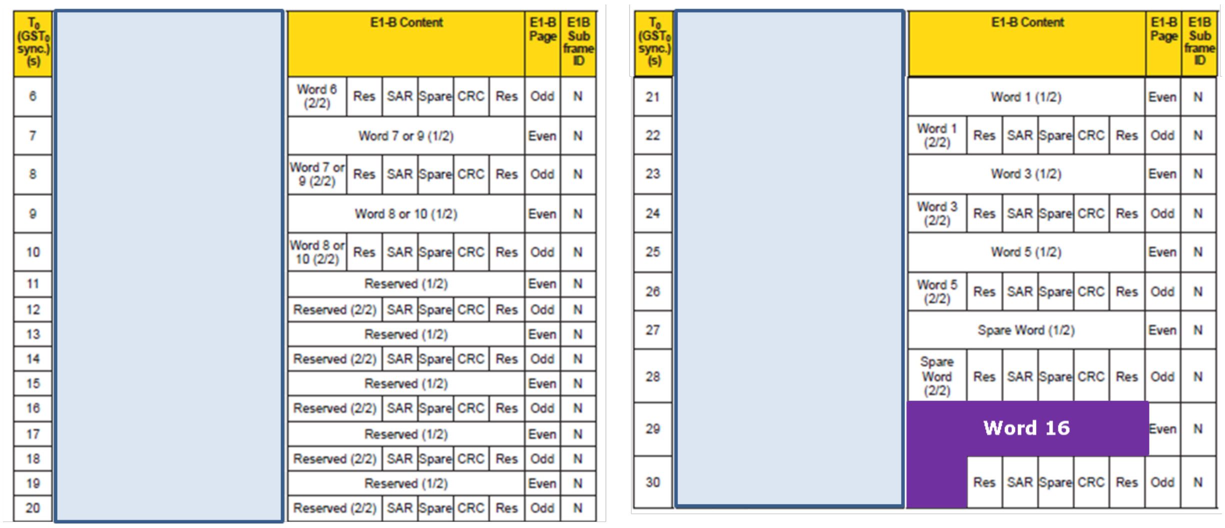
Table 21: ISM dissemination of Type 1A (for two constellations) and Type 2 for Galileo and GPS

TIME (seconds)	Galileo Signal In Space WORD 16
00:00:29 --- 00:00:30	Message Type 2 (for the conveying Galileo SV)
00:00:59 --- 00:01:00	Message Type 1 (for the Galileo and GPS constellation)
00:01:29 --- 00:01:30	Message Type 2 (for selected GPS SV; based on proximity)
00:01:59 --- 00:02:00	Message Type 1 (for the Galileo and GPS constellation)
00:02:29 --- 00:02:30	Message Type 2 (for the conveying Galileo SV)
00:02:59 --- 00:03:00	Message Type 1 (for the Galileo and GPS constellation)
00:03:29 --- 00:03:30	Message Type 2 (for selected GPS SV; based on proximity)
00:03:59 --- 00:04:00	Message Type 1 (for the Galileo and GPS constellation)
…	…

Table 22: ISM dissemination of Type 2 for Galileo and GPS

TIME (seconds)	Galileo Signal In Space WORD 16
00:00:29 --- 00:00:30	Message Type 2 (for the conveying Galileo SV)
00:00:59 --- 00:01:00	Message Type 2 (for selected GPS SV; based on proximity)
00:01:29 --- 00:01:30	Message Type 2 (for the conveying Galileo SV)
00:01:59 --- 00:02:00	Message Type 2 (for selected GPS SV; based on proximity)
…	…

Note: The sequence of Message Types 1A and Type 2 together with their allocation to constellations (Galileo or GPS) as provided in these tables are only examples to identify the flexibility of this approach. Actual sequencing of information shall take into considerations operational constraints.



T_0 (GST_0 sync.) (s)		E1-B Content						E1-B Page	E1B Sub frame ID
6		Word 6 (2/2)	Res	SAR	Spare	CRC	Res	Odd	N
7		Word 7 or 9 (1/2)						Even	N
8		Word 7 or 9 (2/2)	Res	SAR	Spare	CRC	Res	Odd	N
9		Word 8 or 10 (1/2)						Even	N
10		Word 8 or 10 (2/2)	Res	SAR	Spare	CRC	Res	Odd	N
11		Reserved (1/2)						Even	N
12		Reserved (2/2)		SAR	Spare	CRC	Res	Odd	N
13		Reserved (1/2)						Even	N
14		Reserved (2/2)		SAR	Spare	CRC	Res	Odd	N
15		Reserved (1/2)						Even	N
16		Reserved (2/2)		SAR	Spare	CRC	Res	Odd	N
17		Reserved (1/2)						Even	N
18		Reserved (2/2)		SAR	Spare	CRC	Res	Odd	N
19		Reserved (1/2)						Even	N
20		Reserved (2/2)		SAR	Spare	CRC	Res	Odd	N

T_0 (GST_0 sync.) (s)		E1-B Content						E1-B Page	E1B Sub frame ID
21		Word 1 (1/2)						Even	N
22		Word 1 (2/2)	Res	SAR	Spare	CRC	Res	Odd	N
23		Word 3 (1/2)						Even	N
24		Word 3 (2/2)	Res	SAR	Spare	CRC	Res	Odd	N
25		Word 5 (1/2)						Even	N
26		Word 5 (2/2)	Res	SAR	Spare	CRC	Res	Odd	N
27		Spare Word (1/2)						Even	N
28		Spare Word (2/2)	Res	SAR	Spare	CRC	Res	Odd	N
29		Word 16						Even	N
30			Res	SAR	Spare	CRC	Res	Odd	N

Figure 14:Position of Word 16 in Nav Message

6.3.3 User Algorithm

The same reference algorithm used for Offline V-ARAIM is applicable to Online V-ARAIM.

7 Conclusions and Follow-On Activities

This report is the outcome of Milestone 3 of the ARAIM Technical Subgroup (ARAIM TSG) of Working Group C, which stemmed from the U.S.-EU Agreement on GPS/Galileo Cooperation signed in 2004. Milestone 3 was the last milestone, originally established in the ARAIM TSG Terms of Reference [RD-01].

Following the publication of the Milestone 2 Report [RD-74], the ARAIM TSG gathered feedback on the general concepts, timeline, and implementation options from the aviation community (avionics manufacturers and integrators, Air Navigation Service Providers, standardization bodies) through formal request to the relevant entities.

Taking into account the feedback received, this Milestone 3 Report has expanded upon the concept of Message Types for ARAIM: Modes and Messages for H-ARAIM, Messages for Offline V-ARAIM, and Messages for Online V-ARAIM.

The message types are conceived in such a way that the provision of the services enabled by ARAIM can be implemented in an incremental way.

The ARAIM Implementation Roadmap, which is a key element in this report, was built coherently with this incremental approach. The Roadmap defines the milestones for the introduction of H-ARAIM, together with its specific dates aiming for provision of service in the 2023 timeframe.

For each of the two main milestones – the so-called Feasibility Checkpoint and Readiness Keypoint – the required elements are identified, including specific Concept Paper, Standards, Operational Concept, and Safety Case.

For V-ARAIM, the Implementation Roadmap defines the equivalent milestones, with their associated required elements, but does not identify firm dates at this stage.

The V-ARAIM operational capabilities could be enhanced gradually after the Readiness Keypoint, in accordance with the approach of the message types, and along with the deployment of additional monitoring capabilities, when deemed necessary.

The ARAIM Implementation Roadmap also reflects coexistence with the foreseen SBAS services. In this respect, another key element of this report is the description of the expected complementarity between SBAS and ARAIM.

Identified areas of complementarity include global support to air navigation, first with horizontal and later with vertical guidance, reuse of system infrastructure, support to maritime navigation at high latitudes, in particular in the Arctic region, and the possibility to exploit ARAIM features to toughen GNSS receivers against jamming and spoofing.

For Milestone 3, the ARAIM TSG also progressed addressing the institutional issues related to the provision of ARAIM services. This work included a review of the ICAO Principles and references on which the current GNSS service provision is based, with a specific look at the sovereignty and liability aspects.

In order to properly address those issues in the provision of ARAIM services, the TSG considers it necessary that the framework for the service provision be clearly defined, with assigned roles and responsibilities to all actors. In addition, the TSG considers it important that the set of requirements and assumptions ensuring the integrity of the service (in particular the ISM content) is built in a transparent and verifiable way and that the constellation performance and status information to support service predictions (Aeronautical Information Service) are readily provided.

The institutional implications of a Global ISM have also been pondered. In view of the implications on safety and interoperability, the TSG advocates for a single, globally harmonized ISM, generated through a transparent and standardized methodology building on already existing processes and frameworks.

Nevertheless, the TSG recognizes that individual States may want to generate their own ISM - for various reasons, not necessarily technical. One way to achieve this would be to have geographically separate, State ISMs using a geo-fencing database. These databases are updated on the AIRAC 28 day cycle and could carry the ISM for each individual State. In any case, any entity charged with ISM generation must do so following a standardized methodology and must be able to satisfy the regulatory requirements of all contracting ICAO States, which may include the need for individual contractual agreements.

In terms of ISM dissemination, it is recalled that alternative solutions are still being identified (including storage at avionics level, dissemination through core constellations, and dissemination via existing communications link or database), which should be reflected in the standards to the extent possible. In particular, the community should consider additional techniques to broadcast the Online V-ARAIM message since the latency needed is more stringent than any current or planned capability of GPS.

Furthermore, the ARAIM TSG has complemented the availability results provided in the previous reports with the results for H-ARAIM under various scenarios.

It can be shown that the primary mode of H-ARAIM (DF L1-L5) provides the highest performance. As shown in Table 21, RNP 0.1 is always available when both frequencies (L1 and L5) are available and the two constellations are tracked. Moreover, H-ARAIM with a single baseline constellation (GPS or Galileo) supports RNP 0.1 capabilities[8].

Table 21: Estimated global level of service for DFMC (Pconst = 10^{-4})

Constellation/URA	2.5m	...	20m
<Depleted>	RNP 0.1 (100%)	URA < 9m (89.6%)	RNP 0.3 (97.7%)
<Baseline>	RNP 0.1 (100%)	URA ≤ 15m (91.2%)	RNP 0.3 (100%)
<Optimistic>	RNP 0.1 (100%)	URA ≤ 16m (90.7%)	RNP 0.3 (100%)

For the single frequency mode, which uses ionospheric corrections included in the CSP navigation message, it has been found that RNP 0.1 can be achieved in the Baseline and Optimistic constellation scenarios, while RNP 0.3 can be achieved either in the Depleted constellation scenario or still in the Baseline and Optimistic scenarios with only one of the constellations (GPS or Galileo).

[8] For each constellation, the table indicates the most capable level of service for which a 90% coverage of 99.5% availability is achieved and illustrates robustness of H-ARAIM as a function of URA/SISA bounds. The table window is coloured based on RNP 0.1/0.3 capability, where the label “Low” indicates a global coverage between 80% and 90%.

RNP 0.3 can also be achieved in the single frequency mode with L5, thus providing robustness should the L1/E1 signals be lost.

Finally, the ARAIM TSG has updated the description of the reference user algorithm, which is provided as an Annex A to this Report.

7.1 **Way Forward**

As described above, the ARAIM Implementation Roadmap presented in this Report defines the milestones leading to the introduction of the ARAIM services. In light of that Roadmap, the ARAIM TSG has identified three main areas of work in which WG-C can continue contributing to the execution of this work:

- Contributions to Standards Development

The standards development organizations (ICAO, and the Avionics Standards bodies EUROCAE, RTCA) will require input for the first draft of their respective standards, as well as new input, or comments, on the subsequent iterations of the draft standards until the final version of the standards is completed.

An example mentioned in this report is the case of EUROCAE, where the H-ARAIM standards as an integral element of the DFMC Standards are expected to be completed by 2020, with a first draft available in the 2017/18 timeframe.

- Prototype development and testing for ground and airborne algorithms

Development of prototypes for an ARAIM ground segment as well as for the airborne receivers will start soon. Those developments as well as their testing with real signals will bring in fundamental feedback to the concepts developed by the WG-C, which would then be in an ideal position to refine them in view of their operational implementation.

- Constellation Service Providers requirements development and compatibility coordination

Derivation of appropriate requirements for the Constellation Service Providers necessary for the provision of ARAIM services needs to be completed. WG-C is an ideal forum to ensure coordination and feasibility of those requirements for GPS and Galileo.

In terms of priorities in the medium term, the main focus will be the support to the H-ARAIM Feasibility Checkpoint, the first milestone identified in the Roadmap, to take place around mid-2018.

Continuation of the current R&D activities carried out by the ARAIM TSG, and especially those regarding Vertical ARAIM will be a second objective examined in parallel with the H-ARAIM development and implementation.

Finally, R&D work related to the extension of the ARAIM concept to other user communities (especially maritime and rail) will be initiated.

Annex A. DESCRIPTION OF UPDATED REFERENCE USER ALGORITHM

The purpose of this document is to describe the airborne algorithm that is used in the ARAIM availability simulations within the WG-C Advanced RAIM Technical subgroup (TSG). The availability results should record the version number that has been used, the Integrity Support Message content, and the parameter settings. The starting point of the reference algorithm is the one described in [RD-80].

A.I INTRODUCTION

The GPS Evolutionary Architecture Study (GEAS) outlined an Advanced RAIM concept in the GEAS Phase II report [RD-02], which has been further developed within the Working Group C ARAIM Technical subgroup (ARAIM TSG) [RD-03]. The integrity data used by the airborne receiver is contained in the Integrity Support Message (ISM) that is determined on the ground and broadcast to the airborne fleet [RD-03], [RD-81].

Since the GEAS Phase II Report [RD-02], it has become apparent that multiple simultaneous faults cannot be ruled out, and therefore might need to be mitigated by the airborne receiver. The user algorithm described in [RD-02] only covered the single fault case. Although it was indicated that the algorithm could be generalized to multiple failures, the exact implementation was not made explicit. Methods to compute the Protection Levels with threat models including multiple faults have been described in [RD-04], [RD-08], and [RD-09]. The present document describes each step of an ARAIM user algorithm based on these references and [RD-80]. The primary focus of ARAIM is on vertical guidance. However, there is interest in applying ARAIM to improve horizontal navigation. This version describes how to set the algorithm input parameters for horizontal navigation.

Section A.II describes some of the performance requirements that need to be met by the ARAIM user algorithm, and motivates the need for additional availability criteria. Section A.III describes the main elements of the reference user algorithm step by step for ARAIM, and is an extension of the one described in the GEAS Phase II Report [RD-02], including elements of [RD-04], [RD-08], and [RD-09]. The algorithm is described in the order it is executed.

A.II NAVIGATION REQUIREMENTS

A.II.1. REQUIREMENTS FOR LPV-200 AND LPV-250

The target operational level for ARAIM is LPV-200 [RD-82], which is a relatively new operation and one that is incompletely specified in the ICAO Standards and Recommended Practices (SARPs) [RD-06]. Currently, LPV-200 is only provided by SBAS. The SARPs contain both requirements and guidance material on the desired operational performance, including positioning performance, continuity, and availability. However, ARAIM will have different characteristics than current SBAS, and it is important to understand how these differences may affect operational behaviour and the feasibility of meeting LPV-200 requirements. In particular, there is a concern that the test statistics in ARAIM, while protecting against errors exceeding the VAL, could allow large errors to remain undetected (for vertical guidance, it is not sufficient to have position errors below the VAL). Therefore, it is necessary to understand the operational requirements of LPV-200 and ensure the final ARAIM algorithm addresses these concerns.

For continuity, the SARPs specify a continuity risk requirement of $8x10^{-6}$ per 15 s. For ARAIM, the airborne algorithm tests have a finite probability of false alert, which can cause a loss of continuity. For this reason, a fraction P_{fa} of the total continuity budget must be allocated to the airborne algorithm.

The SARPs describe four vertical positioning performance criteria:

- 4 m, 95% accuracy;
- 10 m, 99.99999% fault-free accuracy;
- 15 m, 99.999% Effective Monitoring Threshold (EMT); and
- 35 m, 99.99999% limit on the position error, (i.e., the VPL has to be below a VAL of 35m).

Two of the criteria: 95% accuracy and VPL are described in Chapter 3 of Annex 10, Volume 1, of the ICAO SARPs [RD-06]. The other two criteria: fault-free accuracy and EMT, are only described in the guidance material in Attachment D to Annex 10 which also provides more information on the previous two criteria. For the Wide Area Augmentation System (WAAS), it was determined by the Federal Aviation Administration (FAA) that if the VPL requirement is met, the other conditions are also all met. This is because of the inherent accuracy of WAAS and that the VPL is driven by rare fault-modes. Any condition that supported a VPL below 35 m, also assured that the accuracy requirements and EMT would be met.

ARAIM will have different error characteristics than SBAS. Unlike any SBAS currently implemented, ARAIM makes use of the dual-frequency ionosphere-free pseudorange combination. Additionally, ARAIM will not use differential corrections (at least in the offline architecture). Therefore, it will likely have worse accuracy than current SBAS systems. Further, its method of error detection may allow fault modes to create larger position errors before they are identified and removed. Thus, conditions that support an ARAIM VPL below 35 m may not always lead to error characteristics that support LPV-200 operations.

Therefore, we introduce two additional real-time tests in the aircraft to ensure that every supported condition has error characteristics that meet the intent of the SARPs. Specifically an accuracy test and an EMT test are described in Section A.III. A single accuracy test assures that both the 4 m 95% and the 10 m 99.99999% tests are met (the tests are of identical form, but the 10 m test is more stringent). The EMT test prevents faults that are not large enough to ensure detection from creating vertical position errors greater than 15 m more often than 0.00001% of the time.

The requirements for LPV-250 are less stringent than LPV-200. The vertical positioning criteria is given by:

- 50 m, 99.99999% limit on the position error, (i.e., the VPL has to be below a VAL of 35m).

As was described in [RD-02] and [RD-03], there are two error models: an integrity error model and an accuracy (or continuity) error model (A.VI). The integrity error model is used in the terms that have an impact on the integrity requirements, whereas the accuracy error model is used for all others. More details can be found in [RD-02] and [RD-03].

A.II.2. Horizontal ARAIM navigation requirements

RNP has multiple levels of performance [RD-83]. For prediction purposes, it is considered sufficient to show that the HPL is below the RNP number (Appendix 4 of [RD-83]). The rationale for this criteria is the following: The number after RNP specifies the 95% bound on the Total System Error (TSE), which is the combination of Flight Technical Error (FTE) and Navigation System Error (NSE). Further, RNP also specifies that 99.999% of the time, TSE shall be contained within twice the specified number. Thus, for RNP 0.1 95% of TSE values should be within 0.1 NM and 99.999% of TSE values should be within 0.2 NM. When modelling RAIM performance, NSE is typically allocated half of the budget (this is conservative as FTE is typically well below 100 m 95%). The corresponding requirement can be viewed as 95% of NSE should be within 0.05 NM (~93 m) and 99.999% of NSE should be within 0.1 NM (~185 m). Although the integrity requirement is specified at the $1 - 10^{-5}$ level, RAIM calculates this bound at the 10^{-7} level for comparison against the 99.999% NSE requirement.

A.III ARAIM USER ALGORITHM

A.III.1. Definitions

***ΔPR*:** when computing the position solution, the vector of pseudorange measurements minus the expected ranging values based on the location of the satellites and the position solution given at each iteration.

***y*:** vector of pseudorange measurements minus the expected range for an all-in-view position solution.

***x*:** receiver position and clock states (offset with respect to a position close enough to the true position so that the linear approximation of the observation equation is valid).

***G*:** geometry matrix in East North Up (ENU) coordinates with a clock component for each constellation.

***Q*:** tail probability of a zero mean unit normal distribution. The *Q* function is defined as:

$$Q(u) = \frac{1}{\sqrt{2\pi}} \int_{u}^{+\infty} e^{\frac{t^2}{2}} \, dt \qquad (1)$$

$\boldsymbol{Q^{-1}}$:inverse of the *Q* function.

PL: Protection Level.

A.III.2. List of inputs

Table 23: List of inputs

Name	Description	Source
PR_i	Pseudorange for satellite *i* after dual frequency correction, tropospheric correction, and smoothing	Receiver

	are performed	
$\sigma_{URA,i}$	standard deviation of the clock and ephemeris error of satellite *i* used for integrity	ISM
$\sigma_{URE,i}$	standard deviation of the clock and ephemeris error of satellite *i* used for accuracy and continuity	ISM
$b_{nom,i}$	maximum nominal bias for satellite *i* used for integrity	ISM
$P_{sat,i}$	prior probability of fault in satellite *i* per approach	ISM
$P_{const,j}$	prior probability of a fault affecting more than one satellite in constellation *j* per approach	ISM
$I_{const,j}$	index of satellites belonging to constellation *j*	Receiver
N_{sat}	number of satellites	Receiver
N_{const}	number of constellations	Receiver

The Integrity Support Message contains parameters that allow the receiver to compute $\sigma_{URA,i}$, $\sigma_{URE,i}$, $b_{nom,i}$, and $P_{sat,i}$ for each satellite *i;* and $P_{const,j}$ for each constellation *j*.

A.III.3. LIST OF CONSTANTS DERIVED FROM THE REQUIREMENTS

Table 24: List of constants

Name	Description	Value (preliminary)
PHMI	total integrity budget	10^{-7}
P_{FA}	continuity budget allocated to disruptions due to false alert. The total continuity budget is 8×10^{-6} per 15 s [RD-44] (because of the temporal correlation of the error, it is adequate to use this value per 150 s).	4×10^{-6}
TOL_{PL}	tolerance for the computation of the Protection Level	5×10^{-2} m
K_{ACC}	number of standard deviations used for the accuracy formula	1.96
K_{FF}	number of standard deviations used for the 10^{-7} fault free vertical position error	5.33
P_{EMT}	probability used for the calculation of the Effective Monitor Threshold	10^{-5}

A.III.4. LIST OF DESIGN PARAMETERS

The parameters in the table below can be changed within constraints. These parameters set:

- the allocation of the integrity budget between vertical and horizontal,

- the false alert rate allocation to the monitors in the vertical domain and horizontal domain,

- the false alert rate to the chi-square test, and

- the parameter used to limit the number of fault modes that are monitored by the airborne algorithm.

These different parameters should be adjusted as a function of the range of the expected ISM content, and the targeted operation. For example, for a horizontal operation, one could choose to allocate all of the integrity budget to the horizontal dimension. Similarly P_{THRES} should be adjusted to remove most of the fault modes. If P_{THRES} is set too low, some fault modes that could be neglected are actually triple counted (because they are counted in full in VPL, HPL1, and HPL2).

Table 25: Design parameters (tunable)

Name	Description	Value for LPV-200 and LPV-250	Value for RNP
$PHMI_{VERT}$	integrity budget for the vertical component	9.8×10^{-8}	0
P_{FA_VERT}	continuity budget allocated to the vertical mode	3.9×10^{-6}	0
P_{FA_HOR}	continuity budget allocated to the horizontal mode	9×10^{-8}	3.99×10^{-6}
P_{THRES}	threshold for the integrity risk coming from unmonitored faults	8×10^{-8}	4×10^{-8}
$N_{ITER,MAX}$	maximum number of iterations to compute the PL	10	10

The constraints on these parameters are:

$$PHMI_{HOR} = PHMI - PHMI_{VERT} > 0$$

$$P_{THRES} < PHMI$$

A.III.5. PSEUDORANGE COVARIANCE MATRICES C_{INT} AND C_{ACC}

The first step of the proposed baseline ARAIM algorithm consists of computing the pseudorange error diagonal covariance matrices C_{int} (the nominal error model used for integrity) and C_{acc} (the nominal error model used for accuracy and continuity). They are defined by:

$$C_{int}(i,i) = \sigma^2_{URA,i} + \sigma^2_{tropo,i} + \sigma^2_{user,i}$$

$$C_{acc}(i,i) = \sigma^2_{URE,i} + \sigma^2_{tropo,i} + \sigma^2_{user,i} \tag{2}$$

Preliminary error models for $\sigma_{tropo,}$ and $\sigma_{user,i}$ for both Galileo and GPS are given in A.VI.

Results of this step: C_{int} and C_{acc}

A.III.6. ALL-IN-VIEW POSITION SOLUTION

To be included in the all-in-view position solution, a satellite must not have been flagged for a given period T_{RECOV} (this period has not been determined yet) and have a valid set of input parameters from the ISM. The all-in-view position solution $\hat{x}^{(0)}$ is computed as defined in Appendix E of [RD-10]. A weighted least-squares estimation is performed at each iteration. The update for $\Delta\hat{x}$ is given by:

$$\Delta\hat{x} = \left(G^T W G\right)^{-1} G^T W \Delta PR \tag{3}$$

The geometry matrix G is an N_{sat} by 3+N_{const} matrix, where N_{const} is the number of independent constellations. The first three columns of G are defined as in Appendix E of [RD-10]. Each of the remaining columns corresponds to the clock reference of each constellation. Labelling the constellations from j=1 to N_{const}, we define:

$$\begin{aligned} G_{i,3+j} &= 1 \text{ if satellite } i \text{ belongs to constellation } j \\ G_{i,3+j} &= 0 \text{ otherwise} \end{aligned} \tag{4}$$

The weighting matrix W is defined as:

$$W = C_{int}^{-1} \tag{5}$$

ΔPR is the vector of pseudorange measurements minus the expected ranging values based on the location of the satellites and the position solution given by the previous iteration. When the position solution has converged, the last ΔPR is the vector $\boldsymbol{y}$ as defined above. Equation (3) assumes that all measurements are in a common reference coordinate system.

Results of this step: y, G, $\hat{x}^{(0)}$

A.III.7. DETERMINATION OF THE FAULTS THAT NEED TO BE MONITORED AND THE ASSOCIATED PROBABILITIES OF FAULT

The ISM does not specify explicitly which fault modes need to be monitored or their corresponding prior probabilities. This determination must be made by the receiver based on the contents of the ISM, which specifies the probabilities of independent events.

This paragraph provides a method to establish a list of event combinations (the fault modes) to be monitored. This list is only sufficient (there could be shorter lists that also meet the integrity requirements. For example, it is shown in [RD-85] and [RD-62] that for some combinations of P_{sat} and P_{const}, the integrity requirements can be met with a shorter list than the one derived with the approach described below. However, for the combinations of P_{sat} and P_{const} assumed for the availability/coverage analysis results contained in this report, the approach presented below is adequate. To lighten the notations in this paragraph, we define:

$$\begin{aligned} P_{sat,i} &= P_{event,i} \\ P_{const,j} &= P_{event,N_{sat}+j} \end{aligned} \tag{6}$$

First, we determine the maximum number $N_{fault,max}$ of simultaneous faults that need to be monitored (be they satellites or constellations). To compute $N_{fault,max}$, we define the probability of all fault modes comprised of r or more independent events. This probability will be noted as $P_{multiple}(r,P_{event,1},\ldots,P_{event,Nsat+Nconst})$. The number $N_{fault,max}$ is defined by:

$$N_{fault,\max} = \max\left\{ r \in 1,\cdots,N_{sat} \mid P_{multiple}\begin{pmatrix} r+1, P_{event,1}, \\ \cdots, P_{event,Nsat+Nconst} \end{pmatrix} \le P_{FAULT\_THRES} \right\} \tag{7}$$

Section A.VIIIA.VIII provides an explicit way of determining the above number and an upper bound of $P_{multiple}(r,P_{event,1},\ldots,P_{event,Nsat+Nconst})$. We define:

$$P_{multiple,not\ monitored} = P_{multiple}\left(r+1, P_{event,1}, \ldots, P_{event,N_{sat}+N_{const}}\right) \tag{8}$$

Once $N_{fault,max}$ is determined, all subsets corresponding to the combination of $N_{fault,max}$ or less events are formed. We note idx_k as the indices of the satellites included in subset k (this subset is used to monitor the fault indexed by k). For example, if subset k corresponds to the failure of satellites 1 and 2, the subset contains all satellites except 1 and 2. For the subset idx_k corresponding to the events $\{i_1,\ldots,i_r\}$, the corresponding probability is given by:

$$p_{fault,k} = \prod\nolimits_{s=1,\ldots,r} P_{event,i_s} \tag{9}$$

To illustrate this step, assume there are 18 satellites (N_{sat} = 18) and 2 constellations, with $P_{sat} = 10^{-4}$ and $P_{const} = 10^{-4}$. We have:

$$P_{multiple,upper\,bound}\left(2, P_{event,1}, \dots, P_{event,N_{sat}+N_{const}}\right) = 1.9 \times 10^{-6}/approach$$

$$P_{multiple,upper\,bound}\left(3, P_{event,1}, \dots, P_{event,N_{sat}+N_{const}}\right) = 1.33 \times 10^{-9}/approach \quad (10)$$

$N_{fault,max}$, the maximum number of simultaneous independent failures that needs to be considered, is therefore two, because the contribution of all subset faults resulting from the combination of two or more independent events exceeds P_{THRES}, and the contribution resulting from three or more independent events is less than $P_{THRES,}$ (which is only a fraction of the total integrity budget). There are 20 one-event subsets and 190 two-event subsets. The contribution from all three-or-more fault cases is below $1.33 \cdot 10^{-9}$.

A.III.7.1. FILTERING THE SUBSETS

Among the subset faults determined in the previous section, there could be some that cannot be monitored (because the remaining satellites do not allow the receiver to compute a position). In this case, these events must be removed from the list of faults (and their integrity risk subtracted from the available budget). This is true of all subsets for which N < 3+M where N satellites in the subset are from M different constellations. We note $P_{unobservable}$ as their total integrity risk. The total integrity risk of the modes that are not monitored is:

$$P_{fault,not\,monitored} = P_{multiple,not\,monitored} + P_{unobservable} \quad (11)$$

Results of this step: $p_{fault,k}$,idx_k for k ranging from 1 to the maximum number of fault modes to be monitored ($N_{fault\,modes}$), $P_{fault,not\,monitored}$

A.III.8. FAULT-TOLERANT POSITIONS AND ASSOCIATED STANDARD DEVIATIONS AND BIASES

The monitor chosen to protect against the list of fault modes determined in the previous section is solution separation. Appendix G of [RD-80] shows that, under certain assumptions, it is the optimal statistic. For each k from 1 to $N_{fault\,modes}$, the difference $\Delta\hat{x}^{(k)}$ between the fault-tolerant position $\hat{x}^{(k)}$ and the all-in-view position solution $\hat{x}^{(0)}$, the standard deviations, and test thresholds are determined. For each k, we compute the diagonal weighting matrix:

$$\begin{aligned} W^{(k)}(i,i) &= C_{int}^{-1}(i,i) \text{ if } i \text{ is in } idx_k \\ W^{(k)}(i,i) &= 0 \text{ otherwise} \end{aligned} \quad (12)$$

For all j such that:

$$\left(G^T W^{(k)}\right)_{3+j,*} = \begin{bmatrix} 0 & \cdots & 0 \end{bmatrix}^T \quad (13)$$

G must be redefined by removing its $3+j^{th}$ column. This happens if none of the satellites from constellation j is in idx_k.

The position solution tolerant to fault mode k is obtained by applying the corresponding weighted least squares to the residuals y:

$$\Delta\hat{x}^{(k)} = \hat{x}^{(k)} - \hat{x}^{(0)} = \left(S^{(k)} - S^{(0)}\right) y \text{ where}$$
$$S^{(k)} = \left(G^T W^{(k)} G\right)^{-1} G^T W^{(k)} \tag{14}$$

The computation of $S^{(k)}$ should take advantage of the relationship between $S^{(0)}$ and $S^{(k)}$ through rank one updates (in the case of a multiple satellite fault mode, more than one rank update is necessary)[RD-80] .

Let the index q = 1, 2, and 3 designate the East, North and Up components, respectively. The variances of $\hat{x}_q^{(k)}$ for q from 1 to 3 are given by:

$$\sigma_q^{(k)2} = \left(G^T W^{(k)} G\right)^{-1}_{q,q} \tag{15}$$

The worst case impact of the nominal biases occurs when the nominal bias of each measurement has the same sign as the coefficient projecting the pseudorange onto the position. Since the absolute value of each nominal bias is bounded by $b_{nom,i}$ and the signs of the nominal biases are not known to the receiver (see List of Inputs), the worst case impact on the position solution $\hat{x}_q^{(k)}$ is given by:

$$b_q^{(k)} = \sum_{i=1}^{N_{sat}} \left|S_{q,i}^{(k)}\right| b_{nom,i} \tag{16}$$

We compute the variance of the difference, $\Delta\hat{x}_q^{(k)}$, between the all-in-view and the fault tolerant position solutions:

$$\sigma_{ss,q}^{(k)2} = e_q^T \left(S^{(k)} - S^{(0)}\right) C_{acc} \left(S^{(k)} - S^{(0)}\right)^T e_q \tag{17}$$

in which e_q denotes a vector whose q^{th} entry is one and all others are zero.

Results of this step: $\sigma_q^{(k)}$, $\sigma_{ss,q}^{(k)}$, $b_q^{(k)}$ for k from 0 to $N_{fault\ modes}$, and from q from 1, 2, and 3.

A.III.9. SOLUTION SEPARATION THRESHOLD TESTS AND CHI-SQUARE TEST

A.III.9.1. SOLUTION SEPARATION TEST

For each fault mode, there are three solution separation threshold tests, one for each coordinate. The thresholds are indexed by the fault index *k* and the coordinate index *q* and noted $T_{k,q}$. They are defined by:

$$T_{k,q} = K_{fa,q}\sigma_{ss,q}^{(k)} \tag{18}$$

where:

$$K_{fa,1} = K_{fa,2} = Q^{-1}\left(\frac{P_{FA\_HOR}}{4N_{fault\ modes}}\right) \tag{19}$$

$$K_{fa,3} = Q^{-1}\left(\frac{P_{FA\_VERT}}{2N_{fault\ modes}}\right) \tag{20}$$

$Q^{-1}(p)$ is the (1-*p*)-quantile of a zero-mean unit-variance Gaussian distribution. Protection Levels can be computed only if for all *k* and *q* we have:

$$\tau_{k,q} = \frac{\left|\hat{x}_q^{(k)} - \hat{x}_q^{(0)}\right|}{T_{k,q}} \leq 1 \tag{21}$$

If any of the tests fail, exclusion must be attempted.

NOTE: X^2 STATISTIC

This test is not required, as it does not offer additional protection for faults listed in the threat model. As shown in [RD-80], the chi-square statistic is an upper bound of all solution separation tests. Therefore, if a fault is detectable, it will manifest itself in this statistic. The chi-square statistic for the all-in-view set is computed as follows:

$$\chi^2 = y^T\left(W_{acc} - W_{acc}G\left(G^TW_{acc}G\right)^{-1}G^TW_{acc}\right)y \tag{22}$$

In this equation, we have $W_{acc} = C_{acc}^{-1}$. The threshold is defined by:

$$F\left(T_{\chi^2}, n-3-N_{const}\right) = 1 - P_{FA\_CHI2} \tag{23}$$

The false alert allocation P_{FA_CHI2} should be set to have a negligible impact on the overall false alert budget, since it is only a sanity check to protect against threats that are outside the threat model. Consequently, a trade-off exists between high false alert rates and low sensitivity against those threats. This trade-off would need to make assumptions on the characteristics of such additional threats.

The operator $F(u, \deg)$ is the cdf of a chi-square distribution with *deg* degrees of freedom. If $\chi^2 > T_{\chi^2}$, but $\tau_{k,q} \leq 1$ for all q and k, the PL cannot be considered valid and exclusion cannot be attempted. In this case, the chi-square statistic is larger than expected, but none of the solution separation tests have failed, which suggests that the fault is outside the threat model. Therefore, a failed exclusion is declared.

While the chi-square test is not linked to the threat model, it makes the algorithm more robust to violations of the threat model at a small computational penalty. A similar test is required for SBAS [RD-10].

Results of this step: Thresholds $T_{k,q}$, decision on whether to continue with Protection Level calculation, attempt fault exclusion, or declare the HPL and VPL invalid.

A.III.10. PROTECTION LEVELS

A.III.10.1. VERTICAL PROTECTION LEVEL (VPL)

The Protection Levels are determined by the integrity requirement. For the VPL, we need to make sure that the integrity risk (which is the sum of the contribution of each fault mode) is below the integrity risk allocated to the vertical error. The solution to the following equation provides a VPL that meets the required integrity allocation:

$$2Q\left(\frac{VPL - b_3^{(0)}}{\sigma_3^{(0)}}\right) + \sum_{k=1}^{N_{fault\,mode}} p_{fault,k}\, Q\left(\frac{VPL - T_{k,3} - b_3^{(k)}}{\sigma_3^{(k)}}\right) =$$

$$PHMI_{VERT}\left(1 - \frac{P_{sat,not\,monitored} + P_{const,not\,monitored}}{PHMI_{VERT} + PHMI_{HOR}}\right) \tag{24}$$

In Equation (24), each term of the left hand side is an upper bound of the contribution of each fault to the integrity risk. The proof of safety associated with this Protection Level can be found in Appendix H of [RD-80]. The output VPL must be within TOL_{PL} of the solution of this equation. There are several methods available to solve this equation. Appendix B of [RD-80] proposes one of them, as well as an upper bound (which is actually close to the solution).

A.III.10.2. HORIZONTAL PROTECTION LEVEL (HPL)

For the HPL computations, we first compute HPL_q for q=1 and 2. As for the VPL, HPL_q is the solution to the equation:

$$
\begin{aligned}
&2Q\left(\frac{HPL_q - b_q^{(0)}}{\sigma_q^{(0)}}\right) + \\
&\sum_{k=1}^{N_{fault\ modes}} p_{fault,k} Q\left(\frac{HPL_q - T_{k,q} - b_q^{(k)}}{\sigma_q^{(k)}}\right) = \\
&\frac{1}{2} PHMI_{HOR}\left(1 - \frac{P_{sat,not\ monitored} + P_{const,not\ monitored}}{PHMI_{VERT} + PHMI_{HOR}}\right)
\end{aligned}
\tag{25}
$$

The output HPL_q must be within TOL_{PL} of the solution of this equation. This equation can be solved using a half interval search as shown for the VPL in Appendix B. The HPL is given by:

$$
HPL = \sqrt{HPL_1^2 + HPL_2^2} \tag{26}
$$

A.III.10.3. ACCOUNTING FOR POSSIBLE DOUBLE COUNTING OF INTEGRITY RISK

Due to the pre-allocation of the integrity budget to each of the coordinates, there is the possibility that the computed contribution of integrity risk of a fault mode might exceed the probability of the fault mode. This can result in loss of performance. Let us consider mode *k*. The upper bound on the contribution to mode *k* is given by:

$$
IR_k = p_{fault,k}\left(Q\left(\frac{HPL_1 - T_{k,1} - b_1^{(k)}}{\sigma_1^{(k)}}\right) + Q\left(\frac{HPL_2 - T_{k,2} - b_2^{(k)}}{\sigma_2^{(k)}}\right) + Q\left(\frac{VPL - T_{k,3} - b_3^{(k)}}{\sigma_3^{(k)}}\right)\right) \tag{27}
$$

If the term between parenthesis exceeds one, then IR_k exceeds $p_{fault,k}$. However, if we had chosen not to monitor mode *k*, IR_k would have been exactly $p_{fault,k}$, which would have resulted in a smaller Protection Level.

This possible loss of performance can be mitigated by: first, identifying the modes for which we are overestimating the integrity risk; second, by excluding them from the list of monitored faults; and, third, by recomputing the thresholds and Protection Levels with the new list. Specifically, we find the set of indices *k* such that:

$$
Q\left(\frac{HPL_1 - T_{k,1} - b_1^{(k)}}{\sigma_1^{(k)}}\right) + Q\left(\frac{HPL_2 - T_{k,2} - b_2^{(k)}}{\sigma_2^{(k)}}\right) + Q\left(\frac{VPL - T_{k,3} - b_3^{(k)}}{\sigma_3^{(k)}}\right) \geq 1 \tag{28}
$$

Let us call this set I_{excl}. We exclude these modes from the list of monitored modes. Since they are now excluded from this list, we must account for their integrity risk contribution in the term $P_{fault,not\ monitored}$ computed in Equation (11). We define $P_{fault,not\ monitored,new}$:

$$
P_{fault,not\ monitored,new} = P_{fault,not\ monitored} + \sum_{k \in I_{excl}} p_{fault,k} \tag{29}
$$

The new number of monitored fault modes is then:

$$N_{fault\_\mathrm{modes,new}} = N_{fault\_\mathrm{modes}} - \left|I_{excl}\right| \tag{30}$$

Note that the detection thresholds defined in Equations (18), (19), and (20) should be re-computed, as they depend on the number of monitored faults.

Results of this step: VPL and HPL

A.III.11. ACCURACY, THE FAULT FREE POSITION ERROR BOUND, AND EFFECTIVE MONITOR THRESHOLD

The standard deviation of the vertical position solution used for these two criteria is given by:

$$\sigma_{v,acc} = \sqrt{e_3^T S^{(0)} C_{acc} S^{(0)T} e_3} \tag{31}$$

The formulas for the two accuracy requirements are given by:

$$accuracy(95\%) = K_{ACC}\sigma_{v\_acc} \tag{32}$$

$$fault-free\left(10^{-7}\right) = K_{FF}\sigma_{v,acc} \tag{33}$$

Because 10 m / K_{FF} is smaller than 4 m / K_{ACC}, the fault-free test is the only one that needs to be evaluated by the aircraft. We therefore need to test:

$$\sigma_{v\_acc} \leq 1.87m$$

The Effective Monitor Threshold (EMT) can be defined as the maximum of the detection thresholds of faults that have a prior equal or above P_{EMT}. It is computed as follows:

$$EMT = \max_{k|p_{faul,k} \geq P_{EMT}} T_{k,3} \tag{34}$$

Results of this step: 95% accuracy, the 10^{-7} fault free position error bound, and EMT

A.IV OPTIMIZED POSITIONING FOR WEAK GEOMETRIES

An approach to minimize the Protection Levels by adjusting the position was described in [RD-24]. As shown in this reference, there can be an improvement in the integrity error bound by choosing a solution position that is offset from the most accurate position solution under nominal conditions. For geometries where one of the subsets has a much larger standard deviation, this algorithm can be greatly simplified and is specified below. This approach should only be applied when the target protection level is not achieved (for example, for LPV-200 if the VPL exceeds 35 m or the EMT exceeds 15 m and $\sigma_{v\_acc} \leq 1.87m$). This part of the algorithm should be inserted after Equation (16). We describe the algorithm for the vertical protection level. At the end, we show how to use it to compute the horizontal protection level.

Step 1: Among the fault modes that are going to be monitored, and whose *a priori* probability is above PHMI, select the one with the largest $\sigma_3^{(k)}$. We define as s_{max} the corresponding coefficients (the third row of $S^{(k)}$). We also note s_{all} as the third row of $S^{(0)}$. In addition we note $\sigma^2_{acc,req}$ as the required accuracy for LPV 200 (=1.87^2).

Step 2: Compute:

$$\begin{aligned} a &= \left(s_{\max} - s_{all}\right)^T C_{acc}\left(s_{\max} - s_{all}\right) \\ b &= 2 s_{all}{}^T C_{acc}\left(s_{\max} - s_{all}\right) \\ c &= s_{all}{}^T C_{acc} s_{all} - \sigma^2_{acc,req} \end{aligned} \tag{35}$$

Step 3: Compute:

$$t = \min\left(1, \frac{-b + \sqrt{b^2 - 4ac}}{2a}\right) \tag{36}$$

Step 4: Compute:

$$s = s_{all} + t\left(s_{\max} - s_{all}\right) \tag{37}$$

Once the all-in-view coefficients have been computed according Equation (37), the algorithm continues at Equation (17) (replacing the third row of $S^{(0)}$ with s). A more detailed account of this method can be found in [RD-84].

Application to HPL

This algorithm modification can also be applied to each of the horizontal components. Although there is not an equivalent fault free accuracy requirement for RNP, a value of 20 m was chosen (so that the algorithm would not excessively degrade the horizontal accuracy).

A.V BASELINE SIMULATION CONDITIONS

A.V.1. CONSTELLATION CONFIGURATIONS

Four constellation scenarios have been chosen which are meant to represent: a configuration which uses the reference almanac for each constellation (‘baseline’), a configuration in which one satellite has been removed in each constellation (‘depleted’), a configuration that can reasonably be expected given the observed history of GPS (‘expected’), and a configuration that assumes that Galileo will match the number of satellites expected for GPS, although not unrealistic given GPS history and Galileo replenishment strategy (‘optimistic’):

1. Baseline: GPS 24 (24-slot nominal GPS constellation), Galileo 24 (baseline)
2. Depleted: GPS 24 - 1, Galileo 24 - 1
3. Expected: GPS 24 + 3, Galileo 24
4. Optimistic: GPS 24 + 3, Galileo 24 + 3

Table 26: Table of Almanac Files

	GPS	Galileo
24-1	almmops-1.txt	almanac Galileo 24-1 Week 703.alm.txt
24	almmops.txt	almanac Galileo 24 Week 703.alm.txt
24+3	almgps24+3.txt	almanac Galileo 24 + 3 Spare Week 703.alm.txt

The almanacs can be downloaded at [RD-61].

A.V.2. USER MASK ANGLE

Table 27: User Mask Angles

	GPS	Galileo
User mask angle in degrees	5 degrees	5 degrees

A.V.3. USER GRID AND TIME STEPS

Users are simulated as follows:

- 5 by 5 degree user grid
- 10 sidereal days
- 600 s time steps

A.V.4. EVALUATION CRITERIA

- Coverage of 99.5% of LPV 200 and APV1/LPV 250 between -70 and 70 degrees latitude
- For coverage, user grid points are weighed by the cosine of the latitude to account for the relative area they represent

A.V.5. Availability criteria:

Table 28: Availability Criteria

	VAL	HAL	EMT	σ_{acc} threshold
LPV-200	35 m	40 m	15 m	1.87 m
APV 1 / LPV-250	50 m	40 m	-	-
RNP 0.1	-	185 m	-	-
RNP 0.3	-	556 m	-	-

A.V.6. Simulation settings

For the Milestone 2 Report, the ISM parameters have been set to:

- σ_{URA} = .5m, .75m, 1m, 1.5m, 2m, for LPV-200 and LPV-250 and2.5m for Horizontal
- $\sigma_{URE} = 2/3\ \sigma_{URA}$
- $b_{nom} = 0.75$m
- $P_{sat} = 10^{-5}$
- $P_{const} = 10^{-4}, 10^{-8}$

A.VI Error Models

A.VI.1. Error Models for dual frequency

Two error budgets for GPS and Galileo have been made use of to allow for a performance prediction in the frame of ARAIM. The Galileo user contribution to the error budget is identified in tabular form.

Table 29: Galileo Elevation Dependent SIS user error

(meters)	Galileo			
$\sigma_{n,user}^{Gal}$ **(vs elevation)**	5°	0.4529m	50°	0.2359 m
	10°	0.3553 m	55°	0.2339 m
	15°	0.3063 m	60°	0.2302 m
	20°	0.2638 m	65°	0.2295 m
	25°	0.2593 m	70°	0.2278 m
	30°	0.2555 m	75°	0.2297 m
	35°	0.2504 m	80°	0.2310 m
	40°	0.2438 m	85°	0.2274 m
	45°	0.2396 m	90°	0.2277 m

The $\sigma_{n,user}$ for GPS follows the formula provided in [RD-44] for the Airborne Accuracy Designator – Model A (AAD-A) [RD-45]:

$$\sigma_{n,user}^{GPS} = \sqrt{\frac{f_{L1}^4 + f_{L5}^4}{\left(f_{L1}^2 - f_{L5}^2\right)^2}} \sqrt{\left(\sigma_{MP}\right)^2 + \left(\sigma_{Noise}\right)^2}$$

$$\sigma_{MP}\left(\theta\right) = 0.13[\mathrm{m}] + 0.53[\mathrm{m}]\exp(-\theta / 10[\mathrm{deg}])$$

$$\sigma_{Noise}\left(\theta\right) = 0.15[\mathrm{m}] + 0.43[\mathrm{m}]\exp(-\theta / 6.9[\mathrm{deg}]) \qquad (37)$$

where θ is the elevation angle in degrees. This represents an overbound of the error after carrier smoothing.

The tropospheric delay $\sigma_{n,tropo}$ can be modelled according to [RD-46] as

$$\sigma_{n,tropo}\left(\theta\right) = 0.12[\mathrm{m}] \frac{1.001}{\sqrt{0.002001 + \left(\sin\left(\frac{\pi\theta}{180}\right)\right)^2}} \qquad (37)$$

A.VI.2. NOMINAL ERROR MODEL FOR SINGLE FREQUENCY (L1 OR L5)

The standard deviation of the nominal error model for single frequency (used to compute C_{int}, as in [RD-54]) is given by:

$$\sigma_i^2 = \sigma_{URA,i}^2 + \sigma_{tropo,i}^2 + \sigma_{SFuser,i}^2 + \sigma_{iono,i}^2 \tag{38}$$

The third term, which bounds the code noise and multipath is defined here as a fraction of the code noise and multipath term used for dual frequency (defined in [RD-54]):

$$\sigma_{SFuser,i} = \sqrt{\frac{\left(f_{L1}^2 - f_{L5}^2\right)^2}{f_{L1}^4 + f_{L5}^4}}\sigma_{user,i} \tag{39}$$

(This correction undoes the correction made in [RD-54] for dual frequency GPS and scales down the corresponding Galileo term.)

For L1, the standard deviation of the ionospheric delay error bound is equal to $\sigma_{i,UIRE}$ as defined in Appendix J of [RD-10]. For L5, the error bound must account for the increased uncertainty due to the difference between the L1 and L5 frequencies f_{L1} and f_{L5}. We have in this case:

$$\sigma_{iono,i}^2 = \frac{{f_{L1}}^4}{{f_{L5}}^4}\sigma_{i,UIRE}^2 \tag{40}$$

A.VII METHODS TO SOLVE THE VPL EQUATION

A.VII.1. ITERATIVE METHOD

The VPL can be obtained by solving the following equation using a half interval search:

$$P_{exceed}\left(VPL\right) = PHMI_{VERT,ADJ} \tag{41}$$

where:

$$P_{exceed}\left(VPL\right) = 2Q\left(\frac{VPL - b_3^{(0)}}{\sigma_3^{(0)}}\right) + \sum_{k=1}^{N_{fault\ modes}} p_{fault,k} Q\left(\frac{VPL - T_{k,3} - b_3^{(k)}}{\sigma_3^{(k)}}\right) \tag{42}$$

and:

$$PHMI_{VERT,ADJ} = PHMI_{VERT}\left(1 - \frac{P_{sat,not\ monitored} + P_{const,not\ monitored}}{PHMI_{VERT} + PHMI_{HOR}}\right) \tag{43}$$

This search can be started with the lower and upper bounds which relate to full and even allocation of the integrity risk, respectively, and are given by:

$$VPL_{low,init} = \max\left\{\begin{matrix} Q^{-1}\left(\dfrac{PHMI_{VERT,ADJ}}{2}\right)\sigma_3^{(0)} + b_3^{(0)}, \\ \max\limits_k Q^{-1}\left(\dfrac{PHMI_{VERT,ADJ}}{p_{fault,k}}\right)\sigma_3^{(k)} + T_{k,3} + b_3^{(k)} \end{matrix}\right\} \tag{44}$$

$$VPL_{up,init} = \max\left\{\begin{matrix} Q^{-1}\left(\dfrac{PHMI_{VERT,ADJ}}{2\left(N_{faults}+1\right)}\right)\sigma_3^{(0)} + b_3^{(0)}, \\ \max\limits_k Q^{-1}\left(\dfrac{PHMI_{VERT,ADJ}}{p_{fault,k}\left(N_{faults}+1\right)}\right)\sigma_3^{(k)} + T_{k,3} + b_3^{(k)} \end{matrix}\right\} \tag{45}$$

The iterations stop when:

$$\left|VPL_{up} - VPL_{low}\right| \leq TOL_{PL} \tag{46}$$

or when the number of iterations exceeds $N_{iter,max}$. The final VPL is given by VPL_{up} at the end of iteration. In the case of HPL_1 and HPL_2, the approach is identical, but the appropriate parameters must be changed.

A.VII.2. APPROXIMATION NOT REQUIRING AN ITERATIVE ALGORITHM

The function P_{exceed} is convex so a linear approximation provides a tight upper bound of the VPL:

$$\begin{aligned} &VPL_{approx,upper} = VPL_{low,init} + \\ &\left(PHMI_{VERT} - P_{exceed}\left(VPL_{low,init}\right)\right)\times \\ &\frac{VPL_{upper,init} - VPL_{low,init}}{P_{exceed}\left(VPL_{upper,init}\right) - P_{exceed}\left(VPL_{low,init}\right)} \end{aligned} \tag{47}$$

Similarly, the function log P_{exceed} is concave, so a linear approximation provides a tight lower bound:

$$VPL_{approx,low} = VPL_{low,init} + \left(\log PHMI_{VERT,ADJ} - \log P_{exceed}\left(VPL_{low,init}\right)\right)\times \frac{VPL_{upper,init} - VPL_{low,init}}{\log P_{exceed}\left(VPL_{upper,init}\right) - \log P_{exceed}\left(VPL_{low,init}\right)} \quad (48)$$

This approximation does not provide a bound as tight as the iterative method, but it might be sufficient.

A.VIII ALGORITHM THAT DETERMINES THE MAXIMUM SIZE OF THE SUBSETS THAT NEED TO BE MONITORED AND THE CONTRIBUTION TO THE INTEGRITY BUDGET OF ALL UNMONITORED SUBSETS

A.VIII.1. PROBABILITY OF SUBSET FAULT

In the following equations, $P_{event,i}$ is the prior probability of the independent fault event i, which is included in the Integrity Support Message. The probability of the set of events i_1, i_2,…, i_r, and no other fault is:

$$\prod_{s=1,\cdots,r} P_{event,i_s} \prod_{s\neq 1,\cdots,r}\left(1-P_{event,i_s}\right) = \prod_{k=1}^{N_{sat}+N_{const}}\left(1-P_{event,k}\right)\prod_{s=1,\cdots,r}\frac{P_{event,i_s}}{1-P_{event,i_s}} = P_{no\_fault}\prod_{s=1,\cdots,r}\frac{P_{event,i_s}}{1-P_{event,i_s}} \quad (49)$$

where:

$$P_{no\,fault} = \prod_{k=1}^{N_{Sat}+N_{const}}\left(1-P_{event,k}\right) \quad (50)$$

This probability is bounded by the probability of the simultaneous events i_1, i_2,…, i_r:

$$\prod_{s=1}^{r} P_{event,i_s} \quad (51)$$

A.VIII.2. PROBABILITY OF R OR MORE INDEPENDENT EVENTS

For $r = 1$, $r = 2$, and $r = 3$, the exact probability can be easily computed.

The probability that there are one or more faults is given by:

$$1 - P_{no\,fault} \quad (52)$$

The probability that there are two or more faults is given by:

$$1 - P_{no\,fault} - P_{no\,fault} \sum_{i_1=1}^{N_{sat}+N_{const}} \frac{P_{event,i_1}}{1-P_{event,i_1}} \tag{52}$$

The probability that there are three or more simultaneous faults is given by:

$$1 - P_{no\,fault}\left(1 + \sum_{i_1=1}^{N_{sat}+N_{const}} \frac{P_{event,i_1}}{1-P_{event,i_1}}\right) - P_{no\,fault} \sum_{i_1<i_2} \frac{P_{event,i_1}}{1-P_{event,i_1}} \frac{P_{event,i_2}}{1-P_{event,i_2}} \tag{53}$$

The probability that *r* or more satellites are faulted is smaller than:

$$P_{multiple}\left(r, P_{event,1}, \dots, P_{event,N_{sat}+N_{const}}\right) \leq \sum_{i_1<i_2<\cdots<i_r} \prod_{i_1,i_2,\dots,i_r} P_{event}, i_j = \sum_{i_1<i_2<\cdots<i_r} P_{event,i_1} \dots P_{event,i_r} \tag{54}$$

The formula increases in complexity with *r*. An upper bound is given by:

$$P_{multiple}\left(r, P_{event,1}, \dots, P_{event,N_{sat}+N_{const}}\right) =$$

$$= \sum_{i_1<i_2<\cdots<i_r} P_{event,i_1} \cdots P_{event,i_r} \leq \frac{\left(\sum_{k=1}^{N_{sat}+N_{const}} P_{event,k}\right)^r}{r!} \tag{55}$$

This upper bound can be shown by considering the development of the right term and noticing that the left term is a subset of the resulting terms.

A.VIII.3. DETERMINATION OF $N_{FAULT,MAX}$

Using Equation (56), $N_{fault,max}$ can be determined by:

$$N_{faul,max} = \varphi_{P_{THRES}}\left(\sum_{k=1}^{N_{sat}+N_{const}} P_{event,k}\right) \tag{56}$$

$\varphi_{P_{THRES}}$ is defined by:

$$\varphi_{P_{THRES}}(u) = \min\left\{r \middle| \frac{u^{r+1}}{(r+1)!} \leq P_{THRES}\right\} \tag{57}$$

With this definition, we have:

$$\varphi_{P_{THRES}}(u) = 0 \text{ for } u \leq P_{THRES}$$

$$\varphi_{P_{THRES}}(u) = 1 \text{ for } P_{THRES} \leq u \leq (2P_{THRES})^{\frac{1}{2}}$$

$$\varphi_{P_{THRES}}(u) = 2 \text{ for } (2P_{THRES})^{\frac{1}{2}} \leq u \leq (6P_{THRES})^{\frac{1}{3}} \tag{58}$$

More generally:

$$\varphi_{P_{THRES}}(u) = r \quad for$$

$$(r!\,P_{THRES})^{\frac{1}{r}} \leq u \leq \left((r+1)!\,P_{THRES}\right)^{\frac{1}{r+1}} \tag{59}$$

A.VIII.4. EXAMPLE OF MINIMUM SUBSET SIZE

The table below shows the minimum number of simultaneous satellite faults that need to be tested as a function of P_{event} (assuming it is the same for all events) and $N_{sat}+N_{const}$. For example, for 35 events and a prior of $5\text{x}10^{-4}$, the total probability of 4 or more simultaneous events is below the threshold P_{THRES}, and only subsets with 1, 2, or 3 faults need to be taken into account.

Table 30: $N_{fault,max}$ as a function of P_{event} and $N_{sat}+N_{const}$

$P_{event}/N_{sat}+N_{const}$	10	15	20	25	30	35	40
10^{-5}	1	1	1	1	1	1	1
10^{-4}	2	2	2	2	2	2	2
$5 \text{ x } 10^{-4}$	2	2	3	3	3	3	3
10^{-3}	3	3	3	3	3	3	4

A.IX NUMERICAL EXAMPLE

We consider the geometry defined by G:

$$G = \begin{bmatrix} 0.0225 & 0.9951 & -0.0966 & 1 & 0 \\ 0.6750 & -0.6900 & -0.2612 & 1 & 0 \\ 0.0723 & -0.6601 & 0.7477 & 1 & 0 \\ -0.9398 & 0.2553 & -0.2269 & 1 & 0 \\ -0.5907 & -0.7539 & -0.2877 & 1 & 0 \\ -0.3236 & -0.0354 & -0.9455 & 0 & 1 \\ -0.6748 & 0.4356 & -0.5957 & 0 & 1 \\ 0.0938 & -0.7004 & -0.7075 & 0 & 1 \\ 0.5571 & 0.3088 & -0.7709 & 0 & 1 \\ 0.6622 & 0.6958 & -0.2780 & 0 & 1 \end{bmatrix} \tag{60}$$

We assume that for all satellites:

$$\sigma_{URA,i}\text{=.75 m} \quad \sigma_{URE,i}\text{=.50 m} \quad P_{sat,i}=10^{-5}$$

$$b_{nom,i} = 0.5 \text{ m} \tag{61}$$

For the two constellations we assume:

$$P_{const,j}=10^{-4} \tag{62}$$

Following the steps outlined in the paper and using the preliminary values introduced in the list of constants we have:

$$C_{\text{int}} = diag\left(\begin{matrix} [3.8865 & 1.4377 & 0.8604 & 1.6383 & 1.3229 \\ 0.8434 & 0.8963 & 0.8669 & 0.8573 & 1.3616] \end{matrix} \right)$$

$$C_{acc} = diag\left(\begin{matrix} [3.5740 & 1.1252 & 0.5479 & 1.3258 & 1.0104 \\ 0.5309 & 0.5838 & 0.5544 & 0.5448 & 1.0491] \end{matrix} \right)$$

$$N_{fault,max} = 1 \tag{63}$$

That is, subset fault modes include all *n-1* subsets, as well as the two constellation fault modes. Let k and k' be the indexes corresponding to the two constellation fault modes. We have:

$$\begin{aligned} \sigma_3^{(k)} &= 2.5760 \text{ m} & \sigma_3^{(k')} &= 2.5577 \text{ m} \\ \sigma_{ss,3}^{(k)} &= 1.5307 \text{ m} & \sigma_{ss,3}^{(k')} &= 1.5292 \text{ m} \\ b_3^{(k)} &= 2.8935 \text{ m} & b_3^{(k')} &= 2.0875 \text{ m} \end{aligned} \tag{64}$$

(We do not write the standard deviations for all the other subsets.) We have:

$$K_{fa,3} = Q^{-1}\left(\frac{P_{FA\_VERT}}{2N_{fault \text{ modes}}}\right) = Q^{-1}\left(\frac{3.9\times10^{-6}}{2\times57}\right) = 5.3953 \tag{65}$$

The solution to Equation (24) is:

$$VPL = 19.2\ m$$

The HPL is given by Equation (26) and is:

$$HPL = 14.5\ m$$

The EMT is given by Equation (34) and is:

$$VPL = 8.3\ m$$

The standard deviation of the all-in-view given by Equation (31) is:

$$\sigma_{v,acc} = 1.47\ m$$

Annex B. **ARAIM FAULT ASSERTIONS**

The purpose of this annex is to expose certain key definitions and assertions that are considered to be foundational to design of ARAIM architectures, algorithms, and integrity support messages. These definitions and assertions are based on a current perspective of ARAIM, with special emphasis on integrity. It is expected that they will be amended or revised as the ARAIM concept evolves over time.

DEFINITIONS

Definition 1: An SIS *fault state* is said to exist on satellite i in constellation j when the magnitude of the instantaneous SIS ranging error $e_{i,j}$ is greater than $k_{f,j} \times \sigma_{URA,i,j}$ at the worst user location.

> NOTE 1 — For the purpose of this definition the values of $k_{f,j}$ and $\sigma_{URA,i,j}$ are to be interpreted as known quantities. These parameters will be defined in the Assertions below.
>
> NOTE 2 — It is expected that the Galileo SISA will be equivalent in purpose to the GPS URA.

Definition 2: The probability that, at any given time and due to a common cause, any subset of two or more satellites within constellation j are in a fault state is no greater than $P_{const,j}$.

> NOTE 1 — Common cause satellite faults are also known as *wide faults* (WF). One example is blundered navigation data broadcast by multiple satellites, with a common cause originating at the CSP ground segment.

Definition 2a: The probability that, at any given time and due to a common cause, any subset of two or more satellites within constellation j and at least two in view of user u are in a fault state is no greater than $P_{const,j,u}$.

> NOTE — $P_{const,j,u}$ depends on how many (and possibly which) satellites the user is tracking and varies with user location and time of day.

Definition 3: The probability that, at any given time, satellite i in constellation j is in a fault state, excluding the multiple-satellite faults covered by Definition 2 is no greater than $P_{sat,i,j}$.

> NOTE — Such faults are called independent satellite faults—also known as narrow faults (NF)—and can be caused by erroneous satellite navigation data or anomalous satellite payload events. The probability that satellites i and k are simultaneously affected by independent fault modes is no greater than $P_{sat,i,j} \times P_{sat,k,j}$.

ASSERTIONS

Assertion 1: When using constellation j = GPS for H-ARAIM, it is acceptable to use $P_{const,GPS}$ = 0.

Rationale:

1. Misleading information during en route, terminal, or non-precision approach navigation is designated a *major* failure in FAA AC 20-138B [RD-71].

2. Existing RAIM (RTCA DO-229D) operates with GPS only, and has been certified and used for these aviation applications for over 15 years with $P_{const,GPS}$ = 0.

3. H-ARAIM will be used for the same applications as existing RAIM.

4. H-ARAIM will use GPS satellites for the same function as they are used in existing RAIM.

5. FAA AC 23.1309-1E states that "similarity" arguments are acceptable in the analysis of major failure conditions [RD-72] (See note below).

6. Therefore it is acceptable to use $P_{const,GPS}$ = 0 for H-ARAIM.

NOTE — Relevant text from FAA AC 23.1309-1E (Sec. 17c, p. 29):

"c. Analysis of major failure conditions. An assessment based on engineering judgment is a qualitative assessment, as are several of the methods described below:

(1) Similarity allows validation of a requirement by comparison to the requirements of similar certified systems. The similarity argument gains strength as the period of experience with the system increases. If the system is similar in its relevant attributes to those used in other airplanes and if the functions and effects of failure would be the same, then a design and installation appraisal and satisfactory service history of either the equipment analyzed or of a similar design is usually acceptable for showing compliance. It is the applicant's responsibility to provide data that is accepted, approved, or both, and that supports any claims of similarity to a previous installation."

Assertion 2: When using constellations other than GPS for H-ARAIM, it is not initially acceptable to assume $P_{const,j}$ = 0. However, as operational experience with H-ARAIM is gained over time, RAIM 'similarity' arguments may eventually also support the use of $P_{const,j}$ = 0 for other constellations.

Rationale:

1. H-ARAIM will also use Galileo, and possibly other constellations.

2. This is initially dissimilar to existing RAIM, which uses only GPS.

3. Therefore, a similarity argument following FAA AC 23.1309-1E cannot be used at the onset of service.

Assertion 3: For V-ARAIM, it is not acceptable to assume $P_{const,j}$ = 0 for any constellation, including GPS.

Rationale:

1. The existence of misleading information during precision approach navigation is designated a *hazardous* failure in FAA AC 20-138B [RD-71].

2. FAA AC 23.1309-1E (Sec. 17d, p. 30) states that a detailed safety analysis is required for each hazardous failure [RD-72].

Assertion 4: Each CSP *j*, for each SV i in constellation *j*, shall make σ_{URA,i,j^*}, or its equivalent, available to ANSPs and airborne users, by means of broadcast navigation data or written specification.

NOTE 1 — During fault-free operation, the SIS ranging error is intended by CSP j to follow a normal distribution with zero mean and standard deviation of less than or equal to σ_{URA,i,j^*}.

NOTE 2 — Constellation subscript j^* is used for parameters defined by CSP *j*, whereas the constellation subscript j is used for parameters defined, or adjusted, by an ANSP.

NOTE 3 — It is expected that the Galileo SISA will be equivalent in purpose to the GPS URA.

Assertion 5: Each CSP j will provide to ANSPs, by means of written specification or broadcast navigation data, sufficient information to compute values of state probabilities $P_{sat,i,j}$ and $P_{const,j}$ for faults in Definitions 1, 2, and 3.

NOTE — There are many possible ways to convey such information. Parameters A, B, and C below are the ones currently used by GPS in the SPS Performance Specification [RD-70]. It is possible that in the future GPS may choose to specify the two parameters in D (instead of C) to individually define NF and WF rates. Parameters A through D are used as the basis for Assertions 7, 8, and 9. However, other CSPs (or GPS in the future) may choose different parameter sets. For example, it is possible that in the future some ANSPs could provide $P_{sat,i,j}$ and $P_{const,j}$ directly, instead of parameters C or D below. In this case B would still be needed to assess continuity (not yet addressed in these assertions). Parameter A, used in Assertion 6, is applicable in all cases.

A. $k_{f,j}$ — positive scalar chosen by CSP j to define the fault state via Definition 1, and

B. $MTTN_{j^*}$ — mean (or maximum) time for CSP to notify users of a fault, and either C or D below:

C. R_{TF,i,j^*} — *total fault* (TF) rate for satellite *i* in constellation *j*, including both NF and WF events.

NOTE — R_{TF,i,j^*} may be specified to be the same for all satellites in constellation *j* (as it currently is for GPS: R_{TF,i,j^*} = R_{TF,j^*} = $10^{-5}/\mathrm{hr}/\mathrm{SV}$).

D. R_{NF,i,j^*} and R_{WF,i,j^*} — respectively the NF rate for satellite *i* in constellation *j*, and the rate of occurrence for the set of all WF affecting satellite i in constellation *j*.

NOTE — R_{NF,i,j^*} and R_{WF,i,j^*} may each be specified to be the same for all satellites in constellation *j*.

Assertion 6: ANSPs will implement ground-based offline monitoring of current and archived satellite measurements to compute parameters $b_{nom,i,j}$ and $\alpha_{URA,i,j}$, such that:

A. $\alpha_{URA,i,j} \geq 1$ and $\sigma_{URA,i,j} = \alpha_{URA,i,j} \times \sigma_{URA,i,j^*}$.

B. The CDF of the instantaneous SIS range error is left- and right-CDF overbounded using the distributions $\mathrm{N}\left(-b_{nom,i,j}, \sigma^2_{URA,i,j}\right)$ and $\mathrm{N}\left(b_{nom,i,j}, \sigma^2_{URA,i,j}\right)$ over the range $[\ \Phi^{-1}\left(-k_{f,j} \times \sigma_{URA,i,j}\right),\ 1 - \Phi^{-1}\left(-k_{f,j} \times \sigma_{URA,i,j}\right)\ ]$, where Φ is the standard normal CDF.

C. The following additional effects are accounted for in the computation of $b_{nom,i,j}$ and $\alpha_{URA,i,j}$:

   i. Repeatable or persistent biases in receiver-observed SIS errors – for example, due to signal deformations originating at the satellite. Biases common to all satellites in a constellation are excluded.

   ii. Statistical uncertainty due to limited sample sizes available to the offline monitor function.

   iii. The possibility that satellite SIS ranging errors may not be stationary over long periods.

   iv. SIS ranging errors from different satellites will be combined linearly by aircraft with the assumption of statistical independence.

Assertion 7: ANSPs will implement ground-based offline monitoring to observe operational performance of the satellites and validate or, if necessary, adjust the parameters $MTTN_{j^*}$ and R_{TF,i,j^*}, or R_{NF,i,j^*} and R_{WF,i,j^*}, specified by the CSPs in Assertion 5. The validated or adjusted parameters are denoted $MTTN_j$ and $R_{TF,i,j}$, or $R_{NF,i,j}$ and $R_{WF,i,j}$, and together with $\sigma_{URA,i,j}$, are subject to the constraints:

$$R_{TF,i,j} \geq R_{TF,i,j^*} \quad \text{or} \quad \{\, R_{NF,i,j} \geq R_{NF,i,j^*} \quad \text{and} \quad R_{WF,i,j} \geq R_{WF,i,j^*} \,\}$$

$$\Phi^{-1}(-k_{f,j} \times \sigma_{URA,i,j}) = \begin{cases} R_{TF,i,j} \times MTTN_j \\ \text{or} \\ R_{NF,i,j} \times MTTN_j \end{cases}$$

NOTE 1 — The ANSP-adjusted fault rates $R_{TF,i,j}$, $R_{NF,i,j}$ and $R_{WF,i,j}$ should not be reduced below the CSP-provided values R_{TF,i,j^*}, or R_{NF,i,j^*} and R_{WF,i,j^*}, but may be increased by the offline monitor in case of elevated observed fault rates or statistical uncertainty due to limited sample sizes.

NOTE 2 — The adjusted $MTTN_j$ could potentially be reduced relative from the CSP-provided value $MTTN_{j^*}$, but only if the latter is a specified <u>maximum</u> time to notify and the former is the actual <u>mean</u> time to notify determined from long term observation by the offline monitor.

Assertion 8: From Definition 3, $P_{sat,i,j} := \text{Prob}\{NF_{i,j}\}$, where $NF_{i,j}$ is a narrow fault on satellite i in constellation *j*. If $R_{NF,i,j}$ is available, then $P_{sat,i,j} = R_{NF,i,j} \times MTTN_j$. If only $R_{TF,i,j}$ is available, $R_{TF,i,j} \times MTTN_j \geq P_{sat,i,j}$ may be used as an upper bound.

<u>Proof of upper bound</u>:

Recall that the total fault rate $R_{TF,i,j}$ includes *both* NF and WF events for SV i in constellation *j*, and consider a NF on SV i in constellation *j*.

$$P_{sat,i,j} := \text{Prob}\{NF_{i,j}\} \leq \text{Prob}\{NF_{i,j} \cup WF_{i,j}\} = R_{TF,i,j} \times MTTN_j$$

where $WF_{i,j}$ is the set of all wide faults affecting satellite i in constellation j

Assertion 9: If $R_{WF,i,j}$ is available, then the upper bound $\sum_{i=1}^{n_j} R_{WF,i,j} \times MTTN_j \geq P_{const,j,u}$ may be used. If only $R_{TF,i,j}$ is available, then the looser upper bound $\sum_{i=1}^{n_j} R_{TF,i,j} \times MTTN_j \geq P_{const,j,u}$ may be used.

<u>Proof of upper bound</u>:

$$P_{const,j,u} \leq \sum_{i=1}^{n_j} \text{Prob}\{WF_{i,j}\} = \sum_{i=1}^{n_j} R_{WF,i,j} \times MTTN_j$$

$$\leq \sum_{i=1}^{n_j} \text{Prob}\{NF_{i,j} \cup WF_{i,j}\} = \sum_{i=1}^{n_j} R_{TF,i,j} \times MTTN_j$$

Assertion 9a: In place of $P_{const,j}$, ARAIM users may apply $P_{const,j,u}$.

NOTE 1 — ANSPs will not be aware of which satellites from constellation j are in view of an arbitrary ARAIM user u. Therefore, in the case where only $R_{TF,i,j}$ is available, the ISM, instead of defining $P_{const,j}$ directly, may (via a flag or other indicator) inform users that they may use $P_{const,j} := \sum_{i=1}^{n_j} P_{sat,i,j}$, rather than using the larger value from Definition 2.

NOTE 2 — Alternatively, when selecting a value for $P_{const,j}$ in the ISM, it is sufficient for ANSPs to select a value greater than or equal to maximum value of $P_{const,j,u}$ over all users, rather than using the larger value from Definition 2.

NOTE 3 — Tighter upper bounds may be found in subsequent analysis.

Assertion 10: The GNSS core constellations are sufficiently independent such that the only potential source of common mode error between them comes from incorrect Earth Orientation Parameters (EOPs).

Rationale:

Provided in Milestone 2 Report, Annex C [RD-74].

Assertion 11: The likelihood that incorrect EOPs lead to consistent and harmful errors on more than one constellation at a time is negligible.

Rationale:

Provided in Milestone 2 Report, Annex C [RD-74].

Annex C. **ONLINE MESSAGE FOR V-ARAIM (MESSAGE TYPE 2)**

The proposed concept for the Online V-ARAIM Message Type (Message Type 2) follows that of the established SBAS, which provides correction data to the broadcast GNSS navigation message. Although the ARAIM Ground Segment derives the orbital positions and the onboard clock state independently with respect to the broadcast GNSS navigation messages, only correction data is disseminated by the Message Type 2 to save data bandwidth capacity.

The following naming convention is adopted in this Annex:

MT2	Message Type 2
SOA	Start Of Applicability of the MT2
EOA	End Of Applicability of the MT2
ALOC	Along Track Orbit Correction
ACOC	Across Track Orbit Correction
RTOC	Radial Track Orbit Correction
CC	Clock Correction
ALOE	Along Track Orbit Error
ACOE	Across Track Orbit Error Fim
RTOE	Radial Track Orbit Error
CE	Clock Error
Qe	Quantization Error
LSB	Least significant Bit
OCD	Orbit and Clock Determination & prediction algorithm

The following conventions are adopted for deriving the MT2 content:

- The ECEF orbit position error is expressed in the satellite orbit reference frame {Along-track, Across-track, Radial-track} as defined by the broadcast GNSS navigation message.
- The clock error is expressed relative to the ARAIM Ground Segment System Time.

The maximum orbit-correction and maximum clock-correction at SOA is derived considering that the ARAIM Ground Segment will only overlay satellites flagged healthy by the GNSS Core Constellation provider. For the GPS constellation, the previous consideration limits the GPS SIS URE to 4.42 times the broadcast URA, which is valid for the worst-case location within the satellite footprint. Assuming that in the future GPS III CNAV ephemerides, the URA is below 2.4 m (currently for LNAV this condition is fulfilled ≈ 85% of time), the maximum orbit-correction and maximum clock-correction can be established as follows:

- Max |GPS URE| < 4.42 · 2.4 m ≈ 10.60 m.
- Max |ALOC| is bounded by the ALOE which would result on a 10.60 m URE at a location seeing the SV at 0° elevation. Therefore:
    - Max |GPS URE| > Max |ALOC| · β[9] → Max |ALOC| < 10.60 / 0.24 = 44.2 m
- Max |ACOC| is bounded by the ACOE which would result in a 10.60 m URE at a location seeing the SV at 0° elevation. Therefore:

[9] β = Radius Earth/SMA of satellite, β > 0.24 for all GNSS constellations

  - o Max |GPS URE| > Max |ACOC| · β → Max |ACOC| < 10.60 / 0.24 = 44.2 m
- Max |RTOE| is bounded by the RTOE which would result in a 10.60 m URE at a location seeing the SV at 90° elevation. Therefore:
  - o Max |GPS URE| > Max |RTOC| → Max |RTOC| < 10.60 m
- Maximum |CE| is bounded by the CE which would result in a 10.60 m URE. Therefore:
  - o Max |GPS URE| > Max |CC| → Max |CC| < 10.60 m

The results above are valid for the GALILEO I/NAV (FOC) navigation message given that the GALILEO URE (rms) < 0.65 m, and that 10.60 / 0.65 > 15 σ.

The range quantization-error at SOA is < 3 cm (σ). This is derived hereafter, under the assumption of uniformly and independent distributed quantization errors (σ ≈ 0.29 LSB):

$$Qe(\sigma)^2 < 0.24^2 \cdot [Qe(ALOC)^2 + Qe(ACOC)^2] + Qe(RTOC)^2 + Qe(CC)^2$$

$$< 0.07^2 \cdot [LSB(ALOC)^2 + LSB(ACOC)^2] + 0.29^2 \cdot [LSB(RTOC)^2 + LSB(CC)^2]$$

$$< 0.10^2 \cdot LSB(ALOC)^2 + 0.42^2 \cdot LSB(RTOC)^2$$

considering: LSB(ALOC) = LSB(ACOC) & LSB(RTOC) = LSB(CC)

It can be observed that the range quantization error (σ^2) < 0.03^2 m, for LSB(ALOC) = LSB(ACOC) = 0.2496 m and LSB(RTOC) = LSB(CC) = 0.0312 m.

From the above it can be concluded that the orbit-correction and clock-correction at SOA can be formatted as follows:

Table 31: Format of orbit and clock correction at SOA

CORRECTION AT SOA	|MAX| Required (m)	LSB (m)	BITS	≈ RANGE (m)
Orbit Along Track (ALOE)	50.5	0.2496	09	[-63.89 m, +63.64 m]
Orbit Across Track (ACOE)	50.5	0.2496	09	[-63.89 m, +63.64 m]
Orbit Radial Track (RTOE)	10.6	0.0312	10	[-15.97 m, +15.94 m]
Clock (CE)	10.6	0.0312	12	[-63.89 m, +63.86 m]
TOTAL			**40**	

To validate the adequacy of the numerical range for the SOA corrections, an ESA orbit and clock determination and prediction algorithm (OCD), which is assumed to reasonably represent the GNSS Core Constellation OCD, has been used to evaluate the navigation message error degradation over time for GPS IIR satellites. Concretely, more than 3500 prediction realizations over a 10 month period have been analysed, and the maximum |ALOE|, |ACOE|, |RTOE|, and |CE| error excursions have been compared against the above established maximums. The comparison is detailed in the next four figures, which indicate on the right the ALOE, ACOE, RTOE, and CE time series over the 12 hour prediction for each of the 3500 realizations; and on the left the ALOE, ACOE, RTOE, and CE error percentiles over prediction time. It can be observed that:

- Max |ALOE| < 15 m $\rightarrow$ 2 · Max |ALOE| << 64 m $\approx$ Max |ALOC|
- Max |ACOE| < 08 m $\rightarrow$ 2 · Max |ACOE| << 64 m $\approx$ Max |ACOC|
- Max |RTOE| < 04 m $\rightarrow$ 2 · Max |RTOE| << 16 m $\approx$ Max |RTOC|
- Max |CE| < 06 m $\rightarrow$ 2 · Max |CE| < 64 m $\approx$ Max |CC|

where the factor 2 on the right inequalities, is used to extrapolate the results from 12 hours to 24 hours (considering the linear trend observed on the stable percentiles) and the nominal GPS policy for navigation message uploads (once per day).

A complementary validation of the numerical range for the SOA corrections has been performed by evaluating the actual ALOE, ACOE, RTOE, and CE error time series of all GPS navigation messages (throughout the four hours validity) broadcast over a one year period with URA not higher than 2.4 m (representative of future GPS III CNAV ephemerides). The results are detailed on the following four figures, and indicate that 1 bit can be saved for Max |ACOE|.

The orbit-correction at EOA is expressed as the orbit-correction at SOA + ∆orbit-correction at EOA (∆ALOC, ∆ACOC, ∆RTOC). Analogously the clock-correction at EOA is expressed as the clock-correction at SOA + ∆clock-correction at EOA (∆CC). Considering that the MT2 is refreshed every 12 min (GAL I/NAV frame refresh period), EOA-SOA is assumed to be 12 min.

The maximum EOA ∆orbit-corrections (Max |∆ALOC|, Max |∆ACOC|, and Max |∆RTOC|) and the maximum EOA ∆clock-correction (Max |∆CC|) have been derived from an inspection of the above mentioned ALOE, ACOE, RTOE, and CE time series. It is observed that:

- |ALOC at EOA - ALOC at SOA| = |∆ALOC| = |∆ALOE| << 8 m
- |ACOC at EOA - ACOC at SOA| = |∆ACOC| = |∆ACOE| << 4 m
- |RTOC at EOA - RTOC at SOA| = |∆RTOC| = |∆RTOE| << 2 m
- |CC at EOA - CC at SOA| = |∆CC| = |∆CE| << 2 m

The range quantization-error at EOA associated with the ∆orbit-correction/∆clock-correction quantization error is < 3 cm (σ).

From the above, the ∆orbit-correction and ∆clock-correction at EOA can be formatted as indicated in the next table where the ∆corrections have been expressed as correction rates by dividing by [t_{EOA} - t_{SOA}]. Note that 2 bits margin have been included for the ∆clock-correction.

Table 32: Format of orbit and clock correction at EOA

Δ CORRECTION AT EOA	**LSB (m/s)**	**BITS**	**RANGE**
Orbit Along Track Error Rate	0.000346666	06	[-0.0111 m/s … +0.0107 m/s]
Orbit Across Track Error Rate	0.000346666	06	[-0.0111 m/s … +0.0107 m/s]
Orbit Radial Track Error Rate	0.000043333	07	[-0.0028 m/s … +0.0027 m/s]
Clock Error Rate	0.000043333	11	[-0.0444 m/s … +0.0443 m/s]
TOTAL		**30**	

The corrections at any other time t within [SOA, EOA] are derived from the expressions:

- ALOC(t) = ALOC(tSOA) + [t - tSOA] / [tEOA - tSOA] · ΔALOC(tEOA)
- ACOC(t) = ACOC(tSOA) + [t - tSOA] / [tEOA - tSOA] · ΔACOC(tEOA)
- RTOC(t) = RTOC(tSOA) + [t - tSOA] / [tEOA - tSOA] · ΔRTOC(tEOA)
- CC(t) = $CC(t_{SOA}) + [t - t_{SOA}] / [t_{EOA} - t_{SOA}] \cdot \Delta CC(t_{EOA})$

The quantization error at an arbitrary time within [SOA, EOA] can be estimated considering that for each user the range error ε(t) varies within [SOA, EOA] according to the following equation:

$$\varepsilon(t) = \varepsilon(t_{SOA}) + [t - t_{SOA}] / [t_{EOA} - t_{SOA}] \cdot [\varepsilon(t_{EOA}) - \varepsilon(t_{SOA})]$$

Therefore

$$Qe(\varepsilon(t)) = Qe(\varepsilon(t_{SOA})) + [t - t_{SOA}]^2 / [t_{EOA} - t_{SOA}]^2 \cdot Qe(\Delta\varepsilon(t_{EOA}))$$

and given that the quantization errors $Qe(\varepsilon(t_{SOA}))$ and $Qe(\Delta\varepsilon(t_{EOA})$ are independent

$$Var\{Qe(\varepsilon(t))\} < Var\{Qe(\varepsilon(t_{SOA}))\} + Var\{Qe(\Delta\varepsilon(t_{EOA}))\} \approx 4^2 \text{ cm}$$

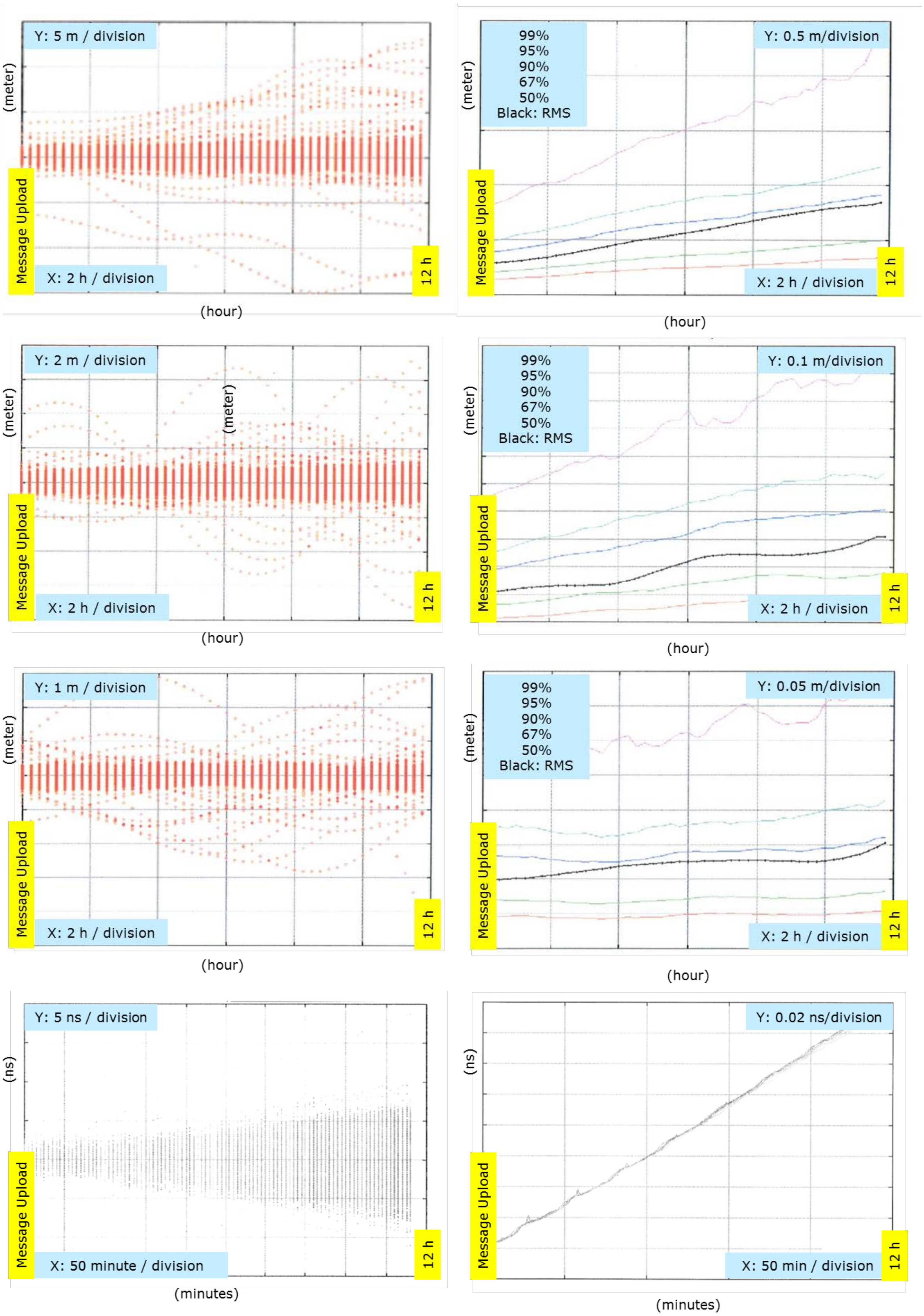


Figure 15 1st row: ALOE. 2nd row: ACOE. 3rd row RTOE. 4th row CE (in all cases over prediction time).

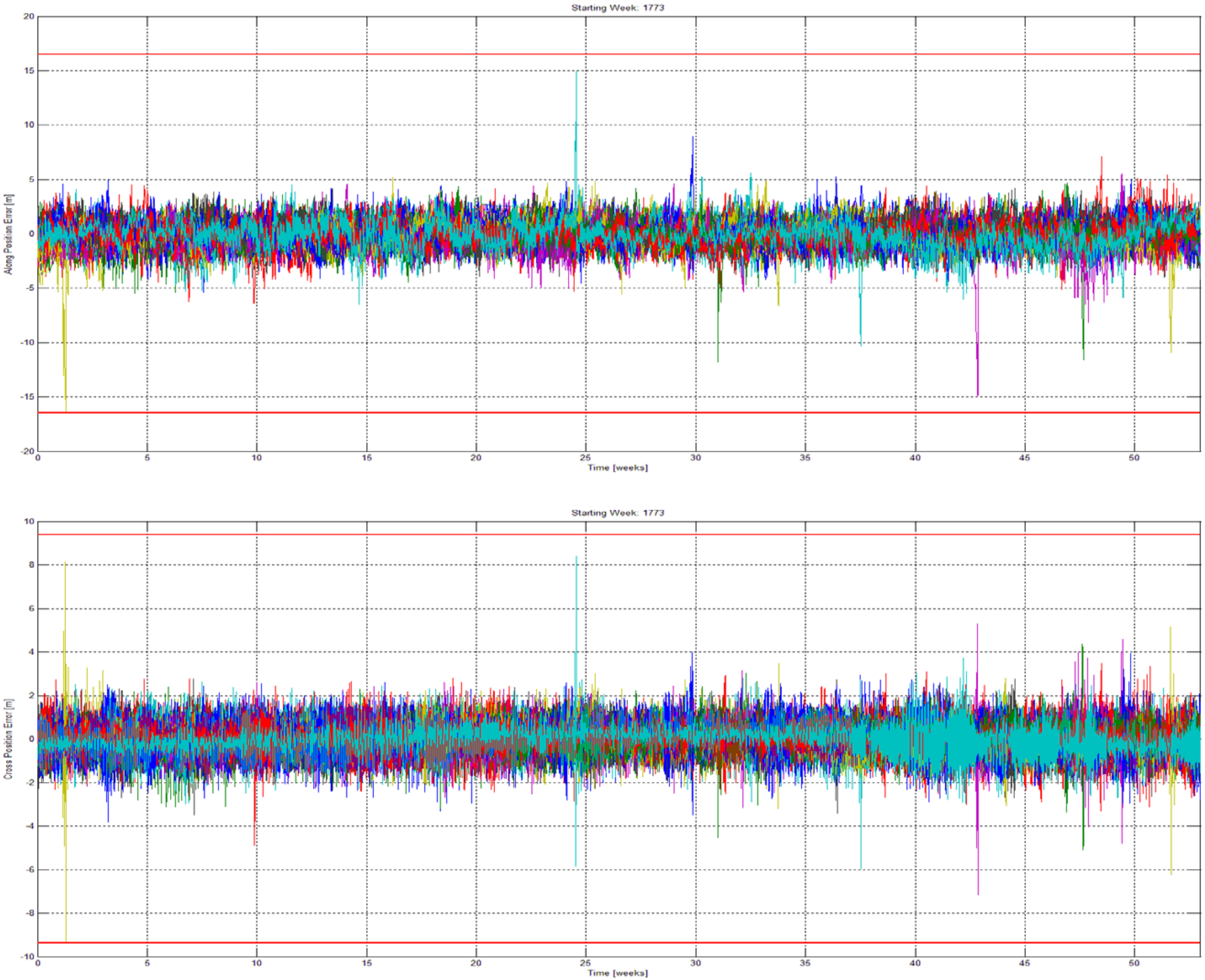


Figure 16 . 1st row: ALOE. 2nd row: ACOE (red line corresponds to max observed error).

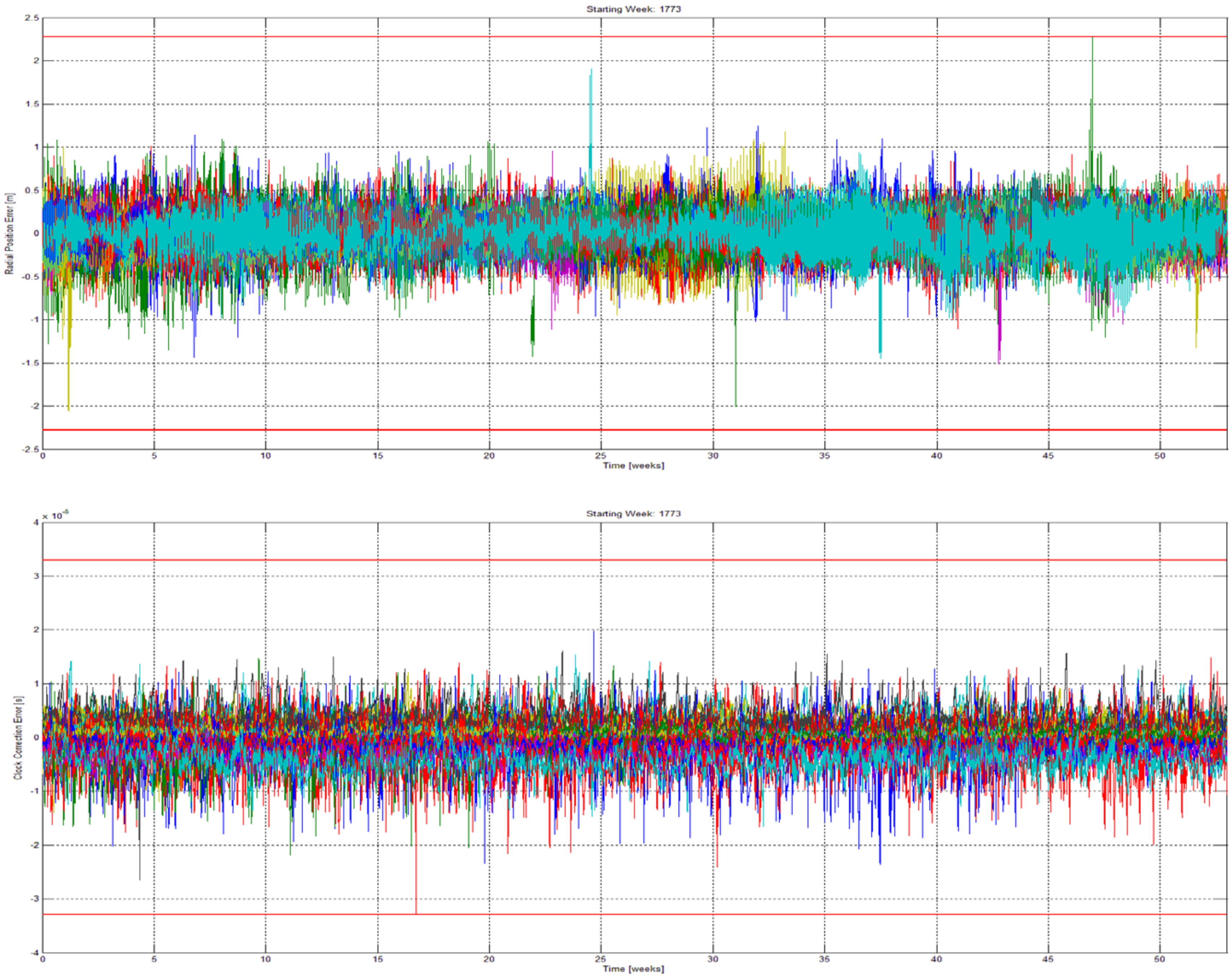


Figure 18. 1st row: RTOE. 2nd row: CE (red line corresponds to max observed error).

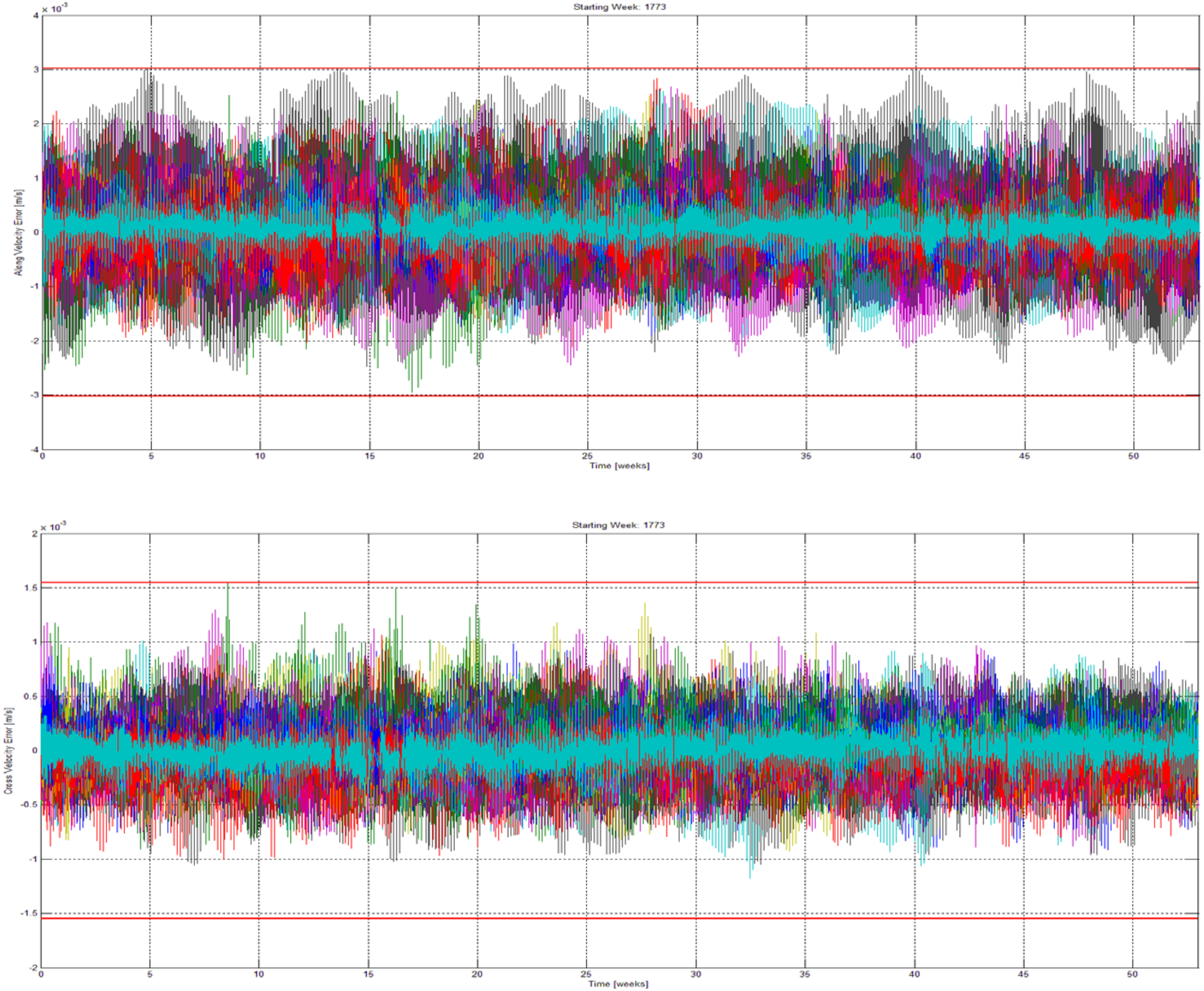


Figure 20. 1st row: ALOE rate. 2nd row: ATOE rate (red line corresponds to max observed error).

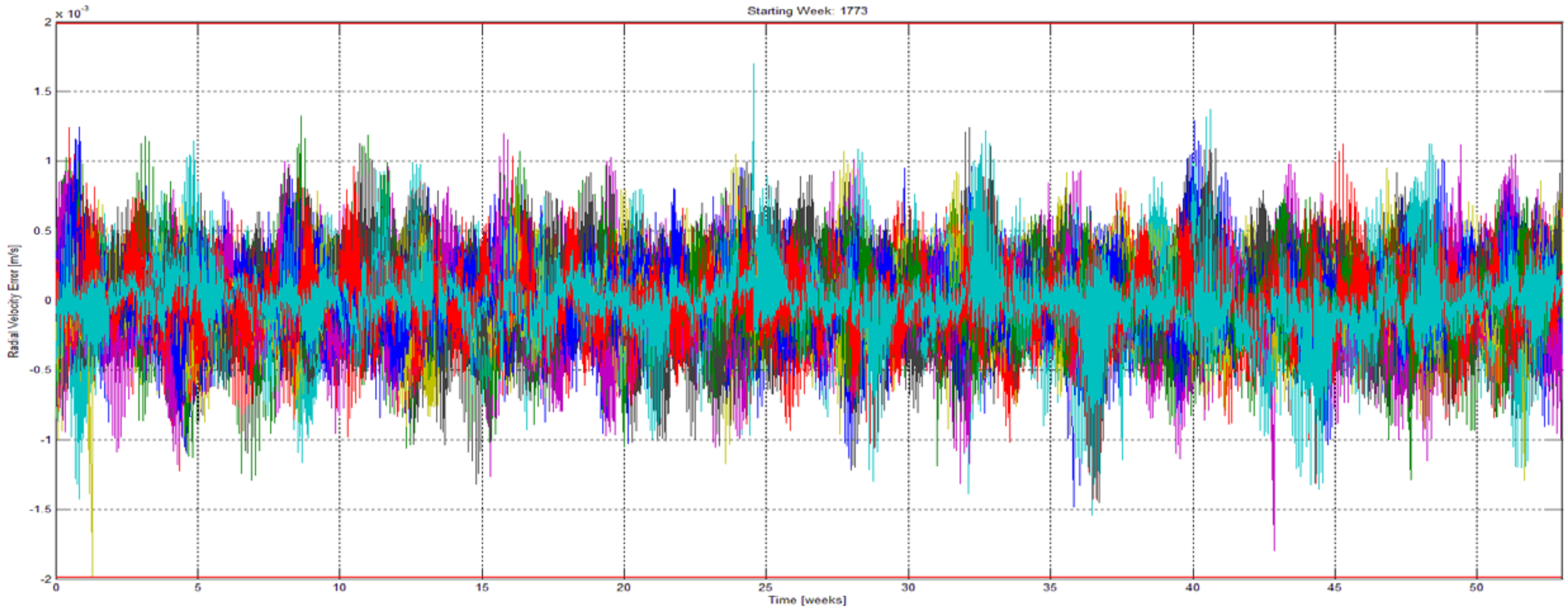


Figure 19. Radial velocity error (operational GPS) (red line corresponds to max observed error)

The above described ALOE, ACOE, RTOE, and CE correction formats at SOA are compacted in the MT2 as described in the next table.

Table 33: MT2 ALOE, ACOE, RTOE and CE corrections at SOA

CORRECTION AT SOA	LSB (m)	BITS	MAXIMUM RANGE (m)
Orbit Along Track	0.2496 m	09	[-63.8976 m, +63.6480 m]
Orbit Across Track	0.2496 m	08	[-31.9488 m, +31.6992 m]
Common	0.0312 m	12	[-63.8976 m, +63.8664 m]
Distance	0.0312 m	5	[-00.4992 m, +00.4680 m]
TOTAL		**34**	

The optimization profits from the saving of 1 bit in ACOC and from the transformation of the {“Orbit Radial Track,” “Clock”} correction pair into the {“Common,” “Distance”} correction pair, which is elaborated afterwards. The following naming convention is adopted:

- RTOE: ε_r .
- CE: ε_c .
- Common: ε_{co} .
- Distance: ε_{di} .
- Line of sight vector: $\vec{u}_r$.
- Maximum off-nadir-axis angle within the satellite coverage area: β .
- Off-nadir-axis angle for an arbitrary user within the coverage area: β^* .

The { ε_{co} , ε_{di} } correction pair is defined by the following transformation from the { ε_r , ε_c } correction pair:

$$\begin{bmatrix} \varepsilon_{co} \\ \varepsilon_{di} \end{bmatrix} = \begin{bmatrix} \cos\beta & 1 \\ 2\sin^2\dfrac{\beta}{2} & 0 \end{bmatrix} \begin{bmatrix} \varepsilon_r \\ \varepsilon_c \end{bmatrix}$$

$$\varepsilon_{co} = \varepsilon_r \cdot \cos\beta + \varepsilon_c$$

$$\varepsilon_{di} = \varepsilon_r - \varepsilon_r \cdot \cos\beta = 2\varepsilon_r \sin^2\left(\frac{\beta}{2}\right)$$

The range for the ε_{co} correction can be derived conservatively (without considering negative correlation effects) considering that:

$$\sigma(\varepsilon_{co}) = \sqrt{\sigma^2(\varepsilon_r)\cdot\cos^2\beta + \sigma^2(\varepsilon_c)} < \sqrt{\sigma^2(\varepsilon_r) + \sigma^2(\varepsilon_c)} = f\cdot\sigma(\varepsilon_c)$$

Given that $\sigma^2(\varepsilon_r) << \sigma^2(\varepsilon_c)$ and given the existing margin for the clock representation, $f=1$ is a good practical approximation. Based on these considerations, the proposed range for the ε_{co} correction is identical to the range for the ε_{co} correction.

The range for the ε_{di} correction can be derived considering that:

$$\max\{|\varepsilon_{di}|\} = 2\sin^2\left(\frac{\beta}{2}\right)\cdot\max\{|\varepsilon_r|\} \approx 0.03\cdot\max\{|\varepsilon_r|\}$$

Therefore the necessary range for the “Distance” correction is 0.03 · [-15.9744 m, +15.9432 m] = [-0.479232 m, +0.478296 m] which is achieved by a representation based on 5 bits (actual range provided is [-0.4992 m, +0.4680 m]). The compact representation of the orbit and clock corrections at SOA requires just 34 bits.

The orbit and clock Δcorrections at MT2 EOA are replaced, as before, by the correction rates considering the time span between SOA and EOA (12 minutes).

Table 34: MT2 ALOE, ACOE, RTOE and CE corrections at EOA

CORRECTION RATE	LSB (m/s)	BITS	MAXIMUM RANGE (m)
Orbit Along Track	0.000346666	06	[-0.011093333 m/s, +0.010746666 m/s]
Orbit Across Track	0.000346666	05	[-0.011093333 m/s, +0.010746666 m/s]
Common	0.000043333	11	[-0.044373333 m/s, +0.044333333 m/s]
Distance	0.000043333	03	[-0.000173333 m/s, +0.000130000 m/s]
TOTAL		**25**	

Annex D. List Of References

[RD-01] Terms of Reference of the WG-C ARAIM subgroup

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