EU-U.S. Cooperation on Satellite Navigation

Working Group C-ARAIM Technical Subgroup

Milestone 2 Report

Final Version

February 11th, 2015

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 enroute 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 called 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 decision altitude (DA) as low as 200 feet height above touchdown. The ARAIM TSG focuses on ARAIM architectures to support LPV-200 or LPV-250 (250 foot DA) globally.

This document is the second milestone report in a three-phase effort. It describes the ARAIM architectures that will be presented to the larger aviation community for their comments during late 2014 to early 2015. This report has been 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), 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 Overview: ARAIM must ensure navigation integrity for enroute flight, terminal, and approach operations. For the latter, it must detect all hazardous faults in the underlying Global Navigation Satellite System (GNSS) within seconds. In the case of LPV-200 or LPV-250, ARAIM must ensure that the pilot is warned within six seconds of any hazardously misleading information (HMI), i.e., before the navigation sensor error is greater than a certain amount (currently set to be 35 metres vertical for LPV-200 under Satellite Based Augmentation Systems (SBAS)). Auxiliary requirements are identified in Section 2 of the report.

ARAIM is intended to support air navigation for several decades. As such, it must be flexible because we do not want air navigation to have a brittle dependence on the health of the underlying GNSS core constellations (e.g., Global Positioning System (GPS), Galileo, GLONASS, BeiDou/Compass, etc.). Thus, ARAIM must allow new satellites and constellations to come into use by aviators while taking into account their fault rates and nominal error characteristics. These fault rates may be higher for new constellations and decrease as the constellation matures.

ARAIM is an advanced version of receiver autonomous integrity monitoring (RAIM), which has been known to the aviation community since the late 1980s. While RAIM supports lateral navigation only, ARAIM may support horizontal and vertical guidance (LPV-200), which changes the severity level of an HMI event from major (RAIM) to hazardous (ARAIM). The original version of RAIM was based on a set of fixed assertions regarding the nominal performance and fault rates of GPS. In contrast, ARAIM allows a ground system to provide updates regarding the nominal performance and fault rates of the multiplicity of contributing constellations. This integrity data is contained in the Integrity Support Message (ISM) that is developed on the ground and provided to the airborne fleet. The ISM enables this update advantage for evolving constellations without requiring equipment changes.

The ARAIM TSG developed ARAIM architectures that support the following navigation objectives:

- **Horizontal ARAIM** to support horizontal navigation based on an occasional ISM from the ground.
- **Offline ARAIM** to support horizontal and vertical navigation based on a monthly ISM from the ground.
- **Online ARAIM** to support horizontal and vertical navigation based on an hourly ISM from the ground.

Figures E-1, E-2, and E-3 show these architectures and they are described in the remainder of this Executive Summary. Horizontal ARAIM is entirely feasible and should proceed in synchronism with the development of new avionics and the build out of the new constellations. It will obviate the RAIM outages currently experienced by airline dispatchers because it is based on multi-constellation satellite navigation. Offline ARAIM is capable of supporting horizontal *and vertical* navigation. It requires no communication with an aircraft after departure, but it is subject to *availability risk* based on potentially weak commitments from constellation providers relative to the achieved ranging performance of their satellites. Online ARAIM attempts to obviate this availability risk by replacing the navigation messages from the constellations with ones purpose-built to support ARAIM. However, it requires ISMs to be broadcast to aircraft that are in flight. Thus, Online ARAIM is subject to *connectivity risk*.

Horizontal ARAIM: Figure E-1 shows the ARAIM architecture for horizontal guidance. ARAIM for horizontal navigation is similar to traditional RAIM that has supported navigation since 1993. However, it can utilize dual frequency ranging signals to reduce the effect of ionospheric uncertainty, or it can reduce the impact of radio frequency interference by reverting to L1-only or L5-only operation (with somewhat reduced performance). Horizontal ARAIM utilizes multiple constellations to reduce sensitivity to the strength of any individual constellation. Indeed, current RAIM can be troublesome at dispatch, because it is based on GPS alone and outages result. Some of these outages are predictable and some cannot be forecast.

Unlike traditional RAIM, Horizontal ARAIM has a provision to input new integrity data. This data is not frequently required and would only be used to communicate large changes in the core constellations. For example, it would carry data to enable early use of a new constellation by aviation receivers. It also allows for larger uncertainties to be applied to newer constellations. This data could also communicate improved confidences in the ranging accuracy or *a priori* failure probabilities as these constellations mature. In traditional RAIM, the significant parameters only refer to GPS, and are hardcoded into the receiver. They can only be changed if the receiver software is updated. In Horizontal ARAIM, these parameters can be updated because a multiplicity of constellations dictates some ability to adapt to differing performances by the constellations as they change or mature. However, there would be no effort or need to adapt to short-term variations in constellation status or performance.

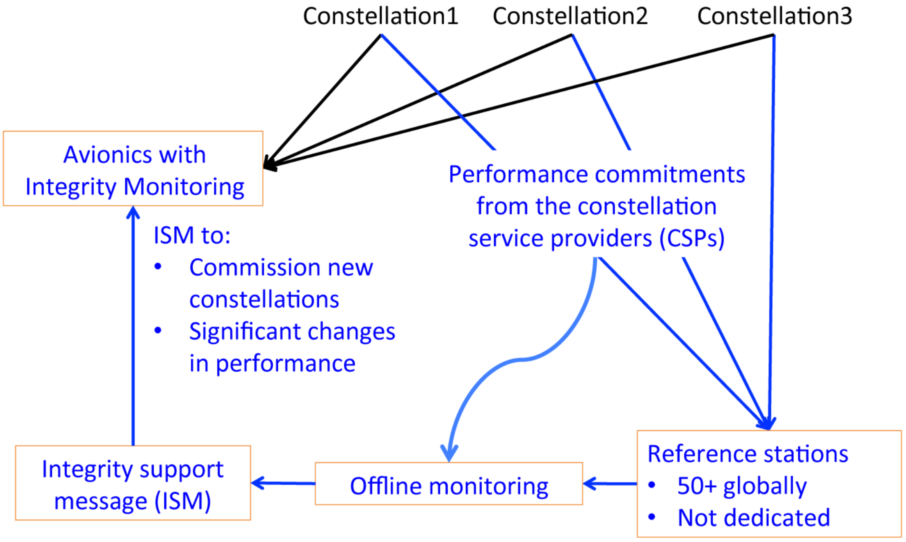

Figure E-1: Horizontal ARAIM can be used to support lateral navigation worldwide based on multi-constellation satellite navigation. As shown, the ground can update the avionics when large changes to the constellations occur.

Table E-1 approximates the availability of horizontal navigation from ARAIM. The table indicates the conditions under which ARAIM can support the following horizontal capabilities: RNP 0.1, RNP 0.3, RNP 1.0, and RNP 2.0. More specifically, each entry indicates the most capable level of service for which a 90% coverage of 99.5% availability is achieved. Coverage is measured between 70° North and 70° South latitude.

Of the above listed horizontal capabilities, RNP 0.1 is the most demanding; it is based on required navigation performance (RNP) that would provide a total system error of 0.1 nautical miles at the 95% level, and 0.2 nautical miles at the 10^{-5} level. Lower RNP levels are more desirable because they support a greater variety of aircraft operations.

Table E-1 shows this level of service as a function of the constellation strength (depleted, baseline, and optimistic). The top half of the table describes the performance of ARAIM when both GNSS signalling frequencies are available. The bottom half of the table gives operational availability when the weaker L1 signal has been lost and the GNSS receiver has reverted to L5 operation only (losing L5 and reverting to L1-only will always result in equal or better performance). In both cases, the analysis includes the requirement that ARAIM also detect any constellation-wide faults, where several or many satellites in one of the core constellations are experiencing a fault. The *a priori* probability for these constellation-wide faults is given along the horizontal axis (e.g., 10^{-4} and 10^{-8}). For the last column a single constellation with stringent *a priori* probability is assumed (GPS alone with 10^{-8})[1] in order to ensure a constellation-wide fault well below the total integrity allocation of 10^{-7}.

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[1] Note that this is below the current GPS Service Performance Commitment, but is comparable to current implementations of RAIM for GPS.

As shown in the top table, RNP 0.1 is almost always available when both signalling frequencies (L1 and L5) are available. In contrast, a single constellation with low *a priori* probability (e.g., GPS alone with 10^{-8}) can only support RNP 0.3 when GPS is in a depleted state. The bottom table shows that ARAIM with GPS and Galileo supports RNP 0.3 even when L1 is lost and L5 alone is useable. Thus Horizontal ARAIM supports RNP 0.1 under all normal conditions and reverts to RNP 0.3 when the L1 signal has been lost (e.g., due to radio frequency interference).

L1 and L5 Constellation/P_{const}	**GPS 10^{-8} Gal 10^{-8}**	**GPS 10^{-8} Gal 10^{-4}**	**GPS 10^{-4} Gal 10^{-4}**	**Single (10^{-8}) Constellation**
Depleted (GPS 23 - Gal 23)	RNP 0.1	RNP 0.1	RNP 0.1	RNP 0.3
Baseline (GPS 24 - Gal 24)	RNP 0.1	RNP 0.1	RNP 0.1	RNP 0.1
Optimistic (GPS 27- Gal 27)	RNP 0.1	RNP 0.1	RNP 0.1	RNP 0.1

L5 Only Constellation/P_{const}	**GPS 10^{-8} Gal 10^{-8}**	**GPS 10^{-8} Gal 10^{-4}**	**GPS 10^{-4} Gal 10^{-4}**	**Single (10^{-8}) Constellation**
Depleted (GPS 23 - Gal 23)	RNP 0.1	RNP 0.3	RNP 0.3	RNP 2
Baseline (GPS 24 - Gal 24)	RNP 0.1	RNP 0.3	RNP 0.3	Low RNP 0.3
Optimistic (GPS 27- Gal 27)	RNP 0.1	RNP 0.3	RNP 0.3	RNP 0.3

Table E-1. Estimated global level of horizontal service for user range accuracy = 2.5 m. The top table is for dual frequency GNSS, and the bottom table is for a reversionary mode based on L5 only.

Offline ARAIM: Figure E-2 shows ARAIM to support horizontal *plus* vertical navigation. The ARAIM architecture shown in Figure E-2 is known as *Offline ARAIM* because the update rate associated with the integrity support message (ISM) is very modest; monthly updates are sufficient. Like Horizontal ARAIM, it supports multiple constellations to remove sensitivity to the health of any single constellation.

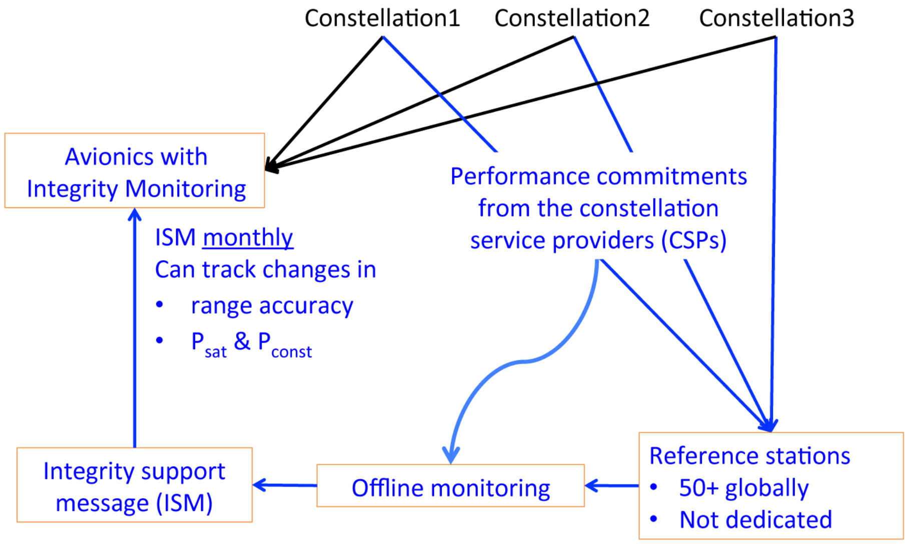

Figure E-2: Offline ARAIM would support horizontal *plus* vertical navigation worldwide based on dual-frequency, multi-constellation satellite navigation and monthly updates of the integrity support message (ISM).

As shown, Offline ARAIM includes a link from the ground to the avionics because a multiplicity of constellations dictates some ability to adapt to a changing signal environment. However, there would be no effort to adapt to short-term variations in constellation status or performance. Instead the parameters should be conservatively chosen to cover short-term performance variations. In short, Offline ARAIM employs three mechanisms to provide navigation safety:

- The airborne algorithm identifies and eliminates dangerous faults rapidly.
- The Constellation Service Providers (CSPs) continue to operate their constellations in a manner consistent with performance commitments and history, and remove faulty satellites and conditions within hours.
- The Offline ARAIM parameters are chosen conservatively to cover the expected short-term performance variations of the core constellations.

Importantly, the link from the Offline ground segment to the airborne fleet may be a suitable wireless link (e.g., core constellations, geostationary satellite, or terrestrial radio), or this ground-to-air link may be a database updated monthly.

Offline ARAIM utilizes the navigation messages from the core constellations. Hence, it does not need to communicate with inflight aircraft and can avail itself of the greatest variety of ISM communication links including monthly database updates. However, Offline ARAIM is sensitive to the user range accuracies (URAs) that are contained within the navigation messages from the core constellations. These need to be consistent with published CSP performance commitments and verified by service history. Some of the new constellations may not be able to initially achieve the needed level of URA performance. Thus Offline ARAIM is subject to *availability risk*.

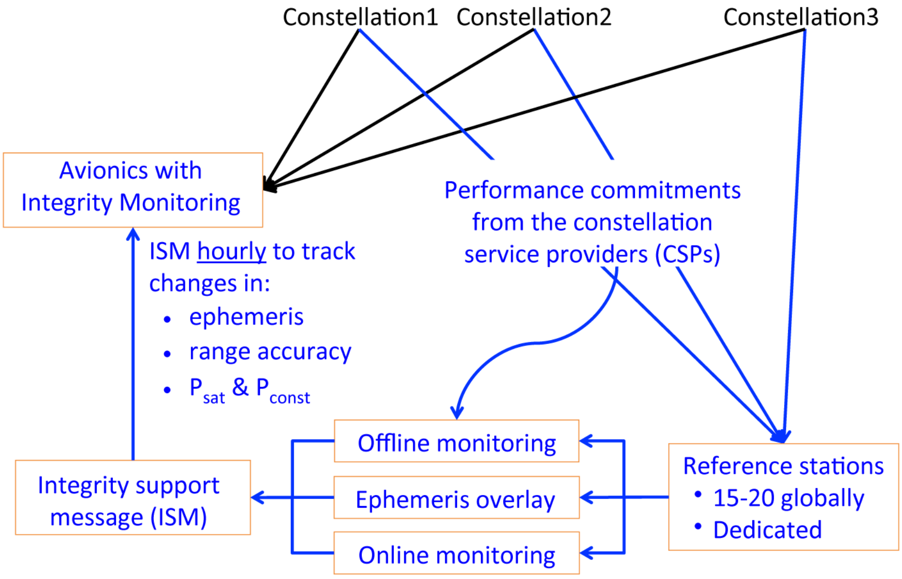

Figure E-3: Online ARAIM mitigates availability risk by replacing the ephemeris and clock information broadcast by the core constellations. Thus Online ARAIM differs from Offline ARAIM because the online version relies on hourly ground updates.

Online ARAIM: The online architecture mitigates availability risk by using a ground system to estimate and replace the ephemeris and clock information broadcast by the core constellations with data created by trusted hardware and software; and to remove faulty satellites within one hour reducing the exposure time to failures. Figure E-3 depicts this strategy. Online ARAIM has roots in SBAS and the previously proposed Galileo Safety-of-Life (SoL) service. However, the ground system does not need to provide the six-second time to alert associated with LPV-200 and LPV-250. Like Horizontal ARAIM and Offline ARAIM, Online ARAIM relies on the autonomous ARAIM fault detection function at the aircraft to detect abrupt faults. Thus, Online ARAIM automatically updates both the integrity support message and the navigation data for all satellites hourly, and the air algorithm is responsible for protecting the six-second time to alert associated with LPV-200 and LPV-250.

Online ARAIM should be able to mitigate the availability risk that characterizes Offline ARAIM. First, the ground segment of Online ARAIM can detect and flag failures in single satellites. It can also detect failures in entire constellations such as the GLONASS failure in April of 2014, where most of the satellites in the constellation were faulted. Second, the user range accuracy (URA) may be reduced relative to the URAs provided by the core constellations.

However, Online ARAIM also has an appreciable risk: the aircraft must receive the ISM not more than one hour before conducting an approach operation that uses satellite navigation for vertical guidance. The ephemeris and clock corrections provided by the ground must be less than a few hours old; otherwise they do not provide the URA benefit. And, the data rate required by Online ARAIM is large compared to any capacity available from the core constellations or SBAS satellites. Thus Online ARAIM is subject to *connectivity risk.*

ARAIM residuals test used to do constellation check. $P_{sat} = 10^{-5}$, $P_{const} = 10^{-4}$					
Constellation/URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	LPV-250	LPV-250	🟥	🟥	🟥
Baseline (GPS 24 – GAL 24)	LPV-200	LPV-200	LPV-200	LPV-250	🟥
Optimistic (GPS 27 – GAL 27)	LPV-200	LPV-200	LPV-200	LPV-250	LPV-250

ARAIM residuals test not used to do constellation check. $P_{sat} = 10^{-5}$, $P_{const} = 10^{-8}$					
Constellation/URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	LPV-200	LPV-200	LPV-200	LPV-250	LPV-250
Baseline (GPS 24 – GAL 24)	LPV-200	LPV-200	LPV-200	LPV-200	LPV-250
Optimistic (GPS 27 – GAL 27)	LPV-200	LPV-200	LPV-200	LPV-200	LPV-250

Table E-2: Vertical Service Available from ARAIM as a Function of Constellation Strength and User Range Accuracy (URA). The top half of the table describes the performance of ARAIM when the residuals test contained in the avionics must also be used to check for constellation-wide faults. The bottom half of the table assumes that other means are used to check for constellation-wide faults.

Availability of ARAIM for Vertical Navigation: Table E-2 approximates the availability of vertical navigation from ARAIM. The table indicates whether or not vertical guidance is available to a decision altitude of 200 feet (LPV-200) or 250 feet (LPV-250, which is equivalent to an APV-1 level of service). The coverage is global and the availability threshold is 99.5%. More specifically, each entry indicates the most stringent level of service for which a 90% coverage of 99.5% availability is achieved. Coverage is measured between 70° North and 70° South latitude. The top half of the figure describes the performance of ARAIM when the residuals test contained in the avionics must also be used to check for constellation-wide faults. The bottom half of the figure assumes that other means are used to check for constellation-wide faults.

Table E-2 shows the level of service as a function of the constellation strength (depleted, baseline, and optimistic) and the user range accuracy (URA). The latter quantifies the quality of the signals coming from the core constellations as guaranteed by the CSP. Today, the minimum broadcast URA for GPS is 2.4 metres, but smaller values will become possible later, when the new GPS CNAV message format is implemented. The 2.4-metre value cannot support LPV-200 based on ARAIM because Table E-2 shows that a URA of 2.0 metres does not support LPV-200. However, the ARAIM TSG has studied the achieved performance of GPS in depth, and the achieved range accuracies of GPS are approximately one metre or better. If this achieved performance is reflected in the broadcast URA, then Offline ARAIM would support LPV-200 with the baseline or optimistic constellations.

Way Forward and Outreach: The following architectures have been developed to support air navigation based on GNSS:

- **Horizontal ARAIM** to support horizontal navigation based on an occasional ISM from the ground to the aircraft.
- **Offline ARAIM** to support horizontal and vertical navigation based on a monthly ISM from the ground to the aircraft.
- **Online ARAIM** to support horizontal and vertical navigation based on an hourly ISM from the ground to the aircraft.

As discussed, Horizontal ARAIM is entirely feasible and should proceed in synchronism with development of new avionics and the build out of the new constellations.

For vertical guidance, Offline ARAIM would support LPV-200 or LPV-250 without the need to communicate with the aircraft in flight. Offline ARAIM can be regarded as an evolution of Horizontal ARAIM. However, it requires that the CSPs provide user range accuracies (URAs) of one metre or better. Otherwise, vertical guidance may not be available from ARAIM with sufficient availability. Our studies have shown that the GPS constellation currently supports accuracies at the needed level, but the CSPs may be reluctant to initially commit to these realizable values from their future navigation satellites until they establish significant service histories.

Online ARAIM seeks to obviate this availability risk by using a ground system to estimate and replace the ephemeris information broadcast by the core constellations. As such, Online ARAIM is a bigger step from Horizontal ARAIM. Moreover, the aircraft must receive and apply this data no more than one hour before an approach operation. Not all constellations have the capacity to carry this extra data (GPS, for example). Another option is to use geostationary satellite links for this purpose. Although certainly a feasible and potentially attractive solution, it is not consistent with a goal to eliminate or reduce costs of the SBAS geostationary broadcasts sometime in the distant future. Terrestrial data links, such as: Ground Based Augmentation System (GBAS) VHF Data Broadcast (VDB), Aeronautical Mobile Aircraft Communication System (AeroMACS), or L-band Digital Aeronautical Communications System (LDACS) are also potentially viable options.

The ARAIM Technical Subgroup respectfully asks for guidance from the greater aviation community on the way forward relative to these two alternatives to enable global vertical navigation.

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0 INTRODUCTION AND PURPOSE

This report is the outcome of the Milestone 2 established by the ARAIM Technical Subgroup (ARAIM TSG) in its Terms of Reference [RD-01]. The ARAIM TSG was established on July 1, 2010 by the Working Group C, which was created following the U.S.-E.U. 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 horizontal and possibly vertical guidance.

For Milestone 1, the TSG produced a first report [RD-54] (dated December 19, 2012), which described: relevant performance requirements; the definition of ARAIM user algorithms; an initial evaluation of achievable performance; and a first characterization of the ARAIM threats. For Milestone 2, the TSG has produced this second report, detailed below.

Chapter 1 provides a review of ARAIM and lists the integrity challenges that must be addressed for air navigation. Chapter 2 provides an overview of the ARAIM availability results, extending the performance evaluation given in Milestone 1 by considering a range of Ranging Accuracy (RA) errors (URE/SISE) as well as additional scenarios for the GPS and Galileo operational constellations. The results also show an improved availability with respect to the results presented in [RD-54], thanks to an optimization of the reference user algorithm, which is described in Annex B.

Chapters 3, 4, and 5 detail the architectures for Horizontal ARAIM, Offline ARAIM for vertical guidance, and Online ARAIM for vertical guidance. Starting from a wide range of initial proposals, the TSG converged on one option for horizontal guidance and two options to support vertical navigation. This Milestone 2 Report has been prepared with the objective of providing a clear description of these three ARAIM architectures and their risks so that we can gather feedback from the greater aviation community. The descriptions include: the necessary ground infrastructure, ARAIM threat allocation, threat mitigation within the architectures, Integrity Support Message (ISM) contents, and potential ISM broadcast means.

Chapter 6 describes the open points associated with the offline and online architectures for vertical navigation. Finally, Chapter 7 presents the conclusions of the work conducted by the TSG so far and outlines the steps that will be carried out in the next phase.

1 ARAIM OVERVIEW

This section identifies the basic elements of ARAIM and the assumptions used by the ARAIM TSG. The ARAIM concept was originally proposed within the U.S. GNSS Evolutionary Architecture Study (GEAS) report [RD-02]. The GEAS results and conclusions were reviewed and incorporated into the ARAIM TSG's own work.

1.1 Airborne Algorithm

The ARAIM airborne algorithm performs three main functions. First, it ensures that the pseudorange measurements are consistent with the nominal assumptions, including the assertions carried by the ISM. Second, if the measurements are found to be consistent, it computes the figures of merit associated with the geometry including the Protection Levels (PL), the Effective Monitor Threshold (EMT), and the standard deviation of the accuracy. Third, if the pseudorange measurements are found to be inconsistent, it attempts exclusion until a consistent set is found. As is the case with ground monitoring, which is discussed in Section 1.2, it is likely that there is more than one acceptable design for the ARAIM algorithm. The main steps of an example ARAIM airborne algorithm are described in [RD-54] and [RD-47]. A summary of these steps follows:

1. The receiver forms the pseudorange error covariance matrices from fixed error models and from the content of the ISM.

2. An all-in-view position solution using these error models is computed.

3. The receiver determines which fault modes need to be monitored from the content of the ISM (specifically, from the prior probabilities of satellite fault P_{sat} and the prior probabilities of constellation fault P_{const}).

4. The receiver computes the position solutions that are tolerant to each of these fault modes. For a satellite fault, this is simply the solution obtained by removing the satellite assumed to be faulted.

5. If each of the solution separations between the all-in-view and the fault tolerant position solution are within a predefined threshold, then the receiver computes the Protection Levels, the Effective Monitor Threshold, and the standard deviation of the accuracy, which ends the processing.

6. If the pseudoranges are found to be inconsistent, then exclusion is attempted. Exclusion candidates are chosen and ordered based on the chi-square statistic of the remaining set.

7. Once a set of satellites is found to be consistent, the receiver computes the Protection Levels, the Effective Monitor Threshold, and the standard deviation of the accuracy.

8. The above values are compared to their respective thresholds for the desired operation. If they are below, the operation is available.

Although not evaluated by the ARAIM TSG, there are alternative algorithms [RD-63], [RD-64].

1.2 Ground Monitoring

Potential ground monitoring architectures can be divided into two distinct approaches: online and offline. Offline monitoring does not automatically create ISM content nor does it send frequent updates of the ISM. Instead, the ISM is only updated as needed and there is time to perform cross-validation.

Online monitoring directly connects the observations to the integrity parameters broadcast in the ISM. The online ARAIM ground segment generates and disseminates its own navigation messages (satellite orbits and clocks predictions) overlaying those broadcast by the constellations as part of the ISM. This allows for direct air navigation service provider (ANSP) control over the orbits and clocks to improve the accuracy and, consequently, availability.

1.3 ISM Content and Dissemination Options

The ISM may contain different parameters depending on the level of trust placed in the navigation data broadcast by the GNSS core constellations and the amount of optimization desired. A set of parameters broadcast in the ISM may include:

- Time of applicability
- Use/don't use flag per satellite/constellation
- σ_{URA} (1-sigma ranging error integrity overbound) per satellite
- σ_{URE} (1-sigma expected ranging accuracy bound) per satellite
- b_{nom} (maximum nominal bias for integrity) per satellite
- P_{sat} (likelihood that a satellite is in a faulted state) per satellite
- P_{const} (likelihood that multiple satellites are in a faulted state) per constellation
- Navigation data overlay (description of Satellite Vehicle (SV) position and clock over time) or navigation data corrections per satellite

This list is representative, but not exhaustive. An ISM component may broadcast all of these parameters or it may only include a subset. If full trust could be placed in all of the constellations and their satellites, then there would not be a need for an ISM at all. The required parameters for the airborne algorithm could be hardcoded into the receiver and would not need to be updated. This latter approach is the case for today's use of RAIM to support horizontal guidance. At the other extreme, the ANSP may elect to update all of the required parameters as well as replace the broadcast navigation data from each GNSS satellite. Different approaches may be better suited to support specific levels of service as more demanding operations may require more information to be provided via the ISM.

The first item on the list merely provides an indication of the validity of the remaining parameters used by the airborne algorithms. The other parameters provide a means of optimizing the service. Depending on the data capacity of the available broadcast channel and the ANSP approach, some or all of the other parameters could be broadcast. Further, fully independent, per satellite, values of the parameters may be broadcast or the set σ_{URA}, σ_{URE}, and b_{nom} may each be reduced to a single scale factor per satellite or per constellation. In this case, the user would rely on the broadcast URA (or equivalent) to multiply the scale factors in order to determine the specific values to use at that time. If the broadcast channel has sufficient data capacity, the ANSP may elect to replace the broadcast navigation data for each satellite with its own information. This approach eliminates any possible failure modes associated with the broadcast data from the CSPs, but it may require a significant amount of data capacity in the channel.

Depending on the proposed architectures, the data volume differs as does the means for broadcasting it. Possible solutions are explained later along with the discussion of each architecture.

1.4 List of Challenges

1.4.1 Reliance and Technical Verifiability on Service Performance Commitments

CSPs or related institutions are expected to follow the example of GPS and publish their Service Performance Commitments (SPC) in line with the ICAO Charter on GNSS (Assembly Resolution 32-19). The Standard Positioning Service (SPS) Performance Standard of GPS published in 2008 (GPS SPS PS) defines the levels of performance the U.S. government makes available to users of the GPS L1 C/A code. Future updates will also include the new civil signals L2C, L5, and L1C. Galileo will provide a similar characterization regarding the quality of its navigation signals through the Galileo Service Definition Document (GSDD) in the future.

Experience over the last 20 years has shown that the actual GPS performance was better than the specifications given in the applicable GPS SPS PS.

Despite the excellent record of GPS performance in relation to its SPS PS, there is concern as to what extent the specifications given in the GPS SPS PS or in any other SPC document can be exploited for safety-of-life (SoL) purposes, particularly for stringent precision-like approach operations in civil aviation.

One challenge to be addressed is the verifiability of the quantitative characteristics included in an SPC. The performance figures indicated in the SPC can only be verified by very long measurement collection campaigns (years), and thus must be derived from past observations but do not automatically ensure performance into the future.

1.4.2 Reliance on Constellation Strength for Availability

The protection level cannot be better than the error bound corresponding to the weakest subset solution, that is, the one with the largest standard deviation (this is only an approximation as this error bound is also regulated by the prior probability of the fault). It is for this reason that ARAIM requires very strong geometries. This is particularly true in the case where constellation faults must be monitored by the airborne algorithm because it means that the remaining constellation, or constellations, must have good geometry at all times. The loss of just one satellite could imply a very large degradation in the Protection Levels and the EMT, as shown in the simulation results in [RD-54]. The possibility of a constellation fault is currently the baseline assumption for the offline architecture (with a prior probability ranging from 10^{-8} to 10^{-4}), so the requirements on the constellation strength are very high, at least for a two-constellation scenario. The architectures in which the constellation faults can be neglected by the airborne algorithm are much more robust against the weakness of any one constellation, although the effect is less pronounced when more than two constellations are present.

1.4.3 Sovereignty and Liability

Sovereignty and liability were identified as possible challenges for ARAIM. However, these issues can be addressed through the inclusion of an ISM provider ID for each approach. This is currently the case for SBAS, where a provider ID is included in the database for each Final Approach Segment (FAS). Aircraft and automated interaction management functionalities will then be required to only provide guidance for a particular approach if the correct and valid ISM is available in the avionics database.

1.4.4 Persistence of Faults

Once a fault occurs on a satellite, it must be assumed that the fault will remain unless it is corrected or flagged. Even if it is assumed that the probability of fault onset is bounded, unless there is a mechanism to flag the faults, then the state probability will increase and exceed the assumed state probability. The airborne ARAIM algorithm can only protect the user against a limited number of worst-case simultaneous satellite faults. It cannot protect the user from an arbitrary number of worst-case faults.

This means that there must be a mechanism to flag satellite faults within a certain time period, so that the state probability is bounded. This mechanism must be exterior to the user receiver. Although it is expected that the CSPs will flag faults in a timely manner, the ANSPs might not be willing to trust the CSP's implementation mechanism or its response time with sufficient confidence and therefore might wish to introduce either a performance margin, or monitor and flag the faults independently.

1.4.5 Constellation Wide Faults

Earth Orientation Parameters

Earth Orientation Parameters (EOPs) are used by CSPs during satellite orbit determination (OD) to convert between Earth-Centered Inertial (ECI) and Earth-Centered, Earth-Fixed (ECEF) coordinate systems. There are three key parameters needed to carry out the transformation: two angles that specify the direction of Earth's rotation axis (polar motion x and polar motion y) and one time-difference (UT1–UTC), which accounts for variability in Earth's rotation rate. In the case of GPS orbit determination, EOP parameters are estimated using EOP Prediction (EOPP) coefficients provided daily by the National Geospatial-Intelligence Agency (NGA).

If faulty EOPPs are used in the OD, then the ephemeris parameters uploaded to the satellites will also be faulted, inevitably resulting in user position error. The credibility of the EOP threat is established by the fact that it is explicitly listed as a potential integrity failure mode in the current GPS SPS PS [RD-19]. This statement together with the fact that an EOP fault was observed on GPS PRN 19 on June 17, 2012 and possibly on all GLONASS SV on April 1-2, 2014 provides enough motivation to address the threat in the course of ARAIM architecture development.

It is possible to separate potential EOP threats into two basic types (analogous to GBAS ephemeris fault types):

- Type A: EOPPs used in the OD process and broadcast in the navigation message. were good, but Earth's motion has changed since upload (e.g., due to a strong earthquake).

- Type B: E EOPPs used in the OD process and broadcast in the navigation message. were bad, and the situation was not detected by the CSP ground segment prior to upload.

These two types of EOP threats can have the same effect on ephemeris parameters and user positioning errors, but can differ in magnitude and also in the sufficiency of the detection methods. Type A faults can only be detected by monitoring *real-time* ground station data. However, given that EOP updates are generated daily or even weekly, any abrupt changes in Earth angular rate would need to be extremely large to accumulate significant orientation errors between EOP update periods. In turn, these rotation changes could only be caused by abrupt changes in Earth mass distribution, for which only two potential mechanisms are known: geological events and large-scale meteorological phenomena. Fortunately, geological events, which include earthquakes or volcanic eruptions, are far too small to cause a measurable impact on Earth rotation[2]. In contrast, large-scale meteorological phenomena can certainly cause measurable Earth rotation changes, but these develop very slowly over timescales of several months and would be directly accounted for in the EOPs/EOPPs used in constellation OD. Therefore we can safely rule out Type A events and focus only on Type B from this point forward. This is significant because Type B events, unlike like Type A, can potentially be detected with or without ground station data, for example, at the user level via comparison of current broadcast ephemerides with previously validated broadcast ephemerides (or with civil-generated ephemerides if provided in the ISM).

Incorrect Clock Updates

There is at least one known potential type of clock error that could create errors across multiple satellites within a constellation. This type of error can happen when a system timing change gets uploaded to the satellites at different time intervals. In this type of threat, some of the satellites are using older estimates of the constellation system time, while others have a newer, incompatible estimate. Examples of this type of threat occurred on GPS in the early 1990s [RD-57] and more recently on GLONASS [RD-58].

Additional Wide Faults

Wide faults could be caused by mechanisms other than wrong EOPs or incorrect clock updates. These include: non-certified code errors (e.g., erroneous values for the speed of light or Earth's gravitational constant), design flaws in the satellites, operator actions (e.g., initiating maneuvers or clock resets without setting the satellite unhealthy), and undetected contamination of more than one broadcast navigation message due to a ground system malfunction.

1.4.6 Ground Monitoring

Ground Monitoring is an important element and unavoidable within any ARAIM architecture and shall ensure identification and removal of threats. Depending on the particular ARAIM architecture under consideration the Ground Monitoring may be

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[2] NASA models estimate < 10 μsec change in day length following recent major earthquakes (8.8 - 9.1 mag). This would lead to a user position error growth < 5 mm/day. According to the U.S. Naval Observatory (USNO) earthquake impact on EOPs is so small that it has not thus far been possible to measure. They have never seen any physical evidence of an earthquake affecting the rotation rate of the Earth.

realized following different requirements and will lead to different implementation forms.

Obsolescence management and technology refresh are to be covered for ground monitoring elements. Any ground monitoring will need to ensure sufficient Signal-in-Space (SIS) error monitoring without penalizing SIS availability.

The ground monitoring does not necessarily observe errors in the same way as the users. Satellite signal deformations may affect different receivers in different ways, depending e.g. on the pre-correlation filter transfer function (3 dB bandwidth) and on the implemented signal processing (correlator bank, discriminator, tracking loop settings etc.). This may need specific receivers. Notice however that this is not something specific to ARAIM, as the issue is well known in the case of current SBAS and GBAS systems.

The ground monitoring data can also be used to generate integrity assured navigation data, considering the particular configuration of the avionics receiver, such that the user is not subject to erroneous values from the CSPs. This latter approach is not only effective against erroneous EOPPs, but also against any other form of erroneous navigation data. However, the ANSP must ensure that its replacement navigation data itself is error free and thus SoL assurance requirements apply to its generation.

To ensure that the ground monitoring data is error free, adequate ground infrastructure is needed as for current or planned SBAS.

1.4.7 Airborne Receiver Complexity

Conceptually, the Advanced RAIM algorithm is very similar to any RAIM algorithm. However, the consideration of multiple faults can lead to a large computational load. For each fault, the algorithm computes the subset solution and the corresponding error covariance for each one of the fault modes that needs to be monitored. In RAIM, there are only as many subsets as there are satellites, but in ARAIM the number of subsets depends on the number of satellites in view and their prior probabilities of fault (P_{sat}). For example, for 20 satellites in view, a required PHMI of 10^{-7}, and a P_{sat} of 10^{-5}, there are 20 subsets to be monitored (if we ignore for the moment the constellation wide faults, like in RAIM). However, the number increases to 180 for a P_{sat} of 10^{-4}, and could increase to more than a thousand for a P_{sat} of 10^{-3}. Although there are ways to reduce the number of subsets with respect to the baseline algorithm [RD-62], it remains that large P_{sat} values will lead to an increased computational load relative to existing RAIM.

2 AVAILABILITY RESULTS

This section provides the estimated performance for ARAIM under a range of assumptions chosen taking into account the architecture descriptions. Two levels of service were evaluated for the vertical guidance scenarios: LPV-200 (the target of ARAIM under the terms of reference [RD-01]) and APV1/LPV-250, a less demanding level of service and therefore more likely to be feasible. For Horizontal ARAIM, two additional levels of service were evaluated: RNP 0.1 and RNP 0.3.

2.1 Constellation configurations

Three constellation scenarios were considered. They are meant to represent three situations: a baseline configuration, a depleted configuration, and an optimistic configuration. The 'baseline' configuration uses a reference almanac for each constellation. For GPS it is the 24-slot nominal constellation described in [RD-19]. 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 the three non-primary and non-expanded slot 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 of three orbital planes. 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. To summarize, the three configurations are:

1. Depleted: GPS 24-1, Galileo 24-1
2. Baseline: GPS 24, Galileo 24
3. Optimistic: GPS 24+3, Galileo 24+3

The almanacs can be downloaded from [RD-61]. A user elevation masking angle of five degrees was applied to both constellations (although the Galileo ICD only specifies that its signals can be tracked above ten degrees, it is assumed that the actual signals in an airborne environment will be usable down to five degrees).

2.2 Nominal User Pseudorange Error

For each pseudorange, the nominal error has two characterisations: 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 and ephemeris error and the nominal signal deformation). For the single frequency case, it also includes the effect of ionospheric delay error.

Error models for the first two sources can be found in Annex B of [RD-54] for the dual frequency case. For the single frequency case, the code noise and multipath and the ionospheric delay error are modelled as indicated in Annex B of this report.

The signal in space error is characterized by the URA (SISA for Galileo) and the URE (SISE for Galileo) [RD-54]. To span the range of likely future values for the URA, the following values were considered: 0.5 m, 0.75 m, 1 m, 1.5 m, and 2 m (for the vertical guidance availability scenarios), and 2.5 m (for the horizontal guidance availability scenarios). The URE, which is used for accuracy and continuity purposes, was set to be two thirds of the URA. The nominal bias for integrity purposes (b_{nom}) was set at 0.75 m, and at 0 for accuracy purposes.

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

The probability of satellite fault P_{sat} was set at 10^{-5}, since this value appears to be conservative for the current GPS performance (as shown in the offline architecture section). In addition, previous studies have shown that results did not change substantially for P_{sat} at 10^{-4} [RD-54].

Two values were chosen for the probability of constellation fault P_{const}. The first one, 10^{-4}, reflects a situation where a constellation-wide fault could appear and the CSP takes several hours to flag the fault. As explained in the offline architecture section, this is a value that could potentially be acceptable for the offline architecture. The second one, 10^{-8}, would represent a situation where constellation wide faults are managed by a means other than the snapshot residual check (for example, by the overlay navigation data and the online ground monitor in the online architecture).

For Horizontal ARAIM it can be assumed that a P_{const} below 10^{-8} for GPS can be ensured by the CSP alone (current implementations of RAIM do not take into account constellation faults and therefore assume $P_{const} = 0$).

σ_{URA}	σ_{URE}	P_{sat}	P_{const}	b_{nom}	Constellations
0.5 m 0.75 m 1 m 1.5 m 2 m 2.5 m (Horizontal ARAIM)	2/3 σ_{URA}	10^{-5}	10^{-4} 10^{-8}	0.75 m	'Depleted' 'Baseline' 'Optimistic'

Table 2-1. ISM Parameters and constellation configurations

2.4 User Algorithm - Nominal and Availability Criteria

The airborne algorithm used in the simulations is a modified version of the ARAIM reference algorithm described in [RD-54] or [RD-47]. The modification is a simplified version of the algorithm described in [RD-60] and is explained in detail in Annex B.4. For each user geometry, the algorithm computes the VPL, HPL, EMT, and standard deviation of the accuracy, σ_{acc}.

RNP has multiple levels of performance [RD-69]. For example, RNP 4 requires the aircraft be positioned within 4 NM of the estimated position. For RNP 0.1 the true aircraft position must be within 0.1 NM of the estimated position. More specifically, 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.

The availability criteria for LPV-200, APV1/LPV-250, RNP 0.1, and RNP 0.3 used in this report are summarized in Table 2.2. Some of the results below mention RNP 1 and RNP 2, in which case the HAL was taken to be 1852 m and 3704 m, respectively. Further discussion of all of the LPV-200 requirements can be found in [RD-7].

	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	-	-

Table 2-2. Availability criteria

2.5 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 2-1 shows a map of the availability of LPV-200 for the baseline constellation configuration, $P_{const} = 10^{-4}$, $P_{sat} = 10^{-5}$, and $\sigma_{URA} = 1$ m.

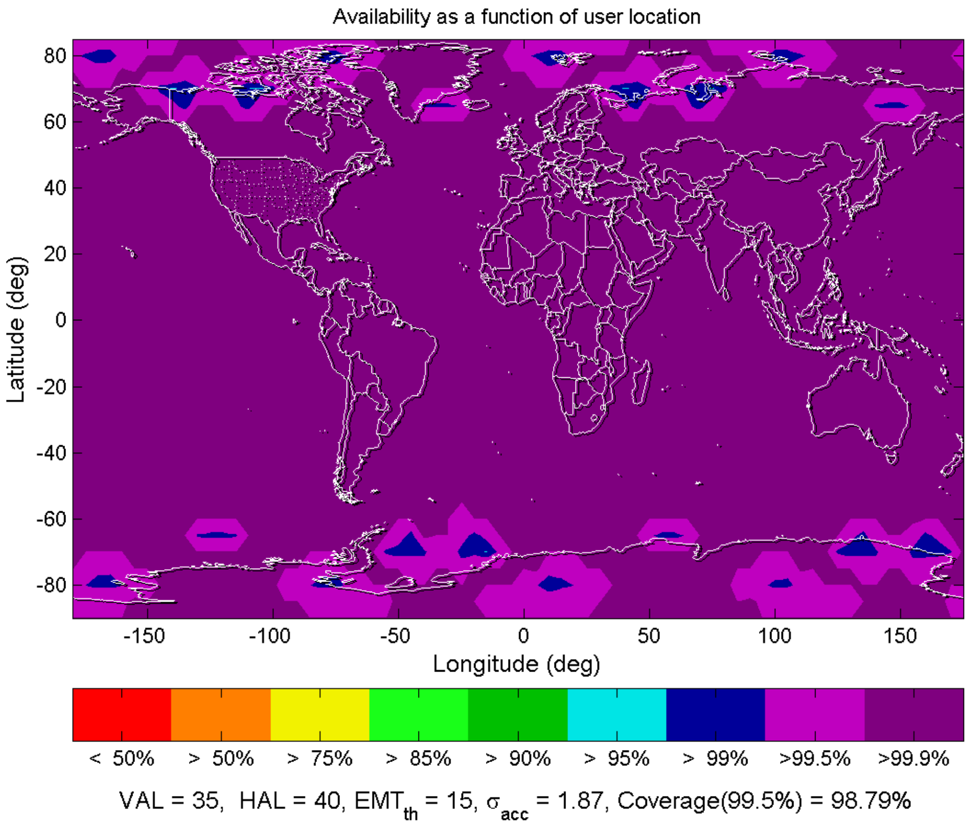

Figure 2-1. Availability map for the baseline constellation configuration, $P_{const} = 10^{-4}$, $P_{sat} = 10^{-5}$ and σ_{URA} = 1m

The results for all scenarios are summarized as a function of the constellation configuration and the URA in Tables 2-3, 2-4, 2-5, and 2-6 (vertical guidance results), and as a function of constellation configuration and P_{const} in Tables 2-7, 2-8, 2-9, 2-10, and 2-11 (horizontal guidance results). Each table shows the worldwide coverage of 99.5% availability of LPV-200, APV 1/ LPV-250, RNP 0.1, or RNP 0.3. Here, the coverage is defined as the fraction of the users between -70° and +70° latitude that have availability above 99.5%. (Because a rectangular grid was used, each user is weighted by the cosine of the latitude to account for the relative area they represent.) In addition to the 99.5% availability coverage (in bold), the tables provide the 99% availability coverage, as coverage is very sensitive to the target availability.

Constellation/ URA	.5 m		.75 m		1 m		1.5 m		2 m	
Depleted	**88.14**	92.23	**86.14**	89.89	**81.25**	86.86	**38.10**	56.26	**0**	0.04
Baseline	**100**	100	**100**	100	**98.79**	99.91	**88.16**	93.16	**3.02**	13.21
Optimistic	**100**	100	**100**	100	**99.79**	100	**94.94**	97.92	**21.82**	40.64

Table 2-3. 99.5% (bold) and 99% availability coverage of LPV-200 with $P_{const} = 10^{-4}$

Constellation/ URA	.5 m		.75 m		1 m		1.5 m		2 m	
Depleted	**94.03**	97.44	**91.77**	96.42	**87.71**	93.03	**74.99**	83.61	**35.44**	52.49
Baseline	**100**	100	**100**	100	**100**	100	**99.04**	99.89	**89.51**	95.05
Optimistic	**100**	100	**100**	100	**100**	100	**100**	100	**93.85**	97.86

Table 2-4. 99.5% (bold) and 99% availability coverage of LPV-250 with $P_{const} = 10^{-4}$

Constellation/ URA	.5 m		.75 m		1 m		1.5 m		2 m	
Depleted	**100**	100	**100**	100	**100**	100	**81.24**	95.71	**0**	0.11
Baseline	**100**	100	**100**	100	**100**	100	**99.32**	100	**3.1**	13.46
Optimistic	**100**	100	**100**	100	**100**	100	**100**	100	**25.14**	44.64

Table 2-5. 99.5% (bold) and 99% availability coverage of LPV-200 with $P_{const} = 10^{-8}$

Constellation/ URA	.5 m		.75 m		1 m		1.5 m		2 m	
Depleted	**100**	100	**100**	100	**100**	100	**100**	100	**100**	100
Baseline	**100**	100	**100**	100	**100**	100	**100**	100	**100**	100
Optimistic	**100**	100	**100**	100	**100**	100	**100**	100	**100**	100

Table 2-6. 99.5% (bold) and 99% availability coverage of LPV-250 with $P_{const} = 10^{-8}$

In Tables 2-7 through 2-11, the last column corresponds to the single constellation case: GPS only, where P_{const} for GPS has been set to 10^{-8} and Galileo is not included. Setting P_{const} to 10^{-8} effectively eliminates the constellation fault as it is well below the total integrity allocation of 10^{-7} (it also corresponds to no more than one hour of simultaneous faults every 10,000 years). This column is shown for comparison. We note however that the results corresponding to GPS only could significantly differ from other estimates of current RAIM performance due to differences in the user algorithm, constellation scenarios, and error model.

Constellation/P_{const}	GPS 10^{-8} Gal 10^{-8}		GPS 10^{-8} Gal 10^{-4}		GPS 10^{-4} Gal 10^{-4}		Single Constellation	
Depleted	**100**	100	**100**	100	**100**	100	**78.6**	90.0
Baseline	**100**	100	**100**	100	**100**	100	**98.4**	99.9
Optimistic	**100**	100	**100**	100	**100**	100	**99.9**	100

Table 2-7. 99.5% (bold) and 99% availability coverage of RNP 0.1 for dual frequency and URA = 2.5 m

Constellation/P_{const}	GPS 10^{-8} Gal 10^{-8}		GPS 10^{-8} Gal 10^{-4}		GPS 10^{-4} Gal 10^{-4}		Single Constellation	
Depleted	**100**	100	**89.7**	94.4	**71.5**	79.1	**1.0**	1.6
Baseline	**100**	100	**100**	100	**100**	100	**29.4**	45.1
Optimistic	**100**	100	**100**	100	**100**	100	**65.8**	81.5

Table 2-8. 99.5% (bold) and 99% availability coverage of RNP 0.1 for single frequency (L1) and URA = 2.5 m

Constellation/P_{const}	GPS 10^{-8} Gal 10^{-8}		GPS 10^{-8} Gal 10^{-4}		GPS 10^{-4} Gal 10^{-4}		Single Constellation	
Depleted	**100**	100	**100**	100	**100**	100	**57**	76.7
Baseline	**100**	100	**100**	100	**100**	100	**94.4**	98.4
Optimistic	**100**	100	**100**	100	**100**	100	**100**	100

Table 2-9. 99.5% (bold) and 99% availability coverage of RNP 0.3 for single frequency (L1) and URA = 2.5 m

Constellation/P_{const}	GPS 10^{-8} Gal 10^{-8}		GPS 10^{-8} Gal 10^{-4}		GPS 10^{-4} Gal 10^{-4}		Single Constellation	
Depleted	**96.5**	98.4	**18.4**	37.9	**0.4**	0.7	**0**	0
Baseline	**100**	100	**53.1**	58.0	**46.8**	54.1	**0**	0.1
Optimistic	**100**	100	**56.3**	63.2	**50.0**	57.8	**2.2**	4.9

Table 2-10. 99.5% (bold) and 99% availability coverage of RNP 0.1 for single frequency (L5) and URA = 2.5 m

Constellation/P_{const}	GPS 10^{-8} Gal 10^{-8}		GPS 10^{-8} Gal 10^{-4}		GPS 10^{-4} Gal 10^{-4}		Single Constellation	
Depleted	**100**	100	**97.7**	99.9	**97.6**	99.9	**23.0**	36.2
Baseline	**100**	100	**100**	100	**100**	100	**83.5**	93.0
Optimistic	**100**	100	**100**	100	**100**	100	**96.1**	99.5

Table 2-11. 99.5% (bold) and 99% availability coverage of RNP 0.3 for single frequency (L5) and URA = 2.5 m

2.6 Summary of Results

Tables 2-12, 2-13, 2-14, 2-15, and 2-16 show the level of service expected as a function of the URA and the constellation. Each entry indicates the most stringent level of service for which 90% coverage of 99.5% availability is achieved. The label "low" indicates a global coverage between 80% and 90%.

Constellation/ URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted	**LPV-250 Low LPV-200**	**LPV-250 Low LPV-200**	**Low LPV-250 Low LPV-200**	**-**	**-**
Baseline	**LPV-200**	**LPV-200**	**LPV-200**	**LPV-250 Low LPV-200**	**Low LPV-250**
Optimistic	**LPV-200**	**LPV-200**	**LPV-200**	**LPV-250**	**LPV-250**

Table 2-12. Estimated global level of service for $P_{const} = 10^{-4}$

Constellation/ URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted	**LPV-200**	**LPV-200**	**LPV-200**	**LPV-250 Low LPV-200**	**LPV-250**
Baseline	**LPV-200**	**LPV-200**	**LPV-200**	**LPV-200**	**LPV-250**
Optimistic	**LPV-200**	**LPV-200**	**LPV-200**	**LPV-200**	**LPV-250**

Table 2-13. Estimated global level of service for $P_{const} = 10^{-8}$

Constellation/P_{const}	GPS 10^{-8} Gal 10^{-8}	GPS 10^{-8} Gal 10^{-4}	GPS 10^{-4} Gal 10^{-4}	Single Constellation
Depleted	RNP 0.1	RNP 0.1	RNP 0.1	RNP 0.3
Baseline	RNP 0.1	RNP 0.1	RNP 0.1	RNP 0.1
Optimistic	RNP 0.1	RNP 0.1	RNP 0.1	RNP 0.1

Table 2-14. Estimated global level of service for dual frequency and URA = 2.5 m

Constellation/P_{const}	GPS 10^{-8} Gal 10^{-8}	GPS 10^{-8} Gal 10^{-4}	GPS 10^{-4} Gal 10^{-4}	Single Constellation
Depleted	RNP 0.1	RNP 0.3	RNP 0.3	RNP 1
Baseline	RNP 0.1	RNP 0.1	RNP 0.1	RNP 0.3
Optimistic	RNP 0.1	RNP 0.1	RNP 0.1	RNP 0.3

Table 2-15. Estimated global level of service for single frequency (L1) and URA = 2.5 m

Constellation/P_{const}	GPS 10^{-8} Gal 10^{-8}	GPS 10^{-8} Gal 10^{-4}	GPS 10^{-4} Gal 10^{-4}	Single Constellation
Depleted	RNP 0.1	RNP 0.3	RNP 0.3	RNP 2
Baseline	RNP 0.1	RNP 0.3	RNP 0.3	Low RNP 0.3
Optimistic	RNP 0.1	RNP 0.3	RNP 0.3	RNP 0.3

Table 2-16. Estimated global level of service for single frequency (L5) and URA = 2.5 m

3 HORIZONTAL ARAIM ARCHITECTURE

The horizontal architecture is modelled on the current implementation of RAIM [RD-46] [RD-70]. A standard set of parameters is determined and established prior to operational approval. These parameters are then used by the airborne algorithm to support the desired flight operations. This parameter set is based upon CSP commitments and observational history. These parameters should be set to values that are expected to be safe for use for the foreseeable future. In RAIM, this set of parameters is hardcoded into the receiver and can only be changed if the receiver software is updated. In Horizontal ARAIM architecture, these parameters can be updated, but updates would be needed only very rarely (or perhaps not at all). Primarily, updates would be used to include new constellations or to reduce conservatism of earlier values. There should be no effort to chase short-term behaviours in constellation status. Instead the parameters should conservatively cover both the short-term and long-term performance of the constellations and be selected to be safe even if they are never updated. Any immediate action results from the airborne algorithm identifying and eliminating faults based upon the CSPs continuing to operate their constellations in a consistent manner.

3.1 Architecture Description

As illustrated in Figure 3-1. The Horizontal ARAIM Architecture is very similar to today's RAIM architecture. The additions are: the ability to include other core constellations besides GPS; the ability to use signals at L1/E1 and L5/E5a; and the ability to update the key integrity parameters through the ISM.

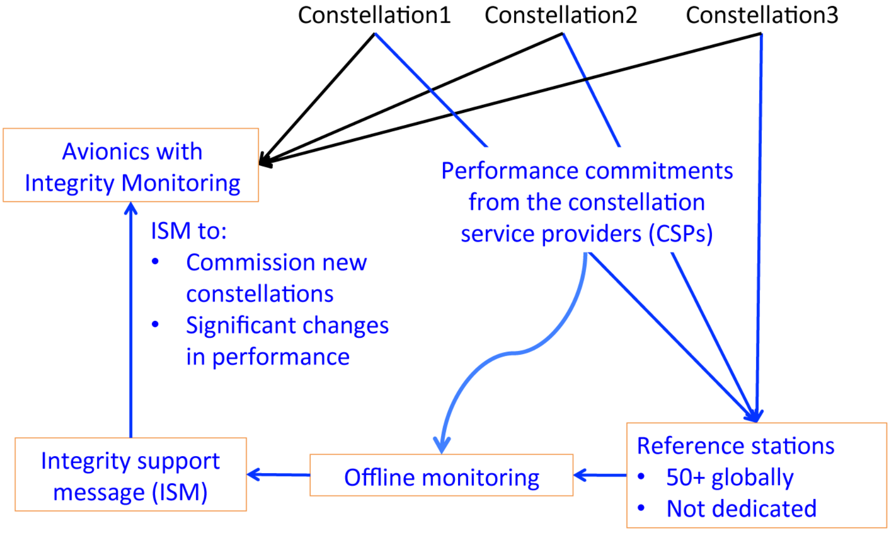

Figure 3-1. The Horizontal ARAIM Architecture

The core constellations provide single or dual frequency ranging signals and navigation data that describe the satellite locations and satellite clock and health states. Each core constellation is operated by a CSP. The CSPs maintain their own ground segments that include monitoring stations and control stations.

For a State to authorize the use of a core constellation in its airspace, each CSP must meet a set of requirements. Technical requirements are proposed as follows:

- The CSP must publish an interface specification that clearly describes the RF characteristics of the signals and the content of the navigation data
    - The specification must also clearly indicate how the data is to be used and when it can or cannot be safely used
- The CSP must also publish a performance standard that clearly describes the level of performance that can be expected. This is to include:
    - Nominal ranging accuracy
    - A list and description of possible faults that violate the expected accuracy (the list would not need to be full fault modes and effects analysis; but should at least show aggregate probabilities of faults that violate the expected accuracy)
    - The probability that such faults will occur
    - The expected and maximum time to alert users about faults and to restore service to nominal performance
    - The expected availability of ranging signals and positioning accuracy
- A long term commitment to maintaining this level of performance

It is best that these requirements be met both through publication of formal documents and through direct dialogue with civil aviation authorities. Furthermore, the commitments must also be confirmed by extensive observation utilizing the offline ground segment. A period of several years of observation and confirmation may be necessary to gain sufficient confidence in the operational performance of each constellation for supporting wide scale applications of a fully equipped aviation user fleet.

Horizontal ARAIM ground monitoring consists of a global network of reference stations that include dual-frequency, multi-constellation receivers, one or more analysis centres in charge of the offline analysis and ISM data generation, and a means to distribute the ISM. The reference receivers record their observations of the satellites ranging and navigation data. The network must be sufficiently dense such that multiple reference receivers can observe each satellite at all times. Because the ground segment is not being used to make instantaneous or even relatively quick decisions, it does not have to consist of dedicated receivers. There is time to corroborate the data from each receiver with its historical observations and against many other receivers.[3]

It is desirable to have a single analysis centre and a commonly agreed upon set of ISM parameters, as well as commonly agreed upon methods to establish the values of those parameters. However, it is likely that many different ANSPs will want to have greater control over this information and its use in their airspace. Therefore, multiple different analysis centres may be established, each generating different ISM values for use in specific regions. However, it should be noted that a horizontal ISM with regional differences introduces significant complications, in that an aircraft flying from one region to the other would have to store both sets of the ISM, and know when to switch. The ISM would then need to include data to determine its geographic area of applicability. The

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[3] As an example, the International GNSS Service (IGS) is a voluntary federation of more than 200 worldwide agencies that pool GNSS station data to generate precise GNSS information. They currently maintain over 380 functioning receivers worldwide that collect data at 30-second (or shorter) intervals and transmit this data within 24 hours (or most often within one hour). This data is used to generate highly accurate estimates of the satellite orbits and is freely available.

analysis centre must collect the reference station data and determine which constellations are safe to use and what ISM values should be assigned to each. This process will be described in greater detail in the offline section. Once safe ISM values are determined they must be distributed to the users.

There is no urgency to broadcast these parameters when they are updated, as prior values will have been chosen to remain safe for the very long term. Parameters should be primarily changed only to introduce new constellations and reduce conservatism in prior information. Therefore the ISM should be delivered to the aircraft by the most convenient means possible. This choice is to be decided upon by including input from receiver manufacturers, airframe manufacturers, airlines, and ANSPs. For the time being, we will assume that the parameters can be included in a database.[4] However, if an alternate preferred method is identified (e.g., maintenance interface or aeronautical datalink), it too should be easy to accommodate from a technical point of view.

3.2 Horizontal Navigation

Currently RAIM supports horizontal-only navigation and is used for oceanic, enroute, terminal, approach, and departure operations. Typically, the most stringent currently supported operation (non-precision approach) has a horizontal alert limit (HAL) of 555 m (compared to LPV procedures that have an HAL of 40 m). Some specific applications can be more demanding. Consequently, such horizontal-only navigation carries less risk than the more demanding vertically guided operations. A failure of horizontal-only HAL to bound the true horizontal positioning error (HPE) is considered a major risk whereas a failure to bound either the HPE or the vertical positioning error (VPE) of an LPV operation is a hazardous risk. The increase in the risk level means that systems that provide more precise guidance require greater scrutiny. An undetected 10 m pseudorange error poses little threat against a 185 m HAL but creates a significant threat against a 40 m HAL or 35 m vertical alert limit (VAL). Horizontal-only ARAIM targets the same operations as RAIM: those supporting Required Navigation Performance (RNP).

ARAIM has several advantages over conventional RAIM: it supports multi-constellation, it enables and leverages dual frequency capabilities, and it has an updatable ISM. Multiple constellations provide many more ranging sources which allow the user to have much better geometries than can be obtained by GPS alone. Dual frequency operation allows the user to directly estimate and remove the ionospheric delay. The single frequency ionospheric model places significant uncertainty on each of the pseudorange measurements. By removing this uncertainty with a direct ionospheric observation, the overall range measurement confidence for each line of sight is significantly reduced. Each of these two improvements leads to significant availability benefit over current RAIM. Together, they ensure 100% availability under all examined cases. ARAIM also incorporates the possibility to address simultaneous satellite failures. If so directed by the ISM parameters, the airborne algorithm is capable of detecting and excluding multiple satellite failures.

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[4] For example, the FAA maintains the national flight database that already contains important navigation data and that is updated every 28 days.

The updatable ISM allows performance to adapt to the changing GNSS environment. In May of 2000, GPS dramatically improved its accuracy by removing a deliberate degradation of its satellite clocks (this degradation was called Selective Availability or SA). RAIM receivers manufactured before this event assumed vary large clock uncertainty. Later receivers were able take advantage of this improved accuracy. However, there are still a large number of receivers in aircraft that have much worse performance because they are hardcoded to assume SA is still present. Having an updatable ISM allows ANSPs to include new constellations as they become available. Further, many of the parameters will initially be set very conservatively because the new signals and constellations will not have a very long service history. As time goes on, and they are able to establish a longer history of good performance, these parameters can be improved leading to better ARAIM availability. Instead of having to replace the entire ARAIM receiver, an ISM update can provide this service improvement. However, there may also be a desire by some to avoid having any ISM updates. The possibility of a static hard-coded ISM is still being considered.

3.3 Airborne Algorithm

A baseline airborne ARAIM algorithm has been previously described [RD-47]. The airborne receiver makes measurements of the ranges to the satellites. Navigation data is collected from the individual GNSS satellites, including a broadcast confidence parameter, σ_{URA}. The ISM includes a parameter that may increase this value if the ANSP so desires. These range measurements and navigation data are evaluated for consistency. Conflicting measurements are identified and discarded in accordance with the evaluated subsets. If a fault is indicated, but cannot be isolated, the operation is declared unavailable. Only a consistent set of satellites is usable for navigation.

The reference algorithm described in [RD-47] has been optimized for both horizontal and vertical guidance as described in Annex B. In the horizontal case, the full integrity allocation is given to the horizontal mode (for vertical operations most of the allocation is for the vertical mode). Vertical estimates need not be computed at all when in horizontal only mode.

3.4 ISM Content

The ISM for the horizontal-only architecture includes a header to identify which satellites are described in the parameter set and a time of applicability for the set. It also contains data for each of the satellites that the ANSP has decided to include. The header has a satellite mask that 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. 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 pre-empt any earlier information, and any earlier ISM data should be discarded. A variant that may be considered is that ISM data have a finite window of effectivity and that any data older than a certain threshold can also be discarded. This would ensure that the user maintains the most current information.

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. The aircraft database may need to contain multiple ISMs, one from each ANSP. However, operational concepts associated with such functionalities still need to be developed. Finally, there is a flag to indicate whether these parameters may be used for more precise or 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. In this event, it may be necessary to inform the receiver to restrict this content to horizontal only modes that have larger alert limits. Table 3-1. Horizontal and Offline ISM Parameters, depicts the full horizontal ISM data content. This same format will also be used by the offline architecture to support vertical guidance.

	Parameter	Description	Value	Size (bits)
Data Header	Satellite Mask	ISM Satellite Mask	[0, 1] per sat	210
	ISM_WN	ISM Week Number	[0 … 1024]	10
	ISM_TOW	ISM Time of Week	[0, 1 … 31] x 18,900	5
	ANSP ID	Service Provider Identification	[0, 1, … 255]	8
	Criticality	Usable for Precise/Vertical?	[0, 1]	1
	Total Header = 233 bits			
ISM Core	$P_{const,i}$	Probability of constellation fault at a given time	$[0 \ldots 10^{-5} \ldots 10^{-3}]$	$4N_{const}$
	Health_Flag	Satellite Health Flag	[0, 1]	N_{sat}
	$P_{sat,j}$	Probability of satellite fault at a given time	$[10^{-8} \ldots 10^{-5} \ldots 10^{-3}]$	$4N_{sat}$
	$\alpha_{URA,j}$	Multiplier of the URA for integrity	[1, 1.1, …, 100]	$4N_{sat}$
	$\alpha_{URE,j}$	Multiplier of the URA for continuity & accuracy	[0.2, 0.25, …, 2]	$4N_{sat}$
	$b_{nom,j}$	Nominal bias term in metres	[0.0, 0.1, … 10]	$4N_{sat}$
	Total Core = $4N_{const} + 15N_{sat}$ bits			

Table 3-1. Horizontal and Offline ISM Parameters

The core ISM data contains parameters specific to each constellation and satellite. For each constellation included in the satellite mask, there is a four-bit parameter specifying the value for P_{const}. The four-bit number specifies one of 16 predefined values that notionally range from 0 to 10^{-3}. Similarly, for each satellite included in the mask, there are five additional parameters provided. The health flag indicates whether or not a satellite should be used. A zero indicates a usable satellite and a one indicates the satellite is unhealthy and should not be used for ARAIM. The four-bit number for P_{sat} specifies one of 16 predefined values that notionally range from 10^{-8} to 10^{-3}. The next two values multiply the broadcast σ_{URA} value from the satellite. Thus, as the CSP increases or decreases the broadcast σ_{URA} (or its equivalent), the sigma values used by the aircraft will also change. α_{URA} allows the ANSP to increase the overbounding sigma term used in the protection level computation, σ_{URA}. Similarly, α_{URE} allows the ANSP to set the sigma term used to describe the expected accuracy of the ranging signal, σ_{URE}. Finally, b_{nom} allows the ANSP to specify the overbounding nominal bias term used in the protection level computation.

The ISM may also require data bits to support error correction, data bit validation (check sum), and/or authentication. These details will need to be further examined when the method of dissemination is selected.

3.5 ISM Parameter Determination

Currently RAIM uses the following parameters for GPS: $P_{const} = 0$, $P_{sat} = 10^{-5}$, $\alpha = 1$, and $b_{nom} = 0$. These values have a long established safety record for supporting RNP operations. It is expected that these parameters will continue to be safe to use for GPS in the future, including L1 and L5 combined and L5-only operations. 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. However, such a determination cannot be firmly made until these new constellations achieve their initial operating capability.

3.6 Horizontal Architecture Summary and Next Steps

The horizontal architecture is a minor extension of today's RAIM architecture. It adds three vital elements: multiple constellations, dual-frequency, and an updatable ISM. The ground monitoring and ISM determination are performed as today using a large redundant global network of receivers. One important difference is that these ground monitoring receivers would need to be both multi-constellation and dual-frequency capable. The other important difference is that the airborne receivers would need a mechanism to obtain new ISM parameters. Many options are possible including databases, terrestrial datalinks, or satellite transmissions.

The horizontal-only ARAIM service is expected to have even better availability of RNP procedures than today's RAIM. The anticipated performance of both dual-frequency GPS and Galileo should further improve availability.

4 OFFLINE ARAIM ARCHITECTURE

The offline architecture to support vertical operations is simply a version of the horizontal-only ARAIM architecture, designed to support the more stringent vertical integrity requirements. As with the horizontal-only architecture, the ISM parameters should be set to values that are expected to be safe for use for the foreseeable future. However, because they are serving smaller alert limits and more stringent integrity requirements, they will need to receive much more scrutiny and are likely to be more conservative than the horizontal-only values. Like the horizontal-only, there would be no effort to chase short-term behaviours in constellation status. Instead the parameters should conservatively cover short-term and long-term performance of the constellations and be selected to be safe even if they were never updated. However, they will be updated monthly to ensure that they are consistent with up to date monitoring results.

4.1 Architecture Description

As illustrated in Figure 4-1, the offline architecture consists of a space segment, a ground segment, and an airborne segment. These segments are essentially the same as those described in Section 3.1. However, there may be a desire for tighter control over the ground receivers and analysis centres to ensure that the ISM supports the required integrity level. The ISM content is the same as that described in Section 3.4.

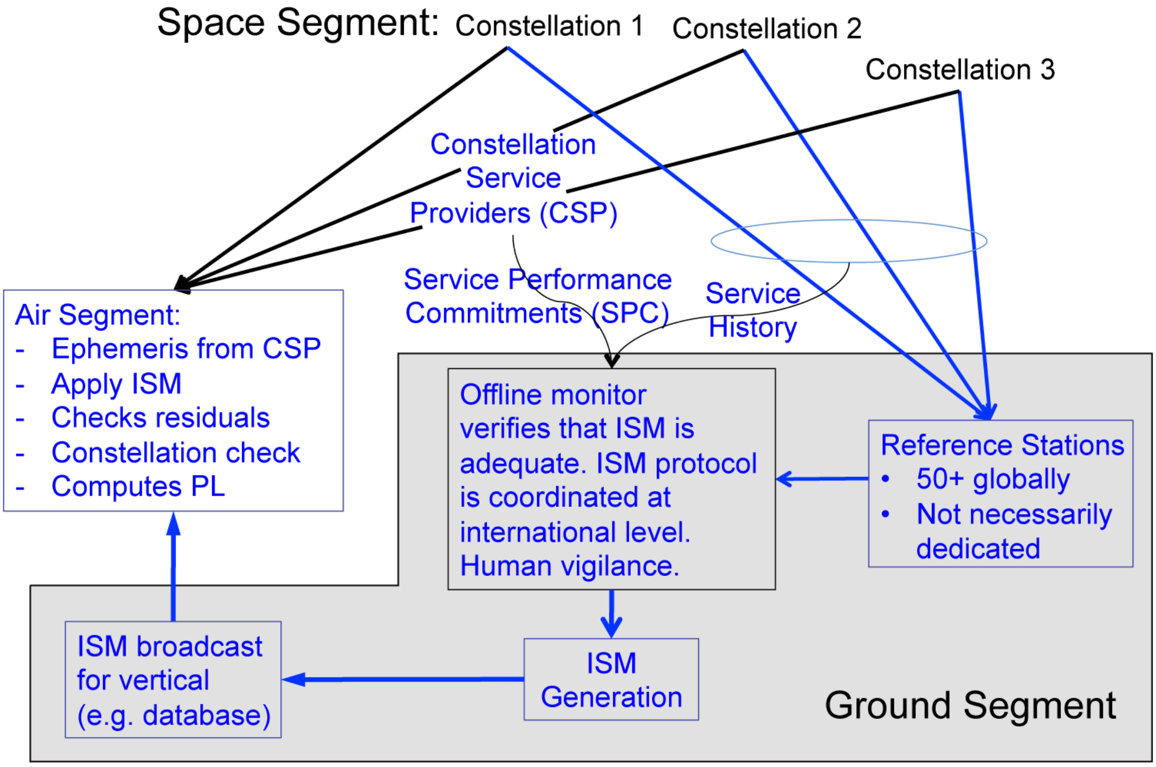

Figure 4-1. The Offline Architecture

4.2 ISM Parameter Determination

The ANSP must select the ISM parameters so that safety will be maintained for the duration of their use. However, the parameters should not be so conservative that performance is needlessly sacrificed. This requires a delicate balance that initially will be skewed to the more conservative side. In determining the parameters, the ANSP must consider the following threats [RD-54]:

- Satellite clock and ephemeris errors
- Ranging signal deformation errors
- Incoherence between the signal code and carrier
- Biases between the signals at different frequencies
- Biases in the satellite's broadcast antenna

There are other error sources, such as those arising from the signal propagation environment or in the local aircraft environment. However, these other sources are addressed by parameters and terms not included in the ISM.

The above threats contribute to nominal ranging errors, that is, the RF signals and navigation data are not perfect; there is some expected amount of error that is virtually always present. In the offline architecture, this nominal error is described by α_{URA} x σ_{URA} and b_{nom}. In addition to the nominal errors, there is a small probability that faults lead to larger errors on one or more of the satellites. These rare faults are referred to as "narrow" if only one satellite may be affected and "wide" if more than one satellite may be affected. These faults are accounted for in the airborne algorithm and their likelihood of being present is specified by the parameters P_{sat} and P_{const}, respectively.

These threats must all be evaluated for their potential impact on vertical navigation. For RAIM, only the first threat, clock and ephemeris errors, was considered to be sufficiently large and sufficiently likely to be a factor. In order to support LPV operations, the offline and online architectures must evaluate the latter threats as well. These architectures must demonstrate that all threats are sufficiently mitigated to meet the smaller alert limits that come with these operations.

4.2.1 GPS Service History

The largest errors in the above list normally are the clock and ephemeris errors. These errors have been characterized for GPS using data from the International GNSS Service (IGS) network [RD-29]. The IGS network records the broadcast navigation data, in addition to the ranging measurements. The ranging measurements are used to create very precise, post-processed estimates of the satellite's position and clock over time. The navigation data files are screened for outliers then used to determine the real-time broadcast estimates for the satellite position and clock. These two estimates are differenced and the residual errors are projected along lines of sight to users on Earth. The navigation data also contains the σ_{URA}, which is then used to normalize the residuals. These normalized residuals have been analysed every fifteen minutes from January 1, 2008 through March 31, 2014. The cumulative distribution function (CDF) for each individual satellite is shown in Figure 4-2 (left) and grouped together by GPS satellite block type (right). The heavy black line in both plots shows the aggregate CDF across all satellites. The rightmost red line shows the expected CDF value corresponding to a normal distribution with a zero-mean and unity variance.

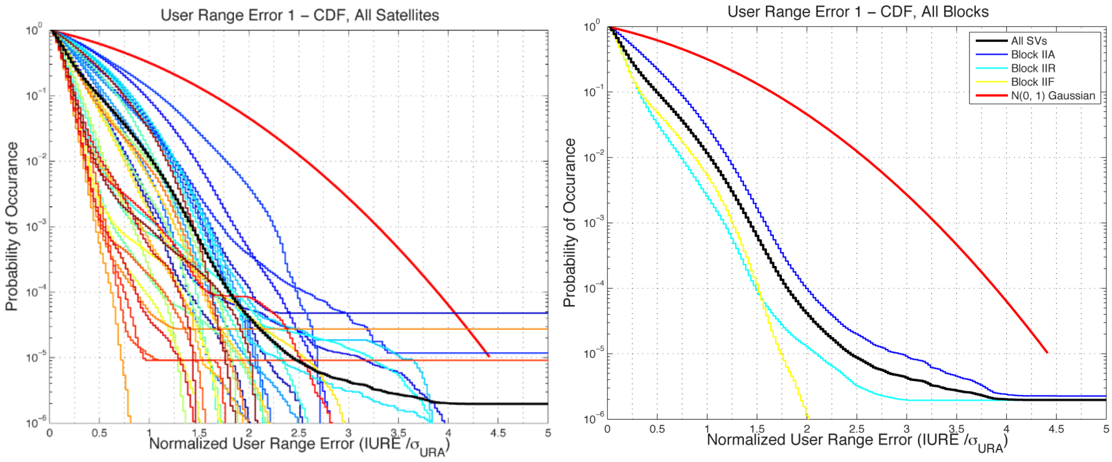

Figure 4-2. CDF of normalized ranging errors: (a) all satellites (b) grouped by Block

Figure 4-2 shows that during this time period there were four satellites affected by much larger than normal errors. These events correspond to:

1. PRN 25, SVN 25, June 26, 2009, 09:30 – 10:15
2. PRN 30, SVN 30, February 22, 2010, 21:00 – 21:30
3. PRN 16, SVN 56, June 24, 2010, 18:45 – 20:15
4. PRN 19, SVN 59, June 17, 2012, 00:15 – 00:30

Three of these events lasted long enough compared to the total amount of data for the satellite to affect the CDF above the 10^{-5} level. A much smaller fifth event occurred on PRN 9, SVN 39, April 25, 2010, 19:45-20:00. It was sufficiently short and small so as to have little visible impact on the CDF. Note that these events are subject to further investigation, and not all have been confirmed by the Air Force as true faults. Figure 4-2 (b) shows what the distributions look like when combined for the various satellite blocks. For all three blocks, the nominal clock and ephemeris errors are very conservatively described by the broadcast σ_{URA} value down to well below the 10^{-5} level. In fact, the broadcast σ_{URA} would still be safe if it were significantly reduced. Additional partitioning of the data should be performed to look for satellite specific effects or short-term effects [RD-48] [RD-49].

Although the individual satellite error distributions may be Gaussian bounded to the desired level, it is even more important to quantify how these satellite errors combine together to create the position error. If the satellite errors are correlated, they can combine to form unexpectedly large position errors. The protection level equations bound the position errors by treating the satellite errors as though they are independent from one another. Figure 4-3 shows the distribution of the square root of the sum of the squared normalized errors (after removing times with major service failures[5]). This metric[6] evaluates the behaviour of unfaulted subset solutions [RD-48]. The protection

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[5] A satellite is considered to have a major service failure if at any location it has an absolute projected error greater than 4.42 x σ_{URA} The described method identifies 3.25 cumulative satellite hours with major service failures in this six and a quarter year period.

[6] At each time step and user location, a weighted common-mode error is subtracted from each projected satellite error at that location. This residual is then divided by its corresponding σ_{URA}. All of the residuals are then squared, summed together, and a square root of the whole is taken. This process was repeated at 200 evenly spaced user locations and for the 219,072 15-minute time steps in this period.

level is a valid overbound of the position error if at least one subset contains only unfaulted measurements and the corresponding position error is conservatively characterized.

The histograms in Figure 4-3 demonstrate that the clock and ephemeris errors are exceedingly well behaved. At no time was there more than one faulty GPS satellite present in the constellation. Further, the RSS satellite errors show even greater reduction (~ one third) compared to the expected chi-square distribution than can be seen in the individual satellite error distributions (~ one half) compared to the Gaussian distribution in Figure 4-2. This indicates that the positioning errors of the unfaulted subsets will have significant margin against the formal error term used in the protection level equation and that treating the errors as though they are independent is conservative. Figure 4-2 and Figure 4-3 clearly demonstrate that the historically broadcast σ_{URA} values for GPS conservatively describe the observed clock and ephemeris error down to probabilities of 10^{-5} and lower.

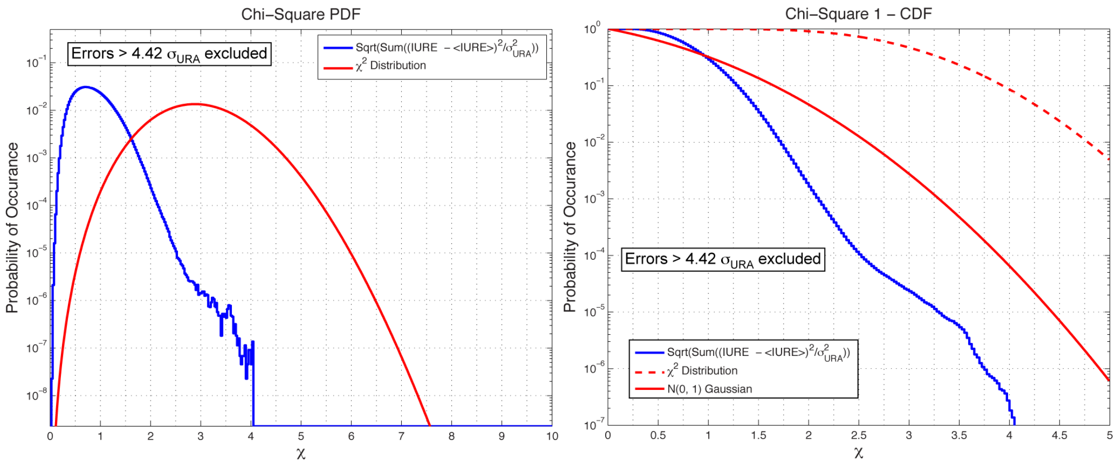

Figure 4-3. Chi-square of the normalized ranging errors (a) PDF (b) CDF

Another potential fault affecting satellite clock and ephemeris information arises from the possibility of a CSP using erroneous Earth Orientation Parameters (EOPs). If incorrect EOPs are used by a CSP, then all of the broadcast clock and ephemeris data for that constellation could consistently lead to the wrong position solution. There is one known instance in its history where GPS used incorrect EOP values and broadcast erroneous ephemeris information on one of its satellites.[7] The master control segment identified and corrected the error before it was broadcast to any other satellites. If this type of error were to be broadcast on all satellites, the airborne algorithm would be unable to detect any inconsistency when using that constellation alone. The offline architecture relies on the assertion that it is sufficiently unlikely that two constellations would make similarly inconsistent errors simultaneously (see Annex C). It detects such errors by excluding each constellation in turn to assure at least one subset unaffected by this fault.

Another error source arises from subtle variations in the shape of the broadcast waveform from the satellite. Rather than containing perfectly rectangular chips, the signals have imperfections in their formation caused by subsequent filtering via various components

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[7] PRN 19, SVN 59, on June 17, 2012.

of the transmission chain. Each satellite has slightly different imperfections than the others. This so called nominal deformation effect leads to small differences in ranging measurements made by different receivers to different satellites. The magnitude of the difference depends on user receiver characteristics. Studies have shown that for very different receiver designs, these biases can be on the order of one metre. However, by limiting the receiver design space and by increasing commonality with the reference receivers, these errors can be reduced to being on the order of 10 cm [RD-50].

Another concern is the possibility of misalignment between the code and carrier portions of the ranging signals. If these are not in perfect coherence, the act of carrier smoothing will introduce a bias that increases with the length of the smoothing time. The code and carrier have never been observed to be incoherent on GPS L1 signals. However, such an effect has been observed on the L5 signals of the GPS Block IIF satellites. The magnitude of that error appears to be on the order of 10 cm [RD-39]. However, for most satellites, the nominal effect is expected to be much smaller.

The iono-free combination of the L1 and L5 signals assumes that the two signals are synchronized in time at their broadcast. However, electronic components introduce different amounts of signal delay at different frequencies. Thus, the signals at two different frequencies have an offset that is nominally constant. The value of this inter-frequency bias is estimated and broadcast to the user as part of the navigation data. However, this inter-signal correction has some uncertainty, as the estimation process is affected by noise. This nominal effect of this error term is included in the satellite clock estimate error.

The final threat to be considered comes from the satellite antenna. Ideally each antenna is treated as a point source for the signals. However, real antennas have biases that vary with look angle. That is, the path length from the antenna appears to be different depending on the direction to the user. These biases affect code and carrier differently and are also different for the two frequencies. Great effort has been made to minimize the satellites' carrier phase antenna biases; they appear to be below 4 cm in variation. Unfortunately, the code phase variations have been observed up to 50 cm in variation [RD-41].

4.2.2 Preliminary Determination of α_{URA} and b_{nom} for L1 GPS Service

The offline architecture ideally uses α_{URA} x σ_{URA} to bound the satellite ephemeris, clock and inter-frequency bias nominal errors; and b_{nom} to bound the nominal errors arising from signal deformation, code-carrier incoherence, and antenna phase centre variations. In reality, the two parameters together must bound the convolution of all of the errors with sufficient probability. At the moment, both parameters are set very conservatively in the offline architecture. The minimum possible broadcast σ_{URA} value has a corresponding sigma of 2.4 m (lower values will become possible within the next few years). Currently, there is no need to set α_{URA} above its minimum value of 1. When smaller URA values are broadcast in the future, it will be necessary to again carefully scrutinize the behaviour and it is possible that larger α values will be required at that time. As described above, the three bias terms together nominally can be conservatively bounded by a 75 cm value for b_{nom} [RD-65].

4.2.3 Preliminary Determination of P_{sat} and P_{const} for L1 GPS Service

The prior subsections describe the nominal behaviours arising from the described threats. However, these threats can also lead to rare faults that are not well described by the nominal parameters. The GPS performance standard [RD-19] defines major service failures as occurring any time the signal-in-space error exceeds 4.42 x σ_{URA}. From Figure 4-2, it is obvious that, on average, errors below 4.42 x σ_{URA} occur no more frequently than would be expected from a Gaussian distribution. Major service failures, however, require separate handling. The airborne algorithm compares subset solutions to find inconsistencies. As long as the true probability of encountering such failures is below the assumed probability, the airborne algorithm can maintain integrity as expected. The GPS performance standard states that there will be no more than 10^{-5} probability of satellite fault, per satellite, per hour. The commitment further states that major service failures will be flagged or removed within six hours. A satellite fault observed at any given time could have initiated sometime in the prior six hours and now be present to affect the user. These specifications imply an extreme upper bound for P_{sat} of 6 x 10^{-5}.

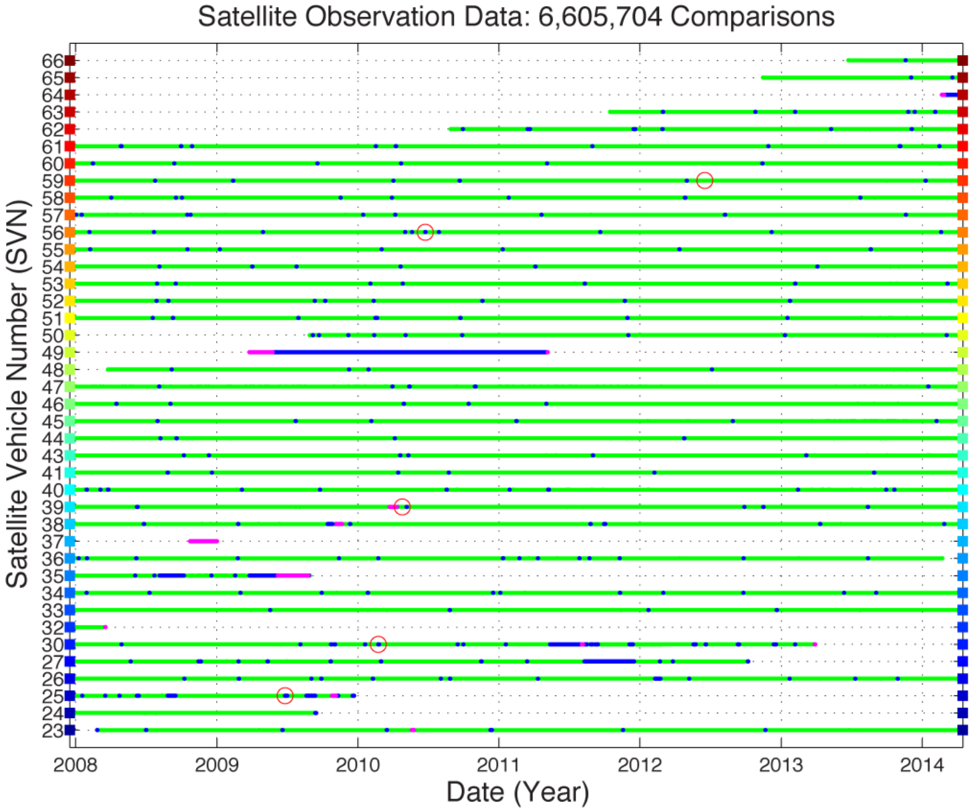

Figure 4-4. Summary of Observations by Satellite (green: good observation, blue: satellite is unhealthy, magenta: no broadcast ephemeris, red: circle is an error > 4.42 x URA)

Figure 4-4 shows the history of GPS satellite observation from January 2008 through March 31, 2014. Over that time period, the described process has identified five major service failures with a cumulative duration of just over three hours. This data implies an observed value for P_{sat} of approximately 2 x 10^{-6}. Thus, there is more than an order of magnitude between the observed fault rate and the extreme upper bound from the commitment. The numbers in the SPS PS (10^{-5} probability of fault onset/satellite/hour and six hours to alert) are meant to represent upper bounds, not expected values. The product of two upper bounds creates an even more conservative value. RAIM assumes a 10^{-4}/hour probability that one of the satellites in view may have a failure [RD-71]. By assuming that there are ten satellites in view (and a one hour fault duration) this corresponds to a value of 1 x 10^{-5} for P_{sat}. This value, while smaller than the extreme upper limit of the commitment is still at least five times greater than the historically observed value. It represents a good compromise and is a value that we endorse for use in the offline architecture for GPS.

In addition to narrow faults, there is concern over the possibility of wide faults or faults that can lead to uncharacteristically large errors on more than one satellite at a time. The GPS performance commitment does not prohibit the possibility that the faults occur concurrently. The upper limit of 10^{-5} faults per satellite per hour implies approximately three satellite faults within any given year for a constellation of ~30 satellites. Again using a six-hour upper bound and assuming at least two of these faults occur concurrently, this would imply an upper limit for P_{const} of approximately 7 x 10^{-4}. No concurrent major service failures have ever been observed on healthy GPS satellites[8] since it was declared operational in 1995. However, over the ensuing twenty year time frame, it would be difficult to empirically demonstrate values below ~5 x 10^{-6}. Furthermore, it is not clear whether operations from more than ten years ago are as relevant to current operation. Therefore, an empirical upper bound of 10^{-5} appears to be reasonable. We have found that it makes little difference in practice whether we use 10^{-4} or 10^{-5} [RD-54], so we have evaluated performance using 10^{-4} to be conservative. At first glance, it appears contradictory to use a value for P_{const} that is equal to or greater than P_{sat}. However, the numbers are describing different types of events and are not directly comparable. Because there are ~30 GPS satellites but only one GPS constellation, using the same probability for P_{sat} and P_{const} means that the likelihood of a narrow satellite failure being present is 30 time more likely than a wide failure being present at any given time.

It is at the discretion of the ANSP to set these probabilities to values that they find acceptable. Some ANSPs may find the observational evidence compelling while others may not be willing to use values below the worst-case committed interpretation. Still others may not even trust the published commitments. It is hoped that any such differences will be minimized through ICAO harmonization processes to the maximum extent possible to ensure a globally consistent level of safety and service performance. We find that for GPS, the commitment is set very conservatively and recommend accepting values below the extreme upper limits of the commitments for both P_{sat} and P_{const}. However, GPS does not yet provide formal, combined L1 and L5 service, nor do any of the other constellations. Therefore these analyses need to be continued and extended to the dual frequency operations that we expect to see in the future.

4.3 Offline Architecture Summary and Next Steps

The offline architecture is a more conservative implementation of the horizontal only architecture. Its ISM parameters receive greater scrutiny and may be set to more conservative values. Further, users should update their ISM every month to make sure they are consistent with the long history observations including recent data. While GPS has both a published performance commitment and a long track record of operation, this is not yet the case for other constellations. Therefore the values of the parameters described in the above paragraphs apply only to GPS. For Galileo, a σ_{URE} value of the

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[8] Health status is indicated by GPS through various mechanisms including the health bits and the broadcasting of non-standard code and/or non-standard data.

order 65 cm is expected [RD-51], [RD-52], [RD-53], which is in line with expected modernized GPS values. However, it remains to be seen what the achieved values will be for all of the parameters.

The offline architecture takes advantage of a consistent level of performance from the CSPs. In order to be accepted for use, the CSPs must publish a performance commitment and then consistently perform better than the commitments. GPS has met both of these requirements with its L1-only service. We anticipate that both GPS and Galileo will be able to similarly meet these goals with their dual frequency services.

As discussed above, the offline ARAIM integrity case is based on a combination of CSP assurances and assertions, which are supported by service history. Although even better performance levels than measured today are predicted for Galileo and GPS in the future, these levels have not yet been obtained, and it will also take time to gain confidence in them. In addition, the observed performance levels will not necessarily be guaranteed by the core-GNSS SPCs, because it is expected that the CSPs will choose to maintain margin between their performance commitments and the actual performance they provide to the user, as is done today in the case of GPS. As a consequence, there is some risk that the ranging accuracy needed to achieve the LPV-200 ARAIM target service availability may not be consistent with the commitments provided by the SPCs.

5 ONLINE ARAIM ARCHITECTURE

The online architecture aims at giving a larger degree of control to ANSPs over the GNSS performance characteristics affecting ARAIM users. The relevant features of the online ARAIM concept are

- the *ephemeris overlay*, where the ARAIM ground segment computes high-accuracy ephemerides that are carried by the ISM, and
- *online monitors* capable of removing faulty satellites.

Online monitoring of the ephemeris overlay is required to ensure integrity against ephemeris faults. Additional online monitoring of satellite payload faults is an option, which is not required for integrity, but can potentially shorten the time to operational capability.

The ephemeris overlay gives control over one of the main components of the nominal error. In addition, online monitoring of the ephemeris overlay can reduce the probability of a constellation fault (P_{const}) and potentially P_{sat} as well by limiting the exposure time of faulty satellites. With the overlay and online monitoring, P_{const} could be negligibly small.

The online concept has roots in SBAS and the previously proposed Galileo Safety-of-Life (SoL) service. However, there is one simplification over either of these based on the existence of the ARAIM fault detection function at the aircraft. Therefore, the Online Ground Architecture is expected to be easier to implement because of the longer Time to ISM Alert (TIA), which is the time the ground system needs to get its update out in order to satisfy its assumptions (compared to the 6 sec TTA which is met by the airborne algorithm).

Not surprisingly, in addition to its potential benefits, Online ARAIM also comes with some challenges and costs, including:

- A short latency ISM (approximately 1 hr) and associated datalink(s)
- A worldwide sparse network of dedicated reference receivers.
- Development and validation of orbit determination and monitor functions.

These issues and the details of a representative Online ARAIM architecture are discussed below.

5.1 Online ARAIM Ground Architecture

The Online ARAIM system consists of a number of key functions, as shown in the flow diagram in Figure 5-1. These include a sparse worldwide network of reference receivers, short-latency ISM generation and dissemination mechanisms, an ephemeris overlay generator, and an online monitor. These functions are described in detail below. Because the Online ARAIM system is an augmentation to the Offline system, it implicitly includes all Offline ARAIM monitoring functions. Those functions were described earlier and will not be discussed further here. It is important to note that, as with the Offline system, it will be necessary to wait until Galileo has established a suitable performance history before the Online integrity case for aircraft vertical guidance can be successfully closed. The online architecture can potentially, if satellite payload faults are also monitored, shorten the time to initial operational capability, similar to what was accomplished for EGNOS and WAAS. The addition of satellite payload monitoring is an option, which is not required for integrity.

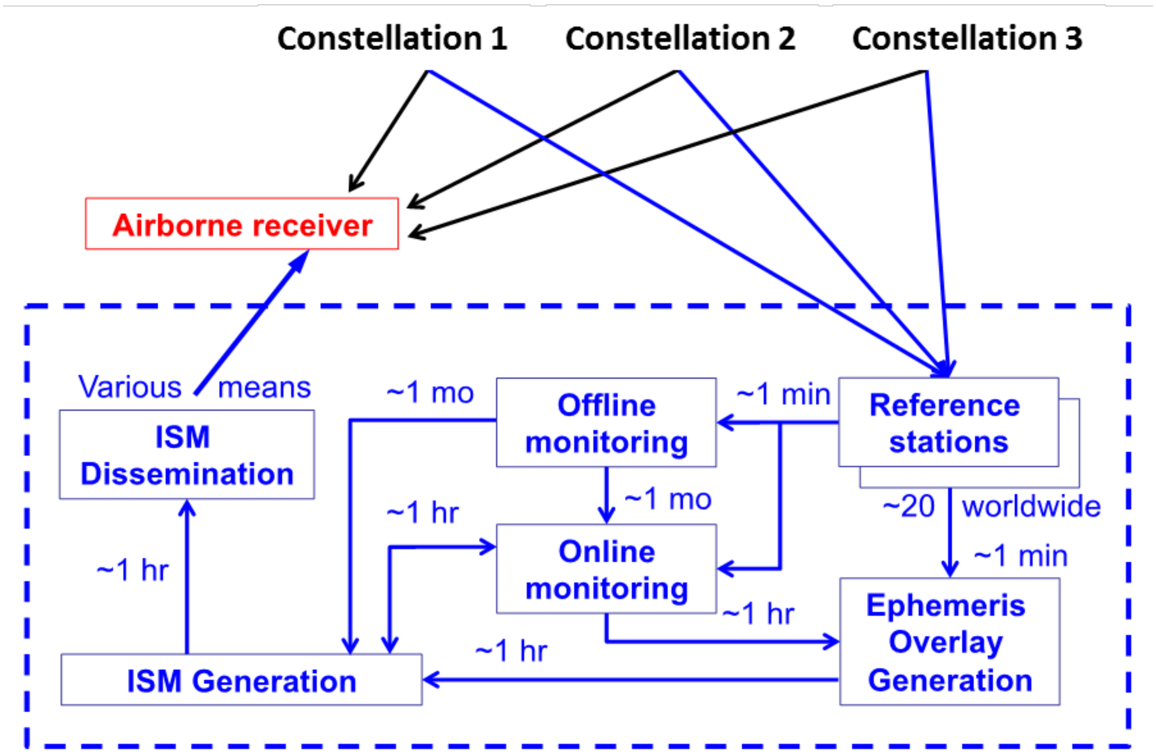


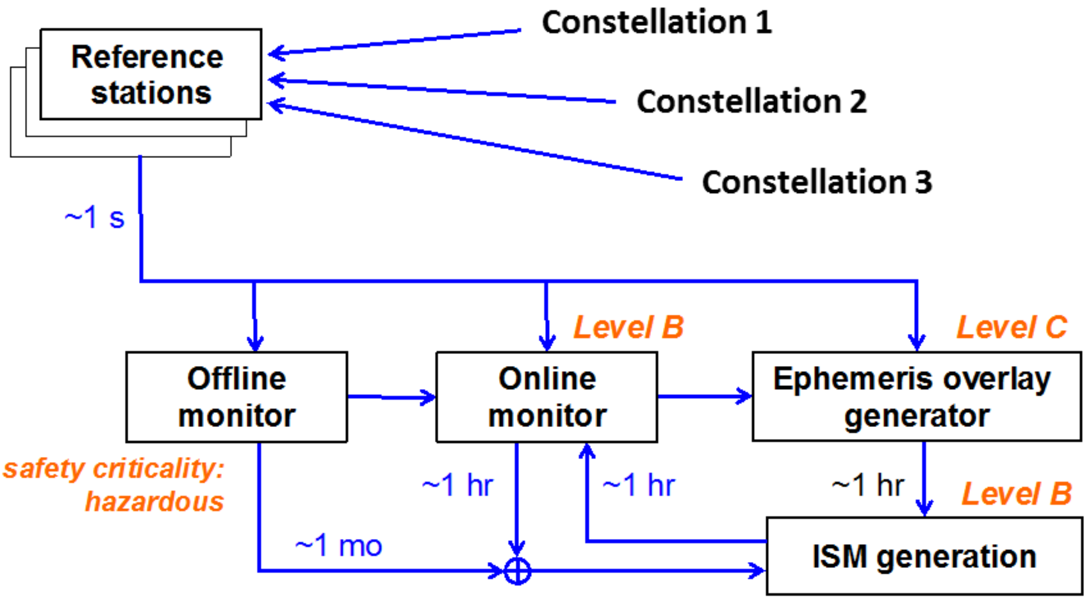
Figure 5-1. Online ARAIM architecture

5.2 Reference Stations

To achieve sufficient orbit determination and monitoring accuracy for the ephemeris overlay and monitoring functions it is likely that visibility of each satellite by two reference stations (RSs) will be needed. Considering the additional need for redundancy in the event of RS failure, visibility of each satellite by three RSs is recommended. A visibility analysis has shown that this can be achieved with a sparse worldwide network of about 20 stations. More detail about RS quantity, spatial distribution, and relation to orbit determination performance will be provided in the description of the Overlay Function later in this section.

The operation and maintenance of the RSs would be the responsibility of various ANSPs making use of the ISMs generated by the ARAIM ground system. It is expected that existing SBAS infrastructure would be leveraged to the greatest extent possible. Indeed, a valid interpretation of Online ARAIM architecture is as an evolution of SBAS – with a simplification of the ground segment made possible by the addition of dual-frequency multi-constellation (DFMC) ARAIM at the aircraft.

RS receivers measure DFMC code and carrier phase measurements and navigation data from all visible satellites. To ensure integrity and continuity of the RS output in the event of reference receiver failure, it is envisioned that each RS would be equipped with 2-3 receivers certified to Design Assurance Level (DAL) D. As shown in Figure 5-2 punctual raw measurements and data are sent to the offline monitor, online monitor, and ephemeris overlay generator.



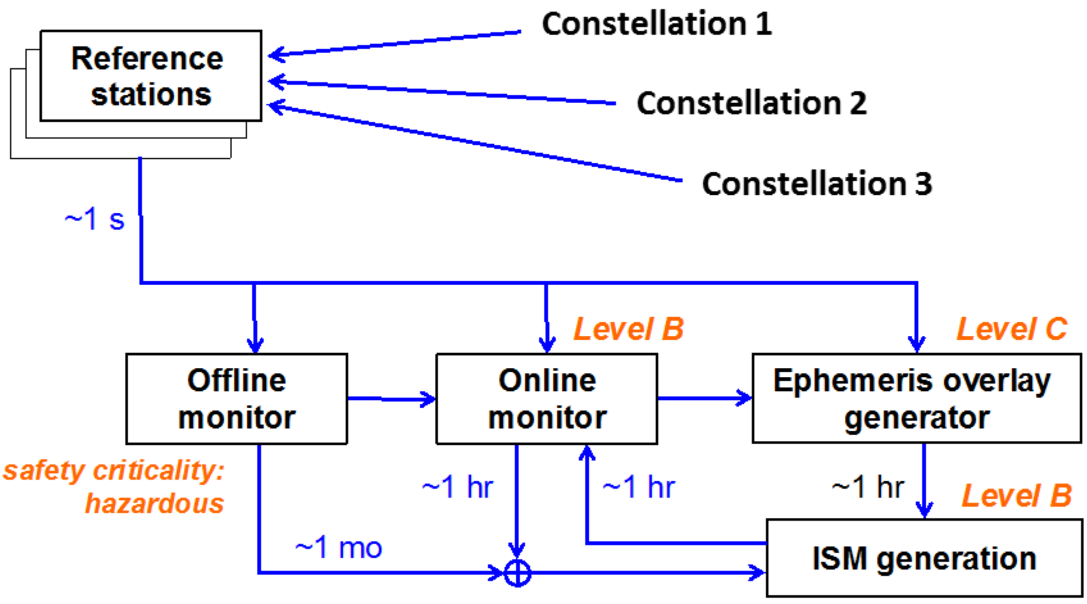


Figure 5-2. ARAIM Online functional flow

5.3 Ephemeris Overlay Function

The navigation overlay implemented in an ARAIM online architecture establishes an independent and transparent navigation data function for the ARAIM user that can also be open for inspection. This may be an important element in a future ARAIM certification process. The overlay can provide improved ranging accuracy for any of the constellations contributing to the ARAIM service.

In order to achieve good LPV-200 availability with ARAIM, the ranging error of the GNSS signals needs to be sufficiently low (see Results). In the ARAIM Online architecture this goal is achieved by means of the ephemeris overlay, which performs Orbit Determination and Time Synchronisation (ODTS) of the core GNSS constellations. It does not largely constrain the design, operations, and evolution of the core GNSS systems as long as SPCs similar to those in [RD-19] are met for all constellations used by ARAIM. Newly launched satellites can be introduced into the operational ARAIM system following similar procedures as currently applicable to WAAS and EGNOS.

Analyses have been carried out in order to dimension (i.e., number of necessary reference stations) a global ARAIM monitoring network that can achieve a necessary ODTS accuracy sufficient for ARAIM LPV-200. Three networks with 16, 13, and 10 stations have been selected. The stations coincide with IGS stations and real IGS observations have been used to estimate the achievable ODTS performance. The location of the stations has been selected arbitrarily (Figure 5-3). The resulting orbit and clock estimation and prediction errors are provided in Figure 5-4.

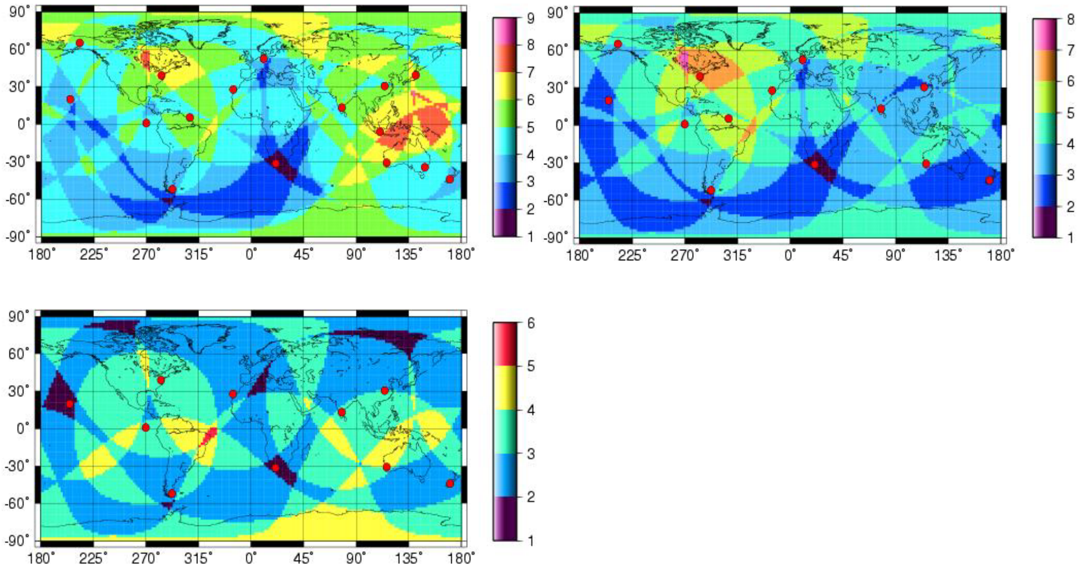


Figure 5-3. Location of monitoring sites (16 sites, 13 sites, and 10 sites) and corresponding Depth of Coverage (DoC)[9]

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[9] The Depth of Coverage indicates the number of stations seeing a satellite

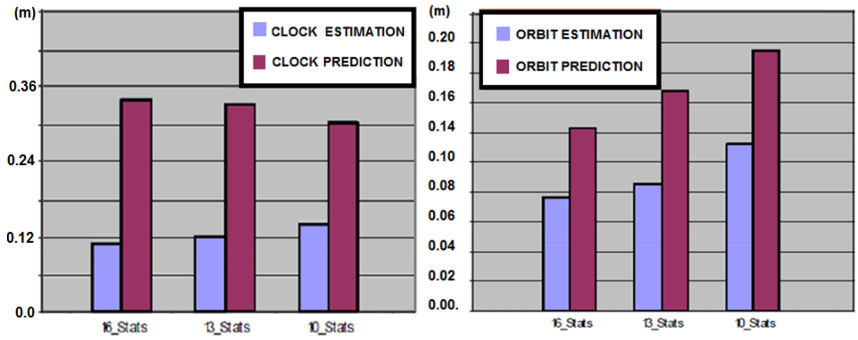

Figure 5-4. Achievable orbit and clock estimation and prediction performance (RMS values) with 10, 13, and 16 ground stations

The orbit estimation and orbit prediction errors shown in Figure 5-4 are derived from real data and are based on 12 arcs of data corresponding to GPS Block IIR satellites. The figure of merit shown is the root mean squared (rms) of the ranging error at the worst user location over the prediction interval and over all satellites. These results are within typical ranges for this type of scenario and this type of process.

Note that there is also quite a significant margin with respect to the proposed operation of an online Ephemeris Overlay process as the indicated prediction performance is representative of the one achievable at the end of a navigation message with a validity period of 3 hours, while the ISM refresh interval is instead 1 hour. These analyses show that even with a network size of 10 stations, the ranging accuracy to guarantee an ARAIM LPV-200 service can be achieved (see Results in Section 2.5). For redundancy purposes, a slightly higher number of stations is preferable.

It is recognized that achieving the ephemeris accuracy described above will require complex orbit and clock estimation algorithms and software, which will likely be difficult and costly to certify at the level of *hazardous* severity for the algorithm, and DAL-B for software. A more realistic option is to certify the overlay generation function to *major* severity and DAL-C and implement a separate, simpler online monitor, which would be easier to certify to hazardous/DAL-B.

5.4 Online Monitor

The purpose of the ONline Monitor (ONM) is to ensure integrity of ephemeris overlay by establishing and controlling b_{nom}, P_{sat}, and P_{const} for ephemeris overlay faults. In the current online architecture model, the overlay generator and online monitor use raw data from the same receivers. However, the ONM function is otherwise independent of the overlay generation function. RS receiver faults are handled using redundant receivers with physically separated antennas at each RS, and redundant RS visibility to each satellite.[10] Because the ONM outputs integrity information directly to the ISM generator, it must ensure safety critical hazardous operations and its software must be developed to DAL-B.

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[10] The implicit assertion here is that simultaneous, consistent receiver faults do not occur on multiple receivers at multiple remote RSs simultaneously. However, we note that receivers of same design having a consistent, simultaneous timing fault can cause an orbital node longitude fault in the ephemeris overlay, which would not be detectable by the ONM. Such faults will need to be addressed through receiver design specifications or other means.

An example ONM implementation is presented in three steps:

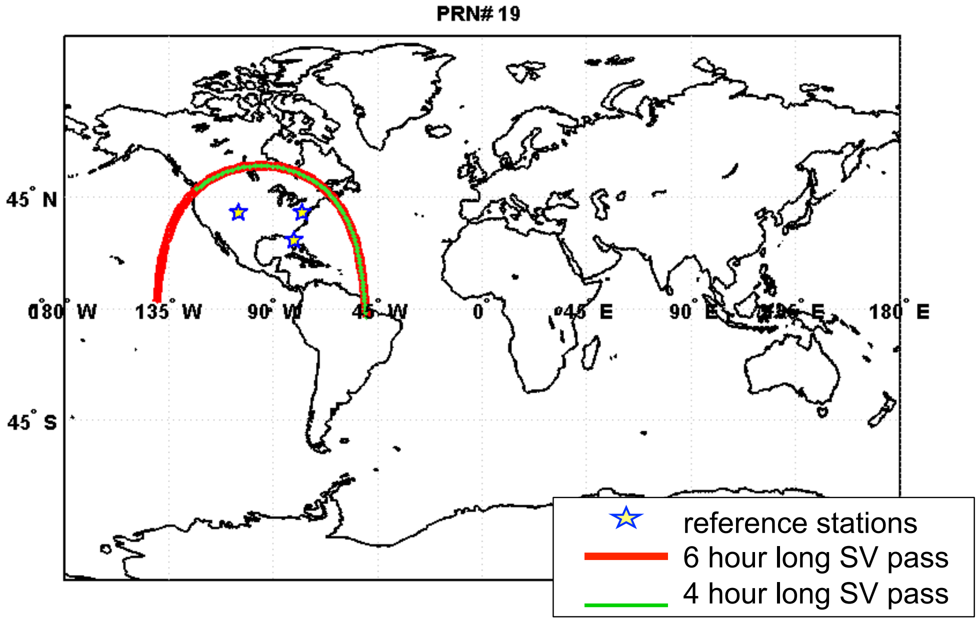
1. Satellite positions are individually estimated for each SV using ground measurements and a simple parametric model.

2. These ONM-generated satellite position estimates are subtracted from those obtained using the ephemeris overlay to produce a residual error history.

3. The residual error is processed, for example, using an algorithm to detect changes in the mean residual.

The critical step in the process is the first step because the sensitivity of the monitor of ephemeris overlay faults will scale directly with the accuracy of the ONM's satellite position estimates. However, the ONM has an advantage relative to the overlay function in that it need not *predict* satellite orbit positions, but simply validate in c*urrent time* that errors in the overlay's satellite position prediction are small.

To investigate the feasibility of such a monitor, a covariance analysis of a single satellite pass was performed. Figure 5-5 shows the ground track of the satellite and three ground stations, which are denoted by stars in the figure. The green portion of the ground track corresponds to a 4-hour interval; when the red segment is included the total interval is 6 hours. The three reference stations continuously track the satellite over both intervals. Raw, dual frequency code and carrier phase measurements[11] from the three RSs were fitted over the two time periods to the nominal 18-parameter GPS orbit/clock ephemeris model. Covariance analysis results of the resulting ONM satellite position estimation error (radial components) are shown in Figure 5-6.



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[11] Standard deviations of raw code and carrier measurement errors of 0.5 m and 0.01 m, respectively, were assumed for this analysis, as was a 4 min sample interval to decorrelate multipath error. A zenith tropospheric error model with standard deviation of 0.05 m and time constant of 2 hours was also used.

Figure 5-5. ONM example: satellite ground track in view of 3 RSs

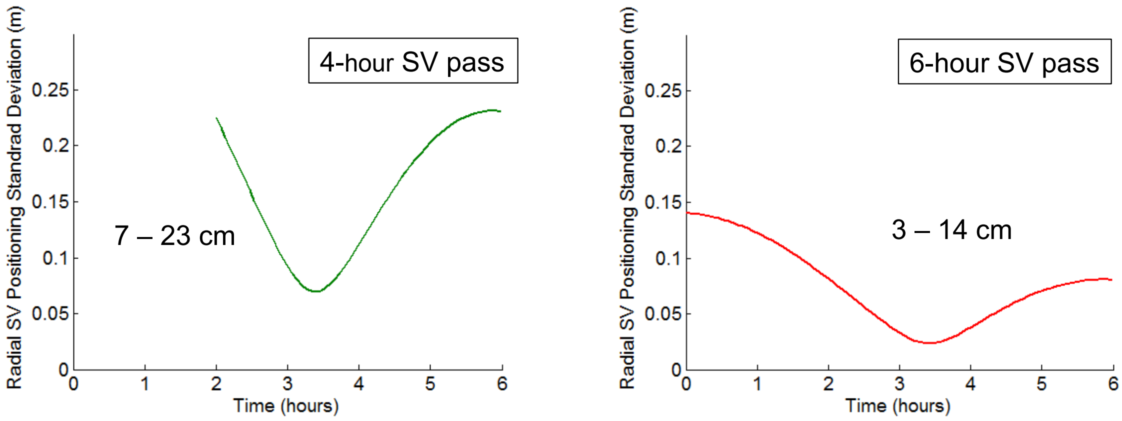

Figure 5-6. ONM example: covariance analysis results for 4- and 6-hour passes

The results in Figure 5-6 show promising performance using the 18-parameter GPS ephemeris model. Because the method uses ranging measurements directly it will work equally well regardless of whether ephemeris faults are due to blunders in the overlay message itself or an unannounced satellite manoeuvre. It should be noted that the preliminary covariance analysis assumed perfectly time synchronized RSs, so actual performance will likely be worse, as the receiver clock offsets will need to be estimated as well. A related issue for the online architecture is the ARAIM reference time in which the overlay and ONM would work. The reference time would need to accommodate time bases from multiple CSP constellations, so likely it would be steered to UTC. However this is still an open issue.

Further, the results in Figure 5-6 demonstrate only that high accuracy (decimetre level) ONM estimation of the orbit parameters is possible. They do not quantify the modelling errors using the simple 18-parameter GPS ephemeris.

To evaluate model error, the 18-parameter model was fit to International GPS Service (IGS) truth data over 4 hour intervals for different GPS satellites. One typical result—radial position error for a single satellite—is shown in Figure 5-7. In the figure, t_{oe} indicates the time of ephemeris, which is at the centre of each overlapping 4-hour window. Each colour represents a different set of ephemeris parameters. The results show that orbit model accuracy relative to truth appears to be about 10 cm RMS over 4 hours. This can probably be reduced further using the GPS CNAV orbit model, which has more parameters.

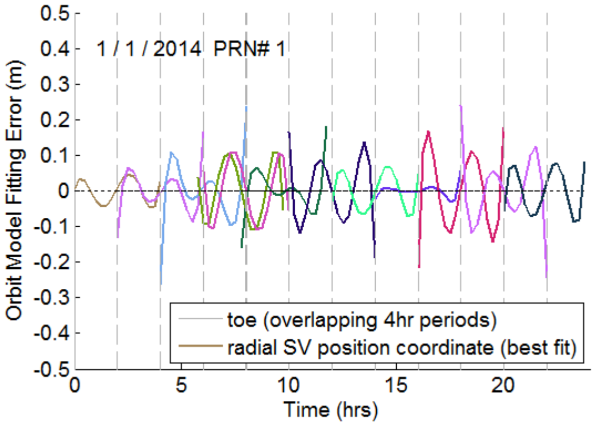

Figure 5-7. ONM example: 18-parameter orbit model accuracy over adjacent 4-hour intervals

The ONM's minimum detectable overlay-ephemeris error, b_{nom}, for a given probability, P_{sat}, will be proportional to the root-sum-square (RSS) of the model accuracy error and the orbit estimation error. For a given ONM detection function, b_{nom} can be traded against P_{sat} to maximize ARAIM availability. However, specific detection functions have not been analysed at this level yet.

5.5 ISM Generation

The message size, time to integrity alert (TIA) by the ONM, and message update rate will be primarily driven by ephemeris overlay design and performance (i.e., duration of applicability). The TIA may also be influenced by ONM detection performance – more specifically, mean-time-to-detect (MTTD) as a function of b_{nom}, the minimum fault magnitude guaranteed to be detectable by the ONM. This is true because $P_{sat} \approx$ (TIA +MTTD)/MTBF, where MTBF is the mean time between overlay failures. Given an overlay function designed to DAL-C, this will be about 10^5 hours. For example, for TIA equal to 1 hour, the minimum value of P_{sat} will be 10^{-5}. It can be significantly larger if a small value of b_{nom} is selected. P_{const} can potentially be made much smaller than P_{sat}, perhaps even negligibly small, by updating ephemeris overlay parameters one satellite at a time. However this has not been conclusively proven yet.

The Integrity Support Message for the Online ARAIM architecture can be broken down into three major elements:

1. Data management bits
2. ISM core data (similar to the ARAIM Offline ISM)
3. ISM ephemeris and clock correction data

Table 5-1 shows an example of ISM format and content for items 1 and 2. **Table 5-2** shows the additional data for the overlay. Ultimately, ISM content would be automatically generated by the ARAIM ground system using methods and algorithms approved by ANSPs, ideally at the international level (i.e., ICAO).

	Parameter	Description	Value	Size (bits)
Data Header	Const_ID	ISM Constellation Identifier	[0 … 3]	2
	Sat_ID	ISM Satellite ID	[0 … 31]	5
	ISM_ToA	ISM Time of Week	[0 … 2^{20} -1]	20
	ANSP ID	Service Provider Identification	[0, 1, … 255]	8
	Total Header = 35 bits			
ISM Core	Health_Flag	Satellite Health Flag	[0,1]	N_{sat}
	$P_{sat,j}$	Probability of satellite fault at a given time	[10^{-6} … 10^{-5} … 10^{-3}]	$4N_{sat}$
	$P_{const,i}$	Probability of constellation fault at a given time	[10^{-8} … 10^{-5} … 10^{-3}]	$4N_{const}$
	$\sigma_{Int,j}$	Sigma Int. (URA) as calculated by ARAIM G/S	[0.05, 0.1, … 1.65]	$5N_{sat}$
	$b_{Int,j}$	Bias Integrity	[0.05, 0.1, …, 1.65]	$5N_{sat}$
	$\sigma_{Cont,j}$	Sigma Cont/Acc. (URE) as calculated by ARAIM G/S	[0.05, 0.1, … 1.65]	$5N_{sat}$
	$b_{Cont,j}$	Bias Cont/Acc	[0.05, 0.1, …, 1.65]	$5N_{sat}$
	Total Core = 25N_{sat} + 4N_{const} bits			

Table 5-1. ISM format and content: data management bits and core data

	Parameter	Description	Size (bits)
ISM Ephemeris	M0	Mean anomaly	$32N_{sat}$
	Δn	Mean motion difference	$16N_{sat}$
	e	Eccentricity	$32N_{sat}$
	Sqrt(A)	Sqrt Semi Major Axis	$32N_{sat}$
	Omega0	Longitude of ascending node of orbital plane at weekly epoch	$32N_{sat}$
	i0	Inclination angle at reference time	$32N_{sat}$
	omega	Argument of perigee	$32N_{sat}$
	OmegaDot	Rate of change of right ascension	$24N_{sat}$
	Idot	Rate of Change of Inclination angle	$14N_{sat}$
	Correction terms (C_{UC}, C_{US}, C_{RC}, C_{RS}, C_{IC}, C_{IS})	Harmonic Correction terms	$6*16N_{sat}$
ISM Clock Correction	t_{0c}	Clock correction data reference	$14N_{sat}$
	a_{f0}	Clock bias correction coeff	$31N_{sat}$
	a_{f1}	Clock drift correction coeff	$21N_{sat}$
	a_{f2}	Clock drift rate correction coeff	$6N_{sat}$
			Total Overlay = $414N_{sat}$ bits

Table 5-2. ISM format and content: ephemeris overlay data

Considering two core GNSS constellations each consisting of 30 satellites, the overall ISM data volume is approximately 25 kbit. Thanks to the ARAIM user algorithm these data do not need to be disseminated within the TTA of 6 seconds, but can be spread over a much longer time interval. Considering, for example, an update interval of 15 minutes the resulting effective data rate would be approximately 28 bps. (The example 15 min interval was selected in order to make sure that within a reasonably short time all ISM data is available at the avionics to conduct an ARAIM LPV-200 based approach.) It is important to note that content of the ISM can remain static for a relatively long time interval, on the order of 1 hour or more, but the message update rate can be faster, as demanded by operational considerations, including catering for potential message losses by the datalink.

5.6 ISM Dissemination

There are a wide variety of potential approaches to dissemination of the ISM within the context of Online ARAIM, including:

- Geosynchronous (GEO) satellite datalink (like SBAS)
- VHF Data Broadcast (VDB) from terminal airport (like GBAS)
- Current and future Aeronautical Datalinks such as VDL-2, LDACS, or Aeromacs
- Prior to the approach from APNT/DME or ADS-B Ground-Based Transmitter (GBT)
- Enroute using spare bits by CSPs

Using the VDB option can provide an upgrade path to GBAS Cat II/III for some airports. The GEO option would continue providing high integrity and high accuracy service to current non-aviation SBAS users. On the other hand, note that to cope with the objective of providing a global service in the case of VDB, there would need to be ground transmitters near every airport. The GEO option would not cover high latitudes.

Acceptable method(s) of dissemination would need consensus from all stakeholders, including ANSPs and avionics/aircraft manufacturers. Ultimately, it is possible that different dissemination methods could be implemented by different ANSPs. The operational constraints for the repetition rate of the ISM will be one of the points for which the ARAIM TSG will seek feedback from ARAIM stakeholders.

6 ARCHITECTURAL OPEN POINTS

This section highlights the open points that are common and those that are specific to each architecture.

6.1 Common

6.1.1 Global ISM versus multiplicity of ISMs

Ideally, the ISM would be global. However, States may wish to alternatively use a regional or national ISM in particular when supporting approach operations. Both architectures easily support either method. A single ISM could be applied everywhere, as is essentially done today for RAIM. Alternatively, specific ISMs can be tied to specific airspaces, but this would increase the cost and complexity of the system. Each ISM requires relatively few bits. They can be made specific to an ANSP or group of ANSPs. They could be included in a database or broadcast by each ANSP.[12] The receiver manufacturers, airframe manufacturers, airlines, regulators, and ANSPs must decide the specific method of transmission jointly.

6.1.2 No guarantee of vertical navigation until service history has been established.

Because both architectures require some level of trust in the CSPs' constellation performance, that trust will need to be established over time. After a CSP establishes a dual frequency service and publishes a performance standard, the ANSPs can monitor actual performance for compliance to the standard. To demonstrate that performance can be trusted in the long-term to the required probabilities, a long period of performance must be observed. Initially, the parameter values will be increased (relative to the published CSP performance standards) to add a degree of conservatism. Small values of P_{sat} and P_{const} require years of observation. Therefore, they will initially be large. Over time, if the CSP establishes a good track record of meeting its commitments, these values can be lowered. It may require five or more years to decrease to the current L1 GPS values. A CSP that does not initially meet its commitments could take much longer.

6.1.3 Constellations may be weak

The most significant concern is that the number and distribution of satellites for either or both constellations could be insufficient. Currently GPS has 31 healthy satellites on orbit. However, its performance commitment only assures 21 satellites with 98% availability. The reality has been substantially better, with never fewer than 28 healthy satellites on orbit and (with at least 23 healthy out of 24 primary slots) in the last seven years. However, the official commitment assures far fewer satellites and it is possible that a smaller number could be available for use in the future.

Galileo has similar concerns in that it has to build up its constellation and long-term satellite availability commitments have not yet been made. As with GPS, it is expected that between 24 and 30 healthy satellites will be on orbit.

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[12] Note that this can lead to situations where different, yet valid ISMs, are available for the user. The way to proceed in that situation must be agreed upon in the standard.

An online architecture is less sensitive to constellation weakness, especially if it completely mitigates the constellation faults.

6.1.4 Standards for ISM data formats

Tables 3-1 and 6-1 contain a first draft of the ISM contents, but it is possible that additional useful parameters will be identified in the future. The specific values in the data format need to be decided in order to properly optimize performance. These values will not necessarily be known until dual frequency GNSS services mature.

6.2 Offline Specific

6.2.1 Reference Stations & Analysis Centres (Master Stations (MS))

The IGS network serves as a good starting point for the monitoring of satellite clock and orbit errors. They are already internationally coordinated and the sheer number of sites makes it easy to identify and remove anomalies. The data from these sites are also used for very precise positioning for scientific purposes; inconsistencies at the sub-metre level are easily determined. However, this network is currently lacking the capability to fully observe signal deformations. Therefore, it is desirable to augment this network with receivers that make measurements at several different correlator spacings. For the U.S., the WAAS network already has this capability for GPS L1 signals. WAAS is in the process of upgrading its receivers to also collect GPS L5 signals with multiple correlator spacings. It may also add similar capability for monitoring other constellations in the future. If suitably upgraded, the WAAS and IGS networks could provide excellent monitoring for North America. Other regions can exploit their local SBASs or existing or planned receivers.

Analysis centres for the offline architecture can be relatively simple, as they have no real-time communication or data processing requirements. They do require access to the data and must have trusted and knowledgeable staff. There remains an open question as to whether each ANSP will conduct its own analysis. Alternatively they could pool their resources or defer to the efforts of another trusted ANSP.

6.2.2 Standards for Reference Station & ISM data formats

IGS already has standards for reference station fielding and for data formats. However, the ANSPs may wish to augment these to improve measurement quality and to return more information to the master station. At a minimum, additional data is required to monitor for signal deformations, but other information can also be very helpful in monitoring satellite performance.

6.2.3 Conservative ISM values until service history has been established

P_{sat}, P_{const}, α_{URA}, α_{URE}, and b_{nom} may be initially increased (relative to the published CSP performance standards) to add protection. Over time, if the CSP establishes a good track record of meeting its commitments, these values can be lowered. It may require five or more years to decrease to the current L1 GPS values. A CSP that does not initially meet its commitments could take much longer.

6.2.4 Interface between ANSP & airborne receiver

The interface between the ANSPs and the receiver should be decided jointly by the receiver manufacturers, airframe manufacturers, airlines, and ANSPs. However, because the latency can be very large, the available variety of options can also be very large. Notionally, we have proposed using a database that the aircraft will update monthly. However, other methods such as the use of VDBs, or other receiver interfaces such as a maintenance data port, are viable options, too. ANSPs and industry will need to determine the right balance between flexibility of multiple ISM dissemination options and excessive cost/complexity inherent with increasing options.

6.2.5 Availability Risk From:

a. α_{URA} or σ_{URA} too large

There is the possibility that the ranging accuracy from the GNSS satellites will be too large or that the broadcast σ_{URA} will be too conservative. The IGS data analysed so far suggests that GPS ranging accuracy is quite good, especially for satellites that use rubidium clocks. Most of the recent IIR and IIF satellites have sub-metre accuracy. Further, GPS intends to improve its performance with the fielding of its new operational control centre software (OCX) and the GPS III satellites. Figure 6-1 uses only the data from Figure 4-2 that had σ_{URA} = 2.4 m, to determine the minimum safe reduction from that value for σ_{URA}. A 2.4 m σ_{URA} value is broadcast more than 80% of the time. This indicates that the majority of future σ_{URA} values could be below 1.2 m. Figure 6-1 also shows some of the new quantization levels for σ_{URA} (the current minimum value is 2.4, but this will change with OCX). Values at 0.6 and 0.85 m, and perhaps lower, should be possible. Note that this analysis is preliminary and more data and further analysis of specific conditions (e.g., navigation data at the end of its period of applicability) is required.

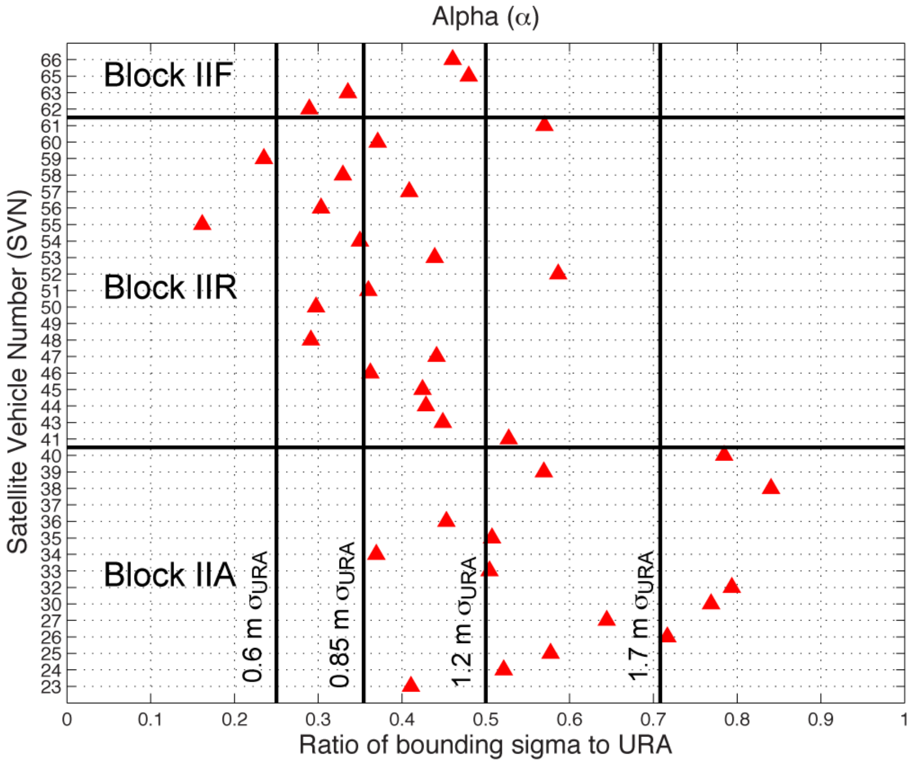


Figure 6-1. Minimum σ_{URA} values that are still individually Gaussian bounded.

The original Galileo requirements listed σ_{URA} equivalent values of 0.85 m as the target. Measurements obtained during the Galileo IOV phase give good confidence that this target performance level can be achieved.

b. P_{const} and P_{sat} are too large

Another concern is that if new satellite failures are observed, they could lead to larger required values for P_{sat} or P_{const}. It requires years of observation in order to establish the low values currently proposed for GPS. New constellations will, by necessity, start with larger values until both the CSP and the ANSPs can gain sufficient confidence. This may also be necessary in some cases for new satellite designs within existing constellations.

c. Constellations may be weak

The main concern with weaker constellations is that for the current range of P_{const} (10^{-5} – 10^{-4}), subsets excluding entire constellations need to be evaluated. If the remaining constellation is weak, availability will decrease. Having two strong constellations mitigates this concern. Alternatively, a third viable constellation also solves the problem as now two remain when one is removed for evaluation. Other possible solutions are to add more checks in the aircraft to extend the period of validity for the broadcast navigation data, or to integrate ARAIM with other sensors. The airborne tests are still relatively new and enhancements and improvements are continuously being found [RD-66]. There are many potential enhancements to be investigated that will likely yield further availability improvements.

6.3 Online Specific

6.3.1 Reference Station Network

There are important open questions for the online architecture concerning the ownership and stewardship of the worldwide network of RSs. One reasonable approach, suggested earlier, would be to leverage to the greatest extent possible existing SBAS ground facilities operated by various ANSPs. Preliminary analysis suggests that a total of about 20 reference sites should be sufficient. However, it is unlikely that the distribution of existing SBAS RSs would be adequate to ensure worldwide satellite observability required for online monitoring. It is more likely that additional sites, in areas of the world not currently equipped with SBAS RSs would be required. The question then arises who would be responsible for setting up and operating new sites.

On one end of the spectrum, one may propose—conceptually, at least—that each ANSP would establish and operate their own worldwide network. While this may be feasible for some ANSPs from larger nations, it is clearly impractical for most states. Furthermore, it would lead to costly and unnecessary redundancy in the ground systems. From a technical point of view, the best option would be that the ISM is generated in a collaborative way by making use of a single network of ground stations. Such a network, for example, could be comprised of some existing SBAS stations and additional stations added as needed to provide adequate coverage.

Joint partnerships undertaken to deploy the necessary online ARAIM ground infrastructure would likely require that equipment performance standards first be established at the international level. There is also the related question of data ownership and dissemination. It would seem logical that all RS available data would be freely shared between ANSPs. However, the standards regarding data sharing (e.g., what data, how much, how frequently, etc.) would also need to be agreed upon at the international level, which together with the equipment performance standards, will take effort and time to establish.

6.3.2 Online Monitoring, Ephemeris Overlay, and ISM Generation

Following this, it is necessary to ask who generates the ISM message and who distributes it. The second question is perhaps more easily answered than the first. Following the model of SBAS, the ANSP responsible for a specific airspace would also be responsible for ISM dissemination within that airspace. SBAS provides a good example of this as neighbouring states may utilize nearby SBAS service under formal agreement. Open questions on the possible methods of ISM delivery will be discussed below. However, it is not straightforward to use the SBAS analogy for ISM generation. Again from a technical point of view, the best option would be that a single ISM is generated in a collaborative way. Nevertheless, it cannot be discarded that different ANSPs could produce different ISM (albeit in the same ISM data message format). In any case, it is recommended that ICAO standards be established to carefully define the generation and also the monitoring of the ISM message content (e.g., σ_{URA}, P_{sat}, etc.).

In case different ISMs are generated, it would be advisable that the ISMs are shared between ANSPs. This would also allow for ANSPs to use ISMs already generated by others.

On the technical side, much further development, implementation, experimental validation of the ephemeris overlay and online monitor functions will be required. Concerning the ephemeris overlay, precise ODTS processes similar to those currently used to support SBAS will need to be developed and validated. (Performance standards will be discussed below.) Undoubtedly this will be a time consuming process, but there is probably not significant technical risk involved because similar software has been developed many times by different organizations, including SBAS contractors and IGS member organizations. Rather, the main issue is that these are complex algorithms, which would be difficult and costly to certify at the level of *hazardous* severity for the algorithm, and DAL-B for software.

As discussed earlier, a more realistic option is to certify the overlay generation function to *major* severity and DAL-C, but subsequently implement a separate, simpler online integrity monitor, which would be easier to certify to hazardous/DAL-B. This method has roots in SBAS.

In the case of ARAIM however, it is not necessary that the online monitor achieve a 6-sec time to alert, but rather to ensure that the overlay ephemeris parameters contained in the ISM have undetected fault probabilities consistent with the selected values of P_{sat} and P_{const}, for all fault magnitudes exceeding the selected value of b_{nom}. This must be ensured through the design and validation of the online monitor itself. In contrast, the performance requirements for the ephemeris overlay function will be set by the need to maintain small URAs for user orbit predictions over the ISM update interval.

The goal is to design an online monitor as simply as possible to make certification easier. However, based on prior experience with SBAS and GBAS, even if it is possible to design a simple online monitor algorithm, it is highly likely that the associated integrity analysis will not be simple at all, especially given the interrelationships between the monitor performance and the selected ISM values of P_{sat} and P_{const} and b_{nom}. There is significant technical development required here, which would probably require several years of work for development and validation.

6.3.3 Interface between ANSP & airborne receiver

As with the offline architecture, ISM dissemination methods should be decided by consensus from all stakeholders, including ANSPs, avionics manufacturers, aircraft manufacturers, and airlines. It is possible that more than one method of dissemination could be deemed acceptable in the end, and that different dissemination methods could be implemented by different ANSPs. But achieving such a consensus internationally, regardless of the ultimate outcome, will take time.

7 CONCLUSIONS

This Milestone 2 Report presents the progress made by the ARAIM Technical Subgroup since the previous Milestone 1 report (dated December 19th, 2012). It reports on:

- **Horizontal ARAIM** to support horizontal navigation based on an occasional Integrity Support Message (ISM) from the ground to the air.
- **Offline ARAIM** to support horizontal and vertical navigation based on a monthly ISM from the ground to the air.
- **Online ARAIM** to support horizontal and vertical navigation based on an hourly ISM.

Horizontal ARAIM: ARAIM for horizontal navigation is similar to traditional RAIM that has supported aviation navigation operations since 1993. However, Horizontal ARAIM also tracks multiple constellations to reduce sensitivity to the strength of any individual constellation. Indeed, current RAIM can be troublesome at dispatch, because it is based on GPS alone and outages result. Most of these outages are predictable and some cannot be forecast.

Horizontal ARAIM can also mitigate the effects of accidental radio frequency interference by reverting to either L1 only or L5 only operation. As shown in Chapter 2, RNP 0.1 is always available when both signalling frequencies (L1 and L5) are available and the two constellations are tracked. The analysis of Chapter 2 also shows that ARAIM with GPS and Galileo supports RNP 0.3 even when L1 is lost and L5 alone is useable. Thus Horizontal ARAIM supports RNP 0.1 under all normal conditions and reverts to RNP 0.3 when the L1 signal has been lost (perhaps to radio frequency interference).

Unlike traditional RAIM, Horizontal ARAIM has a provision to input new integrity data if needed. This data is not frequently required and would only be used to communicate large changes in the core constellations. For example, it would carry data to commission a new constellation. It could also communicate improvements in the ranging accuracy or *a priori* failure probabilities. In traditional RAIM, the significant parameters only refer to GPS, and are hardcoded into the receiver. They can only be changed if the receiver software is updated. In Horizontal ARAIM, these parameters can be updated, because a multiplicity of constellations dictates some ability to adapt to a changing signal environment. However, there would be no effort to adapt to short-term variations in constellation status or performance.

Importantly, Horizontal ARAIM is entirely feasible and should proceed in synchronism with the build out of the new constellations. It will obviate the RAIM outages currently experienced by airline dispatchers because it is based on multi-constellation satellite navigation. It would also provide a reversionary mode to mitigate the impact of radio frequency interference.

Offline ARAIM: This architecture follows the approach of the current implementation of RAIM; it is also very similar to Horizontal ARAIM. The ISM consists of a standard set of parameters determined prior to operation, and used by the airborne algorithm to support the desired operations. These parameters are based on the CSP commitments, and the history of the actual constellation performance. They are expected to be valid for months or longer. In traditional RAIM, this set of parameters is hardcoded into the receiver and can only be changed if the receiver software is updated. In the offline architecture, these parameters would be updated with long latency (order of 1 month). Primarily, updates would be to include new constellations or to reduce conservatism as the constellation matures. Any immediate action comes from the airborne algorithm identifying and eliminating faults. The overall safety case for Offline ARAIM would thus rely on the CSP commitments and the observed service performance history. ANSPs need to trust that the CSPs would continue to operate their constellations in a consistent manner going forward in time.

The ground segment would comprise a global network of receivers, sufficiently dense so that many reference receivers can observe all satellites at all times (50 or more stations). Since the ground segment is not responsible for time to alert, the receivers don't have to be dedicated, nor does the reference data need to be processed in real-time. In this architecture ARAIM can make use of receivers from already existing global networks (IGS, Jet Propulsion Laboratory (JPL), SBAS).

The ISM broadcast rate for Offline ARAIM is low. Initially it is assumed that the ISM can be included in a database, which is updated every 28 days. However, if an alternate preferred method is identified (e.g., VDB or satellite link), the low data rate should be easy to accommodate. Ultimately, the constraints for broadcast are driven by the required repetition rate of the ISM, rather than by its validity time. Final means of broadcast require input from receiver manufacturers, airframe manufacturers and operators. Ideally, the receivers initially fielded during the ARAIM horizontal only operations would be developed in a way that they could support vertical navigation as well once such ISMs are approved. This is an open question to the community as to whether such a development process is possible and/or desirable.

As described in the report, Offline ARAIM utilizes the navigation messages from the core constellations. Hence, it does not need to communicate with inflight aircraft and can avail itself of the greatest variety of ISM communication links including monthly database updates. However, Offline ARAIM is sensitive to the user range accuracies (URAs) that are contained within the navigation messages from the core constellations. These need to be guaranteed by the CSPs and verified by service history. Some of the new constellations may not be able to achieve the needed level of URA performance. Thus Offline ARAIM is subject to *availability risk.*

Online ARAIM: This architecture follows a different approach, with less dependence on the CSP commitments and constellation performance history. To reduce this dependence, the online ARAIM ground segment generates and broadcasts its own navigation messages (satellite orbits and clock predictions) replacing those broadcast by the core constellations. This independent navigation message gives the ANSP control over the ground contributions of orbit and clock error, and may improve the accuracy, P_{sat} and P_{const}, and consequently, the availability. In particular, the Online ARAIM architecture provides leverage to ensure P_{const} of 10^{-8}, which is assumed in the bottom table in Figure 7-1, and is key to satisfying LPV-200 requirements. Thus, this architecture reduces availability risk at the expense of complexity.

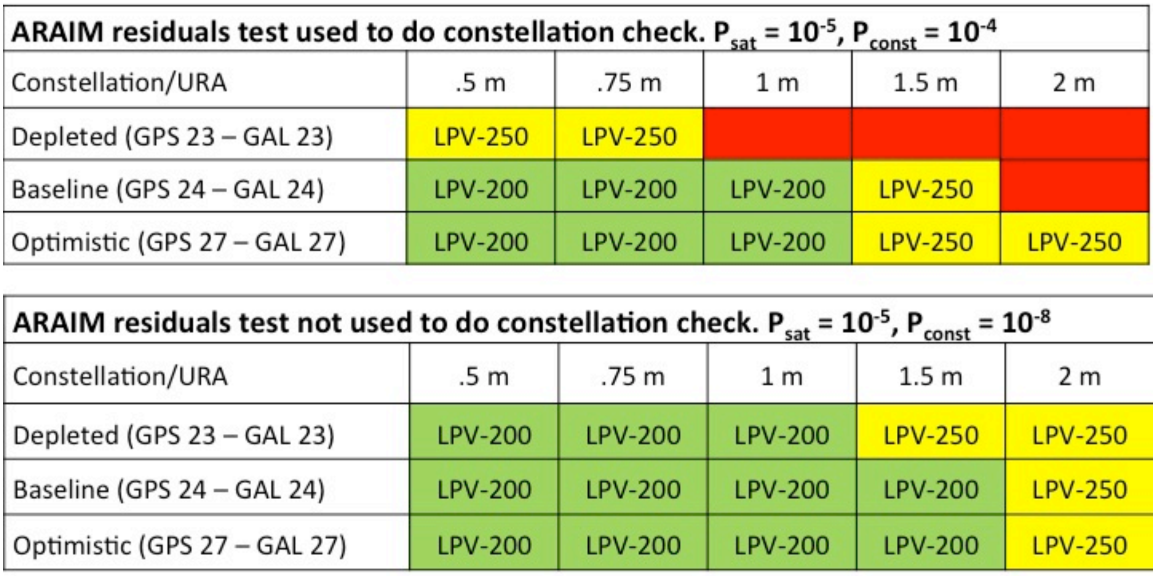
The ground segment in the online architecture comprises a global network of dedicated reference receivers, an ephemeris overlay generator, an offline monitor, and an online monitor. Like Horizontal and Offline ARAIM, the air algorithm is responsible for timely detection of faults. The airborne integrity algorithm is almost the same for Offline and Online ARAIM. They have one significant difference; the Online user algorithm applies the clock and ephemeris parameters received through the ISM rather than the navigation messages from the core constellations. These parameters do not need to be applied with very short latency, but within the one-hour validity time of the clock and ephemeris parameters.

The reference network for Online ARAIM includes about 20 reference stations, each equipped with two or three dual-frequency, multi-constellation receivers, measuring code and carrier phase from all visible satellites. This network is needed to achieve sufficient orbit determination and monitoring accuracy for the ephemeris overlay and monitoring functions, considering the additional need for redundancy to ensure system continuity in the event of receiver failures. Data backhaul and processing must support the one-hour validity time. The operation and maintenance of the receivers would be the responsibility of the ANSPs making use of the ISMs generated by the Online ARAIM ground system. It is expected that existing SBAS infrastructure would be leveraged to the greatest extent possible.

To reach the adequate level of safety for the ISM function (safety critical: hazardous for the algorithm, and Design Assurance Level – DAL - B for software), the Online ground system design may be able to develop the overlay generation function to a lower level (safety critical: major and DAL-C for software), while the online monitor would be developed to the higher level, hazardous/DAL-B. As such, the ground receivers may only need to reach DAL-D.

The Online ISM would contain data fields for the core integrity data, similar to the ISM of the offline architecture, plus fields with the ephemeris and clock correction data for the overlay. The Online ISM message size is primarily driven by the ephemeris accuracy and validity time. Considering two core GNSS constellations, each consisting of 30 satellites, the overall ISM data volume is approximately 25 kilobits. The required broadcast capacity is determined by the required repetition period and the size of the ISM. Assuming a repetition period for the ISM of 15 minutes, the data throughput would need to be approximately of 28 bps (higher periods may be considered to achieve higher repetition periods to better assure reception). While these values seem low, this data rate is large compared to any capacity available from the core constellations or SBAS satellites. Moreover, an eventual goal of ARAIM is to obviate the cost of the geostationary satellites used by SBAS. Thus Online ARAIM is subject to *connectivity risk*.

Availability of ARAIM for Vertical Navigation: The results for ARAIM availability have been detailed in Chapter 2 and are summarized in the tables below. This performance includes the improvement due to the optimization of the reference user algorithm described in Annex B.4. The tables indicate whether or not vertical guidance is available to a decision height of 200 feet (LPV-200) or 250 feet (LPV-250). More specifically, each entry indicates the most stringent level of service for which 90% coverage of 99.5% availability is achieved. The tables in Figure 7-1 give the level of service as a function of the constellation strength (depleted, baseline, and optimistic) and the user range accuracy (URA). The latter quantifies the nominal quality of the signals coming from the core constellations as provided by the CSP. Today, the minimum URA for GPS is 2.4 metres, but smaller values will become possible later, when its new message format is implemented. The 2.4 metre value cannot support LPV-200 or LPV-250 based on ARAIM. However, the ARAIM TSG has studied the achieved performance of GPS in depth, and the achieved range accuracies of GPS are approximately one metre or better. If this achieved performance were to be reflected in the broadcast URA, then Offline ARAIM would support LPV-200 with the baseline or optimistic constellations.



ARAIM residuals test used to do constellation check. $P_{sat} = 10^{-5}$, $P_{const} = 10^{-4}$

Constellation/URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	LPV-250	LPV-250	🟥	🟥	🟥
Baseline (GPS 24 – GAL 24)	LPV-200	LPV-200	LPV-200	LPV-250	🟥
Optimistic (GPS 27 – GAL 27)	LPV-200	LPV-200	LPV-200	LPV-250	LPV-250

ARAIM residuals test not used to do constellation check. $P_{sat} = 10^{-5}$, $P_{const} = 10^{-8}$

Constellation/URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	LPV-200	LPV-200	LPV-200	LPV-250	LPV-250
Baseline (GPS 24 – GAL 24)	LPV-200	LPV-200	LPV-200	LPV-200	LPV-250
Optimistic (GPS 27 – GAL 27)	LPV-200	LPV-200	LPV-200	LPV-200	LPV-250

Figure 7-1. Vertical Service Available from ARAIM as a Function of Constellation Strength and User Range Accuracy (URA).

Way Forward: The ARAIM TSG strongly recommends the optimization and standardization of Horizontal ARAIM. The ARAIM TSG does not immediately recommend either Offline or Online ARAIM for vertical navigation. Succinctly put, the vertical capability of ARAIM requires the input of the greater aviation community.

ANNEX A: LIST OF REFERENCES

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ANNEX B: USER ALGORITHM UPDATES AND SETTINGS

B.1 List of constants used in the simulations

Table B.1 shows the constants related to the navigation requirements that are used in the algorithm.

Name	**Description**	**Value**
$PHMI$	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 15s [RD-06].	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}

Table B-1. Constants related to the navigation requirements

B.2 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, horizontal domain,
- the false alert rate to chi-square test, and
- the parameters used to limit the number of fault modes that are monitored by the airborne algorithm.

The simulations shown in Section 2 used the parameters as shown in Table B.2.

Name	**Description**	**Value for LPV-200 and LPV-250**	**Value for RNP**
$PHMI_{VERT}$	integrity budget for the vertical component	9.8×10^{-8}	2.0×10^{-9}
P_{FA_VERT}	continuity budget allocated to the vertical mode	3.9×10^{-6}	9×10^{-8}
P_{FA_HOR}	continuity budget allocated to the horizontal mode	9×10^{-8}	3.9×10^{-6}
P_{SAT_THRES}	threshold for the integrity risk coming from unmonitored satellite faults	4×10^{-8}	4×10^{-8}
P_{SAT_THRES}	threshold for the integrity risk coming from unmonitored satellite faults	4×10^{-8}	4×10^{-8}

Table B-2. Design parameters (tunable)

B.3 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:

$$\sigma_i^2 = \sigma_{URA,i}^2 + \sigma_{tropo,i}^2 + \sigma_{SFuser,i}^2 + \sigma_{iono,i}^2 \tag{1}$$

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]):

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

(This correction undoes the correction made in [RD-54] for dual frequency GPS in [RD-54] 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:

$$\sigma_{iono,i}^2 = \frac{f_{L1}^{\ 4}}{f_{L5}^{\ 4}}\sigma_{i,UIRE}^2 \tag{3}$$

B.4 Protection Level and Effective Monitor Threshold Equations

This paragraph describes how the PL Equations and the EMT have been modified with respect to [RD-54].

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:

$$\begin{aligned} 2Q\left(\frac{VPL - b_3^{(0)}}{\sigma_3^{(0)}}\right) + \sum_{k=1}^{N_{fault\ modes}} p_{fault,k}\,Q\left(\frac{VPL - T_{k,3} - b_3^{(k)}}{\sigma_3^{(k)}}\right) = \\ PHMI_{VERT}\left(1 - \frac{P_{sat,not\ monitored} + P_{const,not\ monitored}}{PHMI_{VERT} + PHMI_{HOR}}\right) \end{aligned} \tag{3}$$

Horizontal Protection Level (HPL)

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

$$
\begin{gathered}
2Q\left(\frac{HPL_q - b_q^{(0)}}{\sigma_q^{(0)}}\right) + \\
\sum_{k=1}^{N_{fault\ modes}} p_{fault,k} Q\left(\frac{HPL_q - T_{k,q} - b_q^{(k)}}{\sigma_q^{(k)}}\right) = \\
\frac{1}{2} PHMI_{HOR}\left(1 - \frac{P_{sat,not\ monitored} + P_{const,not\ monitored}}{PHMI_{VERT} + PHMI_{HOR}}\right)
\end{gathered}
\tag{4}
$$

The HPL is given by:

$$HPL = \sqrt{HPL_1^2 + HPL_2^2} \tag{5}$$

In both the VPL and the HPL, it is effective allocation of integrity risk that has been changed with respect to [RD-54].

Effective Monitor Threshold

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:

$$EMT = \max_{k|p_{faul,k} \geq P_{EMT}} T_{k,3} \tag{6}$$

B.5 Optimized positioning for weak geometries

An approach to minimize the Protection Levels by adjusting the all-in-view position solution was described in [RD-60]. As shown in this reference, there can be a significant improvement in the integrity error bound by choosing a position solution that is offset from the most accurate position solution under nominal conditions. This is due to the fact that weak geometries deteriorate the Protection Level in two ways; in the term that accounts for the error in the subset solution and in the detection threshold. It is possible to reduce the detection threshold by modifying the all-in-view solution. Here we describe a simple position adjustment that does not increase the computational load. This method provides a significant benefit for geometries where one of the subsets has a much larger standard deviation (in fact, for those geometries, it matches the optimal approach of [RD-60]). It only needs to be applied if the VPL exceeds 35 m or the EMT exceeds 15 m and $\sigma_{v\_acc} \leq 1.87m$ with the algorithm described in [RD-54].

The idea consists of simplifying the Protection Level to only account for the fault mode with the largest subset integrity error bound (however, this simplification is only done to search for the all-in-view estimator coefficients *s*). Using the notations of [RD-54], the partial *PL* for fault *i* is (C_{acc} is the covariance of the measurements and $s^{(i)}$ are the coefficients corresponding to subset *i*):

$$PL_i = K_{fa}\sqrt{\left(s - s^{(i)}\right)^T C_{acc}\left(s - s^{(i)}\right)} + K_{md,i}\sigma_i \tag{7}$$

We note that s_{all} are the coefficients for the least squares position that includes all constellations and s_{max} are the coefficients for the least squares position of the weakest subset. We look for a coefficient of the form:

$$s = s_{all} + t\left(s_{\max} - s_{all}\right) \tag{8}$$

For the weakest mode one can see that as we move towards s_{max}, the partial PL decreases. We have:

$$PL_i = K_{fa}\sqrt{\left(s_{all} + t\left(s_{\max} - s_{all}\right)\right)^T C_{acc}\left(s_{all} + t\left(s_{\max} - s_{all}\right)\right)} + K_{md}\sigma_{\max} \tag{9}$$

However, as one moves towards s_{max}, the accuracy also degrades, and we therefore impose the constraint:

$$s^T C_{acc} s \leq \sigma^2_{acc,req} \tag{10}$$

The left term is the standard deviation of the all-in-view position under nominal conditions. The right term is the required accuracy. If we replace s with its expression, we have:

$$\left(s_{all} + t\left(s_{\max} - s_{all}\right)\right)^T C\left(s_{all} + t\left(s_{\max} - s_{all}\right)\right) \leq \sigma^2_{acc,req}$$

$$\begin{gathered}
s_{all}{}^T C s_{all} - \sigma^2_{acc,req} + 2ts_{all}{}^T C_{acc}\left(s_{\max} - s_{all}\right) + t^2\left(s_{\max} - s_{all}\right)^T C\left(s_{\max} - s_{all}\right) \leq 0 \\
a = \left(s_{\max} - s_{all}\right)^T C\left(s_{\max} - s_{all}\right) \\
b = 2s_{all}{}^T C_{acc}\left(s_{\max} - s_{all}\right) \\
c = s_{all}{}^T C s_{all} - \sigma^2_{acc,req} \\
at^2 + bt + c \leq 0
\end{gathered} \tag{11}$$

The constraint above imposes:

$$t \in \left[\frac{-b - \sqrt{b^2 - 4ac}}{2a}, \frac{-b + \sqrt{b^2 - 4ac}}{2a}\right] \tag{12}$$

Since we want the coefficients to be as close to s_{max} as possible, we choose the upper limit of this interval.

In parallel, another estimator design method, which aims at minimizing the integrity risk in ARAIM, was independently derived in [RD-72]. This method supports Equations (8) to (13) as it calls upon the same fundamental principles. A complete derivation can be found in [RD-73].

Summary of the algorithm

This part of the algorithm should be inserted after Equation (14) in [RD-54].

Step 1: Among the fault modes that are going to be monitored, and whose *a priori* probability is above the integrity budget 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:

$$\begin{aligned} a &= \left(s_{\max} - s_{all}\right)^T C_{acc} \left(s_{\max} - s_{all}\right) \\ b &= 2{s_{all}}^T C_{acc} \left(s_{\max} - s_{all}\right) \\ c &= {s_{all}}^T C_{acc} s_{all} - \sigma^2_{acc,req} \end{aligned} \tag{13}$$

Step 3: Compute:

$$t = \min\left(1, \frac{-b + \sqrt{b^2 - 4ac}}{2a}\right) \tag{14}$$

Step 4: Compute:

$$s = s_{all} + t\left(s_{\max} - s_{all}\right) \tag{15}$$

Once the all-in-view coefficients have been computed according to Equation (15), the algorithm continues at Equation (12) (replacing the third row of $S^{(0)}$ with s).

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 degrade excessively the horizontal accuracy).

ANNEX C: EARTH ORIENTATION PARAMETER ASSERTIONS

Assertion:

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

Supporting points:

1. Each GNSS core constellation provides vital strategic national functionality and each has a stated requirement for independence from the others
2. Each has been independently developed and is independently operated
3. The only common information used by all core constellations are physical constants, coordinate reference frame definitions, and timing standards
    a. Physical constants do not change with time
    b. Each constellation uses its own state's implementation of the International Terrestrial Reference Frame (ITRF), which is consistent to within centimetres of each other.
    c. Timing offsets between the different constellations are directly estimated by the user

Assertion:

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

Supporting points:

1. Each CSP has a separate entity for computing and disseminating the EOPs
2. The EOPs change very slowly over time
3. The satellite orbit estimation errors are not dependent on a constant rotation offset
4. Broadcast navigation data is not updated on all satellites at the same time
    a. The airborne algorithm can detect most scenarios where not all satellites are affected
    b. After all are updated the EOP errors are undetectable at the aircraft but only affect horizontal positioning

Further discussion of supporting points:

The EOPs define the angular rotation between the Earth Centered Earth Fixed (ECEF) ITRF and the International Celestial Reference Frame (ICRF). The ICRF is an inertial frame that is useful for orbital estimation. The orbits of the GNSS satellites are estimated in this inertial frame and then translated to the ITRF using the EOPs. Incorrect EOPs could lead to the wrong position estimate in ITRF. In the worst case, the measurements for this incorrect position fix would all be consistent with one another and therefore not detectable by the aircraft algorithm.

The overall organization responsible for EOP values is the International Earth Rotation and Reference Frame Service (IERS) [RD-67]. In the United States, the U.S. Naval Observatory coordinates with IERS to create and disseminate the EOP values. These are then downloaded by the National Geospatial-Intelligence Agency (NGA) who then provides them to the Air Force for use by GPS. Each organization has its own quality and consistency checking before accepting the EOPs. The details of these checks, the time it takes to complete an update, and the frequency of update are not publicly described. Russia has its own Institute of Applied Astronomy (IAA) that participates in the estimation of EOP values and that provides them to GLONASS. Europe has the Paris Observatory and other national observatories that participate in estimating EOPs and that can provide these values for Galileo. Finally, China also has its own national observatories to provide values for Beidou.

The orbit estimation process begins with pseudorange measurements made to the satellites from terrestrial reference stations. These stations are fixed to an ECEF reference frame. If the orbits were determined instantaneously, an inertial frame would not be necessary. However, because measurements over several days may be used in the estimation process, they are combined with a dynamic model that is best represented in an inertial frame. The EOPs are used to rotate the measurements into this frame and then again to rotate the satellite position estimates back out. Erroneous EOP values that are closely aligned to the true axis of rotation, but that have a constant offset about the axis of rotation, will have a negligible impact on the final position estimates. It would take a significant misalignment of the rotation axis or an inconsistent set of rotational values (several milliseconds change to the length of day) over the course of a couple of days for bad EOP values to create an appreciable positioning error.

The EOPs are predictable to the centimetres level over days and to the metre level over months [RD-68]. The solid Earth exchanges angular momentum with the atmosphere and the hydrosphere, which are the dominant sources of EOP variation. However, these variations are measured in milliarcseconds (mas), which corresponds to one thousandth of 1/3600 of one degree of rotation. One mas corresponds to a 3.1 cm horizontal shift at Earth's surface. Incorrect EOPs can arise from erroneous reported values or from sudden changes to the true values. However, EOPs do not change very quickly. Historically, the largest observed pole motion is less than 25 cm per day and the largest observed change in the length of day is under half a millisecond (also ~25 cm effect) per day (see Figure C-2). Thus, erroneous changes in EOP leading to a metre or larger effect are readily apparent and can be very effectively screened out by any GNSS Constellation Service Provider (CSP).

A common mode consistent and harmful EOP fault would require a sudden EOP change well outside all historical observation. This change would have to fail to be caught at multiple EOP centres and multiple CSPs. Even in such an event, the fault would be sent to satellites over an extended time scale rendering it initially observable to the airborne algorithm. The CSPs would need to continue to fail to observe the error for a long time in order to ultimately reach the state where all satellite measurements were consistently wrong. Even in this final state, the error would be exclusively in the horizontal direction. Any EOP error greater than 1 m should be readily observable. Thus, a multi-metre error or larger would be exceedingly unlikely to escape detection for long enough to be broadcast to multiple satellites.

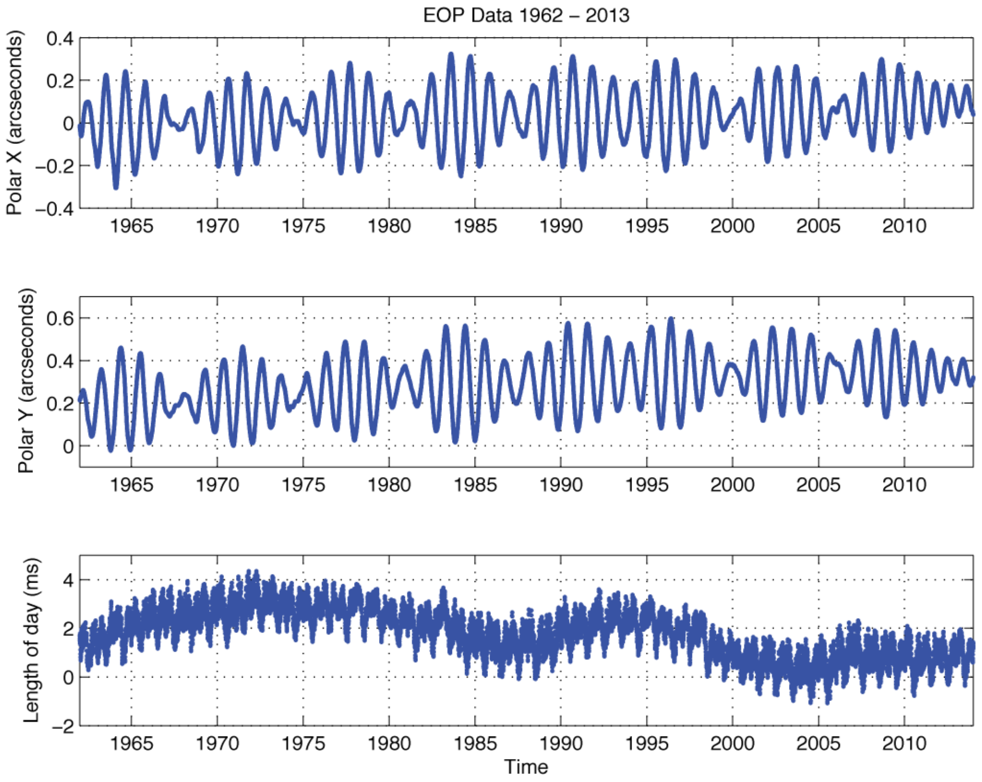

Figure C-1 Historic EOP values

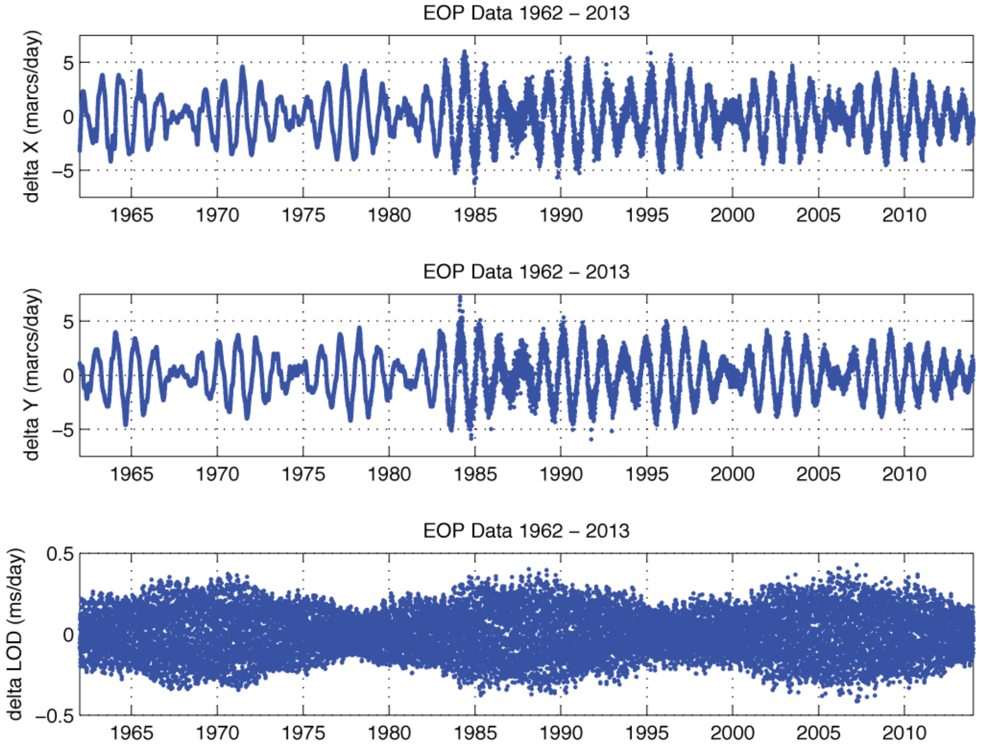

Figure C-2 Historic changes in EOP values from one day to the next