Architectures for Advanced RAIM: Offline and Online

Juan Blanch, Todd Walter, Per Enge.
Stanford University
Boris Pervan, Mathieu Joerger, Samer Khanafseh
Illinois Institute of Technology
Jason Burns, Ken Alexander
Federal Aviation Administration
Juan Pablo Boyero
European Commission, *Belgium*
Young Lee
MITRE/CAASD
Victoria Kropp
University of the Federal Armed Forces, Munich
Carl Milner, Christophe Macabiau
ENAC, France
Norbert Suard
CNES, France
Gerhard Berz
EUROCONTROL, Belgium
Markus Rippl
German Aerospace Center

ABSTRACT

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) is a proposed extension of RAIM to aviation safety of life operations, which include approaches with vertical guidance. ARAIM would exploit the new civilian signals in L5 and new GNSS core constellations. The European Union (EU) and the United States (US) have an agreement establishing cooperation between GPS and Europe's Galileo system. As part of this cooperative agreement a subgroup was formed to investigate ARAIM. As opposed to RAIM, ARAIM would depend on an Integrity Support Message (ISM), approved by the Air Navigation Service Providers. In this work, we describe the two ARAIM ground architectures to determine and disseminate the ISM on which the ARAIM technical subgroup has converged. In the first one, called "offline" a quasi-static ISM would be manually produced and rarely updated. We show that current GPS service performance suggests that the offline architecture could be feasible if new constellations offer a level of performance similar to GPS. In the second one, called "online", a dynamic Integrity Support Message would be automatically updated every hour. In the online architecture, a navigation message overlay and online monitor would allow more control over nominal errors and constellation wide fault by the Air Navigation Service Provider (ANSP). At this point, the ARAIM TSG is not recommending one approach over the other and is seeking feedback on the proposed architectures by stakeholders.

0 INTRODUCTION

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) is a concept that extends RAIM to aviation safety of life operations, which include approaches with vertical guidance [1], [11]. In ARAIM, as in RAIM, the aircraft compares the various ranging measurements that it makes to different satellites to ensure that they are consistent with each other. Achieving lower position error bounds and meeting more demanding integrity requirements would be obtained by using a multi-constellation (for example GPS, Galileo, etc) and dual frequency (L1–L5) solution.

The European Union (EU) and the United States (US) have an agreement establishing cooperation between GPS and Europe's Galileo system. As part of this cooperative agreement a subgroup was formed to investigate the benefits of ARAIM [1]. This EU-US ARAIM subgroup has developed a reference airborne algorithm [2] and identified key issues affecting the potential use of ARAIM [1], [11]. In this work, we describe the two architectures on which the ARAIM technical subgroup has converged (after having considered several approaches [3], [4], [5], [6], [7], [8]).

The defining characteristic of ARAIM (and RAIM) is the reliance on the pseudorange consistency check made by the airborne receiver to determine integrity within the time to alert (TTA). In order to assess the integrity of a position solution, the receiver still needs to make assumptions about the behavior of the satellites. As proposed in [1], these assumptions would be defined in an Integrity Support Message approved by the Air Navigation Service Provider (ANSP). Among other parameters, the ISM would include upper bounds on the probability of satellite fault (P_{sat}), the probability of a constellation fault (P_{const}), and the nominal error statistics due to the ground and space segment (the clock and ephemeris being the largest contributor).

The main distinction between the two architectures is the latency of the Integrity Support Message. In the first architecture, which we will call "offline", the ISM would have a latency of several days and would essentially be static. This architecture would require a stable performance from the constellation service providers (CSPs), and trust from the ANSPs that this performance will remain similar or better in the future. This architecture is called offline because the ISM determination would be an offline process, with a long enough latency to have a human in the loop.

In the second architecture (which we will call "online"), the ISM would have a latency of minutes to hours, and would include an ephemeris overlay. A dedicated global monitoring network (external to the CSPs network) would send a navigation message independent of the CSP broadcast and would automatically update the ISM within hours in the event of a fault in a satellite or a constellation. This architecture would give the ANSPs more control over the ISM parameters and would be similar to SBAS or GBAS in that the ISM would be updated automatically, but with significantly relaxed broadcast update rate requirements.

After a brief description of ARAIM for horizontal guidance, the two architectures for vertical guidance will be described, in particular the functional definition, the communication links, and the operational concept. For both architectures, we will propose an ISM structure. Then, we will evaluate the expected performance for both architectures. Finally, we will highlight the open points for both architectures.

1 HORIZONTAL ARAIM

The first goal of Advanced RAIM is to enable the use of new constellations for horizontal navigation. Adding these new constellations to estimate the position solution and protection levels could provide 100% availability of the most stringent horizontal navigation requirements (down to RNP.1) [9]. This would ideally eliminate the need for a pre-flight availability check. The user receiver would use a static ISM (which could be hardcoded into the receiver). In this respect, ARAIM for horizontal navigation is a straightforward extension of RAIM. It would be different from RAIM in that constellations would have different error characterizations (both for nominal and faulted) according to the CSP commitments and the actual constellation performance. The user receiver would need to account for the heterogeneous probabilities of fault when computing the protection levels. These static ISM parameters will need to be established and agreed to by the stakeholders (receiver manufacturers, ANSPs, etc).

2 OFFLINE ARCHITECTURE

The offline architecture is also modelled on the current implementation of RAIM. A standard set of parameters is determined prior to operation, and then is used by the airborne algorithm to support the desired operations. This parameter set is based upon service provider commitments and observational history. These parameters should be set to values that are expected to be safe for use for the foreseeable future. In the current RAIM implementation, 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 can be updated, but this should happen only very rarely. Primarily, updates would be to include new constellations or to reduce conservatism of earlier values. There should be no effort to chase short-term behaviors in constellation status. Instead the parameters should conservatively cover short-term and long-term performance of the constellations and selected to be safe even if they were never updated. Any immediate action comes from the airborne algorithm identifying and eliminating faults and the CSPs continuing to operate their constellations in a consistent manner.

2.1 Architecture Description

As illustrated in Figure **2-1**, the offline architecture consists of a space segment, a ground segment, and an airborne segment.

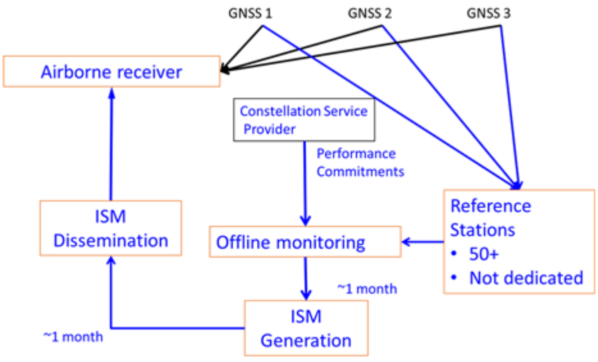

Figure 2-1. The Offline Architecture

The space segment consists of the core GNSS constellations and their services. These constellations provide dual frequency ranging signals and navigation data that describe the satellite locations and satellite clock & health states. Each core constellation is operated by a CSP. The CSPs maintain their own ground segments that include monitoring stations and control stations. From the point of view of the offline system, the CSP ground segment is part of the GNSS service and is viewed as part of the space segment.

To consider its GNSS for use by the offline architecture each CSP has to meet a set of requirements:

- 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 that 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 required to gain sufficient confidence in the operational performance of each constellation.

2.2 Reference Stations and Master Station

The ground segment consists of a global network of dual frequency receivers, one or more analysis centers (or master stations), and a means to distribute the ISM. The reference receivers record and report back their dual frequency observations of the satellites ranging and navigation data. The network must be sufficiently dense that many reference receivers can observe all satellites 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.

The IGS network serves as a good starting point for the monitoring of GNSS 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-meter level are easily determined. However, this network is 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. 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.

Master stations for the off-line 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.

2.3 ISM Message Structure

The ISM for the offline 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, 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 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 also be discarded. This would ensure that the user maintains the most current information. Also included, if necessary, is an identification number for the specific ANSP. This can be matched to the air-route or approach and gives the ANSP the ability to decide which ISM is used in its airspace. A database may need to contain multiple ISMs, one from each ANSP. Table 2-1 depicts the full offline ISM data content.

	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
	Total Header = 232 bits			
ISM Core	$P_{const,i}$	Probability of constellation fault at a given time	[10^{-8} … 10^{-5} … 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} … 10^{-5} … 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 meters	[0.0, 0.1, … 10]	$4N_{sat}$
	Total Core = $4N_{const} + 15N_{sat}$ bits			

Table 2-1. ISM Parameters

The core ISM data contains parameters specific to each constellation or satellite. For each constellation included in the satellite mask, there is a four-bit parameter specifying the value for P_{const}. The 4-bit number specifies one of 16 predefined values that notionally range from 10^{-8} 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. The four-bit number for P_{sat} specifies one of 16 predefined values that also 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 set 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.

2.4 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 [11]:

- 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.

In the next paragraphs we describe how these parameters could be set for GPS L1 service.

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 IGS network [12]. 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 satellites 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 the Earth. The navigation data also contains the σ_{URA}, which is then used to normalize the residuals. These normalized residuals have been analyzed every fifteen minutes from January 1, 2008 through March 31, 2014. The cumulative distribution function (CDF) for each individual satellite is shown in Figure 2-2. The rightmost red line shows the expected CDF value corresponding to a normal distribution with a zero-mean and unity variance.

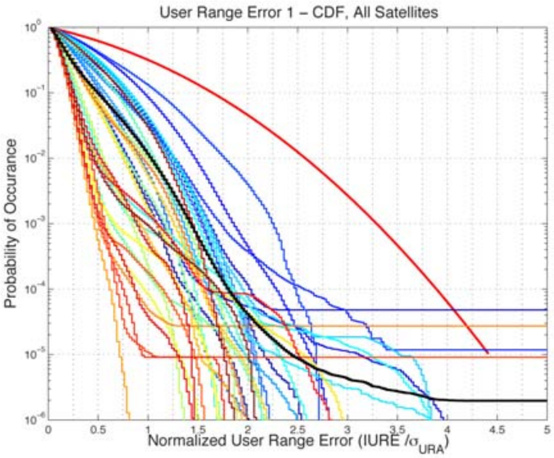

Figure 2-2. CDF of normalized ranging errors (all satellites)

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

The GPS performance specification [13] defines major service failures as occurring any time the signal-in-space error exceeds 4.42 x σ_{URA}. From

Figure 3-2, 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. 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 three major service failures per year. The commitment further states that major service failures will be flagged or removed within six hours. Given approximately 30 functioning satellites at any given time, three failures per year each lasting six hours implies an extreme upper bound for P_{sat} of approximately 7 x 10^{-5}.

From January 2008 through March 31, 2014, there have been five major GPS service failures with a cumulative duration of just over three hours. These 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
5. PRN 9, SVN 39, April 25, 2010, 19:45-20:00

This data implies an observed value for P_{sat} of approximately 2 x 10^{-6}. Thus, there are more than two orders of magnitude between the observed fault rate and the extreme upper bound from the commitment. The numbers in the SPS PS (three major service failures 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 has historically used the 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. One of the mechanisms for wide faults is the use of 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 (PRN 19, SVN 59, on June 17, 2012). The master control segment did identify and correct the error before it was broadcast to any other satellites.

The GPS performance commitment does not prohibit the possibility that the three faults occur concurrently. Again using a six-hour upper bound would imply a limit for P_{const} of approximately 7 x 10^{-4}. No concurrent major service failures have ever been observed on healthy GPS satellites 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}, 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 use values below the worst-case committed interpretation. Still others may not even trust the published commitments. It is recommended 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 and neither 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.

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 center variations. In reality, the two parameters together must bound the convolution of all of the errors with sufficient probability.

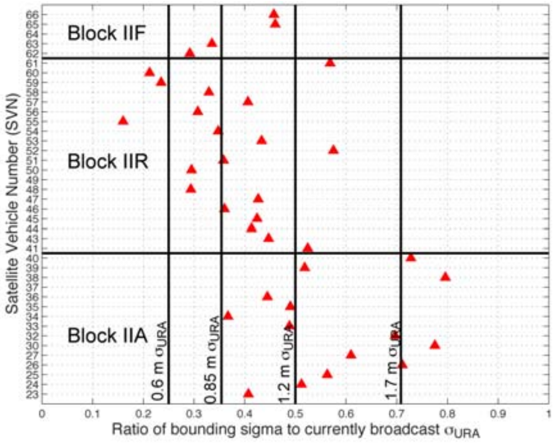

Figure 2-3. Minimum α_{URA} values that are still individually Gaussian bounded.

The IGS data analyzed 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-meter accuracy. Further, GPS intends to improve its performance with the fielding of its new operational control center software (OCX) and the GPS III satellites. Figure 2-3 uses the data from Figure 2-2 to determine the minimum safe reduction from the currently broadcast values for σ_{URA} (after removing the major service failures, which are described by P_{sat} and P_{const}). The majority of the newer satellites could broadcast σ_{URA} values of less than half of their current value. As the broadcast σ_{URA} value is most commonly 2.4 m (the current minimum in the L1 CA message), this indicates that future σ_{URA} values could be below 1.2 m. . Figure 2-3 also shows some of the new quantization levels for σ_{URA} (the current minimum value is 2.4, but lower values will be possible 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.

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 2-4 shows the distribution of the square root of the sum of the squared normalized errors (after removing satellites with major service failures). This metric evaluates the behavior of unfaulted subset solutions. The protection 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 [10].

The histograms in Figure 2-4**Error! Reference source not found.** 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 2-2. 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.

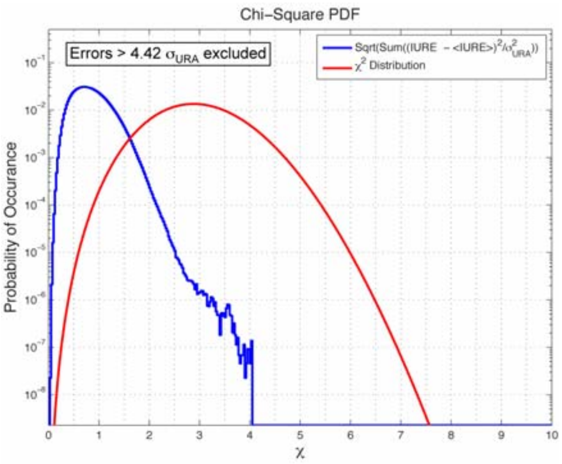

Figure 2-4. Chi-square of the normalized ranging errors (PDF). Empirical distribution for 200 evenly spaced user locations and for the 219,072 15-minute time steps from January 1, 2008 through March 31, 2014

The ISM must also account for nominal errors that are not necessarily present in the analysed data set. This is the case for the errors induced by nominal signal deformation, code carrier incoherence, and satellite antenna biases. For nominal deformation, these errors can be reduced to being on the order of 10 cm by limiting the receiver design space and by increasing commonality with the reference receivers [14]. 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 ten cm [15]. However for most satellites the nominal effect is expected to be much smaller. 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 [16]. The three bias terms together nominally can be conservatively bounded by a 75 cm value for b_{nom} [17].

2.5 ISM Dissemination

There is no urgency to broadcast the ISM parameters, as prior values will have been chosen to remain safe for the very long term. Because the latency can be very large, the available variety of options can also be very large. 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 (For example, the FAA maintains the national flight database that already contains important navigation data and that is updated every 28 days). However, if an alternate preferred method is identified (e.g. maintenance interface, aeronautical datalink, VDB), it should be easy to accommodate.

2.6 Offline Architecture Summary and Next Steps

While GPS has both a published performance commitment and a long track record of operation, Galileo has neither. Therefore the values of the parameters described in the above paragraphs cannot be applied to Galileo. Specification of Galileo performance [18], [19], [20] describe expected equivalent σ_{URE} values of 65 cm and equivalent σ_{URA} values of 85 cm, which should be very much in line with 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 do similarly meet these goals with their dual frequency services.

3 ONLINE ARCHITECTURE

The central feature of the online ARAIM concept is the ephemeris overlay: the ARAIM ground segment computes high-accuracy ephemerides that are carried by the ISM. This gives the ANSP control over the main component of the nominal error. In addition, online monitoring of the ephemeris overlay may reduce the probability of a constellation fault (P_{const}). The online concept has roots in SBAS and the previously proposed Galileo Safety-of-Life (SoL) service. However, it is simpler than either of these because of the existence of the ARAIM fault detection function at the aircraft, and expected to be less costly because of the longer TIA (compared to 6 sec).

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.

3.1 Online ARAIM Ground Architecture

The online ARAIM system consists of a number of key functions, as shown in the flow diagram in Figure 3-1. These include a sparse worldwide network of reference receivers, short-latency ISM generation and dissemination mechanisms, an ephemeris overlay generator, and an online monitor. Because the online ARAIM system is an augmentation to the offline system, it implicitly includes all offline ARAIM monitoring functions. 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.

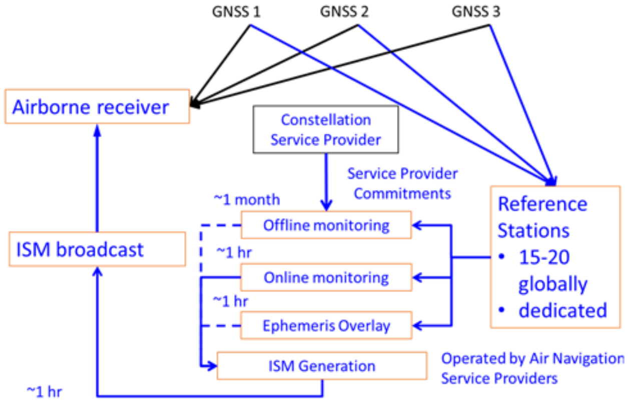

Figure 3-1. Online ARAIM architecture

3.2 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 2 reference stations (RSs) will be needed. Considering the additional need for redundancy in the event of RS failure, visibility of each satellite by 3 RSs is recommended. The next sections suggest that a sparse worldwide network of about 20 stations would be sufficient. 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.

3.3 Ephemeris Overlay Function

The primary goal of the ephemeris overlay function is to provide improved ranging accuracy for any of the constellations contributing to the ARAIM service. In addition, a large number of message driven faults can be mitigated by design, leading to lower fault probabilities. For instance the EOPP fault, one of the most prominent constellation wide failure types, can be controlled through the provision of the guaranteed navigation message as determined by the ARAIM ground segment (for example by avoiding simultaneous uploads by design).

The navigation overlay function within the ARAIM online architecture consists primarily of two major elements, the Orbit Determination and Time Synchronisation (ODTS) function and a set of barriers protecting both the input to the ODTS process and its output. The design, development, implementation and verification of an ODTS process according to the relevant specifications have been already done for all existing SBAS systems, which proves its feasibility. Preliminary analyses suggest that a worldwide network of 16 stations could be sufficient to support σ_{URA} values below .5 m. For redundancy purposes a slightly higher number of stations will be preferable.

3.4 Online Monitor

The purpose of the ONline Monitor (ONM) is to ensure the integrity of the ephemeris overlay by establishing and controlling b_{nom} and P_{sat} 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 separately using redundant receivers at each RS and redundant RS visibility to each satellite. 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.

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 one, 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.

Preliminary covariance analyses (assuming perfectly synchronized receivers) suggest that it might be possible to estimate the radial component of the satellite position with a standard deviation below 0.25 m with as little as three reference stations. In addition to the estimation error, one must account for the modelling error due to the 18-parameter GPS ephemeris. Preliminary results show that the 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.

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 analyzed at this level yet.

3.5 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 = 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.

The Integrity Support Message for the Online ARAIM architecture can be broken down into 3 major elements:

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

	Parameter	Description	Value	Size (bits)
Data Management	GNSS_ID	ISM Constellation Id.	[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 Id.	[0, 1, … 255]	8
				Σ: 35
ISM Core	Health_Flag	Satellite Health Flag	[0,1]	N_{sat}
	$P_{sat,j}$	Prob. of satellite fault at a given time	[10^{-6} … 10^{-5} … 10^{-3}]	$4N_{sat}$
	$P_{const,i}$	Prob. 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]	$5N_{sat}$
				Σ: ~25N_{sat}

Table 3-1. ISM format and content: data management bits and core data

Table 3-1 shows an example of ISM format and content for items 1 and 2. Table 3-2 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 international level (i.e., ICAO).

	Parameter	Description	Size (bits)
ISM Ephemeris	M0	Mean anomaly	$32N_{sat}$
	Δn	Mean motion difference	$16N_{sat}$
	Sqrt(A)	Sqrt Semi Major Axis	$32N_{sat}$
	OmegaA	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	$6N_{sat}$
			Σ: $319N_{sat}$

Table 3-2. ISM format and content: ephemeris overlay data

Considering two core GNSS constellations each consisting of 30 satellites the overall ISM data volume is approximately 20 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 22 bps. 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 data link.

3.6 ISM Dissemination

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

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

Using the VDB option for some airports can provide an upgrade path to GBAS Cat II/III. The GEO option would continue high integrity and high accuracy service to current non-aviation SBAS users. 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 SG will seek feedback for the stakeholders.

4 AVAILABILITY SIMULATIONS

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: LPV-200 and APV1/LPV-250, a less demanding level of service and therefore more likely to be feasible.

4.1 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' uses a reference almanac for each constellation. For GPS it is the 24-slot nominal constellation described in [13]. For Galileo, it is a Walker 24/3/1. In the 'depleted' configuration, one arbitrarily chosen satellite has been removed from the baseline in each constellation. For the 'optimistic' configuration, both constellations have 27 satellites. The 'optimistic' GPS constellation was obtained by removing three satellites from an actual almanac (with 30 satellites flagged healthy) so that the expandable slots are filled. The 'optimistic' Galileo constellation takes into account the planned replenishment strategy (which is meant to ensure that the 24 main slots can be filled with a short delay in case of a satellite failure). It represents a hypothetical case where 3 in orbit spares would be transmitting from optimal positions, one in each 3 orbital plane. While the 'optimistic' GPS constellation is well within what is expected for GPS, 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 here [23]. A user elevation masking angle of 5 degrees was applied to both constellations.

4.2 Nominal User Pseudorange Error

For each pseudorange, the nominal error has two characterizations: a conservative one used for integrity purposes and a less conservative one used for accuracy and continuity purposes [11]. 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). Error models for the first two sources can be found in Annex B of [11]. The signal in space error is characterized by the URA (SISA for Galileo) and the URE (SISE for Galileo) [11]. To span the range of possible values for the URA, the following values were considered: .5m, .75m, 1m, 1.5m, and 2m. The URE, which is used for accuracy and continuity purposes, was set to be two thirds of the URA. The nominal bias for the integrity purposes (b_{nom}) was set at 0.75m, and at 0 for accuracy purposesSatellite 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} [11].

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 appears and it takes the CSP 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 mitigated by a means other than the snapshot residual check (for example, by the online ground monitor in the online architecture).

σ_{URA}	0.5 m, 0.75 m, 1 m, 1.5 m, 2.0 m
σ_{URE}	2/3 σ_{URA}
P_{sat}	10^{-5}
P_{const}	10^{-4}, 10^{-8}
b_{nom}	0.75 m
Constellations	'Depleted','Baseline','Optimistic'

Table 4-1. ISM Parameters and constellation configurations

4.3 User algorithm - Nominal and Availability Criteria

The airborne algorithm used in the simulations is a modified version of the ARAIM reference algorithm described in [11] or [2]. The modification is a simplified version of the algorithm described in [21] and is explained in detail in Annex A. For each user geometry the algorithm computes the VPL, the HPL, the EMT, and the standard deviation of the accuracy σ_{acc}.

The availability criteria for LPV-200 and APV1 / LPV-250 are summarized in Table 4-2.

	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	-	-

Table 4-2. Availability criteria

4.4 Results

Users were simulated on a 5 by 5 degree grid, for a period of 10 sidereal days –the repetition rate of the Galileo constellation - with a time step of 600s. Then, for each user the availability (defined as the percentage of time that the availability criteria are met) was computed. Figure 4-1 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.

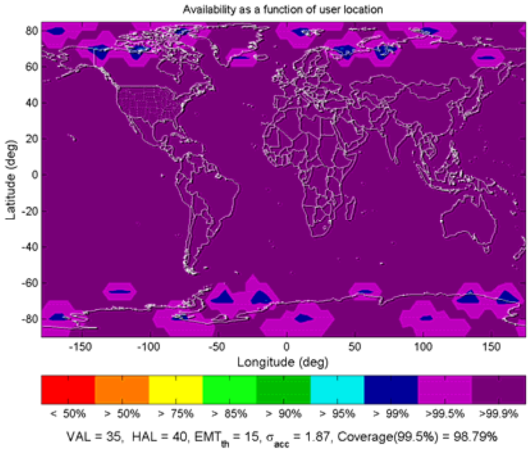

Figure 4-1. Availability map for the baseline constellation configuration, $P_{const} = 10^{-4}$, $P_{sat} = 10^{-5}$ and $\sigma_{URA} = 1$m

The results for all scenarios are summarized in the Tables 4-3, 4-4, 4-5 and 4-6 as a function of the constellation configuration and the URA. Each table shows the worldwide coverage of 99.5% availability of LPV-200 and APV1/ LPV-250. Here, the coverage is defined as the fraction of the users between -70 and 70 degrees latitude that have more than 99.5% availability. (Because we use a rectangular grid, each user is weighed 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 as a metric is very sensitive to the target availability.

Constellation/ URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	88.1	86.1	81.3	38.1	0
Baseline (GPS 24 – GAL 24)	100	100	98.8	88.2	3
Optimistic (GPS 27 – GAL 27)	100	100	99.8	94.9	21.8

Table 4-3. 99.5% availability coverage of LPV-200 with $P_{const} = 10^{-4}$

Constellation/URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	94.0	91.8	87.7	75.0	35.4
Baseline (GPS 24 – GAL 24)	100	100	100	99.0	89.5
Optimistic (GPS 27 – GAL 27)	100	100	100	100	93.8

Table 4-4. 99.5% availability coverage of LPV-250 with $P_{const} = 10^{-4}$

Constellation/URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	100	100	100	81.2	0
Baseline (GPS 24 – GAL 24)	100	100	100	99.3	3
Optimistic (GPS 27 – GAL 27)	100	100	100	100	25.1

Table 4-5. 99.5% availability coverage of LPV-200 with $P_{const} = 10^{-8}$

Constellation/URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	100	100	100	100	100
Baseline (GPS 24 – GAL 24)	100	100	100	100	100
Optimistic (GPS 27 – GAL 27)	100	100	100	100	100

Table 4-6. 99.5% availability coverage of LPV-250 with $P_{const} = 10^{-8}$

For P_{const} as low as 10^{-8} global coverage of LPV-200 is achieved for URA/SISA values of 1.5 m or lower in the baseline and optimistic constellations scenario. With URA/SISA values of around 2 m, global coverage of LPV-250 is achieved with all three constellations scenarios.

For P_{const} as high as 10^{-4}, global coverage of LPV-200 is achieved for URA/SISA values of 1m or lower in the baseline and optimistic constellations scenarios. In the baseline constellation scenario, 88% coverage (for 99.5% availability) is achieved with 1.5 m URA/SISA. Interestingly in the latter case, the area of availability lower than 99.5 is concentrated in a relatively narrow strip around 30deg latitude (-30deg in South Hemisphere). Almost full coverage of LPV 250 is achieved in this scenario. In the depleted constellations scenario, global coverage of LPV-250 is achieved with URA/SISA values of 0.5m or lower, while 88% coverage (for 99.5% availability) is achieved for LPV-200.

5 OPEN POINTS

5.1 Global ISM versus multiplicity of ISMs

It is desirable to have a single analysis center (or master station in the case of online) and a commonly agreed upon set of ISM parameters, or at least commonly agreed 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. 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 significantly 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. The receiver manufacturers, airframe manufacturers, airlines and ANSPs must decide the specific method of transmission jointly.

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

Because both architectures require some level of trust in the performance of the CSPs, that trust will need to be established over time (it may be a shorter time for online). 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.

Over time, if the CSP establishes a good track record of meeting its commitments, these values can be lowered. A CSP that does not initially meet its commitments could take much longer.

5.3 Constellation weakness

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 in last seven years. However, the upgrade to dual frequency operation cannot take advantage of the IIA or IIR GPS satellites. A smaller number than has been historically observed is a possibility.

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 satellite will be on orbit, but funding issues or poor reliability could affect these numbers, and impact availability.

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 suffer. 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 [22]. There are many potential enhancements to be investigated that will likely yield further availability improvements.

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

5.4 Availability Risk From:

a. σ_{URA} or α_{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 original Galileo requirements listed σ_{URA} equivalent values of 0.85 m as the target. However Galileo is still in development mode and it remains to be seen what values it will ultimately be able to achieve. There is a risk that Galileo may not be able to achieve its intended target and have to broadcast larger values. Further Galileo does not yet have an established service history, so it may take longer to validate its dual frequency service than it will for GPS.

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}. An even larger risk is that these parameters are unknown for Galileo. It requires years of observation in order to establish the low values currently proposed for GPS. Galileo will, by necessity, start with larger values until both the CSP and the ANSPs can gain sufficient confidence. If Galileo were to have higher fault rates, then performance could suffer.

6 SUMMARY

We have described two ARAIM ground architectures to determine and disseminate the ISM. In the first one, called "offline" a quasi-static ISM would be manually produced and rarely updated. Using an extensive GPS data set spanning the last six years, we have shown that current GPS service performance suggests that the offline architecture could be feasible if new constellations offer a level of performance similar to GPS. However, there is some uncertainty with respect to the future level of performance of the Constellation Service Providers as well as the performance commitments.

The second architecture, called "online", aims at making ARAIM less dependent on CSP performance. In this architecture, a navigation message overlay and online monitor would allow more control over nominal errors and constellation wide faults by the ANSP. The Integrity Support Message would be automatically updated every hour and would include a re-estimated clock and ephemeris (which would replace the CSP's) as well as the parameters describing the behavior of the satellite. Table 6-1 summarizes the characteristics of both architectures.

Architecture characteristic	Offline	Online
Reference network	Global (50+ stations), non dedicated (e.g. IGS, NASA's GDGPS)	Global (15-20 stations), dedicated, guaranteed latency (2-3 Receivers/station)
Source of clock and ephemeris	Uses Constellation Service Provider navigation message	Ephemeris overlay
ISM generation	Offline analysis with human in the loop.	Online monitoring (automatic)
ISM latency	days	hours
Broadcast channel (driven by repetition rate)	Various options: Maintenance interface, Database, Aeronautical datalinks, CSP spare bits	Various options: Aeronautical datalinks, APNT, GEO, CSP spare bits

Table 6-1. Architecture Comparison

ARAIM performance has been evaluated under several different scenarios. These results were obtained using a simple optimization of the reference user algorithm [11]. The optimization is described in the Appendix. We considered three scenarios for the GPS and Galileo operational constellations (depleted, baseline, optimistic) as well as a set of possible ranging errors parameters. In particular, we chose two values of the probability of constellation wide fault P_{const}. The first one ($P_{const} = 10^{-4}$) would be easily achievable with the offline architecture, as it is very conservative. The second one ($P_{const} = 10^{-8}$) assumes that the constellation wide faults would be mitigated by a mechanism other than the user receiver residual check, for example by the ground monitors in the online architecture. For values of URA up to 1m (as expected for future GPS and

Galileo), global coverage of LPV-200 is achieved with P_{const} 10^{-4} in the baseline and optimistic scenarios. With P_{const} 10^{-8}, global coverage of LPV-200 would be achieved in the depleted scenario as well.

At this point, the ARAIM TSG is not recommending one approach over the other and is seeking feedback on the proposed architectures by stakeholders.

(The opinions expressed in this paper do not represent any government position on a future development of an ARAIM ground segment.)

APPENDIX

An approach to minimize the Protection Levels by adjusting the all-in-view position solution was described in [21]. 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 [21]). It only needs to be applied if the VPL exceeds 35 m or the EMT exceeds 15 m and $\sigma_{v\_acc} \le 1.87m$ with the algorithm described in [11],[2].

The idea consists on 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 [11], 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*):

$$PL_i = K_{fa}\sqrt{\left(s-s^{(i)}\right)^T C_{acc}\left(s-s^{(i)}\right)} + K_{md,i}\sigma_i \quad (1)$$

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

$$s = s_{all} + t\left(s_{\max} - s_{all}\right) \quad (2)$$

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

$$\begin{gathered} PL_i = K_{fa}\sqrt{\left(s_{all}+t\left(s_{\max}-s_{all}\right)\right)^T C_{acc}\left(s_{all}+t\left(s_{\max}-s_{all}\right)\right)} \\ +K_{md}\sigma_{\max} \end{gathered} \quad (3)$$

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

$$s^T C_{acc} s \le \sigma^2_{acc,req} \quad (4)$$

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:

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

$$\begin{gathered} {s_{all}}^T C s_{all} - \sigma^2_{acc,req} + 2t{s_{all}}^T C_{acc}\left(s_{\max}-s_{all}\right) \\ +t^2\left(s_{\max}-s_{all}\right)^T C\left(s_{\max}-s_{all}\right) \le 0 \\ a = \left(s_{\max}-s_{all}\right)^T C\left(s_{\max}-s_{all}\right) \\ b = 2{s_{all}}^T C_{acc}\left(s_{\max}-s_{all}\right) \\ c = {s_{all}}^T C s_{all} - \sigma^2_{acc,req} \\ at^2 + bt + c \le 0 \end{gathered} \quad (5)$$

The constraint above imposes:

$$t \in \left[\frac{-b-\sqrt{b^2-4ac}}{2a}, \frac{-b+\sqrt{b^2-4ac}}{2a}\right] \quad (6)$$

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

Summary of the algorithm

This part of the algorithm should be inserted after Equation (14) in [11].

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}

the third row of $S^{(0)}$. In addition we note $\sigma^2_{acc,req}$ the required accuracy for LPV 200 (=1.87^2).

Step 2: Compute:

$$\begin{aligned} a &= \left(s_{\max} - s_{all}\right)^T C_{acc} \left(s_{\max} - s_{all}\right) \\ b &= 2{s_{all}}^T C_{acc} \left(s_{\max} - s_{all}\right) \\ c &= {s_{all}}^T C_{acc} s_{all} - \sigma^2_{acc,req} \end{aligned} \tag{7}$$

Step 3: Compute:

$$t = \min\left(1, \frac{-b + \sqrt{b^2 - 4ac}}{2a}\right) \tag{8}$$

Step 4: Compute:

$$s = s_{all} + t\left(s_{\max} - s_{all}\right) \tag{9}$$

Once the all-in-view coefficients have been computed according to Equation (9), the algorithm continues at as specified in [11].

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