Prototyping Advanced RAIM for Vertical Guidance

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Abstract

In the next decade, the GNSS environment is going to undergo a major transformation. First, two more GNSS core constellations are expected to be launched, Galileo and Compass. When these constellations are in their final operational capability, there will be three times more ranging sources. Second, GPS and the new core constellations will broadcast signals in two frequencies L1 and L5 (E5 a or b for Galileo). These signals will be available for civil aviation, allowing users to cancel the pseudorange errors due to the ionosphere. Many studies suggest that it could be possible to achieve global coverage of vertical guidance using multi-constellation, dual frequency RAIM, under certain assumptions on the constellation performance. However, to achieve vertical guidance RAIM (which will be referred from then on by ARAIM or Advanced RAIM), it will not be sufficient to apply the current RAIM algorithms that are used for horizontal RAIM. First of all the level of safety required for horizontal RAIM is lower than for vertical guidance (a failure to bound the error for LNAV is classified as a *major* (10^{-5}) failure condition, while a failure to bound in an LPV approach is *severe major* (10^{-7}).) Also, the difference between the achieved accuracy and the necessary accuracy for horizontal RAIM is very large (more than a factor of 20). This will probably be tighter for vertical guidance. For these reasons, a more careful analysis will be need before vertical guidance RAIM can be certified. All the challenges for vertical guidance RAIM are derived from this requirement.

In this paper, we will examine what will be required from the constellation providers both in terms of integrity and availability. Then we will show the results of a prototype ARAIM algorithm using an extensive data set.

INTRODUCTION

The potential of ARAIM to provide vertical guidance has been evaluated under several constellation assumptions [1], [2], [3], [4], [5]. Most of these studies have concluded that once two full constellations with dual frequency are available it will be possible to achieve worldwide precision approach (LPV 200) [1] without an extensive ground infrastructure (unlike SBAS and GBAS). The goal of this paper is to highlight some of the technical challenges that still need to be overcome before ARAIM for vertical guidance can be adopted and propose possible approaches to solve them.

The main challenge in ARAIM is the reliance on the constellation assumptions. RAIM can detect satellite faults, but it does so by relying on the fact that constellation performance is within the assumptions. For example, when it is assumed that at most one satellite is faulted, it is assumed that there exists a subset of N-1 satellites within the nominal expectations (N being the total number of satellites in view). The results of the studies mentioned above are conditional on specific constellation assumptions, namely User Range Errors (URA) below one meter and prior probabilities of satellite faults of 10^{-5} (except [2], which considers fault probabilities up to 10^{-2}). It took several years for the GPS constellation to achieve such levels of performance [6], so it might be too optimistic to assume the same levels for the new constellations. And even if a constellation seems to be within the assumptions, there is the risk that the constellation performance might deteriorate both in terms of nominal performance and failure rate in the future. If the degradation is sufficiently slow, then the proposed Integrity Support Message (ISM) [3] might be sufficient to mitigate the risk. The ISM is a message that could have a latency ranging from months to minutes, depending on the perceived risk of failure. The ISM would contain information on the URA, the prior probability of satellite failure, and the prior probability of constellation failure. The task of the ISM provider will be made easier if there is a large margin between the observed constellation performance and the performance assumed by ARAIM. However, if either the prior probabilities of fault or the URAs are too large, there might not be sufficient availability. After examining the meaning of the parameters describing the integrity of a constellation, we will show for which parameters a constellation can be useful for ARAIM.

Another challenge for ARAIM at this point is the lack of a dual frequency civil service, as ARAIM assumes the use of the open service signals in L1 and L5 (or E5 for Galileo). It is however desirable to evaluate the concept by applying the ARAIM algorithm to real data before civil dual frequency is available. Limited tests have been performed that use flight test data [7], [8]. These tests are necessary, but they typically include data for less than a few hours. This is the motivation for the second part of this work, which presents a plan to systematically test ARAIM using L1 CA and L2 semi-codeless data from ground stations. We will show the preliminary results, which include ARAIM results for ten days for ten stations over the United States. We will show the behavior of the algorithm under different conditions, in particular to illustrate the necessity of characterizing the constellation integrity adequately.

CONSTELLATION INTEGRITY REQUIREMENTS

Nominal Errors

The fundamental requirement under fault free conditions is that the User Range Accuracy (URA) is the standard deviation of a Gaussian overbound of the true pseudorange error –the User Range Error (URE)- distribution due to the space segment (including at least clock and ephemeris and signal deformation). Additionally, the overbound must be conserved through convolution, that is, the distribution of the position error bound due to the space segment must be overbound by the standard deviation of the convolution of the Gaussian distributions representing the URE overbound. Several techniques can be used to prove that an empirical error distribution is overbound by a Gaussian distribution [9]. A more concrete proposal was given in [10]. As pointed out in [10] it is important to note that if a certain prior probability of failure is assumed then some of the data can be excluded from the empirical distribution. For example, if a 10^{-2} is the broadcast probability of failure then one could remove up to 1% of the data of a given period.

Prior probability of failure

The Advanced RAIM algorithm described in [1] and more generally in [2] uses the prior probability of fault P_{sat}. This probability is a function of the onset probability of fault and the time to alert. In turn, the onset probability can be expressed into the number of faults per year in a constellation with a given number of satellites. Table 1 shows how the time to alert, the number of faults per year and the probability of satellite fault P_{sat} are linked. This table shows that the P_{sat} assumed in [1], [3] is actually optimistic, and is not guaranteed by the current GPS Standard Positioning Service specifications.

P_{sat}/time to alert	1 h time to alert	6 h time to alert	24 h time to alert
10^{-5}	3 faults / year	1 fault / 2 years	1 fault / 8 years
10^{-4}	30 faults / year	5 faults / year	1 – 2 faults / year
10^{-3}	25 faults / month	4 faults / month	1 fault / month

Table 1. *Relationship between prior probability of fault, number of faults per year and time to alert for a 30 satellite constellation*

A further difficulty is that the current definition of fault given in [11] is not sufficient for ARAIM, as it only guarantees that the error will be below a certain threshold. The ARAIM algorithm requires that in fault free conditions, the URE distribution is overbound by the URA. This definition means that some faults can only be diagnosed after a long period of time. The fault rate within a data set would then be the fraction of data that needs to be removed such that the URA overbounds the remaining data [10]. This distinction is not important in the case of fast developing faults, but it is relevant for small and persistent faults (like for example an antenna bias [12]). Based on these considerations, it is important that future ARAIM algorithms be able to accommodate higher fault rates than currently assumed.

Probability of constellation failure

Another type of fault that might need to be considered is the constellation wide fault due to a common mode error. There are several possible mechanisms for such a fault. The most likely one seems to be the erroneous use or broadcast of the Earth Orientation Parameters (EOP), as it is specifically mentioned in [11]. Table 2 shows the link between the probability of constellation fault, the onset probability and the time to alert.

P_{const}/time to alert	5 min time to alert	30 min time to alert	1 h time to alert
10^{-6}	1 fault / 10 years	1 fault / 50 years	1 fault / 100 years
10^{-5}	1 fault / 1 year	1 fault / 5 years	1 fault / 10 years
10^{-4}	12 faults / year	2 faults / year	1 fault / year

Table 2. *Relationship between prior probability of constellation fault, number of faults per year and time to alert*

MINIMUM CONSTELLATION REQUIREMENTS

For the authorities that will be responsible for the content of the Integrity Support Message, it will be easier to accept a set of assumptions if there is a large margin between the observed performance and the necessary performance for ARAIM. In this section we evaluate the availability of LPV 200 [3] as a function of URA, P_{sat}, and P_{const} and find how large they can be while maintaining worldwide coverage of LPV 200. For this purpose, we will assume that two full dual frequency GNSS core constellations will be available.

Constellation Assumptions

In this work, we will not study the sensitivity of the availability to the constellation size. Instead, we will make one set of assumptions for GPS and Galileo. (It is already known that sparsely populated constellations -less than 18 satellites-, even when there are two, are not enough to provide LPV 200 worldwide [3]). For GPS, we will assume that there will be at least 27 L1-L5 satellites available in 6 planes [1]. For Galileo, we will assume that there will be at least 27 satellites in 3 planes [13].

Protection Level calculation

The protection level was calculated using the algorithm described in [2] and the error models described in [1]. The nominal biases are assumed to be below .75 m. It is worthwhile pointing out here that the algorithm accounts for the fact that the probability of fault of a given subset of p satellites is given by P_{sat}^{p}. The higher P_{sat} the more subsets need to be considered when computing the Vertical Protection Level (VPL) (the 10^{-7} vertical error bound). In addition, two constellation wide faults are added, whose effect is to add two more subsets solutions (and therefore to increase the VPL).

The availability was evaluated by using the set of MATLAB scripts MAAST [14] to compute the predicted VPL of a set of users distributed over the world during ten sidereal days. The users were placed on a grid every 10 degrees in both longitude and latitude. For each location, the geometries were simulated every 10 minutes.

Availability Results

There are many requirements for LPV 200, but the VPL requirement is usually the critical one. Therefore, it was assumed that if the VPL was below a Vertical Alert Limit of 35 m, then LPV 200 was available. Tables 3, 4, and 5 show the percentage of the globe that have more than 99.5% availability of LPV 200. Table 3 shows the results when constellation wide faults are not considered. Table 4 and 5 show the same results when a 10^{-6} and a 10^{-4} prior probability of constellation fault is assumed.

URA/ P_{sat}	10^{-5}	10^{-4}	10^{-3}
.5 m	**100%**	**100%**	**100%**
1 m	**100%**	**100%**	**100%**
1.5 m	**100%**	**100%**	**100%**
2 m	**100%**	**100%**	**99.6%**
3 m	**100%**	**100%**	**6.62%**
3.5 m	**43.0%**	**7.72%**	**0%**
4 m	**3.6%**	**0%**	**0%**

Table 3. *99.5% availability coverage as a function of URA and P_{sat} for $P_{const} < 10^{-8}$*

URA/ P_{sat}	10^{-5}	10^{-4}	10^{-3}
.5 m	**100%**	**100%**	**100%**
1 m	**100%**	**100%**	**100%**
1.5 m	**95.06%**	**95.06%**	**95.06%**
2 m	**51.47%**	**51.47%**	**51.26%**
3 m	**0**	**0**	**0**
3.5 m	**0**	**0**	**0**
4 m	**0**	**0**	**0**

Table 4. *99.5% availability coverage as a function of URA and P_{sat} for $P_{const} = 10^{-6}$*

URA/ P_{sat}	10^{-5}	10^{-4}	10^{-3}
.5 m	**100%**	**100%**	**100%**
1 m	**100%**	**100%**	**100%**
1.5 m	**79.17%**	**79.17%**	**79.17%**
2 m	**.12%**	**.12%**	**.12%%**
3 m	**0**	**0**	**0**
3.5 m	**0**	**0**	**0**
4 m	**0**	**0**	**0**

Table 5. *99.5% availability coverage as a function of URA and P_{sat} for $P_{const} = 10^{-4}$*

Although preliminary, these results show that there would be a significant benefit if the constellation wide failure was negligible ($P_{const} < 10^{-8}$): with a 2 m URA and a 10^{-3} P_{sat} (two orders of magnitude larger than the current assumptions [3]), there is good coverage. Tables 4 and 5 show how much tighter the requirement on the URA is when the constellation wide failure is included: with $P_{const} = 10^{-6}$, the URA must be below 1.5 m, and for 10^{-4} it must be below 1 m. It is interesting that once the constellation wide failure is added to the threat model, the availability results seem insensitive to the prior probability of satellite fault P_{sat}. This indicates that if the constellation wide failure must be considered, the requirements on P_{sat} can be relaxed (although it would increase the complexity of the receiver algorithm). The results on the URA and P_{sat} must be understood here as upper bounds, since once satellite outages are considered, the dividing line between the acceptable parameters would shift to the left and up.

ARAIM PROTOTYPE

This section shows the results of an ARAIM algorithm applied to dual frequency measurements obtained from ground receivers. The objective of this section is to evaluate the behavior of the algorithm under three types of conditions: no faults, faults within the threat model, and faults outside the threat model.

Data

The data was obtained from ten Continuously Operating Reference Station (CORS) network (Albuquerque, NM, Aurora, IL, Nashua, NH, Leesburg, VA, Denver, CO, Fort Worth, TX, Jacksonville, FL, Los Angeles, CA, Minneapolis, MN, Seattle, WA) for ten days (6/1/2010 – 6/10/2010). L1 CA and L2 semi-codeless code and carrier phase measurements were collected at 1 Hz.

Processing

For each satellite a dual frequency ionospheric free combination was formed and smoothed using the carrier phase measurements. The smoothing filter maximum length was chosen to be 600 s. This is longer than in an airborne receiver because the multipath has a longer correlation time on the ground. The filter is re-initialized after a cycle slip.

Error models

The error models used are the ones described in [3] adapted to L2 (instead of L5). Although the ground multipath tends to be much larger than the airborne multipath [15], [16], we still used the airborne characterization. This was done to put the algorithm under more challenging conditions than it would be on an airborne receiver. For the URA, we used the term broadcast in the navigation message, whose most common value is 2.4 m. The nominal bias was taken to be zero. As with the multipath, this was done to put more strain on the Protection Level algorithm.

ARAIM algorithm

We implemented the ARAIM algorithm described in [3]. The assumed P_{sat} was taken to be 10^{-5}. As in [3], the required Probability of Hazardously Misleading Information is 10^{-7} and the continuity requirement is set at 4.10^{-6}. A simple exclusion algorithm was implemented. The chi-square statistic [17] was computed and if it exceeded a threshold of 50, then the chi-square for each subset was computed. The subset with the smallest statistic below 50 was retained (and the remaining satellite excluded).

Behavior under nominal data

Figure 1 shows the Vertical Position Error and the Vertical Protection Level for 24 hours.

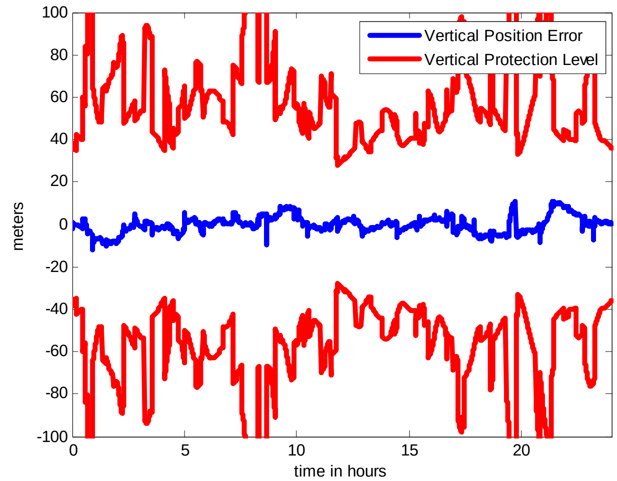

Figure 1. *VPE and VPL as a function of time in nominal conditions*

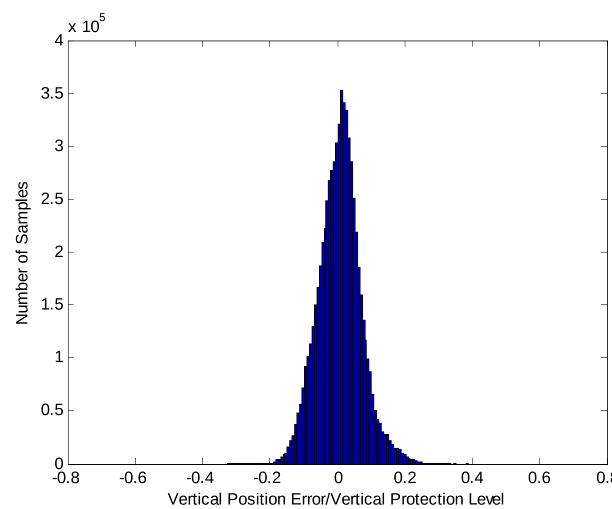

Figure 2. *Histogram of the VPE/VPL ratio in nominal conditions*

Figure 2 shows the histogram of the ratio between the Vertical Position Error and the Vertical Protection Level. The histogram contains 8640000 points, (which cannot be considered independent as the errors are correlated in time). Under nominal conditions, there are, as expected, no Hazardously Misleading Information (HMI) events, that is, no cases where the VPL is below the VPE (the maximum ratio is .4).

Simulation of 1 failure

For this case, a satellite fault was simulated on PRN 2 by adding a 20 m bias on all measurements at all times. We chose 20 m because it is large enough to cause an HMI event but small enough that it will not always be detectable. We show here that even though it might be undetected, the VPL takes the possibility of a failure into account. Figure 3 shows the VPE and the VPL for 24 hours for one receiver, and Figure 4 shows the histogram for all times and all receivers.

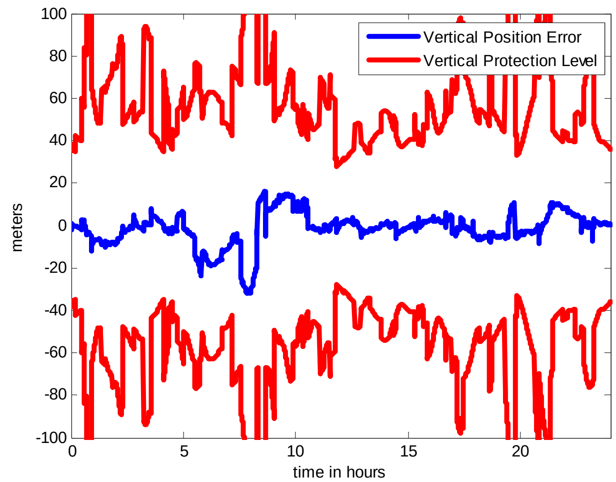

Figure 3. *VPE and VPL as a function of time with one failure*

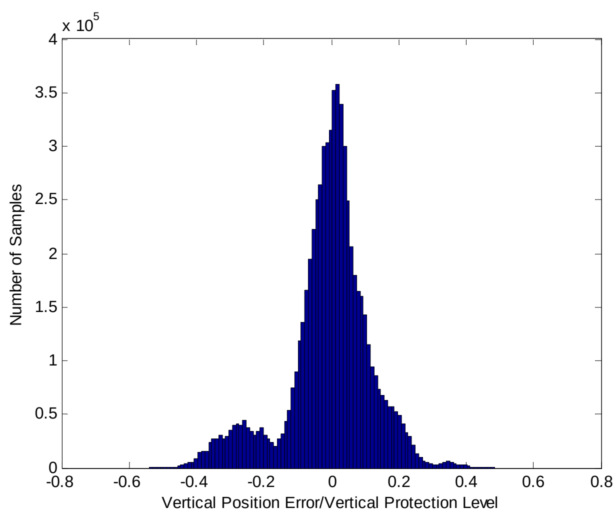

Figure 4. *Histogram of the VPE/VPL ratio in with one failure*

Again, we can see that the VPE are well bounded by the VPL, even though the failure is present for ten days (exceeding substantially the maximum exposure time assumed in the threat model).

Simulation of 2 failures

In this paragraph, we show the results of a threat that lies outside the threat model assumed in the particular implementation of ARAIM evaluated here. Figure 5 the trace of the VPE and the VPL for 24 hours for one receiver, and Figure 6 shows the histogram for all times and all receivers.

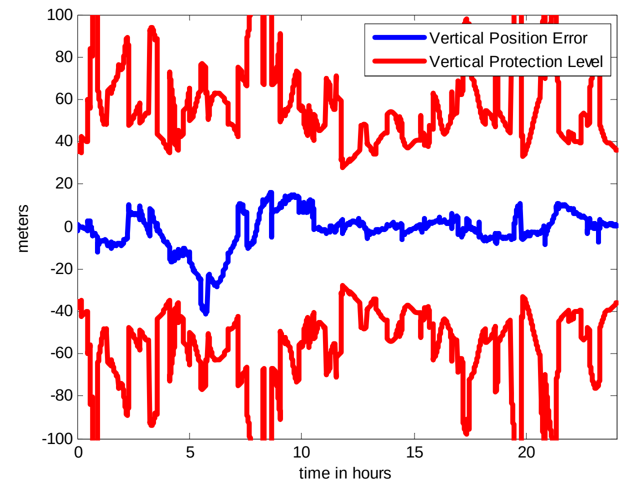

Figure 5. *VPE and VPL as a function of time with two failures*

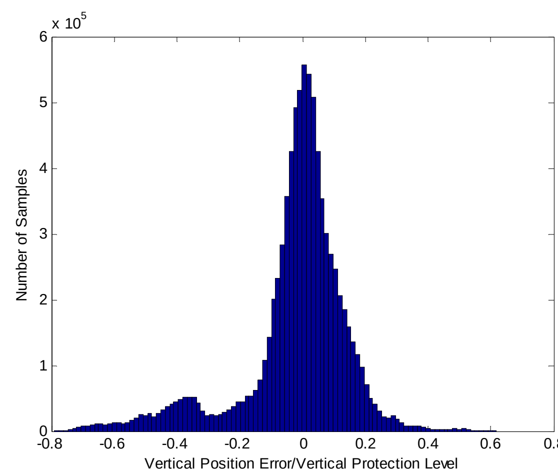

Figure 6. *Histogram of the VPE/VPL ratio in with one failure*

It can be seen here that the ratio is closer to 1 (.8), and there is no doubt that it would reach one if more data were included. Even though the user is still somewhat protected, there could easily be an HMI event.

Underbounding of the nominal error

As in the previous paragraph, we test the algorithm under a threat that is not in considered in the threat model. The goal is to evaluate the behavior of the algorithm if all the pseudoranges have a larger noise than expected. Instead of increasing the noise, we assumed a smaller nominal error model four times smaller than the previous one (again, we try to place the threat at the edge of detectability). The results are shown in Figures 7 and 8 for one receiver during 24 hours.

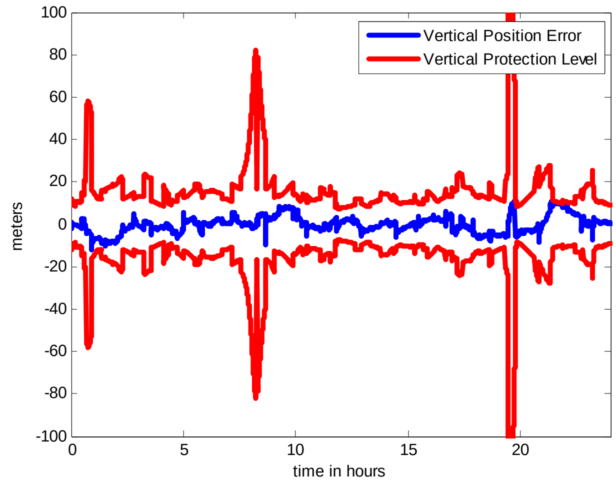

Figure 7. *VPE and VPL as a function of time with wrong nominal model*

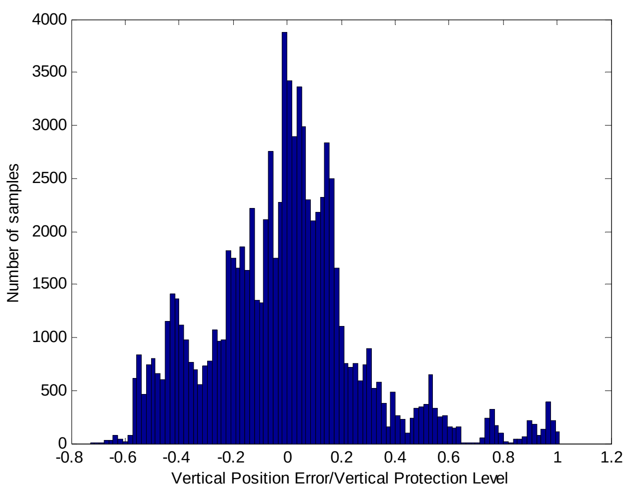

Figure 8. *Histogram of the VPE/VPL ratio with wrong nominal model*

As can be seen from both Figure 7 and 8, there is one instance when the VPE is larger than the VPL. This is not unexpected, as this is a severe threat and it is not taken into account in this implementation of ARAIM. This result stresses the necessity of having a conservative nominal error model for both the URA and the multipath.

CONCLUSION

The results of the prototype demonstrate that the ARAIM algorithm performed as expected on a set of ten receivers over a period of ten days. Faults that are considered in the threat model did not cause any loss of integrity in the data that was analyzed. Faults that lay outside the threat model did lead to a loss of integrity. In particular, the under-bounding of the nominal error for all pseudoranges lead to loss integrity. Although the tests performed here are preliminary, they show that it will be essential to have a conservative characterization of the nominal errors, both for the clock and ephemeris (URA) and the multipath error model (other source of errors are well characterized). To maintain the validity of the constellation assumptions it will be necessary to have a mechanism to alert users: this will be the role of the Integrity Support Message. It will be easier to adopt an ISM if the margin between the actual performance and the necessary performance is large: for same magnitude of errors, a larger URA will pass more easily the integrity requirements. If the constellation wide failure can be shown not to affect the vertical position error, then a constellation with a URA below 2 m will be useful to achieve worldwide coverage of LPV 200. If the constellation wide failure cannot be ruled out, the required URA drops to 1 m.

Although many details need to be defined, this work has supports that the fundamentals of the ARAIM user algorithm are mature –. The major challenges lie in the definition of the threat space, on how to alert users when the threat space is modified (the determination and the dissemination of the ISM), and on the trust that can be put in each constellation (both for availability and integrity).

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