ARAIM for Military Users: ISM Parameters, Constellation-Check Procedure and Performance Estimates

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BIOGRAPHIES

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Sam Pullen is a senior research engineer (part-time) in the Stanford GPS Laboratory. He received M.S. and Ph.D. degrees in Aeronautics and Astronautics from Stanford University in 1990 and 1996, respectively. His research focuses on system safety assurance and design optimization under uncertainty for users of Global Satellite Navigation Systems (GNSS) and enhancements such as GBAS and SBAS. He is the author of several book chapters and more than 150 articles. He supports government, industry, and legal clients as a technical consultant. He was an Associate Editor of the journal *IEEE Transactions on Aerospace and Electronic Systems* from 2007 to 2015. He was a recipient of the Institute of Navigation (ION) Early Achievement Award in 1999 and became a Fellow of the ION in 2017.

Sherman Lo is a senior research engineer at the Stanford GPS Laboratory. He received his Ph.D. in Aeronautics and Astronautics from Stanford University in 2002. He has and continues to work on navigation robustness and safety, often supporting the FAA. He has conducted research on Loran, alternative navigation, SBAS, ARAIM, GNSS for railways and automobile. He also works on spoof and interference mitigation for navigation. He has published over 100 research papers and articles. He was awarded the ION Early Achievement Award in 2004.

ABSTRACT

GNSS is now a cornerstone of civil aviation navigation and supports many applications requiring precise guidance, such as approaches to airports under obstructed visibility. GNSS provides such capabilities through high accuracy and safety assurance of its range measurements and position outputs. GNSS users

with demanding safety or integrity requirements but without access to real-time differential corrections and integrity information (e.g., from SBAS or GBAS) can utilize Advanced RAIM, or ARAIM, which is now a well-developed and understood methodology [1][2]. ARAIM extends and improves upon traditional RAIM algorithms to detect and mitigate independent and correlated GNSS signal faults, making it possible to support applications such as aviation precision approach without requiring continuous integrity messages supporting a 2-to-6 second time-to-alert.

Civil ARAIM uses multiple GNSS constellations to provide availability approaching what is obtainable from augmented GPS while detecting or otherwise mitigating faults correlated across a single constellation. However, ARAIM for U.S. military users may be limited to use of the GPS constellation only [3][4]. This paper describes and evaluates the performance of ARAIM using only GPS M-code for positioning as a function of its Integrity Support Message (ISM) parameters and the frequency with which these parameters are updated. In order to detect potential GPS constellation-wide faults, it also develops a new variant of ARAIM in which open-service signals from another constellation (Galileo) are used in a position-domain constellation check without being used for positioning.

1.0 INTRODUCTION AND MOTIVATION

This paper expands the application of Advanced RAIM (ARAIM) from civil aviation using open signals to military aircraft using GPS M-code on the L1 and L2 frequencies. As described in [1][2], ARAIM is an extension of "traditional" Receiver Autonomous Integrity Monitoring (RAIM) using Multiple Hypothesis Solution Separation (MHSS) to evaluate the integrity risk of any hypothesized failure type, including those with multiple measurement failures that cannot easily be handled by RAIM. In order to mitigate correlated satellite failures within a single GNSS constellation while achieving high availability of approaches requiring vertical guidance, such as localizer performance with vertical guidance (LPV) and LPV-200 approaches with minimum decision heights of 250 and 200 ft, respectively (see [7]), multiple GNSS satellite constellations (preferably three or more) are employed within civil ARAIM.

Military applications of ARAIM were previously considered in [3][4] by evaluating the impacts of GPS modernization in reducing standalone GPS errors and prior failure probabilities such that non-GPS satellites (meaning satellites not controlled by the U.S. Department of Defense) would not be needed within ARAIM. This paper further develops this concept by applying the Integrity Status Message (ISM) developed by the EU-U.S. Working Group C for ARAIM in civil aviation and implemented within the modernized GPS navigation message format [5]. ISM parameters for military use were estimated based on the proposed parameters for civil use, recent estimates of GPS satellite and constellation reliability, and user error estimates from flight tests of GPS L5 and Galileo E1 and E5a signals that are more similar to GPS M-code than is GPS C/A code [6]. To maximize the usefulness of the ISM in military ARAIM, changes to the current civil ISM format are proposed.

This work also investigates the degree of ground monitoring that is needed to generate ISM parameter values good enough to provide high availability of LPV approaches for military aircraft. Three different sets of ISM parameters were created to represent this:

1) "Frozen": ISM parameters are meant to be rarely (if ever) changed.
2) "Offline": ISM parameters can be updated on a monthly to quarterly basis.
3) "Online": ISM parameters can be updated hourly or at least every several hours.

Because more frequent updates allow for ISM parameters to be increased if needed due to worsening satellite performance, the baseline ISM parameters improve significantly from "frozen" to "offline" to "online." In other words, less margin between expected and conservative ISM values is needed if the ISM values can be updated quickly compared to if they can only be updated rarely or not at all (i.e., if no ISM were provided, as in the case of older RAIM for supplemental navigation which relies upon predetermined parameters designed into its standards [16]). All three ISM parameters are significantly less demanding than 6-second updates required of SBAS, but the "online" approach requires ground-monitor response within minutes. In addition, sensitivity studies on key ISM parameters such as (the bound on) satellite User Range Accuracy (URA) and satellite and constellation prior fault probabilities (P_{sat} and P_{const}) were conducted to determine, for example, at what values the "frozen" ISM option becomes non-viable in terms of providing acceptable LPV availability.

2.0 ADAPTING ARAIM FOR MILITARY USE

Military ARAIM using M-code on L1 and L2 is implemented similarly to civil ARAIM on L1/E1 and L5/E5 using the algorithms defined in [1] and updated in [14]. The baseline version (denoted as "GPS") uses only GPS satellites to avoid any dependence on other constellations outside the control of the U.S. military. This version of ARAIM cannot detect a correlated constellation fault across the GPS constellation and must rely on the probability of such an event (given by P_{const} for GPS and converted to R_{const}, which is the fault rate per hour [9]) being well below the total integrity risk requirement of 10^{-7} per approach that applies to LPV operations. Section 3.5.5 of the latest GPS SPS Performance Standard [10] gives P_{const} for GPS as 10^{-8} and a mean fault duration (MFD – the average time between fault onset and GPS Operational Control Segment alert) of 1 hour, thus R_{const} is (P_{const} / MFD =) 10^{-8} per hour and is sufficiently small. However, under the "frozen" ISM scenario where ISM parameters are difficult to change in response to constellation health degradations, the broadcast value of P_{const} may need to be higher than the standard value from [9], and in this case, military ARAIM limited to GPS alone may not suffice for LPV and other operations with integrity risk requirements on the order of 10^{-7} per operation or per hour. Civil ARAIM uses multiple GNSS satellite constellations to address this issue, as position solutions excluding each individual GNSS constellation can be computed and compared against the all-in-view solution to detect single-constellation faults [1][2].

A variant of this approach was developed in this paper that avoids the need for U.S. military users to include non-GPS satellites in their position solutions (as is the case in multi-constellation civil ARAIM). This method is called "Galileo constellation check" (or "GalC") and requires military GNSS receivers to track and process Galileo dual-frequency open-service signals (E1 and E5) in order to generate separate Galileo-only position solutions that are compared to the GPS-only position solution as part of ARAIM. If the internal GPS-Galileo position comparison passes a threshold derived from a false-alert requirement and the normal variation between GPS and Galileo positions, the GPS-only position solution is verified to be safe with the computed ARAIM protection level. Unlike civil ARAIM, Galileo satellites are not included in the "all-in-view" position solution, nor are they used to cross-check individual GPS or Galileo satellite faults. As will be shown in Section 4.0, this approach does not improve on GPS-only ARAIM when P_{const} is small, but it is successful at providing high availability of LPV despite large values of P_{const} for both GPS and Galileo.

3.0 ISM FOR MILITARY ARAIM

Figure 1 shows a diagram of the currently proposed contents of the GPS Integrity Status Message (ISM) format for civil ARAIM within GPS Civil Navigation (CNAV) Message Type (MT) 40 as of September 2020 [5]. The contents of the Military Navigation (MNAV) ISM message are expected to be very similar but are not yet public, so the CNAV message content is shown here for illustration. The six key performance parameters t_{correl}, b_{nom_0}, ν_{nom}, P_{sat}, P_{const}, and MFD for GPS are included in bits 62 through 79, with three bits for each parameter (thus allowing 8 different values for each parameter). Note that many unallocated bits exist in this message in the "Filler" from bit 146 to bit 244, so it would be possible to add further parameters or to extend the fields of the existing parameters.

The first three of the six performance parameters (t_{correl}: error time correlation, b_{nom_0}: nominal bias bound, ν_{nom}: nominal bias scaling factor) are used with the User Range Accuracy (URA) parameters broadcast separately in CNAV and MNAV (see Section 30.3.3 of [11]) to generate a model of the bounding Gaussian distribution of Signal-in-Space range-domain errors. Unlike previous ARAIM ISM proposals, which included parameters expressing or modifying URA and User Range Error (URE, representing a typical instead of bounding one-sigma value) (see [2]), the current ISM has no means to do this directly and instead simply applies the URA derived from the broadcast CNAV values URA_{NED} and URA_{ED} (the non-elevation-dependent and elevation-dependent components of URA, respectively)

In contrast, the "offline" and especially "online" ISM variations proposed above could make use of a 3-bit multiplier of this URA (α_{URA}) to reflect information gained by near-real-time ground monitoring needed to support frequent ISM updates. This multiplier would be set to 1.0 if no recent ground monitor updates were available (or if a particular ARAIM service provider chose not to use it), but otherwise, multipliers somewhat below 1.0 could be supported much of the time due to the additional integrity assurance and error bounding provided by the ground monitor network. The resulting availability benefit would be stronger

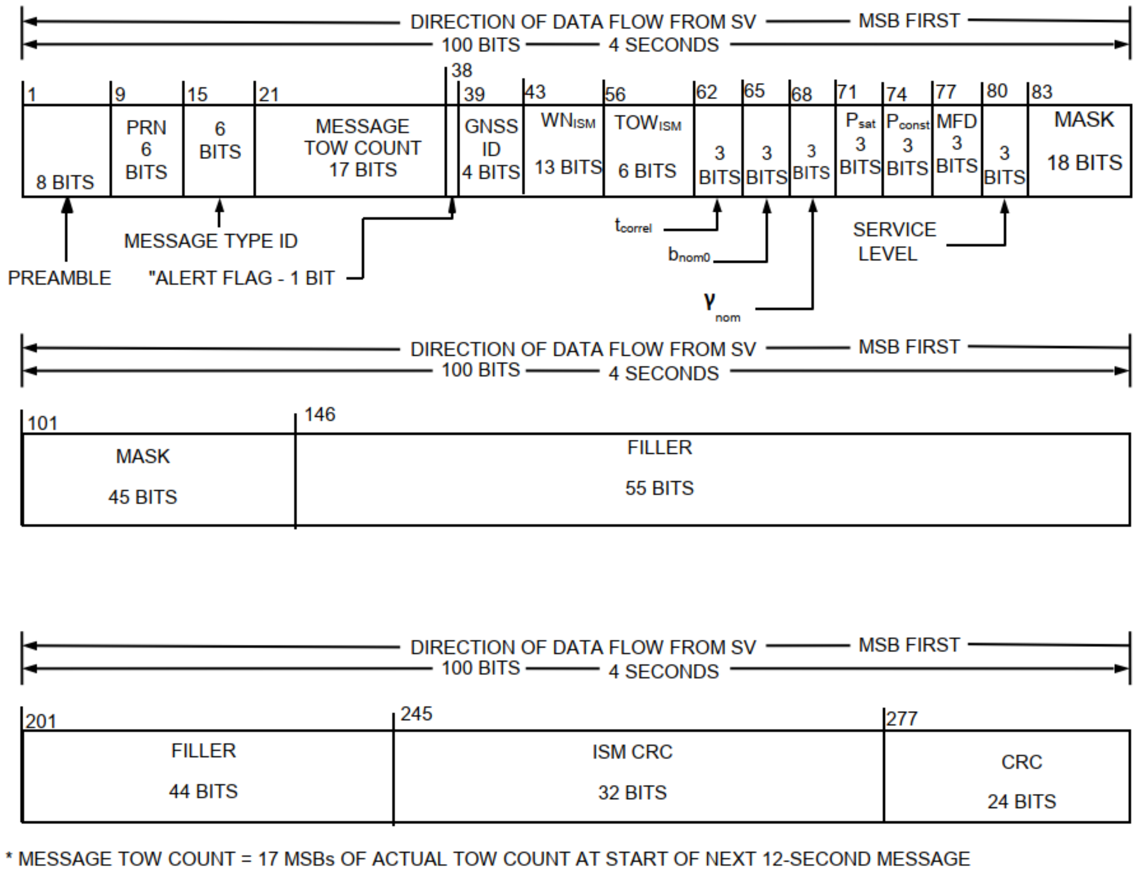

Figure 1: Proposed CNAV ISM Format as of September 2020 [5]

for GPS-only military ARAIM than for multi-constellation ARAIM because the former is more dependent on the level of GPS error bounds. However, at present, there is little interest in restoring a URA modifier to the ISM (note that it was deliberately removed when plenty of bits are available).

We also suggest that, given the large number of undedicated "filler" bits available, an additional bit be added to each of the six performance parameters listed above (along with α_{URA} if it is added to the ISM). Each of these six (or seven) parameters would then have four bits instead of three, which doubles the number of possible values that each parameter may take. For some of these parameters, the 8 possible values provided by three bits are adequate, but for others, the ability to select from 16 possible values helps avoid conservatism due to the need to "round up" to the next most conservative value among those that can be transmitted. In particular, this allows P_{sat} and P_{const} probability values in between multiples of 10^{-p} to be selected at the high, medium, and low ends of the probability scale. As this change has no disadvantages and uses only six of the large number of "filler" bits, it has formally been proposed as a change to Figure 1 and is shown in [12] as awaiting public comment (as of the end of October 2020).

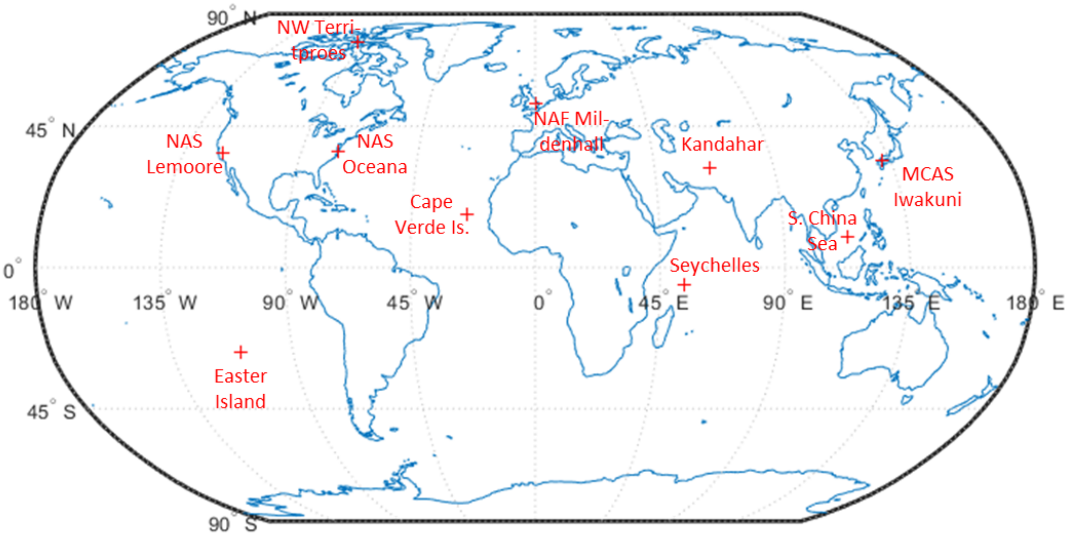

Figure 2: Ten Military User Locations Chosen for ARAIM Performance Evaluation

4.0 MILITARY ARAIM PROTECTION LEVELS AND AVAILABILITY

Simulations of ARAIM integrity performance and availability were conducted using the ARAIM version of the Stanford Matlab Algorithm Availability Simulation Tool (MAAST) software [8], which produces vertical and horizontal protection level (VPL and HPL) results for a pre-selected GNSS satellite almanac and list of user locations. Simulations were conducted with results calculated at 1-minute intervals over one repeatable day of GPS satellite geometries, giving a total of 1440 epochs. Each result was evaluated to determine the availability of approaches modeled after civil LPV approaches to a minimum decision height of 250 ft, which are available when VPL is below a vertical alert limit (VAL) of 50 meters and HPL is below a horizontal alert limit (HAL) of 40 meters [7]. Extensive results for VPL, HPL, and availability have been produced for several sets of ISM parameters, a series of sensitivity studies on these parameters, and two sets of user locations: (a) a list of 10 airbases or military sites of concern scattered around the world (shown in red in Figure 2), and (b) a 5-by-5 degree latitude/longitude grid of locations around the world.

Tables 1 and 2 show the baseline ISM performance parameters assumed for the three ISM update scenarios described in Section 1.0 for GPS and Galileo satellite measurements, respectively. The error parameters URA, URE, and b_{nom} are the same for each signal frequency and for GPS and Galileo in this model. However, P_{sat} and P_{const} are higher for Galileo because there is much less historical data available with which to assess and confirm these probabilities. P_{const} for GPS is higher than the value of 10^{-8} cited in [10] for the frozen and offline ISM scenarios in order to test the sensitivity of the results to this parameter for both GPS and GalC variations of military ARAIM. Finally, the parameter $K_{mcode\text{-}air}$ is not meant to be included in ARAIM or monitored by ground or airborne systems. Instead, it is a fixed coefficient that multiplies the sigma of the standard airborne user error models from [1][2][14] to reflect the error reduction achieved by the use of M-code instead of L1 C/A code and L2C for GPS.

Table 1: GPS M-Code L1 and L2 Error Model Parameters

Parameter	Frozen	Offline	Online
URA	1.60 m	1.30 m	1.00 m
URE	1.07 m	0.87 m	0.63 m
b_{nom}	0.75 m	0.50 m	0.35 m
P_{sat}	5.0×10^{-5} / SV	1.0×10^{-5} / SV	5.0×10^{-7} / SV
P_{const}	5.0×10^{-6}	7.0×10^{-8}	2.5×10^{-9}
Mean Fault Duration (MFD)	1.0 hrs	1.0 hrs	0.6 hrs
$K_{mcode-air}$	0.8	0.8	0.8

Multiplier of airborne error sigma to reflect M-code v/s C/A-code

Table 2: Galileo E1 and E5 Error Model Parameters

Parameter	Frozen	Offline	Online
URA	1.60 m	1.30 m	1.00 m
URE	1.07 m	0.87 m	0.63 m
b_{nom}	0.75 m	0.50 m	0.35 m
P_{sat}	1.0×10^{-4} / SV	3.0×10^{-5} / SV	1.0×10^{-6} / SV
P_{const}	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-8}
Mean Fault Duration (MFD)	1.0 hrs	1.0 hrs	0.6 hrs
$K_{mcode-air}$	0.8	0.8	0.8

Multiplier of airborne error sigma to reflect M-code v/s C/A-code

What follows are the results generated from running MAAST (in Matlab) to emulate the performance of military ARAIM with these (and other) ISM parameter values. All of these simulations used the 27-satellite expandable constellation configuration for GPS given in Section A.2.3 of the 4th (2008) Edition of the GPS SPS Performance Standard [13], while the simulations of Galileo satellites (for GalC) used an example 27-satellite constellation used in earlier civil ARAIM studies [1][2].

Figure 3 and Figure 4 both show Vertical Protection Level (VPL) results at one of the 10 locations shown in Figure 2 (Kandahar, Afghanistan) using the baseline ISM parameters given in Tables 1 and 2. Figure 3

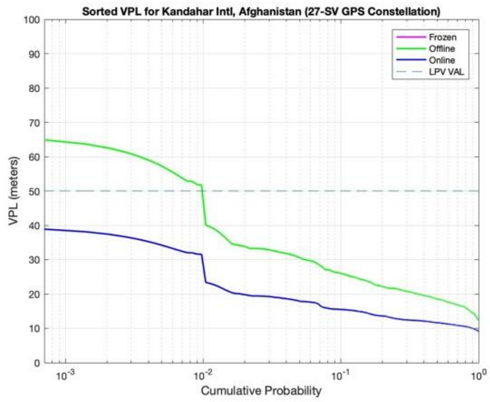

Figure 3: VPL at Kandahar for GPS Only

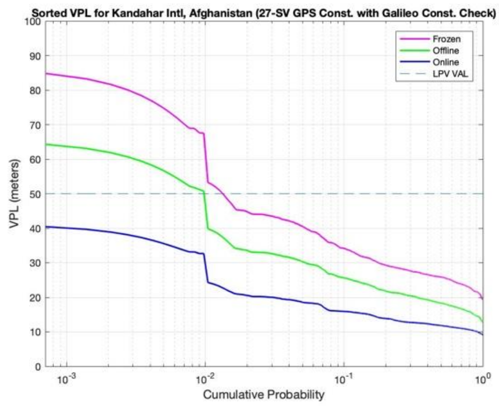

Figure 4: VPL at Kandahar for GalC

shows the results for GPS only (GPS), while Figure 4 shows the results when the Galileo constellation check (GalC) is added. On each plot, there are three curves representing the different ISM scenarios: dark blue for online, green for offline, and purple for frozen. The Vertical Protection Level in meters is plotted on the y-axis, and the x-axis shows a logarithmic scale of cumulative probability of VPL being at or below the specified level. Results were generated for the 10 different user locations in Figure 2, but to save space in this paper, we will only show the results at Kandahar, Afghanistan, which has poorer than average performance among these 10 locations.

MAAST generates a VPL and HPL for each time epoch for each user (each time epoch representing a different satellite geometry visible to each user). After all 1440 epochs in a single day of repeatable GPS satellite geometries (at one-minute intervals) are completed, the vectors of VPL and HPL over time are sorted from smallest to largest and then plotted in this order against the cumulative probabilities on the x-axis. For example, the VPL at a cumulative probability of 10^{-2} represents the VPL that was exceeded in only 1 in 100 epochs. Since 1440/100 = 14.4, about 14 epochs had higher VPLs than this, and they are shown to the left of the VPL at 10^{-2}. Dashed horizontal lines represent the VAL of 50 meters for LPV operations, so the probability of exceeding VPL for a given ISM scenario can be read off the plots.

In Figure 3 for GPS only, notice that there is no curve shown for the frozen ISM case, and there is no LPV availability for this scenario. This is because P_{const} and R_{const} for this scenario exceed the 10^{-7} per operation LPV integrity risk requirement. However, in Figure 4, the addition of the Galileo constellation check (GalC) generates valid VPLs for the frozen case because the combined constellation fault probability ($P_{combined}$), which is the product of P_{const} from GPS and P_{const} from Galileo, is well below 10^{-7}. Of course, the better ISM parameters used for the offline and (especially) online ISM cases give much lower VPLs and higher availabilities. Table 3 shows the LPV availabilities for GalC for all three ISM cases and all 10 user locations in Figure 2.

Comparing Figures 3 and 4 for offline and online ISM cases shows that the addition of the Galileo constellation check (GalC) does not significantly lower VPLs beyond GPS only. The VPLs for GPS only

Table 3: LPV Availability Results for Three ISM Cases Using Galileo Constellation Check (GalC)

LPV Availability Results (VAL ≤ 50 m and HAL ≤ 40 m)			
	Frozen	Offline	Online
NAS Oceana, VA	0.974	0.992	0.996
NAS Lemoore, CA	0.992	1.000	1.000
MCAS Iwakuni, Japan	0.981	0.999	1.000
NAF Mildenhall, England	0.990	1.000	1.000
Kandahar AB, Afghanistan	0.987	0.990	1.000
Hanga Roa, Easter Island, Chile	1.000	1.000	1.000
Fiery Cross Reef, South China Sea	0.963	0.990	0.997
Desroches Island, Seychelles	1.000	1.000	1.000
Mindelo, Cape Verde Islands	0.995	1.000	1.000
Resolute, NW Territories, Canada	0.954	1.000	1.000

below 0.98   below 0.95   below 0.90

for these two cases are very similar, and for certain probabilities, the GPS-only VPL is slightly lower than the GalC VPL. This difference is not significant and is believed to be due to GalC adding the constellation check within ARAIM when it is not needed (because the GPS P_{const} for offline and online is already below 10^{-7}). However, when needed to bring $P_{combined}$ below 10^{-7}, GalC appears to perform its function well. This is explored further in Section 5 as P_{const} for GPS and Galileo is increased beyond the values shown in Tables 1 and 2.

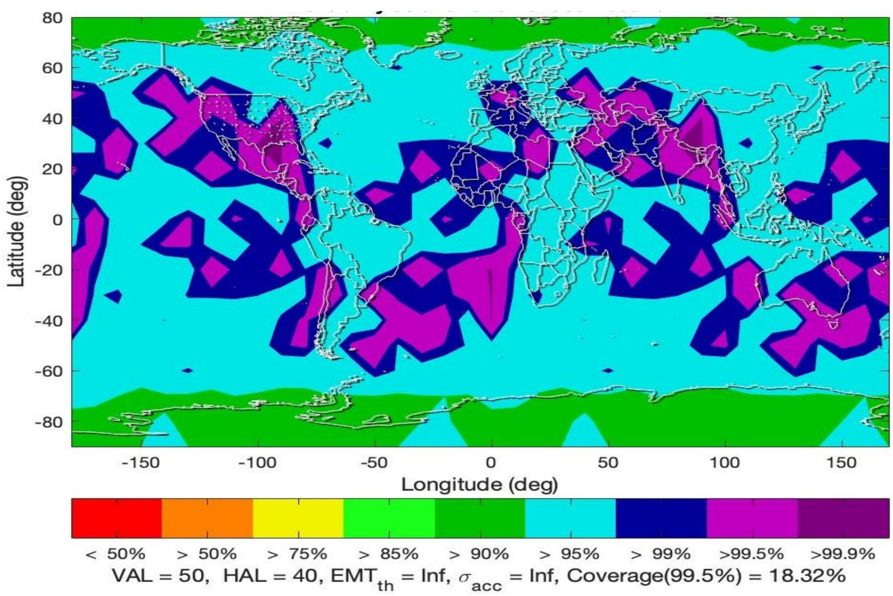

Figure 5: "GalC" Availability Results in Contour Format: *Frozen ISM*

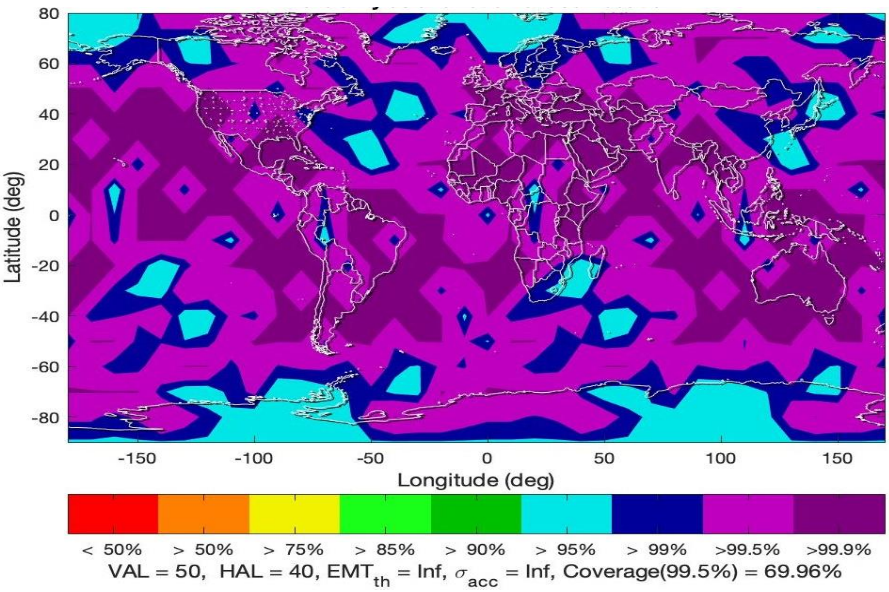

Figure 6: “GalC” Availability Results in Contour Format: *Offline ISM*

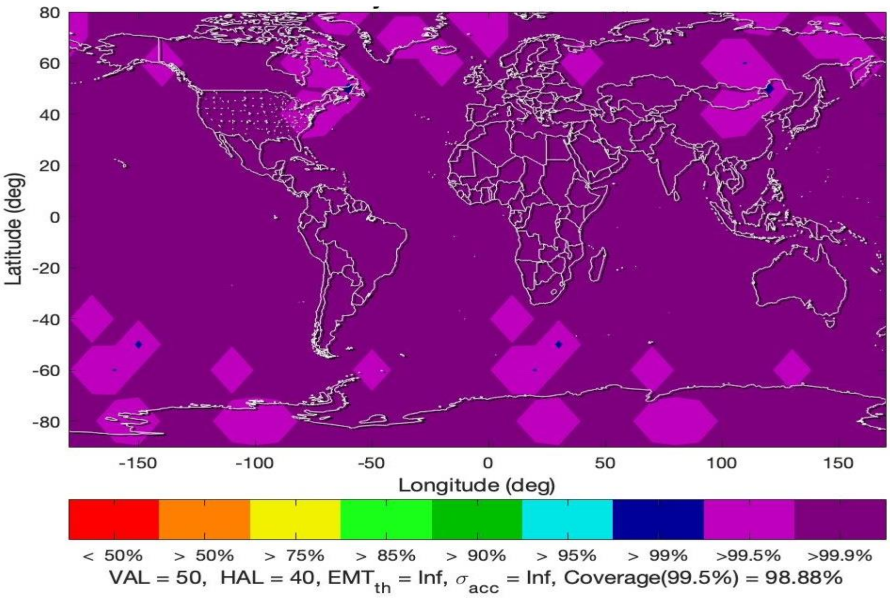

Figure 7: “GalC” Availability Results in Contour Format: *Online ISM*

Figure 5, Figure 6, and Figure 7 show contour plots that depict availability for the GalC configuration over a 5 × 5-degree grid of user locations in latitude and longitude. These plots use the standard MAAST output format and display color-coded regions where availability exceeds the percentages shown on the color spectrum below the contour plot itself. The “Coverage(99.5%)” statistic in the lower right of each figure gives the percentage of locations within the user grid that have availabilities exceeding 99.5%, meaning that they would be shown in pink or purple in the contour plot.

Figure 5 shows that “frozen” ISM for GalC has LPV availability greater than 95% in the non-polar regions of the world with pockets of availability greater than 99%. The coverage statistic shows that availability at or exceeding 99.5% exists for about 18.3% of locations. Figure 6 for "offline" ISM shows greatly improved LPV availability, as about 70% of locations now meet or exceed 99.5% availability, and some of these have availability exceeding 99.9% (meaning, since there are only 1440 epochs, all or all but one of them are available). However, there are various pockets scattered across the globe and in the polar regions with availabilities between 95 and 99% (the light blue regions in Figure 6). These areas of reduced availability are rectified by "online" ISM in Figure 7, which has nearly 100% availability across much of the globe and almost 99% of locations meeting or exceeding 99.5% availability.

Taken together, the results in Figures 3 through 7 show the benefits of increased ground monitoring with more rapid response times and the ability to alter the ISM parameters to reflect these changes, as represented in the "offline" and especially "online" scenarios. Since the Galileo constellation check only benefits conditions where P_{const} and R_{const} for GPS are higher than the integrity risk requirement, use of the GPS constellation only is perfectly feasible under "offline" and "online" scenarios. However, the effort needed to implement extensive and rapid-response ground monitoring and ISM messaging is a major disadvantage, and it appears to have pushed prospective civil ARAIM service providers to adapt a "frozen" approach with multiple constellations to compensate for the greater ISM parameter uncertainties.

5.0 ISM SENSITIVITY STUDIES AND IMPACTS ON RESULTS

Since the actual ISM parameter values that can be supported by any particular constellation or ground-monitoring approach remain uncertain, we have conducted several sensitivity studies by changing one or more ISM input parameters from those shown in Tables 1 and 2. For example, because the Galileo constellation check (GalC) is used to mitigate low values of P_{const} for GPS, it was useful to examine how large P_{const} for both GPS and Galileo could get before GalC could no longer protect against constellation faults and thus not provide valid protection levels.

In the first sensitivity study for GalC shown here, P_{const} for GPS in the "frozen" case was changed from its already conservative value of 5×10^{-6} in Table 1 to an even larger (and unrealistic) value of 10^{-3}. This alteration only slightly reduced the LPV availability. While this difference is difficult to notice when comparing the resulting VPL plots visually, it can be made observable by calculating the ratio of the GalC VPL with the higher P_{const} value to the corresponding VPL for the lower P_{const} value (i.e., the baseline value of 5×10^{-6}), all else being kept the same. Figure 8 was generated in this manner for Kandahar, and it shows that VPL mostly differed at high probabilities (where most VPLs resided) and by less than 20%. In fact, at the probability where VPL grew to reach the VAL of 50 meters, the difference between the two values of P_{const} was less than 2%, thus the availability was almost the same as well.

By continuing to increase P_{const} for both GPS and Galileo in these sensitivity studies, a "break point" at which GalC was no longer able to meet the constellation integrity risk sub-allocation (and thus where VPL became unbounded) was discovered and is shown in Figure 9. This occurred when P_{const} for GPS was increased to 10^{-4} while P_{const} for Galileo was also increased to 3.85×10^{-4} in the right-hand plot (the left-

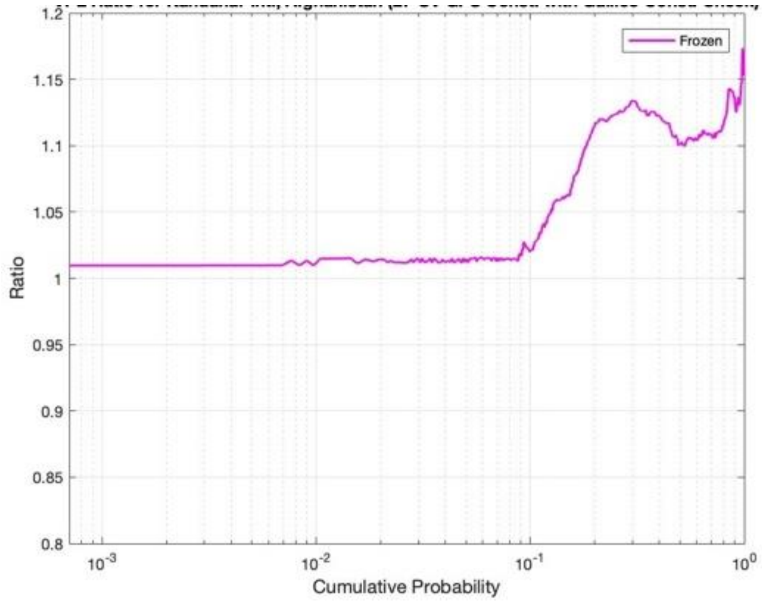

Figure 8: VPL Ratio Comparison at Kandahar, "GalC" Sensitivity Study

("Frozen" ISM Updates, GPS P_{const} changed from 5×10^{-6} to 10^{-3})

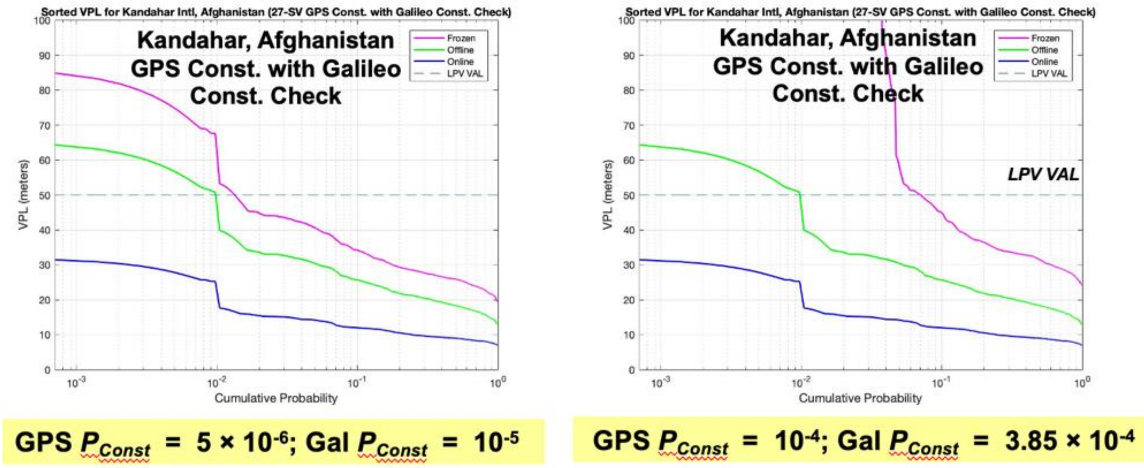

Figure 9: GalC "Frozen" ISM Sensitivity Study at Kandahar

(P_{const} increased for both GPS and Galileo)

hand plot uses the baseline P_{const} values). This comes as no surprise because, with these values, the combined constellation fault probability $P_{combined}$ (calculated by computing the product of P_{const} for GPS and Galileo) is close to 10^{-7}. Note that the VPLs for both offline and online ISM cases did not change at all in Figure 9 because only the P_{const} values for "frozen" were modified from those in Tables 1 and 2.

Sensitivity studies were also performed for the "offline" ISM parameters by increasing P_{const} and studying its effect on VPL and availability. In the example shown here, P_{const} for GPS was increased from 7×10^{-8} to 2.8×10^{-6} and P_{const} for Galileo was increased from 10^{-6} to the unrealistically high value of 10^{-2}. As shown in Figure 10 and Figure 11, there was little change in VPL or availability. The ratio between VPLs

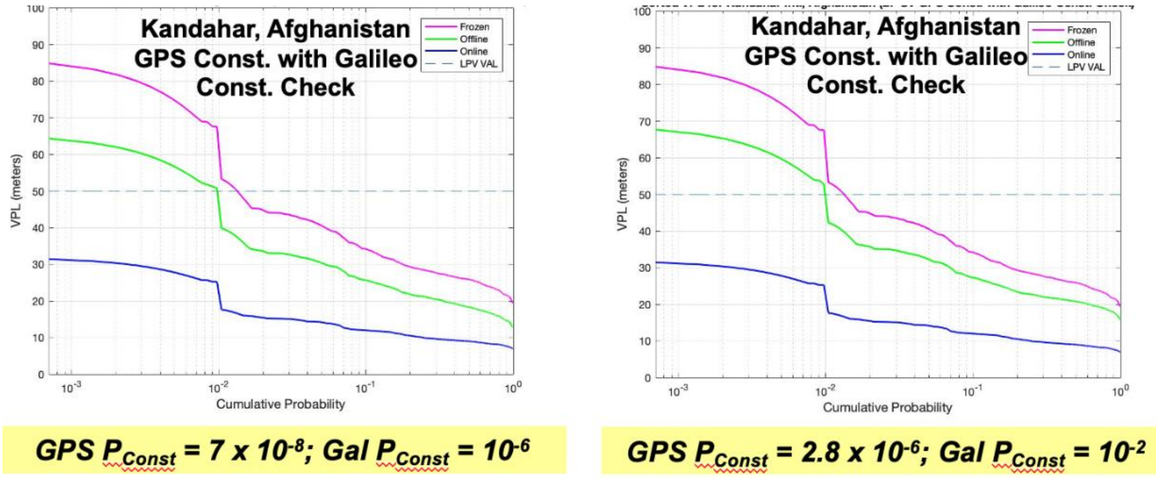

Figure 10: GalC "Offline" ISM Sensitivity Study at Kandahar

(P_{const} increased for both GPS and Galileo)

for increased P_{const} and original P_{const} in Figure 11 shows the same pattern as in the previous case in Figure 8 in that VPL differed more (up to 20%) at high probabilities and by less (5 – 6%) for lower probabilities and as VPL approached VAL around a probability of 0.02 in Figure 10, with the resulting availabilities being nearly the same (about 98%). This further shows how GalC provides robust results for ISM parameter sets in which P_{const} needs to be increased to very conservative numbers. Finally, as expected, sensitivity studies on GalC for the "online" ISM parameters showed no changes in VPL or availability when P_{const} was increased substantially from its very low baseline numbers for online (2.5×10^{-9} for GPS,

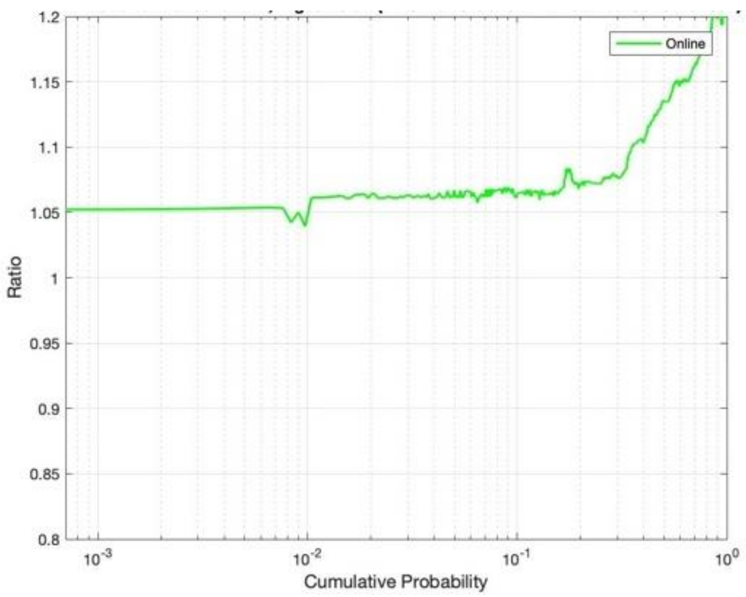

Figure 11: VPL Ratio Comparison at Kandahar, "GalC" Sensitivity Study

("Offline" ISM Updates, GPS and Galileo P_{const} both changed)

10^{-8} for Galileo). With an online ISM, there is little or no benefit to using GalC instead of GPS only, but there of course would be improvements if Galileo satellites were used interchangeably with GPS satellites in the manner of multi-constellation civil ARAIM.

6.0 SUMMARY AND FUTURE WORK

In this paper, we have examined M-code ARAIM performance based on lessons learned from earlier work on civil ARAIM. This was done by investigating the degree of ground monitoring and rapid updating that is needed to generate ISM parameter values good enough to provide high availability of LPV approaches for military aircraft. Of the three sets of ISM parameters chosen to reflect different degrees of ground monitoring intensity and timeliness, the "online" parameters gave near-perfect LPV availability results, even when using only GPS satellites, while those for "offline" achieved excellent but significantly lower availability (e.g., about 70% of the world achieved LPV availability of at least 99.5% for "offline" compared to almost 99% of the world for "online"). The "frozen" ISM parameters also gave potentially acceptable availability (with about 18% of the world reaching LPV availability of 99.5% and most achieving at least 95% availability) but are subject to more uncertainty due to the limited ability of ground monitoring to support ISM parameter updates in a timely manner.

In particular, the correlated (constellation) failure probability P_{const} is a sensitive issue for the "frozen" ISM case. The recent update to the GPS SPS Performance Standard [10] suggests that P_{const} should be 10^{-8}, but assuring such a low prior probability continuously in the future may require ground monitoring and ISM update capabilities beyond those of the "frozen" case. P_{const} for the frozen ISM scenario was set to be much higher than 10^{-8} in this paper, and this required the development of the Galileo constellation check (GalC) variant of ARAIM to allow military users to check their GPS M-code position solutions against a separate open-signal Galileo position solution within ARAIM without integrating Galileo measurements into their own position solutions. This method has been shown to mitigate values of P_{const} for GPS well above 10^{-7} or even 10^{-5}, which significantly enhances the feasibility of the simpler monitoring and ISM-update approach allowed by the "frozen" parameters. However, achieving LPV availability greater than 99.5% over the majority of the world's surface without the civil approach of multi-constellation ARAIM likely requires "offline" or at least significantly better ISM parameters than the baseline for "frozen". This would require more extensive and ground monitoring with faster updates and response times.

Our future work on this project includes delving into the details of the ARAIM algorithm to better understand the small performance differences between the GPS and GalC variants when P_{const} for GPS is high enough to require GalC. More broadly, we will assess ARAIM ground monitoring techniques using existing SBAS algorithms and Kalman Filter/batch approaches published by others (e.g., see [15]). Our goal is to be able to connect the performance of ground monitoring to the ISM parameters that it can support so that the trade-offs between better ISM parameters and more-complicated ground monitoring and ISM update procedures become better understood. Also, since a military version of SBAS is the natural endpoint of increasing the capability and shortening the response time, future work will include research into the potential benefits of military SBAS for operations with demanding integrity requirements in contrast with the variations of ARAIM explored here.

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