Standards for ARAIM ISM Data Analysis

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Abstract

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) relies on accurate and safe information to be provided to the aircraft through an Integrity Support Message (ISM). The ISM safety parameters are based on service commitments established by each core GNSS constellation. Each core constellation is expected to broadcast its own set of parameters that apply to its own satellites. Users can monitor more than one constellation, obtaining the required ISM parameters for each one. While the state associated with each core constellation is responsible for determining and meeting their own chosen set of parameters, it is important that these parameters are independently monitored and evaluated for performance. For example, even though the U.S. will be responsible for determining and broadcasting ISM parameters that apply to GPS, many other countries will be interested in allowing aircraft to use GPS as part of ARAIM to support aircraft navigation over their own airspace. Thus, it is important that these countries be able to evaluate whether or not the GPS ISM parameters are consistent with observed data. This paper provides proposed standards for data collection and evaluation that allows all interested parties to agree on whether or not the provided parameters are safe to use.

Introduction

This paper describes the methods to determine how much data is required to evaluate the provided ISM parameters and how the data may be analyzed to ensure consistency. ISM parameters include the probabilities of individual satellite fault (P_{sat}) and of multiple satellite faults (P_{const}) [Blanch, 2018]. Smaller values for these probabilities require longer data sets to sufficiently verify their values. These data sets require lengthy collections of largely fault-free data. These same data sets can be used to validate the nominal error parameters as specified by α_{URE}, α_{URA} and b_{nom}. We present a set of evaluations that can be used to establish whether or not the chosen parameters are consistent with the observed data. By standardizing the set of evaluations, we hope to eliminate confusion or disagreement about what the data is capable of supporting and whether the chosen parameters may be safely used. Our goal is to increase the transparency of system performance and to ensure that ISM parameters are set to safe values that will support future ARAIM adoption.

ISM Parameter Description

The ISM parameters include 8 key elements. These are:

- P_{sat} – The probability that an individual satellite is in a faulted state at any given time
- P_{const} – The probability that multiple satellites are in a faulted state at any given time
- α_{URE} – A multiplier to obtain the expected uncertainty on the Signal-In-Space (SIS) error
- α_{URA} – A multiplier to obtain the integrity overbound of the uncertainty on the SIS error
- b_{nom} – An overbound on the magnitude of the expected SIS long-term bias error

- MTTN – The Mean-Time-To-Notify to the user that a satellite has become faulted
- Status flag – An indicator of whether or not the satellite may be used for ARAIM
- Validity time – Information on when the ISM parameters may be safely used

More complete definitions may be found in Walter et al. 2019. P_{sat} describes satellite faults that occur independently on a particular satellite and that do not affect the performance of the other satellites. These may occur due to component failure on the specific satellite. Constellation faults are those that arise from a common cause but that affect multiple satellites. These may be due to faults at the ground control segment that then propagate to more than one satellite. The satellites broadcast values to describe their expected accuracy. For GPS these are User Range Accuracy (URA) values. Other constellations have equivalent terms. The α_{URE} parameter is used to multiply the broadcast URA to obtain a 1-σ estimate for a zero-mean Gaussian model of behavior that describes the expected accuracy. This value is used to model the position accuracy and to set thresholds for comparing differing position solution estimates. The α_{URA} parameter is also used to multiply the broadcast URA to obtain a 1-σ estimate except that this value is to be used as an integrity bound. It may be a much more conservative estimate and generally will be larger than α_{URE}. The b_{nom} parameter covers error sources that change very slowly in time, these may be due to antenna biases, signal deformations, inter-frequency biases, or other quasi-static error sources. This term is combined with the above 1-σ estimates to more completely overbound [DeCleene, 2000]the SIS error distributions.

The Mean-Time-To-Notify (MTTN) is an upper bound on the expected average time that it takes to notify the user when a satellite transitions from unfaulted to faulted. This parameter is used to relate the rate at which faults occur to the probability that the satellite is in a faulted state at the current time. The status flags are used to indicate whether or not a satellite is adequately described by the above parameters. Satellites at the beginning of their lives may be under test and may not conform to the ARAIM assumptions but may otherwise be healthy for non-safety-of-life use. Similarly, satellites at the end of their lives may not have enough redundancy to meet the expected ARAIM performance requirements but are useful for other applications. The validity time establishes a time-frame in which the ISM parameters may be considered valid. As these parameters could change over time, there needs to be a mechanism to allow the provider time out older values and ensure that users are only applying the currently applicable values.

ISM Parameter Properties

The ARAIM user algorithm assumes that the Signal-In-Space Range Errors (SISREs) are divided into two categories: faulted and unfaulted. A threshold T is provided by the Constellation Service Provider (CSP) to distinguish between these categories. By definition, all errors below the threshold are considered to belong to the unfaulted category and all that are above the threshold belong to the faulted category. Faulted errors otherwise have an undefined probability distribution; they may take on any arbitrary value. When faults lead to sufficiently large errors for the user's range measurement, the user algorithm will identify the faulted state and potentially exclude these large errors from the position determination. In contrast, unfaulted errors must be bounded by a known Gaussian probability distribution that is characterized by b_{nom} and α_{URA} x σ_{URA}. Thus, the probability of having a pseudorange error greater than $|x|$ must be no larger than $2 \cdot \Phi((-(|x| - b_{nom})) \,/\, (\alpha_{URA}\, \sigma_{URA}))$, where $\Phi(\cdot)$ is the Gaussian cumulative distribution function (CDF). The b_{nom} term can be neglected from the remaining equations provided the sample mean is removed from the observed distribution and its value is accounted for in b_{nom}.

The parameters P_{sat} and P_{const} are upper bounds on the probabilities of being in a faulted state at a given time. They should not be confused with R_{sat} and R_{const}, which are the corresponding fault rates, and are expressed per unit of time. P_{sat} and P_{const} are linked to R_{sat} and R_{const} by the Mean-Time-To-Notify (MTTN) via the relationships: $P_{sat} = R_{sat}$ * MTTN and $P_{const} = R_{const}$ * MTTN. Previous reports we have used the concepts of the expected average fault duration and the MTTN interchangeably. The fault may persist after the user has been notified that the satellite is no longer be used, or the effect of the fault may be removed by correcting the fault and restoring the signal to a fully operational unfaulted condition. Either situation results in a termination of the fault condition from the user perspective. The MTTN parameter in the CSP commitment should be based on design analysis, where worst case conditions of observability and ability to update the information transmitted to the user. The measured MTTN when observing the service history will likely reveal a shorter mean duration. Regardless of the method by which the fault effect is terminated and of the reparation mechanism, we will continue to use MTTN to denote the expected average fault duration.

The probability of any individual satellite being in a faulted state at any particular time is no greater than $P_{sat} + P_{const}$ and the corresponding probability of being in an unfaulted state is at least $1 - P_{sat} - P_{const}$. We can define the total error probability distribution as $f_{total}(x)$. We can further define separate two regions in the error distributions as $f_{unfaulted}(x)$ and $f_{faulted}(x)$ respectively. These distributions have the following relationship: $f_{total}(x) = (1 - P_{sat} - P_{const})*f_{unfaulted}(x) + (P_{sat} + P_{const})*f_{faulted}(x)$. When describing the overbound on the unfaulted errors, one can take into account that it only describes a fraction of the total error distribution in accordance with $1 - P_{sat} - P_{const}$. In particular

$$f_{total}(x) = f_{SISRE}(x) \cdot u(T - |x|) + f_{SISRE}(x) \cdot u(|x| - T)$$

$$\text{with } u(x) = \begin{cases} 1 \; if \; x > 0 \\ 0 \; if \; x \leq 0 \end{cases}$$

then

$$f_{unfaulted}(x) = f_{SISRE}(x) \cdot \frac{u(T - |x|)}{(1 - P_{sat} - P_{const})}$$

$$f_{faulted}(x) = f_{SISRE}(x) \cdot \frac{u(|x| - T)}{(P_{sat} + P_{const})}$$

Figure 1 shows a plot of one minus the cumulative distribution function (CDF) for the signal-in-space range errors, given by: $1 - \Phi(|x|/\alpha_{URA}\sigma_{URA}) \cdot (1 - P_{sat} - P_{const})$. The plot is of 1- CDF rather than CDF so that the small differences from unity may be more easily seen. As is evident in the plot, the $(1 - P_{sat} - P_{const})$ term sets a lower bound on the meaningful probabilities affected by the errors. In this example we have set $P_{sat} + P_{const} = 10^{-5}$.

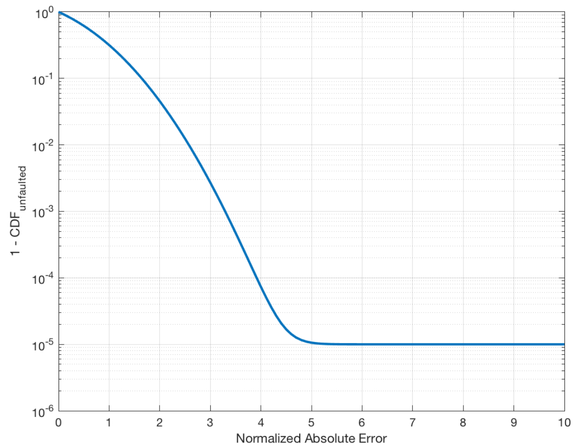

Figure 1 showing the 1 - CDF bounds for the signal-in-space range errors.

This figure does not consider the fault threshold. The fault definition states that values less than or equal to *T* are unfaulted, while the faulted errors correspond to values larger than *T*. However, it is important to remember that the user algorithm also does not take *T* into consideration. It cannot measure the instantaneous SIS error. Instead it merely assumes that the true SIS error distribution can be overbounded by the distribution plotted in Figure 1.

Figure 1 clearly shows that there is a natural region for selecting the threshold separating the two states. This value occurs near the value where $2 \cdot \Phi(-T/\alpha_{URA}\sigma_{URA}) = 1 - P_{sat} - P_{const}$. This equation can be rewritten as $T = \Phi^{-1}((1 - P_{sat} - P_{const})/2) \cdot \alpha_{URA}\sigma_{URA}$. The value $\Phi^{-1}((1 - P_{sat} - P_{const})/2)$ is frequently written as *k*, and we can simplify the previous equation to $T = k\, \alpha_{URA}\sigma_{URA}$.

For GPS *T* is chosen such that $k = \Phi^{-1}(10^{-5}/2) = 4.42$ [GPS SPS PS, 2008]. Traditional RAIM has used $P_{sat} = 10^{-5}$/hour, $P_{const} < 10^{-7}$/hour, and MTTN = 1 hour. Choosing a larger value of *T* might seem to imply that the Gaussian error bound on the errors has to apply down to correspondingly lower probabilities. However, the errors do not need to be bounded to probabilities below $P_{sat} + P_{const}$. Unfaulted errors in this example may occur with probability 10^{-5} and meet the requirement, provided that the 1 - CDF for the actual distribution is below the line shown in Figure 1. However, there is also little benefit to increasing *T* much beyond 4.42 as the error distribution already needs to be below $P_{sat} + P_{const}$ around this region. A Gaussian-like unfaulted error distribution does not change its bounding σ_{URA} value when specifying a larger value for *T*. This is because σ_{URA} will be determined by the part of the curve to the left of the natural transition region. Smaller values of *T* will require that the error be truncated compared to a Gaussian. In our experience, the actual measured data rarely exhibits this property.

For any relevant collection of observed errors, the 1-CDF must fall below the bounding line demonstrated in Figure 1 (using the appropriate values for P_{sat} and P_{const}). A relevant collection of data is one that has sufficient samples to be statistically meaningful and that collects together the data into partitions that have similar expected behavior (e.g. by satellite, satellite block, clock type, age of data, etc.). As stated above, for each and every partition the sample mean is estimated and evaluated against b_{nom}. The value of b_{nom} must be sufficient to bound both this measurable bias contribution as well as to account for unobserved bias sources such as those due to nominal signal deformation.

The sample mean may be removed from the measured distribution and the resulting 1-CDF may be compared against the appropriate upper bound corresponding to the ISM values. If any of the actual 1-

CDF values are above this bounding line, then it is possible that either the unfaulted error distribution is worse than the assumed Gaussian upper bound or the error rate may be greater than the specified values for P_{sat} or P_{const}. If all of the selected data partitions pass this evaluation, then the data may be said to be consistent with the provided integrity parameters.

The question of meeting statistical significance is an important consideration. Ideally, each partition would contain enough independent samples to estimate the sample 1-CDF to below $P_{sat} + P_{const}$. This requirement is met when the number of independent samples is >> $1/(P_{sat} + P_{const})$. It is often difficult to achieve this goal for all partitions, and they may in fact have far fewer values. Such situations are more likely to result in either false negative or false positive results. Such evaluations may require subsequent in-depth analysis and/or validation methods which may introduce margin in the bounding assessment to handle the limited statistical significance.

Example Analysis

Data has been collected for both the GPS and GLONASS constellations. Their fault probabilities and nominal error distributions are now assessed by the method outlined above. For GPS eleven years of data from January 1, 2008 – December 31, 2018 is used to evaluate the parameters. Figure 2 shows 1 – CDF curves for each of the individual satellites (colored lines) as well as for the aggregate of all satellites (heavy black line) [Walter, 2018].

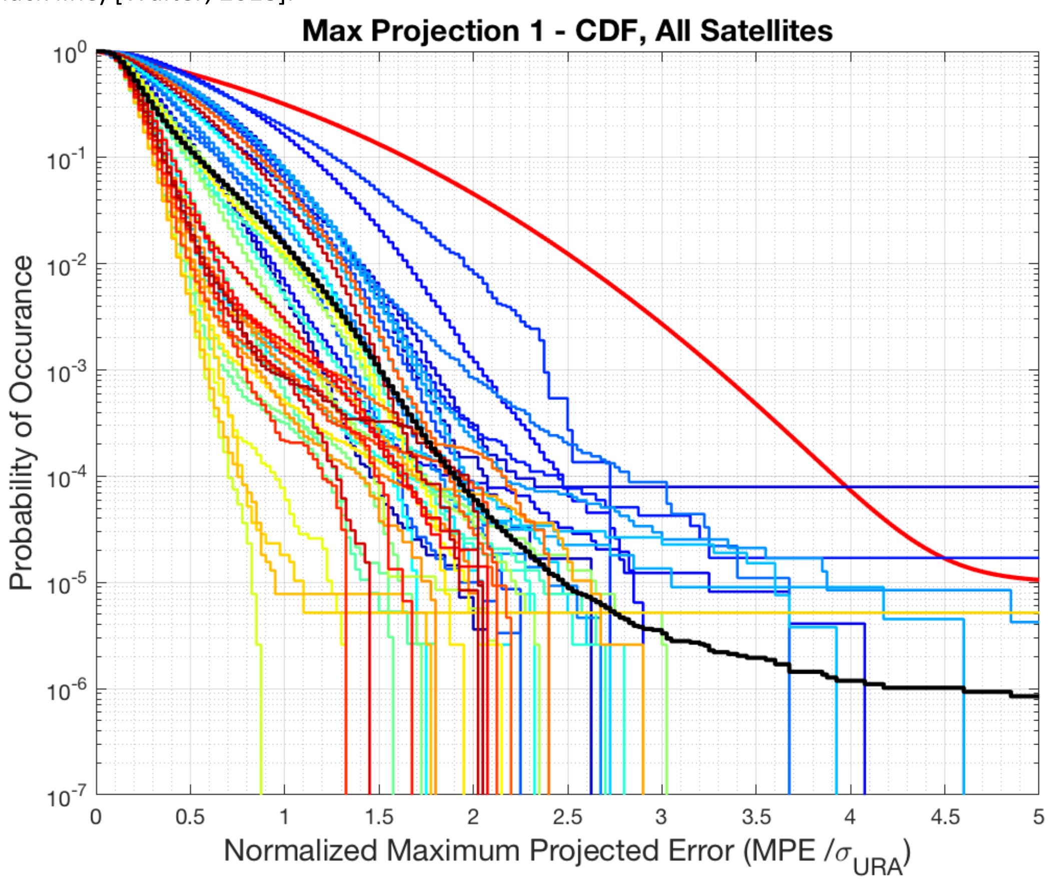

Figure 2 GPS SISRE by Satellite

Two of the satellites have lines that intersect the expected overbounding line from Figure 1. Although undesirable, such behavior is not unexpected as each individual satellite contains a limited amount of data and a single fault will make it impossible to remain below the desired line. However, such faults may have been equally likely to affect any satellite and there is no known reason that SVNs 25 and 30 were more likely to fault than the other satellites. Neither satellite suffered from multiple faults. It may be more reasonable to aggregate the data and use the average fault probability as shown by the heavy black line. This line is well below the red overbound and demonstrates a good match of the data to the proposed GPS ISM parameters (R_{sat} = 10^{-5}/hour, R_{const} = 10^{-8}/hour, α_{URE} = 1, α_{URA} = 1, b_{nom} = 0.75 m, and MTTN = 1 hour). However, there may be concern that not all of the satellites are of equivalent risk and that rather than averaging over all satellites, only satellites of like design should be aggregated.

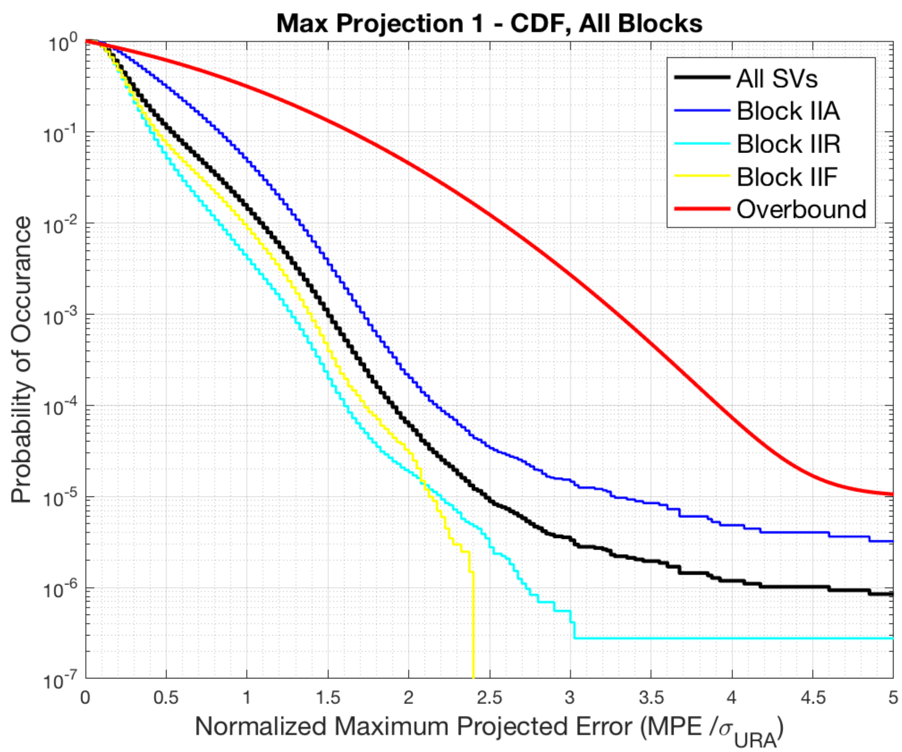

Figure 3 GPS SISRE by Block

Figure 3 groups the satellites by block type. There were three active designs over the period of evaluation. Block IIA, Block IIR, and Block IIF. These three groupings are shown in Figure 3 and all three types are below the red overbound line. It could be further argued that the Block IIA and Block IIF satellites should be further subdivided by clock type (cesium or rubidium). Although not shown here, these subtypes also fall below the red overbounding line.

Figure 4 shows data for one year (2018) for GLONASS[Walter, 2019]. Not all of the GLONASS ISM parameters have been set and due to limitations in the data archive formats we do not have access to the equivalent URA parameter F_T [Gunning, 2017] Therefore, we cannot evaluate α_{URE} or α_{URA}. Nor have we evaluated b_{nom} for GLONASS. However, GLONASS has provided preliminary values for their fault rates of R_{sat} = 10^{-4}/hour and R_{const} = 10^{-4} /hour [Kaplev, 2016]. We have further seen that their MTTN has significant year-to-year variability and is somewhat greater than 1-hour [Walter, 2019]. However, for this analysis we will treat it as though it is 1-hour.

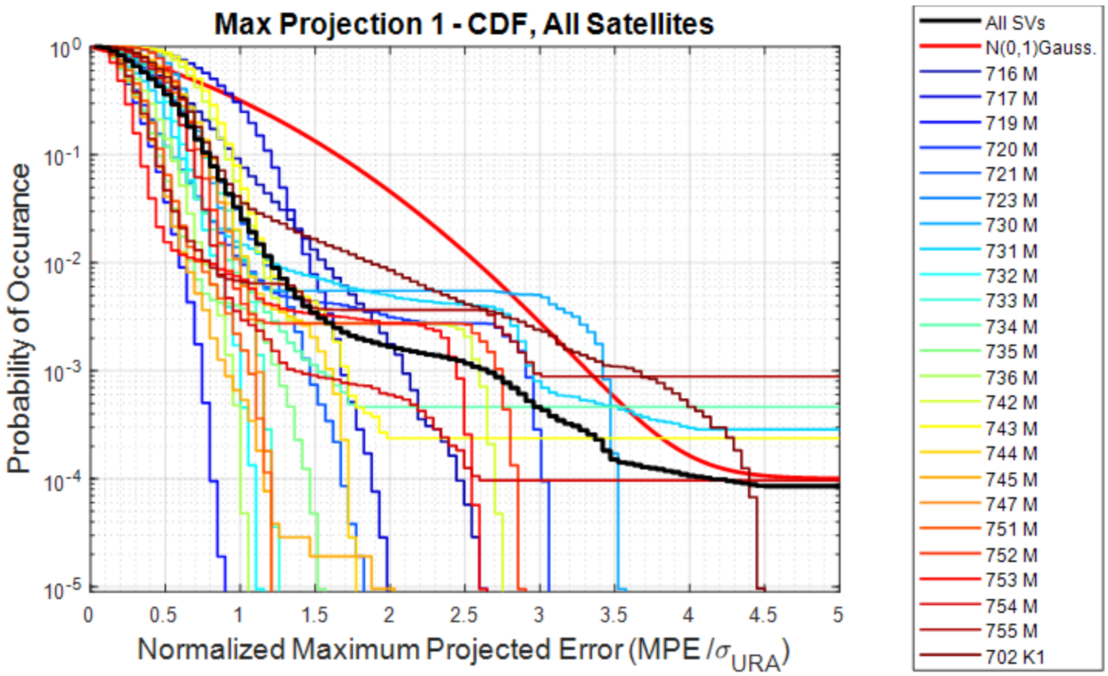

Figure 4 GLONASS SISRE by Satellite

Because we do not have access to their broadcast σ_{URA}, we have chosen it to be a fixed 7 m value throughout as this results in the aggregate data line coming close to but remaining below the red overbound line. This also results in five individual satellites exceeding the overbound line. In the data we have seen that satellites that fault once are more likely to fault again. Therefore, the use of the aggregate requires further investigation. This data analysis is not sufficient to verify the GLONASS parameters, but does indicate that the bounding values are likely not too far from these values.

Conclusions

The ISM parameters are derived from the CSP commitments. The parameters must also be validated through data analysis (as broadly outlined above). Using the CSP commitments provides a rationale to argue that past observations will be indicative of future performance. The parameters should be set very cautiously when dependent on behavior that goes beyond the commitments (e.g. using smaller values of P_{sat} or P_{const}). The data validation methodology should become internationally coordinated such that given the same data sets and ISM parameters, all interested parties would agree on whether or not they are consistent. There also needs to be agreement on how much margin should be required relative to the final ISM parameters. Such margin will likely be a function of constellation maturity. Assuming that the processes for interpreting commitments, analyzing historical data, and assessing required levels of margin can be internationally coordinated, it then becomes possible to agree on acceptable values of the ISM parameters for each constellation. Potential methods to address these issues are still under development. Future updates will focus on providing proposed methods.

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