An ARAIM Demonstrator

D. Salos, M. Mabilleau, *Egis Avia*
N. Dahman, *Airbus Deference and Space*
S. Feng, *Imperial College of London*
JP. Boyero, *European Commission*

Email: daniel.salos@egis.fr

BIOGRAPHIES

Daniel Salos received the M.S. degree in telecommunication engineering from the University of Saragossa (Spain) in 2006 and the Ph.D. degree from the University of Toulouse (France) in 2012. He works in the field of Global Satellite Navigation Systems (GNSS) since 2007 and on aircraft navigation activities since 2014. Daniel joined Egis Avia in 2014, where he has been involved in GNSS integrity monitoring activities, the development of a GBAS ionospheric threat model, EGNOS performance assessment as well as Performance Based Navigation (PBN) activities for the DSNA (the French Air Navigation Service Provider).

Mikael Mabilleau is the navigation services manager in Egis Avia. He is actively participating in activities of the main civil aviation standardisation bodies. He is involved in several projects looking at GNSS evolutions for civil aviation operations such as Advanced RAIM and dual frequency multi-constellation simulator prototypes for ABAS, SBAS and GBAS systems evolutions. He has acquired experience in the international development of GNSS through its involvement in the SAFIR project which has created the EGNOS/Africa Joint Programme Office in Dakar. His main fields of interest are GNSS standardisation and integrity monitoring concept for the mitigation of GNSS threats.

Nidhal Dahman received a postgraduate degree in Communication, Navigation, Surveillance and Satellite Application for Aviation from the ENAC (Ecole Nationale de l'Aviation Civile) in Toulouse. Before joining Airbus Defence and Space, he was a modelling and simulation engineer for Airbus. In this frame, he has contributed to the development of several functional simulators and has been involved in navigation system studies. In 2016, he has joined EGNOS V3 team as a system designer for the upcoming phase C/D ITT.

Shaojun Feng is a Senior Research Fellow at the Centre for Transport Studies within the Department of Civil and Environmental Engineering. He is the leader of positioning and navigation research group. Dr Feng's research interests are GNSS integrity, augmentation systems, high accuracy positioning, integrated navigation systems, Assisted GNSS, software receiver and telematics.

Juan Pablo Boyero is since 2012 working at the EC in the definition of the evolution of the Galileo and EGNOS missions. Before he worked within the Galileo System Performance area and acting both as System Prime as well as Technical Support to System Prime. He received a M.Sc. by the Escuela Técnica Superior de Ingenieros de Telecomunicación of the Universidad Politécnica de Madrid. He has passed the course on Safety Critical Systems by the University of Oxford, UK.

ABSTRACT

Receiver Autonomous Integrity Monitoring (RAIM) relies on GNSS measurement redundancy to provide positioning integrity. RAIM can benefit from future dual frequency multi-constellation (DFMC) GNSS. On that basis, the EU/US Working Group C (WGC) has recently developed the Advanced RAIM (ARAIM) concept, and has quantified its theoretical potential in terms of navigation performance. Such potential can in turn lead to operational and environmental benefits for the aviation community.

The WGC proposes a concept based on an Integrity Support Message (ISM) and a corresponding user algorithm designed to take benefit of the DFMC advantages. Different architectures have been proposed to provide integrity for en-route (Horizontal ARAIM) and precision approach operations (Vertical ARAIM) down to 200ft decision height.

The aviation community now foresees an evolution of the standards to account for the ARAIM technology, starting with H-ARAIM. For example, ICAO NSP, EUROCAE WG62 and RTCA SC 159 have included H-ARAIM in their respective work plans as part of their short term standard productions (between 2018 and 2020).

This paper introduces the overall project scope of activity of the ARAIM Demonstrator project launched by the European Commission and will further detail the design retained for the demonstrator, highlighting its capabilities as a tool for the ARAIM proof of concept. The

International Technical Symposium on Navigation and Timing (ITSNT) 2017
14-17 Nov 2017
ENAC, Toulouse, France

experimentation plan and logic will be presented. The algorithms to be implemented in the demonstrator will be detailed.

Results and lessons learnt throughout the project are expected to provide a major contribution to the preparation of the aviation standards, such as the ARAIM CONOPS, as well as to provide recommendations aimed at future ISM providers.

1 INTRODUCTION

The deployment of new dual-frequency GNSS constellations (modernized GPS, Galileo, GLONASS, Beidou) will support in the coming years aeronautical navigation services with an improved positioning performance and robustness thanks to an increased number of available satellites and signals in different frequency bands. GNSS augmentation systems will evolve to operate in this new dual-frequency multi-constellation (DFMC) environment. The definition and analysis of such system evolutions is an on-going activity.

Receiver Autonomous Integrity Monitoring (RAIM) is an Aircraft Based Augmentation System (ABAS) that relies on the redundancy of the different GNSS signals received by the user to provide integrity to the navigation solution. Current RAIM schemes are algorithms run within the user receiver, with GNSS measurements as their only input (other ABAS schemes can process additional inputs provided by other sensors on board of the aircraft such as the Inertial Measurement Unit, IMU). RAIM algorithms were designed decades ago to operate in a single-constellation, single-frequency environment. One of the consequences is that RAIM design relies in fixed parameters (for example, the probability of satellite fault is a constant value) and assumptions that may not hold in a DFMC scenario (for example, the probability of a constellation fault –multiple simultaneous satellite faults due to a common cause – is assumed to be negligible) [4].

Current RAIM algorithms cannot be used to operate in a DFMC mode. An evolution of current RAIM is needed in order to benefit from the next DFMC GNSS scenario. On that basis, the EU/US Working Group C (WGC) has developed the Advanced RAIM (ARAIM) concept, and has quantified its theoretical potential in terms of navigation performance [1][2][3]. Such potential can in turn lead to operational and environmental benefits for the aviation community.

The ARAIM concept proposed by the WGC has been designed to take benefit of the DFMC advantages and to overcome the limitations of current RAIM schemes. The new concept relies on a user algorithm which is able to monitor multiple constellations broadcasting in dual-frequency, and that is configurable via the so-called Integrity Support Message (ISM). As opposed to current ABAS solutions, the ARAIM system requires additional elements external to the aircraft to compute and transmit the ISM contents. The ARAIM user algorithm works with the iono-free code combination in the dual-frequency mode, which eliminates the first degree of the ionospheric delay, and considers the impact on the integrity budget of any combination of simultaneous faults. Faults can be narrow faults, affecting to individual satellites, or wide faults, where multiple satellites from a constellation are affected by a common error source.

The ISM allows configuring some design parameters of the user algorithm, such as the probability of an individual satellite fault and the probability of a constellation fault. The use of the ISM allows the user algorithm to adapt to the characteristics and evolutions of the different core GNSS constellations (for example after an improvement in a core GNSS constellation that reduces the probabilities of failure).

Different ARAIM architectures have been proposed to provide integrity for en-route (Horizontal ARAIM) and precision approach operations (Vertical ARAIM) down to 200ft decision height. The aviation community now foresees to include in their plans the evolution of the standards to account for the ARAIM technology, starting with H-ARAIM. For example, ICAO NSP, EUROCAE WG62 and RTCA SC 159 have included H-ARAIM in their respective work plans as part of their short term standard productions (between 2018 and 2020).

Under the Horizon 2020 R&D Programme, the European Commission launched, at the end of 2016, the first ARAIM prototyping project to develop an ARAIM Demonstrator and to conduct experiments in a multi-constellation dual-frequency environment, including tests with the real Galileo Signal In Space (tests will include real flights). The end results are intended to serve as proof of concept for ARAIM. The experimental results could be further used as validation material in the development of the corresponding standards, providing technical arguments on the design of the ground/airborne algorithms related to ARAIM implementation. The project is being developed by a consortium involving mainly European expert partners including as well US experts, which should facilitate the endorsement of results by the international community. Results and lessons learnt throughout the project are expected to provide a major contribution to the ARAIM adoption by the civil aviation community including preparation of aviation standards, development of the concept of operation and recommendations for future ISM service providers.

The ARAIM Demonstrator is an end to end tool which comprises both the ground segment as well as the user airborne algorithms. While the latter is well advanced – WGC has produced a reference user algorithm - the design of the different algorithms employed to monitor integrity at user level and to generate the ISM contents at ground level are still under discussion at WGC. The Concept of Operations (CONOPS) is also being drafted at the present by the EU/US WGC. For this reason the presented algorithms proposed to be implemented in the ARAIM demonstrator are based in the work made within WGC until present, but they may differ from the algorithms finally adopted for ARAIM in the future. The demonstrator is modular so it can be adapted easily to the evolutions of the ARAIM concept.

This paper introduces the overall scope of activity of the ARAIM demonstrator project and details further the architecture and algorithms selected for the demonstrator. Section 1 is the present introduction. Section 2 presents an overview of the ARAIM demonstrator project and section 3 provides an overview of the ARAIM demonstrator architecture. Finally, the high level description of the algorithms proposed to be implemented in the demonstrator are detailed in section 4 and section 5.

2 ARAIM DEMONSTRATOR PROJECT OVERVIEW

The ARAIM demonstrator project is structured in three main areas of activity. First, the ARAIM demonstrator architecture and algorithms are designed and developed. Afterwards, a set of experimentations is carried out with the demonstrator under different configurations in order to obtain meaningful results about the behaviour and performance of the ARAIM concept. The outcomes of these tests are the basis to finally derive operational recommendations to support the development and implementation of the ARAIM concept.

ARAIM Demonstrator Design and Implementation

The ARAIM demonstrator has been designed taking into account the latest work done within the WGC, including the different Milestone Reports [1][2][3]. The demonstrator, which is able to process either data coming from a GNSS receiver or from RINEX files, has been designed in a modular architecture that allows implementing future evolutions of the ARAIM concept by simply updating the corresponding module. The architecture, functional description and algorithms of the ARAIM demonstrator is explained in sections 3 and 4 of this paper.

Experimentations

Once the ARAIM demonstrator will be operational a set of experimentations will be carried out in order to obtain meaningful results to support the development of the ARAIM concept. The experimentations include tests with synthetic and real signals to analyse the behaviour and performance of the ARAIM system.

Experimentations with fault free synthetic signals will support the assessment of the ARAIM concept and the identification of the configurations of interest, while tests with faulty synthetic signals will allow the identification and analysis of GNSS threats as well as the validation of the integrity concept. Experimentations with fault free real signals will provide a performance assessment based on real data, including real flight tests. Finally, the tests with faulty real signals will contribute to consolidate the analysis of the ARAIM behaviour.

Operational Recommendations

The development of the ARAIM demonstrator will provide lessons learnt on the implementation of the different elements of the ARAIM concept, including the user algorithm and the ISM generation based on ground monitoring. The outcome of the experimentations will provide recommendations and some insight on the operational capability of the system.

Additionally a draft ARAIM Concept of Operations (CONOPS) has been developed in the framework of the project. This document is currently used in international standardisation fora as the initial document from which develop the ARAIM CONOPS.

3 ARAIM DEMONSTRATOR ARCHITECTURE OVERVIEW

The demonstrator has been designed following a modular architecture that allows implementing future evolutions of the ARAIM concept in a simply manner. The demonstrator has been developed in C++ language, which is key to modularity, thanks to an object-oriented approach for the definition of the computation modules, as well as for run-time performance.

The ARAIM demonstrator consists in two main modules, the simulation and the analysis module.

The simulation module simulates the end-to-end ARAIM chain, from the measurements at monitoring stations to ISM generation/broadcast and user processing. It provides a broad set of functionalities, including:

- Configuration of ground monitoring network, either using true data coming from reference monitoring stations or using synthetic data;
- Monitoring of constellations and ISM generation;
- Broadcast of the ISM;
- User processing;
- Storage of information processed for validation purposes.

The performance analysis module, developed in MATLAB, processes offline the raw outputs of the simulation module in order to characterize intermediary system parameters and end-user results and variables. The analysis module produces outputs interpretable by the demonstrator operator for system performance assessment, such as availability maps for different aviation operations or the temporal evolution of ISM parameters.

4 USER ALGORITHMS

The ARAIM demonstrator will implement two versions of the user algorithm developed within WGC. The first one is described in Annex A of WGC Milestone III Report [3], which is a Multiple Hypothesis Solution Separation (MHSS) solution adapted to the DFMC environment and with tuneable parameters provided by the ISM. The second version that will be implemented is a latest evolution of the above which optimizes the selection of the failure modes (i.e. combination of simultaneous faults) to be monitored and includes the Fault Detection and Exclusion (FDE) function [5].

5 GROUND ALGORITHM

5.1 ISM generation process overview

ARAIM user algorithm is configurable via the Integrity Support Message (ISM). The ISM contains parameters such as a mask indicating the monitored satellites, the probability of constellation fault at a given time $(P_{const,j})$, the probability of satellite fault at a given time $(P_{sat,i,j})$, a multiplier factor of the $\sigma^*_{URA,i,j}$ received from broadcast messages for integrity purposes $(\alpha_{URA,i,j})$ and a bound of the nominal bias $(b_{nom,i,j})$. The notation of the different parameters uses subscript j for constellations and subscript i for satellites.

ISM contents are expected to remain unchanged during relatively long periods of time for horizontal navigation purposes (H-ARAIM) and during shorter periods of time for vertical navigation purposes (V-ARAIM). The ISM update rate for each operation still needs to be assessed, but it is expected to be in the order of several days for H-ARAIM and hours for V-ARAIM. The transmission method for disseminating the ISM to the users considers various options. Possible dissemination methods include implementing the ISM in the aircraft aviation database or transmitting it within GNSS SiS.

The ARAIM system monitors the performance of GNSS SiS, verifies the validity of broadcast ISM parameters and generates updated ISM if necessary.

The ISM generation scheme implemented in the demonstrator estimates first the orbit and clock errors for each monitored satellite by comparing the satellite position and clock obtained from broadcast ephemeris against a precise "truth" reference. Afterwards the impact of the satellite orbit and clock errors at the user level is obtained as the maximum error projection over the satellite's footprint. Then, a database containing the maximum error projections during a given period of time is created for each satellite. Finally these sets of data are analysed and characterized in order to estimate the different ISM parameters (Figure 1). This processing is performed offline.

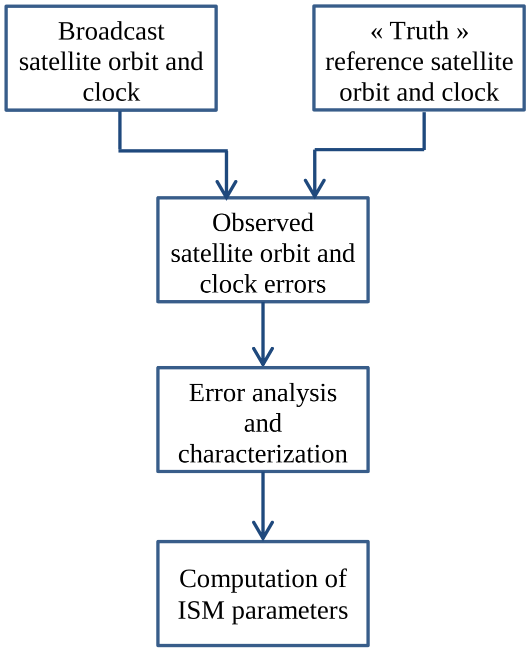

Figure 1 – ARAIM monitoring scheme implemented in the demonstrator

The next subsections detail the different steps of the ISM generation process.

5.2 "Truth" reference satellite orbit and clock

One of the key elements of the ARAIM monitoring system is the determination of the "truth" orbit and clock for each monitored satellite, since it is responsible for the quality of the estimation of the errors used to generate the ISM parameters. The ARAIM demonstrator will implement two solutions.

The first implemented solution, widely used in ARAIM related work, consists in using as "truth" reference the orbit and clock information provided in Standard Product #3 (SP3) format by recognized organizations like the International GNSS Service (IGS). SP3 products provide very precise offline data with orbit errors as low as 2.5 cm and clock errors of 20 ps standard deviation.

The broadcast navigation signals are referred to the satellite's antenna phase center (APC), but the precise satellite orbits in SP3 format are usually referred to the satellite Centre of Mass (CoM). The translation from CoM to APC is done applying the phase center offset information provided for each satellite in the ANTEX product. Note that some organizations provide precise GPS orbit and clock directly referred to the APC, so that the previous translation is not required. However, the provision of SP3 files for other core constellations is at a lower maturity stage and they are provided referred to the CoM.

The computation process used to obtain SP3 data depends on the organisation computing them. It would be of interest for the ARAIM system to have full control of the computation process of the "truth" orbit and clock, in particular during the presence of satellite or constellation faults to assure that those faulty behaviours are correctly captured.

The ARAIM demonstrator will implement a second ground algorithm that estimates the satellite position using measurements made by a station network. This algorithm is intended to be based on an ephemeris-based model [6]. The model will follow that of the GPS broadcast messages.

5.3 Satellite orbit and clock error vector

Once the broadcast and "truth" reference orbit has been obtained, the orbit error vector is obtained at each epoch as follows:

$$\Delta S_i = S_{i,b} - S_{i,r} \quad (1)$$

Where $S_{i,b}$ and $S_{i,r}$ are the broadcast and reference satellite position (in ECEF coordinates) or satellite. The broadcast satellite clock error is estimated directly for each satellite. .

5.4 Determination of the error projection

The same satellite orbit and clock error ΔS_i will have a different impact on the user depending on the relative position between the user and the orbit error vector.

The projection of the satellite orbit and clock error into the direction of a user represents the Instantaneous Signal-In-Space (SIS) User Range Error (URE), also known as IURE. It is defined as the error component of the pseudorange measurement at a given location and at a given epoch, caused only by the error budget components assigned to the Space and Control Segments [7]. The analysis of observed IURE is the base of the ARAIM ground monitoring to detect faults, characterize the nominal error distributions and finally compute ISM parameters.

There are different methods to obtain representative error projections for a given satellite at each epoch. One of them consists in projecting the error into a set of users distributed over the Earth's surface to obtain a set of projections per epoch. Another method consists in calculating the projection at the Worst User Location (WUL), which is the error projection with the maximum magnitude within the satellite's footprint. Both methods are suited to characterize the IURE distribution tails [8], and therefore applicable to ARAIM. The ARAIM demonstrator will implement the WUL IURE projection for the detection of SiS faults, and the error projection over a set of user locations over the satellite footprint to characterize the SiS error distribution - User Range Accuracy (URA) and nominal bias.

Determination of the Worst User Location IURE

The WUL IURE can be computed analytically. The IURE for satellite i is the result of the sum of two components: the orbit error projection ($\mathrm{IURE_o}$) and the clock error ($\Delta \mathrm{b}$). Any user within the footprint of satellite i receives measurements impacted by the exact same clock error. However, the impact of orbit errors at a user location depends on the three-dimensional orbit error vector direction and on the relative positions of user and satellite i.

Depending on the sign of the IURE orbit and clock components, they may tend to add or to cancel each other. In order to take into account this effect, the ARAIM demonstrator computes first the maximum and the minimum orbit error projections $(\mathrm{IURE_{o,max}}\ , \mathrm{IURE_{o,min}})$, adds the clock error $\Delta \mathrm{b}$ to both of them and takes as WUL IURE the result with the largest magnitude.

Satellite orbit errors can be divided in a radial component ($\vec{R}$) in the direction defined by the satellite position and the center of the Earth, and a horizontal component ($\vec{H}$) orthogonal to the radial component [7]. The $\mathrm{IURE_o}$component due to the horizontal orbit error component ($\vec{H}$) has a sinusoidal variation across the satellite's footprint depending on the look angle θ, defined as the angle defined by the direction satellite-user and the radial vector from the satellite towards the center of the Earth [7]. The maximum and minimum values $|H| \times sin(\theta_{max})$ and $-|H| \times sin(\theta_{max})$ are obtained respectively in the plane defined by the orbit error vector and the centre of the Earth. θ_{max} is the maximum angle of the satellite's footprint with respect to the radial vector (13.88° for GPS). The $\mathrm{IURE_o}$component due to the radial orbit error ($\vec{R}$) has a cosinusoidal variation across the coverage footprint depending on the look angle θ. The maximum value equal to |R| is obtained in the radial direction and it decreases until a minimum of $|R| \times cos(\theta_{max})$ at the footprint limits. Since the total orbit error projection $\mathrm{IURE_o}$ is the sum of the horizontal and vertical components, its maximum and minimum values will be contained in the plane defined by the orbit error vector and the center of the Earth. That plane was denoted as "Worst Case Plane" and used to obtain the maximum orbit error projection in [9].

To obtain the WUL IURE, the maximum and minimum orbit error projections are first obtained analytically as a function of the angle between the radial vector and the orbit error. Afterwards the orbit component of the WUL IURE is the one that maximises the magnitude of the total IURE after adding the clock error. Finally, the normalized WUL IURE is then computed dividing the WUL IURE by the broadcast URA for that satellite.

5.5 Estimation of ISM parameters: $\alpha_{\mathrm{URA,i}}$ and $\mathbf{b_{nom,i}}$

The demonstrator determines the ISM parameters $\alpha_{\mathrm{URA,i,j}}$ and $\mathrm{b_{nom,i,j}}$ with the following steps:

1) Compute and store the IURE at user locations over the satellite footprint (including WUL IURE) for each satellite i in constellation j $\left(IURE_{i,j}\right)$ and its normalised value $\left(\overline{IURE}_{i,j} = IURE_{i,j}/\sigma_{URA,i,j^*}\right)$;
2) Create data sets;
3) Process each data set:
   3.1) Compute the mean of all stored values of $\mathrm{IURE_{i,j}}$ to obtain the nominal bias term in metres for each satellite i in constellation j $\left(\mathrm{b_{nom,i,j}}\right)$;
   3.2) Compute the mean of all stored values of $\overline{\mathrm{IURE}}_{\mathrm{i,j}}$ to obtain the normalised nominal bias term for each satellite i in constellation $\left(\bar{\mathrm{b}}_{\mathrm{nom,i,j}}\right)$;
   3.3) Compute the normalised, zero-mean IURE data set $\left(\overline{\mathrm{IURE}}_{\mathrm{i,j,\mu 0}} = \overline{\mathrm{IURE}}_{\mathrm{i,j}} - \bar{\mathrm{b}}_{\mathrm{nom,i,j}}\right)$;
   3.4) CDF overbounding of the tails of $\overline{\mathrm{IURE}}_{\mathrm{i,j,\mu 0}}$ to obtain $\alpha_{\mathrm{URA,i,j}}$.

First, the IURE for each monitored satellite is computed (at a set of locations over the satellite's footprint).

Afterwards, the stored values of IURE are grouped to create data sets that are processed individually to obtain $\alpha_{\mathrm{URA,i,j}}$ and $\mathrm{b_{nom,i,j}}$.The estimated values of $\alpha_{\mathrm{URA,i,j}}$ and $\mathrm{b_{nom,i,j}}$ depend on how the data sets have been defined. Since the traditional approximation for the URE ergodic period is 30 days under a one-upload-per-day scenario [7], the demonstrator creates 1-month datasets for each satellite. This allows updating monthly $\alpha_{\mathrm{URA,i,j}}$ and $\mathrm{b_{nom,i,j}}$ for each satellite.

Nominal errors are expected to be characterized by a Gaussian with a nominal bias. The nominal bias is estimated as the mean value of the data set:

$$b_{nom,i,j} = \frac{1}{N}\sum IURE_{i,j} \tag{2}$$

The normalized nominal bias is computed equivalently as the mean of the normalized data set.

Then, a zero-mean normalized data set is obtained subtracting the normalized bias to the normalized data set. This data set is overbounded with the CDF technique. Core values in the distribution between $[-1\sigma, 1\sigma]$ will not be considered in the overbounding process to avoid issues linked to the CDF overbounding technique [8].

The CDF overbounding is done with the Q-Q (Quantile-Quantile) plot of a zero-mean unitary Normal distribution $N(0,1)$ against the IURE distribution. and visualise the CDF overbounding of the tails. A point (x, y) on this Q-Q plot corresponds to one of the quantiles of the normalized IURE distribution $\left(Q_{p,IURE}\right)$ on the y-coordinate plotted against the same quantile of the $N(0,1)$ distribution $\left(Q_{p,N(0,1)}\right)$ on the x-coordinate.

The inverse CDF of a zero-mean normal distribution with variance σ^2 at a percentile p is:

$$\mathrm{CDF}^{-1}_{\mathrm{N}(0,\sigma^2)} = \sigma \times \Phi^{-1}(\mathrm{p}) \tag{3}$$

Therefore in a Q-Q plot where the x-axis represents a normal distribution $N(0,1)$, zero-mean normal distributions $N(0,\sigma^2)$ are represented by straight lines defined by the x-y coordinates $\{\Phi^{-1}(p), \sigma \times \Phi^{-1}(p)\}$. That is, straight lines crossing the origin, with an angle φ with respect to the x-axis that depends on their standard deviation σ:

$$\varphi = atan\left(\frac{\sigma \times \Phi^{-1}(p)}{\Phi^{-1}(p)}\right) = atan(\sigma) \tag{4}$$

We need to find the minimum standard deviation σ_{ov} that overbounds the tails of IURE. This corresponds to a distribution $\mathrm{N}(0, \sigma_{\mathrm{ov}}^2)$ which Q-Q plot passes through a point of the IURE Q-Q plot $\left(\mathrm{Q_{p,N(0,1)}}, \mathrm{Q_{p,IURE}}\right)$ in the interval $\mathrm{Q_{p,N(0,1)}} \in [-4.42, -1]$ or $\mathrm{Q_{p,N(0,1)}} \in [1, 4.42]$, and still meets the requirements for CDF overbounding of the IURE tails:

- $Q_{p,IURE} \geq Q_{p,N(0,\sigma_{ov}^2)}$
  for all p such that $Q_{p,N(0,1)} \in [-4.42, -1]$, and
- $Q_{p,IURE} \leq Q_{p,N(0,\sigma_{ov}^2)}$
  for all p such that $Q_{p,N(0,1)} \in [1, 4.42]$

Therefore the standard deviation of the overbounding Gaussian distribution is obtained as follows:

$$\sigma_{ov} = min\left(\frac{Q_{p,IURE}}{Q_{p,N(0,1)}}\right) \tag{5}$$

Where $Q_{p,IURE}$ and $Q_{p,N(0,1)}$ are the p-quantile of the zero-mean normalized IURE dataset and the zero-mean unitary Gaussian function respectively.

Finally the $\alpha_{\mathrm{URA,i,j}}$ corresponds to σ_{ov}.

$$\alpha_{\mathrm{URA,i,j}} = \sigma_{ov} \tag{6}$$

5.6 Estimation of ISM parameters: $\mathbf{P_{sat,i,j}}$ and $\mathbf{P_{const,j}}$

The demonstrator determines the ISM parameters $\mathrm{P_{sat,i,j}}$ and $\mathrm{P_{const,j}}$ with the following steps:

1) Compute and store the WUL IURE for each satellite i in constellation j $\left(IURE_{WUL,i,j}\right)$;
2) Determine if an SIS fault state exists on each satellite i in constellation j at each epoch.
3) Obtain $\mathrm{P_{sat,i,j}}$ and $\mathrm{P_{const,j}}$ from the outputs of the fault state detector.

First, the WUL IURE for each monitored satellite is computed as explained in the previous subsection.

Afterwards the demonstrator detects the presence of a fault state for each satellite at each epoch. An SIS fault state exists on a healthy satellite i in constellation j when the magnitude of the instantaneous SIS ranging error at the worst user location is greater than $4.42 \times \sigma_{URA,i,j}$. Note that this fault threshold originally defined for GPS [7] is adopted in ARAIM for Galileo or other monitored constellations [3].

The outcomes of the fault state detector are collected for a given period of time and processed to obtain $P_{sat,i,j}$ (expressed in probability per epoch). $P_{sat,i,j}$ is computed with two methods. The first one determines $P_{sat,i,j}$ as the ratio between the total number of epochs in which a fault state has been detected for a satellite and the total number of epochs observed. The second method groups consecutive fault state epochs in a single fault and computes the fault rate R (expressed in probability per hour) and the mean duration of the faults $MTTN$ (mean time to notification). Then $P_{sat,i,j}$ is the product of R and $MTTN$.

The computation of $P_{sat,i,j}$ depends on the observation period T. The demonstrator evaluates multiple observation periods (6, 12, 18, 24, 30, and 36 months).

The demonstrator determines $P_{const,j}$ considering a wide fault occurs in constellation j whenever there are two or more simultaneous satellite faults on that constellation. In the final implementation of an ARAIM system, an ISM Provider would need to assess (for example in coordination with core constellation providers) case by case that simultaneous satellite faults have been originated by a common cause before accounting them in the constellation fault probability.

6 CONCLUSIONS

The overall scope of activity of the ARAIM Demonstrator project launched under the Horizon 2020 Framework Programme by the European Commission as a proof of concept has been presented. The project comprises the design and development of an end to end ARAIM Demonstrator, an experimentation phase under different system configurations with fault-free and faulty signals and with synthetic and real signals (including real flights), and the derivation of recommendations and lessons learnt for the implementation of the ARAIM concept.

The overall design of the demonstrator has been presented. In particular its modular architecture allows adapting the prototype to future evolutions of the ARAIM concept by updating the corresponding module.

Finally the user and ground algorithms proposed for implementation in the demonstrator have been detailed. These algorithms are in line with those proposed by the EU/US Working Group C (WGC). However, the definition of the ARAIM design is still an on-going activity so the selected algorithms may be different to the ones adopted for ARAIM in the future.

ACKNOWLEDGMENTS

The authors would like to thank the involvement and support of Mathieu Joerger and Boris Pervan from Trunav, of Philippe Estival from DSNA, and Washington Ochieng from Imperial College.

REFERENCES

[1] “Interim Report”, EU-US. Cooperation on Satellite Navigation Working Group C - ARAIM Technical Subgroup, 19 Dec. 2012

[2] “Milestone 2 Report”, EU-US. Cooperation on Satellite Navigation Working Group C - ARAIM Technical Subgroup, 11 Feb. 2015

[3] “Milestone 3 Report”, EU-US. Cooperation on Satellite Navigation Working Group C - ARAIM Technical Subgroup, 25 Feb. 2016

[4] “Minimum Operational Performance Standards (MOPS) for Global Positioning System (GPS) / Aircraft Based Augmentation System (ABAS) Airborne Equipment”, RTCA DO-316, 14 April 2009.

[5] WG-C Advanced RAIM Technical Subgroup Reference Airborne Algorithm Description Document, Version 2.0, Oct. 2016

[6] Mathieu Joerger, Yawei Zhai, and Boris Pervan, “Online Monitor Against Clock and Orbit Ephemeris Faults in ARAIM”, Proceedings of the ION 2015 Pacific PNT Meeting Marriott Waikiki Beach Resort & Spa Honolulu, Hawaii, April 2015

[7] GPS Standard Positioning Service (SPS) Performance Standard, 4th Edition, 2008

[8] “KEYNOTE - Validation of the Unfaulted Error Bounds for ARAIM”; T. Walter, K. Gunning, J. Blanch; Proceedings of the ION 2017 Pacific PNT Meeting, Honolulu, Hawaii, May 2017, pp. 1-19.

[9] "URA/SISA Analysis for GPS-Galileo ARAIM Integrity Support Message"; S. Perea, M. Meurer, M. Rippl, B. Belabbas, M. Joerger, B. Pervan; Proceedings of the 28th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2015), Tampa, Florida, September 2015, pp. 735-745.