

Examples of User Algorithms implementing ARAIM techniques for integrity performance prediction, procedures development and pre-flight operations

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Abstract— Advanced Receiver Autonomous Integrity Monitoring (ARAIM) is a new Aircraft Based Augmentation System (ABAS) technique, firstly presented in the two reports of the GNSS Evolutionary Architecture Study (GEAS). The ARAIM technique offers the opportunity to enable GNSS receivers to serve as a primary means of navigation, worldwide, for precision approach down to LPV-200 operation, while at the same time potentially reducing the support which has to be provided by Ground and Satellite Based Augmented Systems (GBAS and SBAS).

ARAIM is based on the Solution Separation Method and implements other techniques, such as:

- Frequency diversity, using dual-frequency measurements.
- Geometry diversity, using multi-constellation configurations, combining the available satellites from the new and renewed constellations (GPS, Galileo and GLONASS, but potentially Beidou too).
- Integrity Support Message, describing both the nominal error behavior and the probability of fault of one or more satellites.

Previous work analysed ARAIM performance, clearly showing the potential of this new architectures to provide the Required Navigation Performance for LPV 200. However, almost all of the studies have been performed with respect to fixed points on a grid on the Earth's surface, with full view of the sky, evaluating ARAIM performance from a geometrical point of view and using nominal performance in simulated scenarios which last several days. Though, the operational configuration was not examined; attitude changes from manoeuvres, obscuration by the aircraft body and shadowing from the surrounding environment could all affect the incoming signal from the GNSS constellations, leading to configurations that could adversely affect the real performance. In [8] we presented the ARAIM performance in simulated operational configurations. The results showed that the aircraft attitude and the surrounding environment affect the performance of the ARAIM algorithm; each satellite lost generates a peak in the performance parameters that depends on the total number of satellites in view, their relative geometry and on the number of satellites lost at the same time. The main outcome of this research is the identification that the ideal scenario would be to have a tri-

constellation system that provides at the same time high redundancy, reliability and increased safety margin.

In this paper, we summarise and continue the work performed in our project. In our research we developed four different algorithms that integrate the ARAIM technique for performance prediction analysis. These algorithms could usefully be implemented:

- In the design of instrument approach procedures. The algorithms could be used to improve the procedure of the development of new instrument approaches, reducing time, effort and costs.
- In the aircraft Flight Management Systems. The algorithms could support the pilots in the pre-flight briefing, highlighting possible integrity outage in advance and allowing them to select a different approach or making them aware of the need to utilise additional positioning systems.

Increased awareness and better pre-flight planning could ultimately improve the safety of flights and contribute to the safe introduction of GNSS as a viable positioning method for instrument approach.

Keywords— *Advanced Receiver Autonomous Integrity Monitoring (ARAIM); Global Navigation Satellite System (GNSS); performance prediction; aircraft trajectory; shadowing; operational research; optimization; User Algorithm.*

I. INTRODUCTION

In 2000, the FAA formed the GEAS panel to investigate new GNSS-based architectures with a focus on precision approach down to LPV-200 operations. In the first [2] and second [3] report, the GEAS identified ARAIM (Advanced RAIM) as the most promising system because it could reduce the cost of ground infrastructure and eliminate single points of failure (e.g. interference at the monitoring station). In these documents, the GEAS also defined the possible architecture, made assumptions and suggestions related to the Ground Monitoring requirements, the data link and the information that should be provided through the integrity message, the so-called Integrity Support Message (ISM). Moreover, it clearly stated

the necessary performance requirements that ARAIM systems must satisfy to support LPV-200 capabilities;

The EU/US Working Group C (WG-C) established a technical sub-group, for which the main objective was to define a reference multi-constellation ARAIM concept that allows vertical guidance worldwide. The outcome of this subgroup is the report [4] that fully describes a preliminary multi-constellation ARAIM algorithm based on the Multiple Hypothesis Solution Separation method. This was one of the first algorithms to implement multi-constellation RAIM with the possibility of multiple simultaneous failures across the constellations, presented in [5] and also used in [6], [7] and in [9], in which the authors developed an ARAIM algorithm with real-time dual frequency L1-L2 GPS flight data.

In [10], the Working Group C describes the proposed Implementation Roadmap for ARAIM Services, the consideration of institutional issues and their discussion, as well as the elaborated view of ARAIM complementing the services provided by SBAS systems.

In our research, we investigated different approaches to the integration of an ARAIM algorithm for integrity performance prediction, procedures development and pre-flight operations that may increase awareness and improve pre-flight planning, ultimately enhancing the safety of flights and contributing to the safe introduction of GNSS as a viable positioning method for instrument approach. This paper reports on the main outcomes and results of our research project.

In the next chapter, we briefly introduce the ARAIM algorithm and the open source tool developed by Stanford University, the Matlab Algorithm Availability Simulation Tool (MAAST), that has been selected as the base for our developed tools and modified to meet the demands of our research.

Section III briefly revisits the results presented in [8] with the ARAIM Performance on Predicted Aircraft Trajectory Tool Short-Term version (APPATT ST), designed to assist pilots in the pre-flight operations.

Section IV introduces two algorithms constructed to support designers in the development of new procedures, the APPATT Long-Term version (APPATT LT) and the Flight Path Generator and Modifier (FPGM).

Section V describes the implementation of ARAIM prediction capability as a new avionics system for near real-time performance prediction.

Conclusions and considerations are then discussed in the last chapter.

II. ARAIM AND MAAST

In this section the ARAIM algorithm and MAAST, which was developed by Stanford University, will be briefly described, for further details please refer to [11] and [12]:

A. Advanced Receiver Autonomous Integrity Monitoring (ARAIM) Algorithm

The following section explains the ARAIM algorithm functions used in this research, other functions, such as the

Chi-Square test, the fault detection and exclusion or the computation of the integrity and accuracy after the detection of a fault, are not considered, since the main purpose of this research is to analyse the algorithm performance in nominal conditions and evaluate the influence of other factors that might reduce the reliability of the system. The main functions of the algorithm can be easily summarised in the following steps:

- *Covariance Matrices.* The first step of the ARAIM algorithm is the computation of the Covariance Matrices for the two error models (C_{int} for integrity and C_{acc} for accuracy model) using the signal errors and biases characterisation of each satellite:

$$C_{\text{int}}(i,i) = \sigma_{\text{URA},i}^2 + \sigma_{\text{tropo},i}^2 + \sigma_{\text{user},i}^2 \quad (1)$$

$$C_{\text{acc}}(i,i) = \sigma_{\text{URE},i}^2 + \sigma_{\text{tropo},i}^2 + \sigma_{\text{user},i}^2 \quad (2)$$

Where:

TABLE I. DEFINITIONS

Name	Description
$\sigma_{\text{URA},i}$	standard deviation of the clock and ephemeris error of satellite i used for integrity
$\sigma_{\text{URE},i}$	standard deviation of the clock and ephemeris error of satellite i used for accuracy and continuity
$\sigma_{\text{tropo},i}$	Tropospheric delay of satellite i , function of its elevation angle
$\sigma_{\text{user},i}$	User contribution to the error budget function of satellite i elevation angle

- *Computation of All-in-view Position Solution.* Using a weighted least-squares estimation:

$$\Delta x = (G^T W G)^{-1} G^T W \Delta PR \quad (3)$$

Where:

TABLE II. DEFINITIONS

Name	Description
Δx	Corrections of the receiver position and clock states
G	Geometry Matrix in East North Up coordinates with a clock component for each constellation
W	Weighting matrix defined as C_{int}^{-1}
ΔPR	Vector of pseudorange measurements minus the expected ranging values based on the location of the satellites and the position solution given by the previous iteration

- *Determination of the faults that need to be monitored.* Each satellite and constellation is characterised by a probability of failure; the algorithm evaluates the maximum number of simultaneous satellites or constellation faults that need to be considered through the computation of the probability of all the possible

subsets. The subset probabilities that exceed a predefined threshold need to be monitored.

- *Fault-tolerant positions and associated standard deviation and biases.* For each of the k subsets the algorithm computes the position solution $x^{(k)}$, evaluates the differences with the all-in-view position solution $x^{(0)}$ and determines the standard deviations and the test thresholds.

$$\Delta x^{(k)} = x^{(k)} - x^{(0)} = (S^{(k)} - S^{(0)})y \quad (4)$$

Where

$$S^{(k)} = (G^T W^{(k)} G)^{-1} G^T W^{(k)} \quad (5)$$

y : vector of pseudorange measurements minus the expected range for an all-in-view position.

The variances of $x^{(k)}_q$ (where index $q = 1, 2$ and 3 designate the East, North and Up components respectively) are given by:

$$\sigma^{(k)2}_q = (G^T W^{(k)} G)^{-1}_{q,q} \quad (6)$$

The nominal biases of the position solutions $x^{(k)}_q$ are given by:

$$b^{(k)}_q = \sum_i |S^{(k)}_{q,i}| b_{\text{nom},i} \quad (7)$$

The variances of the differences $\Delta x^{(k)}_q$ are given by:

$$\sigma^{(k)2}_{ss,q} = e_q^T (S^{(k)} - S^{(0)}) C_{\text{acc}} (S^{(k)} - S^{(0)})^T e_q \quad (8)$$

in which e_q denotes a vector whose q th entry is one and all others are zero

- *Solution Separation Threshold.* Each fault mode has three solution separation threshold tests, one for each coordinate. These are defined by:

$$T_{k,q} = K_{fa,q} \sigma^{(k)}_{ss,q} \quad (9)$$

Where:

$$K_{fa,1} = K_{fa,2} = Q^{-1}(P_{FA_HOR}/4 N_{\text{fault modes}}) \quad (10)$$

$$K_{fa,3} = Q^{-1}(P_{FA_VERT}/2 N_{\text{fault modes}}) \quad (11)$$

$Q^{-1}(p)$: the (1-p)-quantile of a zero-mean unit-variance Gaussian distribution

P_{FA} : continuity budget allocated to disruptions due to false alert (distributed to the Vertical and Horizontals components).

The Protection Levels can be computed only if the following relation is valid for all k and q :

$$\tau_{k,q} = |x^{(k)}_q - x^{(0)}_q| / T_{k,q} \leq 1 \quad (12)$$

If any of the tests fails, in the full version, the algorithm must attempt the exclusion of the fault.

- *Computation of the Protection Levels (PL).* Vertical Protection Level (VPL) and Horizontal Protection Levels (HPL) are the solutions of the following equations:

$$\begin{aligned} & 2Q((VPL - b^{(0)}_3)/\sigma^{(0)}_3) + \sum_k P_{\text{fault},k} Q((VPL - T_{k,3} - b^{(k)}_3)/\sigma^{(0)}_3) \\ & = PHMI_{\text{VERT}} (1 - (P_{\text{sat,not monitored}} + P_{\text{const,not monitored}}) \\ & / (PHMI_{\text{VERT}} + PHMI_{\text{HOR}})) \end{aligned} \quad (13)$$

$$\begin{aligned} & 2Q((HPL - b^{(0)}_q)/\sigma^{(0)}_q) + \sum_k P_{\text{fault},k} Q((HPL - T_{k,q} - b^{(k)}_q)/\sigma^{(0)}_q) \\ & = 1/2 PHMI_{\text{HOR}} (1 - (P_{\text{sat,not monitored}} + P_{\text{const,not monitored}}) \\ & / (PHMI_{\text{VERT}} + PHMI_{\text{HOR}})) \end{aligned} \quad (14)$$

with $q = 1$ and 2 for HPL_q . The final HPL is given by:

$$HPL = (HPL_1 + HPL_2)^{1/2} \quad (15)$$

Where:

$PHMI$: total integrity budget, shared between the HPL and VPL .

$P_{\text{sat/const,not monitored}}$: removes from the PHMI budget the probability of the unmonitored fault modes.

$P_{\text{fault},k}$: prior probability of fault in satellite k per approach

- *Accuracy, Fault-free position error bound and effective monitor threshold.* Finally, the other two parameters are computed: the accuracy (Equation 16) and the Effective Monitoring Threshold (Equation 17).

$$\sigma_{q,\text{acc}} = (e_q^T S^{(0)}) C_{\text{acc}} S^{(0)T} e_q)^{1/2} \quad (16)$$

$$\text{EMT} = \max_k (T_{k,3}) \quad (17)$$

B. The Matlab Algorithm Availability Simulation Tool (MAAST)

MAAST is a set of Matlab functions developed by the University of Stanford for SBAS, RAIM and ARAIM availability analysis that is intended for use as a fast, accurate and highly customizable experimental testbed for algorithm development. The tool is open source and the original version and its related guides can be downloaded from the University

of Stanford website [13]. The University of Stanford has also developed the ARAIM algorithm used in MAAST and it is based on the published papers [12].

The MAAST has the main objective of computing the four parameter indices of the reliability of the navigation solution provided by GNSS; these parameters are:

- The Horizontal Protection Level (HPL),
- The Vertical Protection Level (VPL),
- The Accuracy
- The Effective Monitoring Threshold (EMT).

The tool takes as input:

- A map of the area of interest and density of the points to be analysed
- The YUMA Almanac files. These contain the orbital parameters for each satellite of the constellation (GPS/Galileo/GLONASS). GPS YUMA almanacs are downloaded from the CelesTrak website [14], which in turn are obtained from the US Coast Guard Navigation Center [15]. Galileo and GLONASS YUMA almanacs are provided with the MAAST and are based on the nominal constellation orbits.
- The Required Navigation Performance (RNP). In order to use GNSS as the primary source for navigation in aviation, stringent requirements have to be met: the so-called Required Navigation Performance (RNP) for civil aviation, a concept endorsed by the ICAO and explained in [16] and [17]. RNP is specified for the different flight phases in terms of the four parameters: accuracy, integrity, continuity of service and availability, and the key characteristics are summarized in Table III and Table IV.

TABLE IV. REQUIRED NAVIGATION PERFORMANCE [18]

Operation	Max Probabilities of Failure		Availability
	Integrity (1-risk)	Continuity (1-risk)	
Oceanic, En-route	10 ⁻⁷ /hr	10 ⁻⁴ /hr	10 ⁻² to 10 ⁻⁵
Terminal, NPA			
LNAV/VNAV			
LPV			
APV I			
APV II			
LPV-200			
CAT I			
CAT II	< 10 ⁻⁹ /150 s	< 4x10 ⁻⁶ /15 s	
CAT III			

- Signal errors and biases characterisation. They can be specified for each satellite of the different constellation and expressed in terms of:
 - User Range Error (URE) and Signal-in-Space-Error for Galileo (SISE).
 - User-Range-Accuracy (URA) and Signal-in-space-accuracy, for Galileo (SISA).
 - Two levels of bias magnitudes for the range measurements: one is the magnitude of a bias in a nominal condition (b_{nom}), used for the evaluation of accuracy and continuity, the other is the maximum bias magnitude used or the evaluation of integrity (b_{int}).
 - Probability of failure for each satellite and constellation (P_{sat} and P_{const}).

TABLE III. REQUIRED NAVIGATION PERFORMANCE [18]

Operation	Accuracy		Integrity		TTA	
	95% (2σ)		Alert Limit (4-5σ)			
	Vertical	Horizontal	Vertical	Horizontal		
Oceanic	N/A	3.7 km or more	N/A	7.4 km or more	1-5 min	
En-route						
Terminal						
NPA		0.22-0.74 km		1.85-3.7 km	10-15 s	
LNAV/VNAV	20 m	220 m	50 m	556 m	10 s	
LPV		16 m		40 m		
APV I						35 m
APV II						20 m
LPV-200						35 m
CAT I	10 m					
CAT II	4 m				6 s	
CAT III	< 2.0 m	< 6.9 m	5.3 m	<15.5 m		< 2 s

III. THE ARAIM PERFORMANCE ON PREDICTED AIRCRAFT TRAJECTORY TOOL SHORT-TERM VERSION (APPATT ST)

In a real configuration, the aircraft attitude and the terrain and objects in the surrounding environment could shadow a certain number of satellites (Figure 1), especially during a safety critical phase (take-off, maneuverings and landing phases), leading to a possible degradation of the integrity performance of the ARAIM algorithm. Aircraft routes and trajectories are predefined through a series of waypoints (Figure 2) and, as previously mentioned, RAIM prediction is required if GPS is to be used to solely satisfy the RNAV requirements [1].

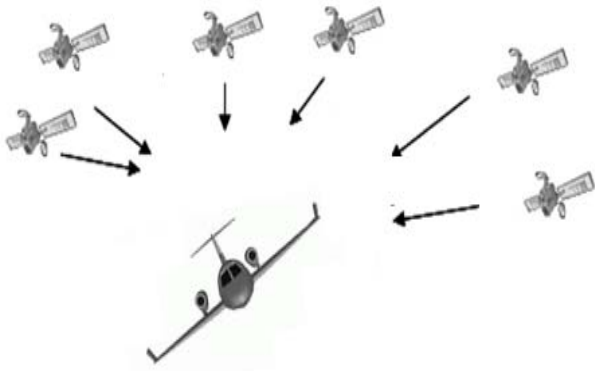


Fig. 1. Attitude shadowing effect

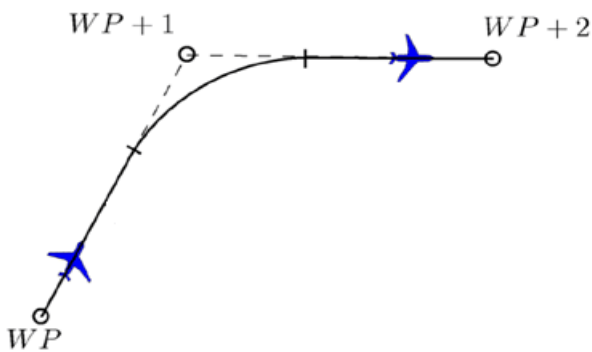


Fig. 2. Trajectory in terms of waypoints

None of the previous analysis considered and integrated into the system the effects of these two factors, only in [19] did the authors notice an effect on the ARAIM performance during flight tests.

For this reason, MAAST has been selected and modified in order to analyse the ARAIM performance along aircraft trajectories considering the shadowing effect of the aircraft attitude and surrounding environments.

In [8] we analysed ARAIM performance prediction for different approach routes in several airports around the World in order to prove the concept. The newly developed algorithm, named APPATT (ARAIM Performance on Predicted Trajectories Tool), has the main objective of computing the four parameter indices of the reliability of the navigation solution provided by GNSS, but with two main differences:

- The tool computes the parameters both while considering and not considering the shadowing effects, in order to evaluate the difference
- The parameters are predicted for a specific point and time; they are not averaged values, but instantaneous, only valid for that well-defined configuration of the satellite constellations and signal errors and bias characterisation.

A. Input and Output

The new tool takes as additional input:

- The aircraft trajectory, defined in terms of waypoints. For each point, the position, attitude and performance of the aircraft are specified in terms of:
 - Latitude, Longitude and Altitude
 - Bank and Heading angles
 - Time (in seconds since trajectory started)
 - Calibrated and True Airspeed (CAS and TAS), Vertical Speed (VS) and Acceleration
 - Fuel Consumption and Thrust (based on the performance of the selected aircraft used for the simulation)
- Flight starting time, expressed in days, hours, minutes and seconds since the beginning of the week (the YUMA almanacs are provided weekly)
- The high-resolution topographic data generated from NASA's Space Shuttle Radar Topography Mission (SRTM) [20].

The tool provides as output for each trajectory waypoint:

- Predicted ARAIM Performance with respect to the East North Up (ENU) reference frame (no shadow effect included, full view of the sky)
- Predicted ARAIM Performance with respect to the aircraft body reference frame (both attitude and environment shadowing effect included)
- Number of satellites in view in the two reference systems
- Number of satellites lost due to the shadowing effects

Figure 3 illustrates the flow chart and functions of the APPATT algorithm.

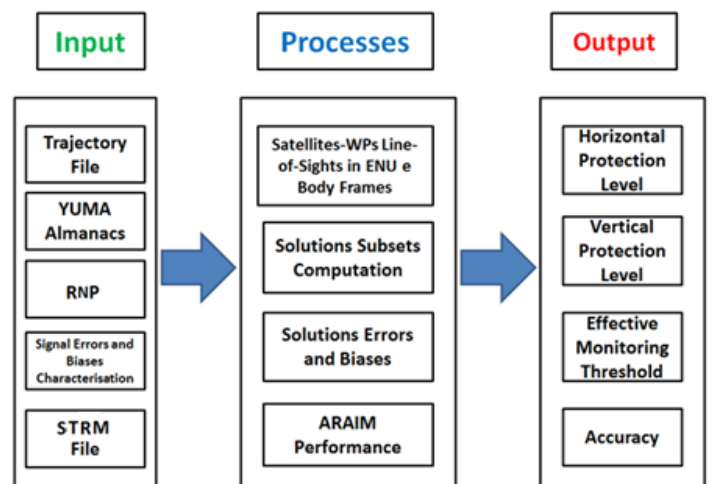


Fig. 3. APPATT Scheme

B. Computation of the shadowing effect of the aircraft attitude

The APPATT algorithm uses the waypoints coordinates, the time information and the orbital elements provided by the YUMA almanacs to compute the aircraft and satellites' positions respect to the Earth Centered Earth Fixed (ECEF) reference system. Afterwards, it computes the Line-of-Sight (LoS) unit vectors between each aircraft position and all of the satellites in the considered constellations. Then the LoS unit vectors are computed in the local East, North and Up (ENU) reference frame for each location and the satellites below the horizon (with the z component of the LoS being negative) are removed from the computation (Figure 4). In order to evaluate the effect of the attitude of the aircraft, the LoS are assessed in the NED (North-East-Down) and Body reference frame (Roll, Pitch and Yaw axes) (Figure 5). NED coordinates to describe observations made from an aircraft are normally given relative to its intrinsic axes, but normally using as positive the coordinate pointing downwards, where the interesting points are located. At each change of reference frame, the algorithm computes and uses the corresponding rotation matrix to transform the LoS unit vectors.

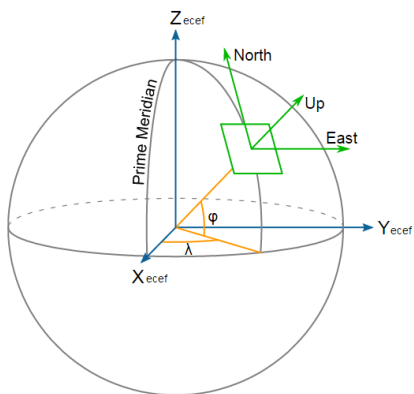


Fig. 4. ECEF and ENU reference frames [21]

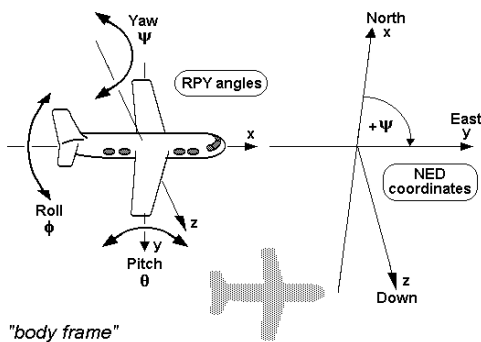


Fig. 5. NED and Body Reference Frames [21]

Figure 6 shows an example of the result of a specific point of the trajectory of an aircraft with banking angle of 20 degrees; there are three different reference systems, two geographical Local Tangent Plane (LTP), the East-North-Up (ENU) and the North-East-Down (NED) and a Body reference system, the Roll-Pitch-Yaw. The numbered dots represent the satellite in view in the ENU reference system, while the

inclined circle is the aircraft horizontal plane (x-y or roll-pitch plane) and on the right side of the picture it is easy to see that there are three satellites below the GNSS receiver's field of view, reducing the number of satellites in view and affecting the ARAIM performance.

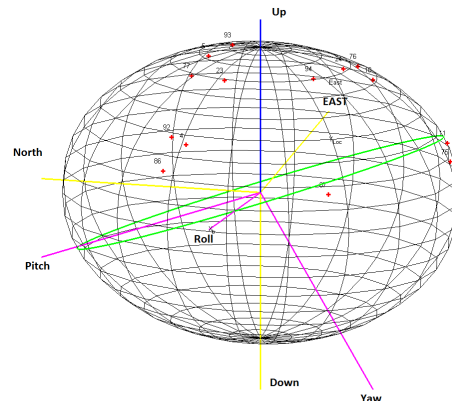


Fig. 6. Example of shadowing effect due to the aircraft attitude

C. Computation of the shadowing effect of the surrounding environment

The APPATT reads and loads the SRTM data, provided as input, which covers the terrain surrounding the trajectory within a certain distance. Then the data passes through a series of filters and checks in order to reduce the computational load (each SRTM file contains around 1.4 million sample points). Figure 7 shows an example of a horizon mask, a 2D representation of the local sky view; the circle centre is the local zenith and each circle is the elevation angle with respect to the local horizon represented by the external circumference. The spokes are the directions (also defined as azimuth or heading angles) with respect to the North direction. The red line and dots are the local terrain profile that could shadow one or more satellites. The main objective of this function is to find the satellites that are shadowed by the terrain.

The following list shows some of the checks that the algorithm performs:

- Remove all of the points with altitude lower than the aircraft.
- Compute the LoS of the remaining points with the aircraft positions and compute their elevation and heading angles with respect to the NED reference system.
- Remove from the computation the satellites with elevation angles higher than the highest elevation angle of the sample points (it reduces the number of satellites to check)
- Find the pair of points that have the closest heading angles for each satellite (one point higher, the other lower).

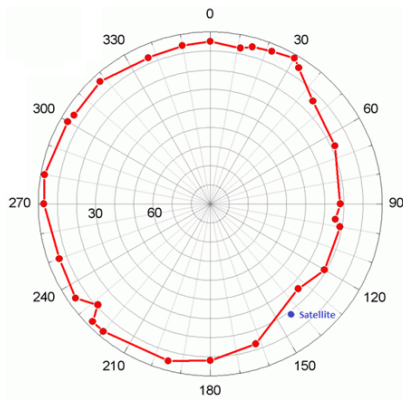


Fig. 7. Example of horizon mask with satellite in shadow

- Linearly interpolate the elevation angle of the pairs of points in order to find the elevation of the points that have the same heading angles of the satellites and compare the elevation angles.
- Determine if the satellite is shadowed (satellite elevation lower than the computed point)

D. Scenarios and Results

Three different approach procedures have been selected for the ARAIM prediction analysis (Figure 8 and Figure 9):

- Fairbanks (Alaska) and Cairns (Australia) due to their positions in areas of low ARAIM performance according to the analysis computed by the University of Stanford using a single constellation configuration [11] (Figure 8).
- Innsbruck (Austria) due to its particular location, where the environment shadowing effect could increase the number of the satellites not available.

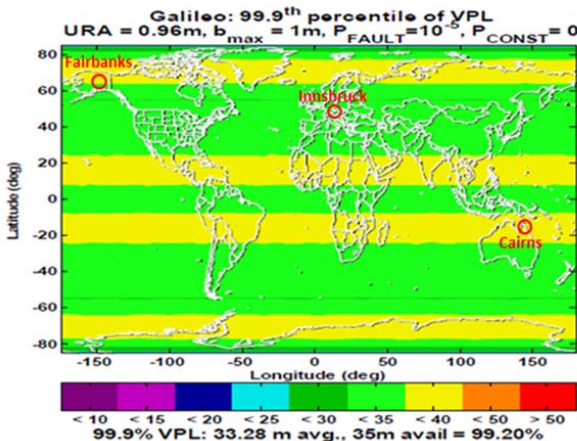


Fig. 8. Selected Airport Locations

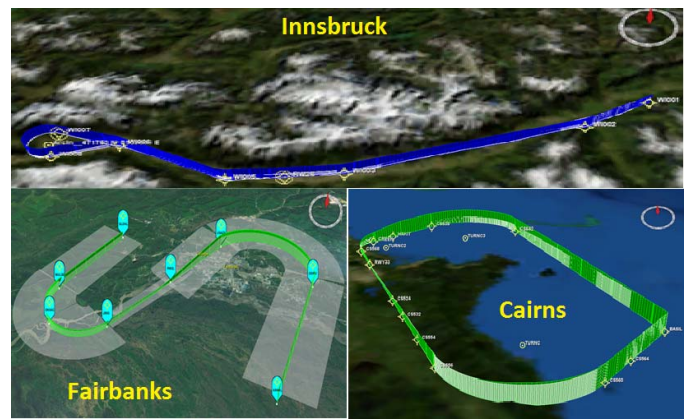


Fig. 9. Selected Airports Approach Procedures

The other main advantage of these three approaches is that they include a wide variety of maneuvers (90, 180 and 270 degrees maneuvers).

The three trajectories have been analysed in different scenarios (single, dual and tri-constellation), combining the different constellations: GPS, Galileo (24 and 27 satellites nominal configuration) and GLONASS (23 satellites nominal configuration). The tool provides as output several graphs:

- Number of satellites in view in the ENU and Body reference system, in order to highlight the difference.
- Horizontal and Vertical Protection Level (HPL and VPL), Accuracy and Effective Monitoring Threshold in the ENU and Body reference frame respect to the Alert Limit

The following tables IV to VI present some of the results. For further details refer to [8]:

TABLE V. PERFORMANCE COMPARISON FOR THE GPS CONFIGURATION

Param.	Location	Max Body Ref	ENU value	Δ Body - ENU%	Δ AL%	AL
HPL (m)	Cairns	14.2	10.8	31.8	-64.4	40
	Fairbanks	15.6	10.1	54.5	-61.1	
	Innsbruck	84.7	14.0	503.8	111.7	
VPL (m)	Cairns	17.4	13.2	31.9	-50.2	35
	Fairbanks	31.84	13.8	131.4	-9.0	
	Innsbruck	84.9	13.2	541.2	142.6	
EMT (m)	Cairns	7.1	5.2	35.7	-52.7	15
	Fairbanks	14.97	5.1	191.7	-0.2	
	Innsbruck	42.0	5.3	697.3	179.7	
Acc (m)	Cairns	1.53	1.5	0.02	-18.3	1.87
	Fairbanks	2.11	1.4	48.2	12.6	
	Innsbruck	3.3	1.3	153.0	76.4	

TABLE VI. PERFORMANCE COMPARISON FOR THE GPS + GALILEO 24SV CONFIGURATION

<i>Param.</i>	<i>Location</i>	<i>Max Body Ref</i>	<i>ENU value</i>	<i>ΔBody - ENU%</i>	<i>ΔAL%</i>	<i>AL</i>
HPL (m)	Cairns	12.3	10.3	19.3	-69.3	40
	Fairbanks	13.4	12.5	7.5	-66.4	
	Innsbruck	30.5	14.3	113.6	-23.8	
VPL (m)	Cairns	21.4	13.1	63.2	-38.8	35
	Fairbanks	22.4	13.8	62.4	-36.0	
	Innsbruck	35.4	16.6	113.1	1.0	
EMT (m)	Cairns	8.6	4.8	79.7	-42.9	15
	Fairbanks	9.5	5.4	76.5	-37.0	
	Innsbruck	15.9	6.2	156.3	6.0	
Acc (m)	Cairns	1.1	0.9	19.6	-42.8	1.87
	Fairbanks	1.0	0.9	15.0	-46.9	
	Innsbruck	1.56	1.0	153.0	-16.4	

TABLE VII. PERFORMANCE COMPARISON FOR THE GPS + GALILEO 24SV + GLONASS CONFIGURATION

<i>Param.</i>	<i>Location</i>	<i>Max Body Ref</i>	<i>ENU value</i>	<i>ΔBody - ENU%</i>	<i>ΔAL%</i>	<i>AL</i>
HPL (m)	Cairns	9.2	7.7	19.5	-77.0	40
	Fairbanks	11.1	9.7	15.1	-72.2	
	Innsbruck	20.0	11.7	71.3	-50.0	
VPL (m)	Cairns	17.3	12.0	44.3	-50.5	35
	Fairbanks	12.5	9.7	29.6	-64.3	
	Innsbruck	18.4	10.5	74.9	-47.6	
EMT (m)	Cairns	6.9	4.5	51.6	-54.0	15
	Fairbanks	4.8	3.1	50.8	-68.4	
	Innsbruck	7.5	3.7	101.2	-50.1	
Acc (m)	Cairns	1.0	0.8	18.5	-46.8	1.87
	Fairbanks	0.8	0.7	14.2	-55.8	
	Innsbruck	1.1	0.8	39.1	-43.0	

The results show that the aircraft attitude and the surrounding environment affect the performance of the ARAIM algorithm; each satellite lost generates a degradation of the performance parameters that depends on the total number of satellites in view, their relative geometry and on the number of satellites which are simultaneously lost. The single GPS constellation configuration could not be enough to comply with the necessary requirements for LPV-200 approaches (the same results were obtained with GLONASS and Galileo individually). The dual constellation configuration seems to satisfy the requirements, but with limited margin with respect to the thresholds, which means that even a small variation in the nominal conditions could trigger an alarm. The main

outcome of this research is the identification that the ideal scenario would be to have a tri-constellation system that provides at the same time high redundancy, reliability and increased safety margin (at least 40% of margin in nominal conditions).

However, further analysis showed that a single constellation could sometimes satisfy the LPV-200 RNP, since the performances are strongly dependent on both the satellite geometry, as one can easily deduce, and the models which are used to estimate signal errors and biases (e.g. ionospheric and tropospheric delays). Consequently, even the same trajectory, performed with a different starting time, could lead to completely different results.

Furthermore, the algorithm could be easily integrated into the aircraft's Flight Management System to be used by the pilots during the pre-flight briefing. Knowing about possible integrity outage in advance might allow the pilots to select a different approach or make them aware of the need to utilise additional positioning systems. Increased awareness and better pre-flight planning could ultimately improve the safety of flights and contribute to the safe introduction of GNSS as a viable positioning method for instrument approach.

IV. ARAIM IMPLEMENTATION FOR PROCEDURES DEVELOPMENT

The development of a new instrument approach at a given airport can greatly enhance the airport's value to the aviation community by increasing the variety of aircraft which can use the airport, or the conditions in which it can operate. Historically, most instrument approaches have been based on terrestrial navigational aids (NAVAIDs) requiring a considerable investment in equipment and resources. However, with the proliferation of GNSS technologies, the infrastructure required to support traditional ground-based facilities may no longer be necessary in order to obtain an instrument approach.

GNSS can be used to shorten routes, save time and fuel, reduce traffic delays, increase capacity, and permit controllers to monitor and manage aircraft with increased safety.

Although GNSS has the potential to support instrument flight procedures at hundreds of facilities, the development and implementation of a new approach is far from a simple undertaking; it is a complex, multi-disciplinary effort requiring the collaboration of many professionals within the Federal Aviation Administration (FAA).

The proposal of a new procedure must first undergo the scrutiny of a cost/benefit analysis before its development will be considered. In addition, the development of an instrument approach procedure must consider factors such as obstruction evaluations, airport requirements/capacity, compatibility with the existing airport master plan, noise and environmental issues, impact to the Air Traffic Control (ATC) system, airspace change, effects on other instrument approaches, and location of existing and proposed NAVAIDs and their limitations.

One of the main phases of the evaluation process for an instrument approach is the flight inspection, where criteria

such as signal availability, integrity, and accuracy are all validated. Once this has been passed, the instrument flight procedure is forwarded for publication.

In our research, we developed two algorithms with integrated ARAIM function that could be used to reduce the time, effort and cost of the flight inspection phase and help the procedures' designer and tester to assess the benefits and limits. It can also help in increasing the automation in the design of possible alternative routes or improvements to the existing routes.

A. APPATT Long Term (LT)

The first algorithm is a variation of the APPATT ST that analyses the trend of the integrity parameters along the aircraft trajectory, showing their fluctuations within a predefined time interval. The objective is to provide the designers with innovative equipment for the evaluation of the availability of new procedures, together with their limits and safety. The tool enables the user to set the time interval, allowing the analysis of the expected trajectory during the repeat pattern of the different GNSS constellations (1 day for GPS, 10 days for Galileo and 8 days for GLONASS). The following graphs show part of the analysis performed on a 90 degrees manoeuvre (Figure 10 shows the aircraft attitude), examining a single constellation (GPS) and a dual-constellation (GPS + Galileo 24SV). Figures 11 to 18 (for GPS) and 19 to 26 (for GPS + Galileo 24SV) show the comparison between the ENU and Body reference frames for the two configurations.

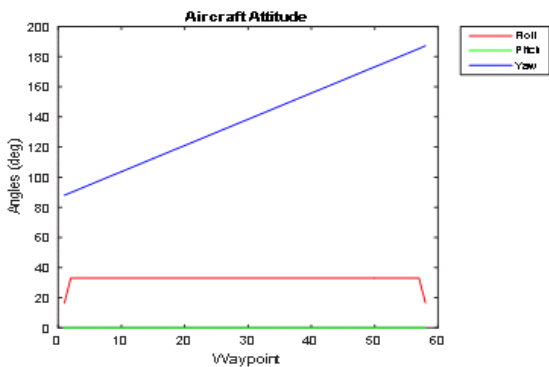


Fig. 10. Attitude angles along the turn

• GPS configuration

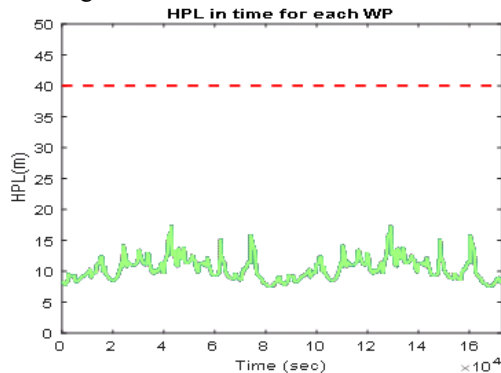


Fig. 11. Horizontal Protection level for each WP in the ENU reference

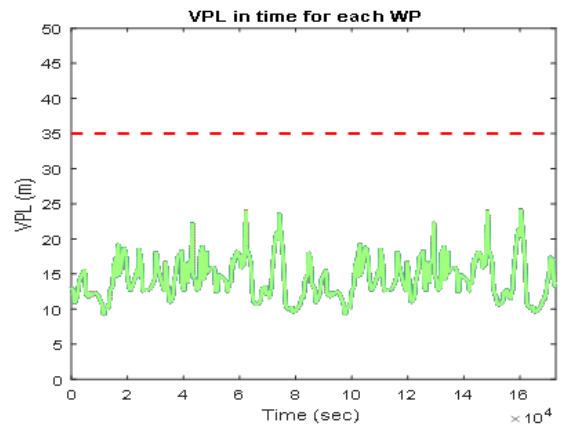


Fig. 12. Vertical Protection level for each WP in the ENU reference

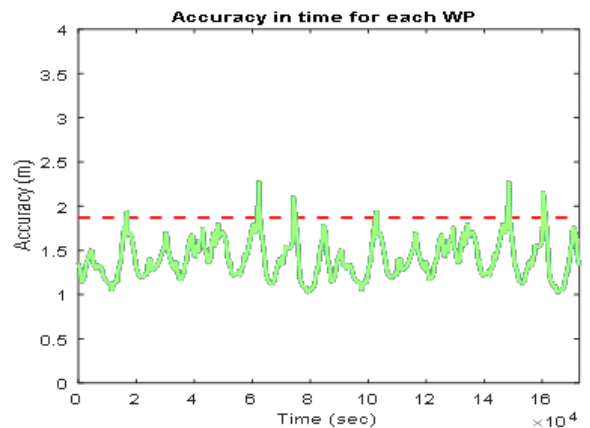


Fig. 13. Accuracy for each WP in the ENU reference

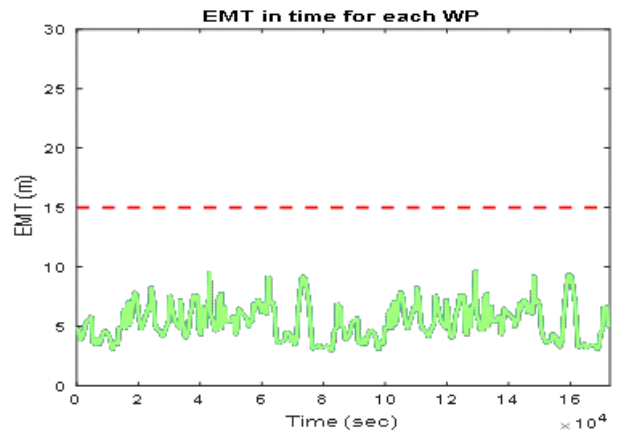


Fig. 14. Effective Monitoring Threshold for each WP in the ENU reference

As we may expect, for each waypoint, represented by a different color, the integrity parameters behave in the same manner, since they benefit from the same number of satellite in view for the entire time interval. However, the single constellation configuration in the ENU reference frame already presents situations in which the RNP for LPV-200 are not satisfied, in particular, the accuracy overtakes the protection level (red dashed line).

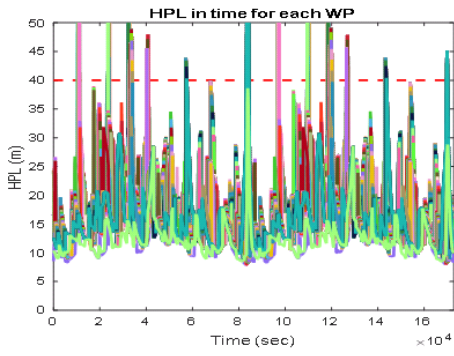


Fig. 15. Horizontal Protection level for each WP in the Body reference

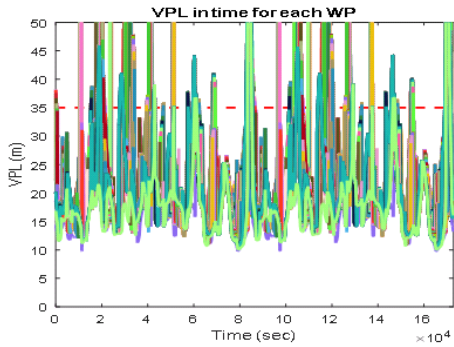


Fig. 16. Vertical Protection level for each WP in the Body reference

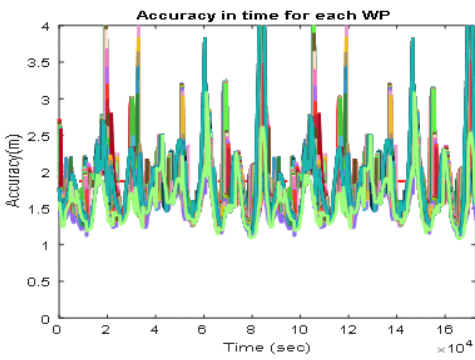


Fig. 17. Accuracy for each WP in the Body reference

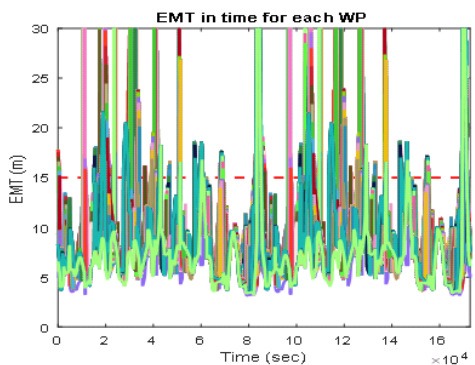


Fig. 18. Effective Monitoring Threshold for each WP in the Body reference

In the Body reference frame, all of the parameters repeatedly exceed the limits, confirming their high time

dependency found in the previous results with the APPATT ST. A single constellation configuration does not satisfy the LPV-200 requirements even in nominal conditions (no faults or failure).

- GPS + Galileo 24SV configuration

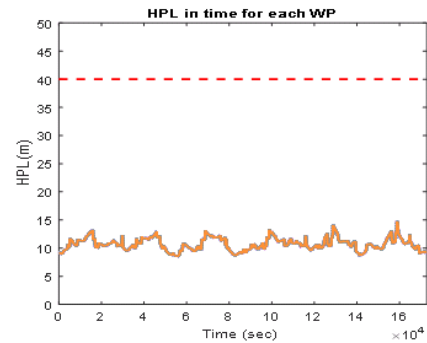


Fig. 19. Horizontal Protection level for each WP in the ENU reference

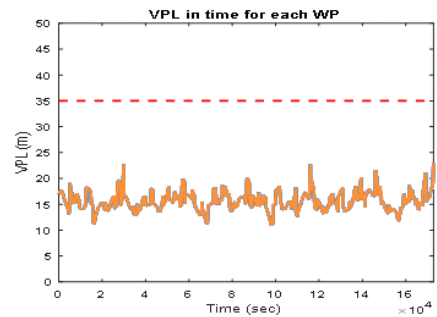


Fig. 20. Vertical Protection level for each WP in the ENU reference

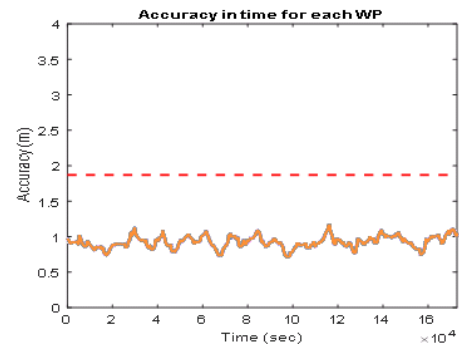


Fig. 21. Accuracy for each WP in the ENU reference

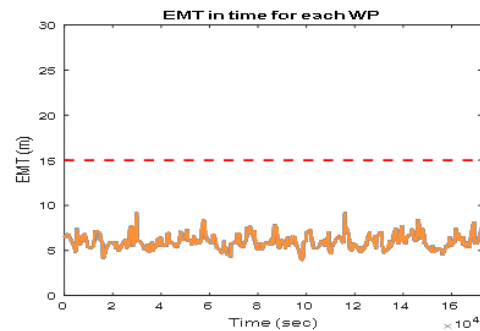


Fig. 22. Effective Monitoring Threshold for each WP in the ENU reference

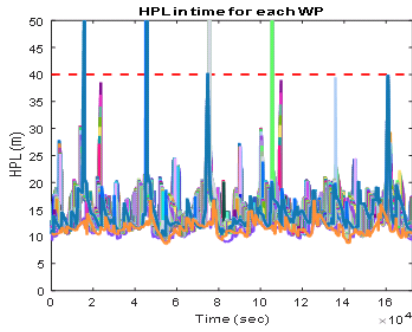


Fig. 23. Horizontal Protection level for each WP in the Body reference

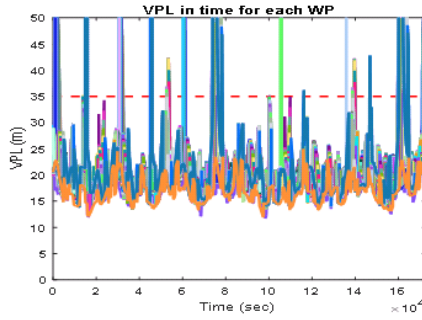


Fig. 24. Vertical Protection level for each WP in the Body reference

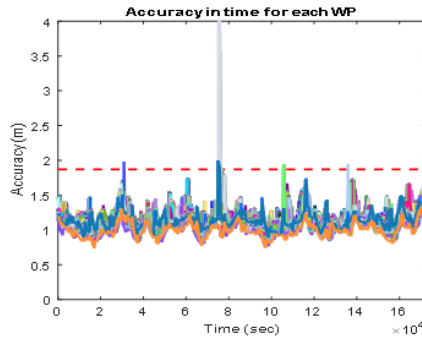


Fig. 25. Accuracy for each WP in the Body reference

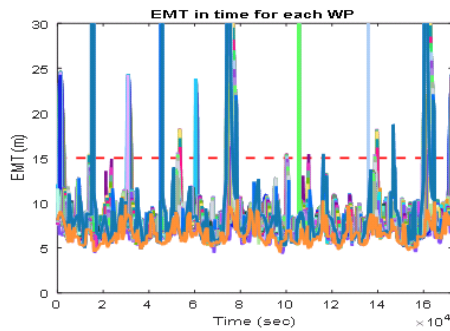


Fig. 26. Effective Monitoring Threshold for each WP in the Body reference

The introduction of a second constellation reduces drastically the average values and the number of peaks that break the protection levels, but it is still evident that a dual-constellation integrity monitoring system does still not guarantee full reliability.

B. Flight Path Generator and Modifier (FPGM)

In [22], ICAO describes design criteria to aid states in the implementation of RNP operational procedures. Moreover, the manual provides a basic model for the determination of manoeuvres based on two parameters: speed and bank angle.

The Flight Path Generator function takes as input a text file containing the list of waypoints of the selected procedure. For each point the following are specified:

- Name
- Latitude, Longitude and Altitude
- Type of WP (check WP, initial turn WP, turn WP, final turn WP, end of procedure WP)
- Turn type, if applicable (clockwise or counterclockwise)
- Preferred heading to next point

We assumed that aircraft perform only a specific type of maneuver to change direction: fly-by turns.

The aircraft avionics provides the Indicated Airspeed (IAS) that needs to be firstly converted in True Airspeed (TAS) using the following standard equation (SI units):

$$TAS = IAS * 171233 * [(288 + VAR) - 0.00198 * H]^{0.5} / (288 - 0.006496 * H)^{2.628} \quad (18)$$

Where:

- VAR = variation from international standard atmosphere (ISA) (standard value +15) or local data for 95% high temperature, if available
- H = altitude (m)

However, the turn radius is calculated using the following equation for the speed:

$$V = TAS + \text{assumed tailwind (TWD)} \quad (19)$$

Then, the rate of turn (R) in degrees/second can be computed as:

$$R = (6355 * \tan(\alpha)) / (\pi * V) \quad (20)$$

Where α is the bank angle.

And last, the turn radius is given by:

$$r = V / (20 * \pi * R) \quad (21)$$

Knowing the radius of turn it is possible to compute the minimum distance from the turn WP at which the aircraft needs to start the turn maneuver, known as Distance of Turn Anticipation (DTA), given by:

$$DTA = r * \tan(A/2) \quad (22)$$

Where A is the turn angle, the change of angle between the initial and final heading.

At this stage, the algorithm approximates the flight path to a series of connected lines and arcs in the 3D space using

basic geometrical and kinematic equations. The generated path describes the aircraft trajectory in terms of position (latitude, longitude and altitude) and attitude (roll, pitch and yaw angles) in time within a user defined time step (e.g. 1s). In particular, the function monitors that the roll angle is always within the aircraft's standard limits (commercial flights standard value is between 25-33°, but it can increase to a maximum of 60-70° in case of emergency).

The trajectory is then analysed by APPATT with the objective of evaluating the integrity performance of the trajectory considering the attitude. If it doesn't satisfy the required navigation performance and it presents one or more integrity outages, the Flight Path Modifier (FPM) function is activated.

In case of activation of the FPM function, the tool tries to modify the trajectory in order to remove the integrity outages and satisfy the required navigation performance. The function analyses the trajectory backwards from the final to the starting WP, examining which sections need to be modified. If the section presents an outage, the FPM performs the following steps:

- Analyses the satellite which was lost due the attitude shadowing effect; if more than one satellite is not in view, it selects the satellite with the highest elevation angle and forces the aircraft to perform the maneuver with a bank angle smaller than the elevation angle. In this way, the satellite is again in the GNSS receiver field of view.
- Forces the bank angle to a defined value, then modifies the values of the turn radius (r), the rate of turn (R) and the distance of turn anticipation (DTA) appropriately. The function checks that the rate of turn stays within the standard values (for commercial flights $R \approx 3 \text{ deg/sec}$) and generates the new trajectory arc using the new DTA value.
- Checks that the new segment is compatible with the following segment, otherwise the FPM attempts to modify the next segment.
- Completes the analysis of the following segments if no incompatibilities occur and the new trajectory is then analysed again by APPATT. If the integrity outage has not been removed and other satellites are still not in view, it selects the second highest elevation angle and repeats the previous steps.

If an incompatibility occurs, the tool warns the user that with the current configuration the trajectory can't be modified in order to meet the required navigation performance.

The FPM is still under development; however preliminary results have been obtained analysing the RNAV STAR procedure Sunny Four Papa Arrival of the International Airport of Cairns, Australia, in a single constellation configuration (GPS). Figure 27 shows the nominal trajectory (upper red line) with banking angle of 25° for each turn maneuver and the modified trajectory (lower blue line) with banking angle force to the value of 12°.

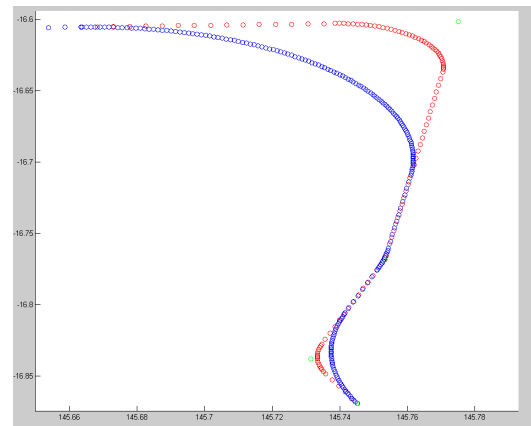


Fig. 27. Standard trajectory (red line) and modified trajectory (blue line)

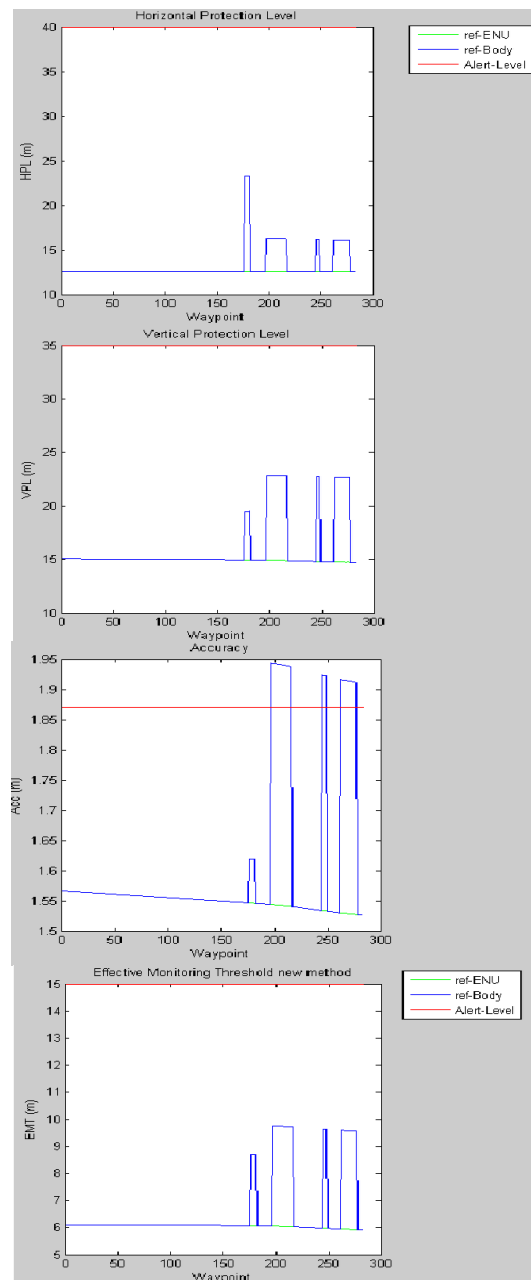


Fig. 28. ARAIM parameters along the standard trajectory

Figure 28 shows the ARAIM parameters (blue lower lines) for the nominal trajectory and in this specific case, the accuracy exceeds the limit (red upper line) due to the loss of a satellite in each turn, while in Figure 29 the modified trajectory all the satellites are in view and none of the parameters exceed the limits (Alert levels for an LPV approach for horizontal, vertical, accuracy and EMT are [40m, 35m, 1.86m, 15m]).

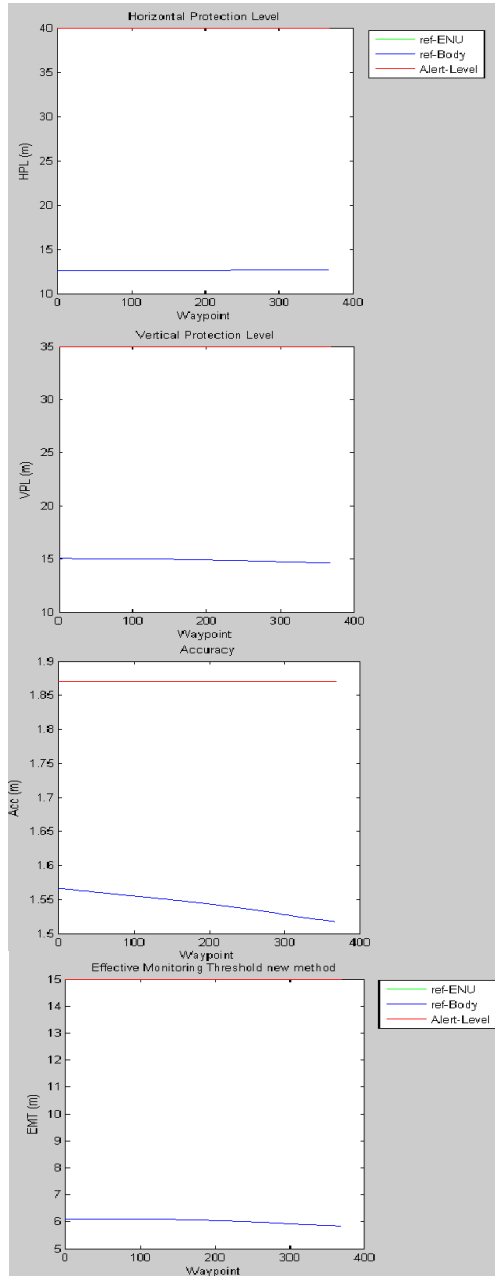


Fig. 29. ARAIM parameters along the modified trajectory

V. NEAR REAL TIME ARAIM PERFORMANCE PREDICTION TOOL (NRT APPT)

The previous results show that a dedicated system, that evaluates the effects of the attitude and the surrounding environment in real time, needs to be developed

The ARAIM tool has been further modified in order to provide a near real-time prediction computation of the parameters. The objective of this process is to develop a system that can be integrated into the Flight Management System or the Avionics of an aircraft/UAV and can provide timely warning to the user/pilot whenever the current aircraft configuration could lead to a dangerous situation. The ARAIM algorithm has been connected to commercial flight simulator software, X-Plane 10, through a tool, X-Plane Connect, developed by NASA [23] to evaluate this.

The X-Plane Connect (XPC) Toolbox is an open source research tool used to interact with the commercial flight simulator software X-Plane. XPC allows users to control aircraft and receive state information from aircraft simulated in X-Plane using functions written in C, C++, Java, MATLAB, or Python in real time over the network. This research tool has been used to visualise flight paths, test control algorithms, simulate an active airspace, or generate out-the-window visuals for in-house flight simulation software. Possible applications include active control of an X-Plane simulation, flight visualisation, and recording states during a flight, or interacting with a mission over User Datagram Protocol (UDP).

For the purpose of this research, the XPC tool is used to extract information related to the attitude and position of the aircraft in real time. These are used in the ARAIM tool to compute the integrity parameters. The tool integrates the dynamics of the aircraft for 6-10 seconds, in order to predict the ARAIM parameters, satisfying the Time-to-Alert (TTA) requirement, and at the same time displaying the expected values on dedicated instrument panels, as shown in Figure 30.



Fig. 30. Real-time ARAIM computation integrated into the X-Plane software

The tool uses a classical Three Degrees of Freedom (3-DOF) point-and-variable mass model. The assumptions are:

- The Earth shape is approximated as an ellipsoid using World Geodetic System 1984 (WGS-84) parameters.
- The atmosphere is considered to be at rest relative to the Earth.
- Temperature, pressure and density are modelled with the International Standard Atmosphere (ISA).

- The aircraft is considered to be a rigid body with a vertical plane of symmetry.
- The mass reduction is due to fuel consumption only.
- Forces (Thrust, aerodynamic and weight) act on the aircraft Centre of Gravity (CoG).
- The flight is symmetric.

The 3-DOF scalar equations are:

$$m \, dV/dt = T \cos \alpha - D(V, h, L) - mg \sin \gamma \quad (23)$$

$$mV \, d\gamma/dt = (T \sin \alpha + L) \cos \phi - mg \cos \gamma \quad (24)$$

$$mV \, d\psi/dt = [(T \sin \alpha + L) \sin \phi] / \cos \gamma \quad (25)$$

$$dm/dt = -c(V, h)T \quad (26)$$

$$d\Phi/dt = (V \cos \gamma \cos \psi) / (r_M + h) \quad (27)$$

$$d\Lambda/dt = (V \cos \gamma \sin \psi) / [\cos \Phi (r_T + h)] \quad (28)$$

$$dh/dt = V \sin \gamma \quad (29)$$

Where:

m = aircraft mass [kg]

V = longitudinal velocity [m/s]

T = thrust magnitude [N]

α = angle of attack [rad]

D = drag magnitude [N]

h = altitude [m]

L = lift magnitude [N]

g = gravity acceleration at sea level [m/s²]

γ = flight path angle [rad]

ϕ = roll or bank angle [rad]

ψ = heading angle [rad]

c = specific fuel consumption [kg/s]

Φ = geodetic longitude [rad]

r_M = meridional radius of curvature [m]

Λ = geodetic latitude [rad]

r_T = transverse radius of curvature [m]

This tool proved to be a useful platform to test the ARAIM algorithm in a real-time configuration, used as an integrated avionic instrument. It allowed saving time, avoiding the development of an aircraft dynamics simulator. Moreover, it could be used as test platform for a real-time trajectory optimiser.

The tool could be further improved, introducing user-defined parameters and settings, such as the selection of the

YUMA almanacs, the constellation and the Integrity Support Message (ISM).

VI. CONCLUSIONS

In our research, we focused on different and innovative approaches to the integration of the ARAIM algorithm for integrity performance prediction, going beyond the basic real-time function. The ARAIM prediction feature may support procedures' development and pre-flight operations, increasing awareness and improving pre-flight planning, ultimately enhancing the safety of flights and contributing to the safe introduction of GNSS as a viable positioning method for instrument approach.

The results of APPATT ST and LT tools clearly show that dedicated systems, that evaluate the effects of the attitude and the surrounding environment in real time, need to be developed and integrated into the flight management system if the ARAIM technique is to be used as an on-board system for integrity monitoring. Moreover, the results of the LT version confirm that a dual-constellation GNSS receiver might not be sufficient for all of the possible scenarios, supporting the need for an international collaboration for the development of multi-GNSS applications.

The implementation of these new algorithms may allow the users to assess the benefits and limits of a selected or new procedure whether they are procedures' designers, testers or pilots.

Figure 31 provides an overview of the overall results and outcome accomplished in our research.

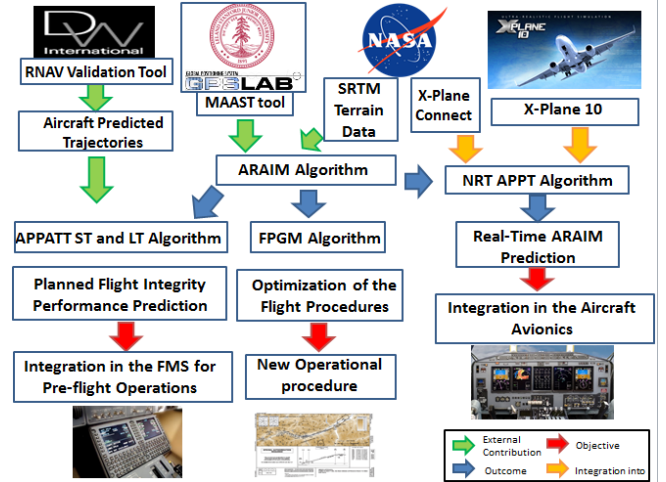


Fig. 31. Overview of research outcome and objectives

Increased awareness and better pre-flight planning could ultimately improve the safety of flights and the introduction of GNSS as a viable positioning method could contribute to shortening routes, saving time and fuel, reducing traffic delays, increasing capacity, and permitting controllers to monitor and manage aircraft with increased safety.

ACKNOWLEDGMENT

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