ARTIFICIAL SATELLITES, Vol. 51, No. 1 – 2016
DOI: 10.1515/arsa-2016-0003

PILOT EVALUATION OF INTEGRATING GLONASS, GALILEO AND BEIDOU WITH GPS IN ARAIM

Ahmed El-Mowafy
Department of Spatial Sciences, Curtin University, Australia
Email: a.el-mowafy@curtin.edu.au

ABSTRACT: In this pilot study, availability of the Advanced Receiver Autonomous Integrity Monitoring (ARAIM) when integrating various combinations of satellite constellations including; Galileo, GLONASS and BeiDou with GPS is investigated. The Multiple Hypothesis Solution Separation method was applied using one month of real data. The data was collected at stations of known positions, located in regions that have different coverage levels by the tested constellations. While most previous studies used simulated data, the importance of using real data is twofold. It allows for the use of actual User Range Accuracy (URA) received within the satellite navigation message, which is a fundamental component for computation of the integrity protection level; and the computation of vertical position errors to validate the integrity approach. Results show that the vertical position error was always bounded by the protection level during the test period and the ARAIM availability can reach 100% of the time when using all constellations even though some constellations are yet incomplete.

Keywords: 1. ARAIM 2. GNSS 3. Integrity Monitoring 4. LPV-200

1. INTRODUCTION

By the end of this decade the four GNSS constellations; GPS, GLONASS, Galileo and BeiDou are expected to provide global coverage with multiple frequency observations. The availability of tens of satellites in view provides improved satellite geometry, and the new civilian signals, such as L5 and E5a coupled with L1 and E1, as well as B1 with B2 or B3 will allow cancelation of the ionosphere delay, the largest GNSS error source. This has led to consider the use of Receiver Autonomous Integrity Monitoring (RAIM) methods for aircraft vertical guidance, an approach known as Advanced RAIM (ARIAM). One important application of ARAIM is its use for the Localizer Performance with Vertical guidance down to 200 feet (LPV-200). The use of multiple-constellation measurements in RAIM has been considered in Ene *el al*. (2007); Lee and McLaughlin (2007); and Rippl *el al*. (2011), for integration of GPS with Galileo, and in Choi *et al.* (2012); and Walter *et al.* (2013), using GPS and GLONASS. Integration of GPS with BeiDou has been demonstrated in Lijun *et al.* (2012); Liu and Zhu (2014); El-Mowafy (2014a) and El-Mowafy and Yang (2015). In this contribution the integration of all constellations in ARAIM is presented.

The paper is organised as follows, a summary of a baseline algorithm for integrity monitoring is presented. The ARAIM baseline method, presented for instance in GEAS (2010); EU-U.S. WG-C ARAIM (2012); and Blanch *et al.* (2014) which is used in this paper is summarized. Next, pilot experimental testing of ARAIM availability when using various combinations of all constellations with GPS is performed and their results are compared at representative sites.

2. GNSS OBSERVATION MODEL

The observation equation of the pseudorange code measurements for satellite m from a GNSS constellation, such as GPS (denoted as G), to receiver r for signal c_j on frequency f_j in length units can be formulated as follows:

$$p(c_j)_r^{m_G} = \rho_r^{m_G} + c\left(dt_{r_G} - dt^{m_G} + d_{r_G}(c_j) - d^{m_G}(c_j)\right) + T^{m_G} + \mu_j I^{m_G} + \varepsilon_{P(c_j)_r^{m_G}} \qquad (1)$$

and for satellite k from a second GNSS constellation, such as BeiDou (denoted as C), with signal c_i, the pseudorange code measurement is:

$$p(c_i)_r^{k_C} = \rho_r^{k_C} + c\left(dt_{r_C} - dt^{k_C} + d_{r_C}(c_i) - d^{k_C}(c_i)\right) + T^{k_C} + \mu_j I^{k_C} + ISB + IST + \varepsilon_{P(c_i)_r^{k_C}} \qquad (2)$$

where $p(c_j)_r^{m_G}$ denotes the code measurement, $\rho_r^{m_G}$ is the satellite-to-receiver geometric range, c is the speed of light in vacuum, dt_{r_G} and dt^{m_G} are the receiver and satellite clock offsets. T^{m_G} is the tropospheric delay, $\mu_j = \frac{f_1^2}{f_j^2}$ is the dispersive coefficient of the ionosphere, I is the ionosphere error for a reference frequency, e.g. L1 for GPS. $\varepsilon_{P(c_j)_r^{m_G}}$ comprises code measurement noise and multipath. $d_{r_G}(c_j)$ and $d^{k_G}(c_j)$ are the receiver and satellite hardware biases in time units, respectively. Similar terms are derived for satellite k on system C and signal c_i. *ISB* and *IST* are the inter-system time offsets between systems G and C (GPS and BeiDou in this example) at the receiver and the satellites, respectively. Both *ISB* and *IST* are considered common for all satellites in system C, and in the estimation process they are combined into one term to avoid rank deficiency since they are linearly dependent in the equation. The effect of code noise is minimised using a Hatch filtered divergence-free carrier-smoothed code observations (Misra and Enge, 2006). To eliminate the first order ionosphere, an ionosphere-free combination of observations is used, combining for instance L1 and L2 or L5 in GPS, E1 and E5ain Galileo, etc.

When integrating data from multiple constellations one has to consider their coordinate frames. GPS satellite coordinates are presented in the World Geodetic System 84 (WGS84), whereas Galileo satellite coordinates are given in the Galileo Terrestrial Reference Frame (GTRF), GLONASS in Parametry Zemli (PZ) 90.02 and the coordinate system of BeiDou is aligned to the China Geodetic Coordinate System 2000 (CGCS, 2000). However, since WGS84, GTRF, PZ90.02 and CGCS are updated to be closely aligned with the International Terrestrial Reference Frame (ITRF) at a few cm levels, positioning errors due to apparent orbit errors arising from using different coordinate frames can be simply adjusted or ignored.

3. THE BASELINE ARAIM METHOD USED IN THIS STUDY

In this paper, the Multiple Hypothesis Solution Separation (MHSS) method is used. The MHSS evaluates the different fault modes given the specified probabilities of faults and determines the optimal probability of missed detection (Blanch *et al.* 2014; Joerger and Pervan 2014). The method is summarized in this section. The linearized fault-free GNSS code measurement model using all satellites in view can be expressed as:

$$y = G\,x + \varepsilon \tag{3}$$

where y is the measurement vector, taken as the difference between the observed code pseudo ranges and the calculated ones from the approximate values of the coordinates. The first order ionosphere delay is eliminated by using ionosphere-free linear combination of code measurements. x denotes the difference between the final and approximate values of the unknown parameters, which include the three dimensional position components and receiver clock error. ε is the nominal noise, which is characterised by a stochastic component and a bias component (Blanch *et al.* 2014). The direction cosine matrix G provides the transformation between the observation domain and the position domain. For the n^{th} satellite, the corresponding row G_n reads:

$$G_n = [-\cos\theta_n \sin\alpha_n \quad -\cos\theta_n \cos\alpha_n \quad -\sin\theta_n \quad 1] \tag{4}$$

where θ_n and α_n denote the elevation angle and the azimuth for satellite n, determined from the broadcast satellite ephemeris and approximate receiver location. When introducing fault modes, the large error (fault) state ∇_f is added to the observation model, which becomes (El-Mowafy and Yang, 2015):

$$y = G\,x + G_f \nabla_f + \varepsilon \tag{5}$$

where the number of columns of the matrix G_f equals the number of errors (faults) considered in ∇_f. To detect faults, this number should not be larger than the degrees of freedom. Each column of G_f has a one in the index corresponding to the satellite assumed to be affected and zeros elsewhere. In the MHSS method, a position error bound is created for each fault mode by computing a position solution unaffected by the fault, computing an error bound around this solution and accounting for the difference between the all-in-view position solution and the fault tolerant position (Blanch *et al.* 2013).

The least square solution of the unknown user position and receiver clock offset for all satellites in view reads:

$$\hat{x} = (G^T W_{URA} G)^{-1} G^T W_{URA}\, y = S \times y \tag{6}$$

where $S = (G^T W_{URA} G)^{-1} G^T W_{URA}$, and W_{URA} is a diagonal weight matrix of the measurement vector y computed using the broadcast *URA* and the assumed standard deviations for multipath, receiver noise ($\sigma_{n,user}$) and troposphere delay ($\sigma_{n,tropo}$). The n^{th} diagonal element of W_{URA} is (GEAS 2010):

$$W_{URA_n} = \frac{1}{URA_n^2 + \sigma_{n,user}^2 + \sigma_{n,tropo}^2} \tag{7}$$

For a fault mode i, which considers one or multiple faulty satellites, S_i is:

$$S_i = ((A_i\, G)^T\, W\, (A_i\, G\,))^{-1}\, (A_i\, G)^T\, W \tag{8}$$

where A_i is a canonical form of an identity matrix of size *m* such that the diagonal elements corresponding to the suspected faulty satellites are replaced by zeros whereas other diagonal elements are ones. The position estimate corresponding to mode *i* is:

$$\hat{x}_i = S_i\, y \tag{9}$$

The threshold corresponding to this fault mode, denoted as T_i, for the vertical position (indicated by the subscript 3) is (Blanch *et al.* 2013):

$$T_i = K_{ffd,i} \times \sigma_{dV,i} + |(S - S_i)_3| \times bias_{acc} \tag{10}$$

where $|(S - S_i)_3|$ is the absolute value of the sum of elements of the third row of $(S - S_i)$. $K_{ffd,i}$ is a scalar used to satisfy the false alert probability, computed from the inverse of the complement of the one-sided standard normal cumulative distribution function. $\sigma_{dv,i}$ is the standard deviation computed from:

$$\sigma_{dv,i} = \sqrt{e_3^T\, (S - S_i)^T\, W_{URE}^{-1}\, (S - S_i)\, e_3} \tag{11}$$

where e_3 denotes a vector whose 3rd entry is one and zero elsewhere, W_{URE} is a diagonal weight matrix structured similar to W_{URA} by replacing the *URA* by the user range error (*URE*) in Equation 7. *URE* is the non-integrity-assured standard deviation of the range component of clock and ephemeris errors and is used to evaluate accuracy and continuity performance. The nominal bias ($bias_{acc}$) is assumed to bound possible nominal satellite biases (given in the observation equation) when assessing accuracy. It is assumed that receiver biases for each constellation are common when using the same ionosphere-free frequency spectrum, and thus is combined with the receiver clock offset estimated for each system.

For all considered fault modes, a fault detection test is applied, where a fault is suspected when (Blanch *et al.* 2013):

$$|\hat{x}_i - \hat{x}|_3 > T_i \tag{12}$$

and faulty satellites are excluded. When the test passes for all *i* modes, *VPL* is computed. The LPV-200 requirements described in the GNSS standards and recommended practices (SARPs) of ICAO (2009) that can be used for evaluation of ARAIM availability are:

i. *VPL* ≤ *VAL* where *VAL*=35m for LPV-200
ii. Effective Monitor Threshold (*EMT*) = *Max* $\{T_i\}$ ≤ 15m
iii. 95% vertical accuracy ≤ 4m
iv. (1- 10^{-7}) fault-free vertical accuracy ≤ 10m.

The first condition is sufficient to practically consider ARAIM available (GEAS 2010). It is assumed that to achieve LPV-200, ARAIM availability should be above 99.5% (this number has not been finalised yet). In this contribution, *VPL* is computed following the baseline method presented in EU-U.S. WG 2012; and Blanch *et al.* 2014. *VPL* is taken as the max$\{VPL_o$, max(VPL_i)$\}$, where VPL_o is the *VPL* for the fault-free full set case where:

$$VPL_o = \text{Gaussian term} + \text{Bias overbound} = K_{md,0} \times \sigma_{v,0} + |S_3| \times bias_{int} \tag{13}$$

For fault mode i, VPL_i is:

$$VPL_i = T_i + K_{md,i} \times \sigma_{v,i} + |S_{i_3}| \times bias_{int} \quad (14)$$

with $\sigma_{v,0} = \sqrt{e_3^T\, S^T\, W_{URA}^{-1}\, S\, e_3}$ and $\sigma_{v,i} = \sqrt{e_3^T\, {S_i}^T W_{URA}^{-1}\, S_i\, e_3}$. $K_{md,0}$, $K_{md,i}$ are scalar factors that are used to satisfy the miss-detection probabilities and are computed from the inverse of the complement of the one-sided standard normal cumulative distribution function (Blanch *et al.*, 2014b). $bias_{int}$ is used for integrity evaluation as the assumed maximum nominal bias that bounds potential satellite biases, which may lead to non-zero mean error distributions.

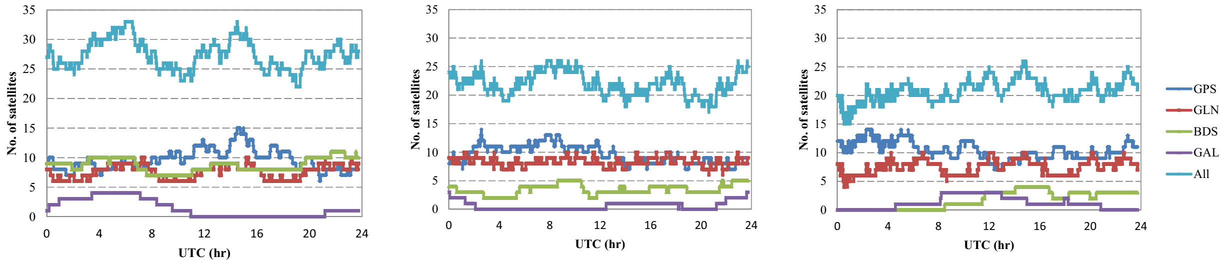
4. TESTING

In this section, availability of ARAIM using the MHSS method in meeting LPV-200 requirements is investigated empolying real data from various combinations of GLONASS, Galileo and BeiDou with GPS. The test is first decribed. Probabilities of fault modes as well as key parameters used in the error model that are needed to compute the protection level of different constellations are next discussed. Finally, results are presented and analyzed.

4.1. Test Description

The pilot evaluation of integrating all-GNSS in ARAIM included test data covering March 2015 collected at 65 International GNSS Service (IGS) stations, which have known coordinates. These stations have a Global distribution and are equipped with receivers capable of tracking all four constellations. All available GNSS satellites were involved in our study, including 31 GPS satellites, 24 GLONASS, 4 Galileo and 14 BeiDou satellites with 30 seconds sampling rate. The use of real data allows for the use of actual *URAs* that are received within the satellite navigation files. The use of real data is also necessary to validate the integrity approach by determination of *VPE* at stations of known positions, where they should be bounded by *VPL,* according to the predefined probability, when ARAIM availability requirement is met. *VPE* is computed as the difference between the station known vertical position and the computed one from observations. Although this was done over a period of one month, this would give an initial indication of the expected performance of the method.

The number of observed satellites, which is dependent on station location, has a direct impact on computation of the *VPL*, and hence on ARAIM availability. In this paper, we restrict attention to present reslts at selected representitive locations of the 65 stations for demonstration purposes rather than showing results on a global scale. Hence, results from three stations; CUT0, ZIM3 and AMBF that represent three geographic regions are discussed. The three stations use the same GNSS receiver model; Trimble Net R9. Station CUT0 is located in Western Australia in the southern hemisphere, representing an area with good coverage by all constellations including all BeiDou satellites. Station ABMF is in the Caribbean and has an excellent coverage by GPS but poor coverage by BeiDou. The two stations CUT0 and ABMF are spaced out in longitude by approximately 165 degrees and in Latitude by 58 degrees. Station ZIM3 is located in Switzerland in-between CUT0 and ABMF, and has a partial coverage by BeiDou and relatively excellent coverage by GLONASS. Figure 1, shows an example of the number of the observed satellites from each system and the total number at the three stations on 1st March 2015. The following symbols were used in the figures: GLN for GLONASS, GAL for Galileo and BDS for BeiDou.



(a) (b) (c)

Fig. 1. Number of observed satellites at stations CUT0 (a), ZIM3 (b) and ABMF (c)

To demonstrate the improvement achieved by the use of observations from multiple-constellations, a comparison is made for ARAIM availability computed from various system combinations with GPS. The considered combinations included: GPS+GLONASS; GPS+Galileo; GPS+BeiDou; GPS+GLONASS+Galileo; GPS+GLONASS+BeiDou; GPS+Galileo+BeiDou; and finally all constellations, i.e. GPS+GLONASS+Galileo+BeiDou.

4.2. Probabilities of Fault Modes

Safety is assured for LPV-200 if the sum of the product of the missed detection (P_{md_mode}) and prior probabilities (P_{prior_mode}) for all suspected fault modes is below the probability of hazardous misleading information in the vertical position direction ($P\{HMI\}_v = 10^{-7}$) such that (Blanch *et al.*, 2013):

$$\sum\nolimits_{modes}(P_{prior\_mode} \times P_{md\_mode}) \le P\{HMI\}_v \qquad (18)$$

For the single fault mode, the prior probability that an individual GPS satellite is in the faulted state at any given instant in time and has no effect on the other satellites is $P_{sat,GPS}$. $P_{sat,GLN}$, $P_{sat,GAL}$ and $P_{sat,BDS}$ are the corresponding probabilities for individual GLONASS, Galileo and BeiDou faults. The Standard Positioning Service - Performance Standard (SPS PS) of GPS (IS-GPS-200H, 2013) has provided assurances that there would not be more than three major service failures per year for the GPS constellation as a whole, which gives $P_{sat,GPS}$ approximately 10^{-5}. We assumed the same value for Galileo, i.e. $P_{sat,GL}$ is assumed 10^{-5}. GLONASS does not yet have a publicly available performance standard. Heng (2012) and Walter et al. (2013) showed that GLONASS SIS errors have statistically larger means and variances compared with GPS, and its historic fault rate is at least an order of magnitude larger than that for GPS. They also showed that GLONASS operation is improving with time and the overall fault rate is decreasing. Hence, a probability of 10^{-4} was used for GLONASS being in a faulted state.

For BeiDou, rigorous basis for assumptions on fault-probabilities are not yet available and will need further investigation over a long period of time. China Satellite Navigation Office has released the BeiDou Navigation Satellite System Open Service Performance Standard and signal ICD (CSNO, 2012, 2013a,b) to provide information on how the system is going to be operated in the future. This would serve as the first base for determining the appropriate degree of trust that can be placed in BeiDou. El-Mowafy (2013) suggested $P_{sat,BDS}$ of 10^{-4}, which was used in this study.

The analysis included the requirement that ARAIM detects any constellation-wide faults, when several or many satellites in one constellation are experiencing a fault. Historically this case may happen. For instance, Heng (2012) reported several instances of concurrent faults on multiple GLONASS satellites. On April 1, 2014, all GLONASS satellites transmitted wrong broadcast messages for several hours and the satellite positions were wrong by up to ± 200 km. GPS also experienced an issue in 2010. In this study, a-priori probability for constellation-wide faults for all systems was assumed 10^{-4} (see EU-U.S. WG-C ARAIM, 2015, for more discussion).

4.3. Used Parameters in the Error Model

Knowledge of the stochastic characteristics of the signals is required in the error models used in ARAIM. Stochastic characteristics of GPS, GLONASS and Galileo observations were comprehensively discussed in the literature, e.g. Walter *et al.* (2013), EU-U.S. WG-C ARAIM (2015). For BeiDou, such studies are somewhat limited, e.g. (Montenbruck et al., 2013; El-Mowafy and Hu, 2014; and El-Mowafy, 2014b). Furthermore, while GPS, GLONASS and Galileo have MEO satellites, BeiDou additionally has Geostationary (GEO) and Inclined Geosynchronous Orbit (IGSO) satellites, which require different modelling as shown in El-Mowafy (2014c). Today, the minimum broadcast *URA* for GPS is 2.4 metres, but smaller values will become possible in the future when the new GPS CNAV message format is implemented for all satellites. For GLONASS, the *URA* value is not stored in the standard broadcast navigation files. Therefore, the used value for GLONASS *URA* is set to 4 m following Walter *el al.* (2013). On the other hand, BeiDou utilizes the same *URA* indexing system applied in GPS. CNSO (2013a) indicates that BeiDou SIS accuracy is ≤ 2.5 m and most current navigation data of BeiDou indicates a *URA* index 0, i.e. *URA* of 2.4 m. The formula given in (CNSO, 2012) can also be utilised, e.g. $URA{=}2^{IN/2+1} \approx 2$ m for an index (IN) = 0.

Overall, based on our past experience, changes in *URA* is numerically shown to affect ARAIM availability most compared with changes in the other error parameters *URE*, $bias_{int}$ and $bias_{acc}$. For the *URE*, we assumed 0.5 m for GPS and 0.67 m for Galileo *SISE*. The *URE* reference values of MEO and IGSO satellites of BeiDou system were assumed similar to those of GPS. This assumption is supported by results of El-Mowafy and Hu (2014). For GEO satellites, which have lower performance compared with MEO satellites, the *URE* index reference value was taken equals to an amplification ratio of the value given to the MEO satellites (Lijun *et al.*, 2012). $bias_{int}$ of 0.75 m and $bias_{acc}$ of 0.10 m were assumed for all systems. Although these assumptions require further refinement, they however, are sufficient for the purpose of this limited experimental study; namely to demonstrate possible improvement in ARAIM availability when integrating various combinations of GNSS constellations with GPS.

5. RESULTS

Table 2 gives a comparison of the achieved ARAIM availability after processing the above data at stations CUT0, ZIM3, and ABMF for the various combinations of GLONASS, Galileo and BeiDou with GPS using the conventional undifferenced observation model. A satellite elevation mask angle of 10 degrees was used to allow for small banking of aircraft. A complete list of the percentage of availability, and the four metrics used in the assessment of meeting LPV-200 requirements, i.e. $VPL<VAL$, 95% and 99.99999% accuracy are given in Table 3 for station CUT0 as an example. The mean and standard deviations of the four metrics are given in the table. The table confirms the fact that GPS should be integrated with other constellations to obtain ARAIM availability above 99%. In almost all epochs processed, the outcome of the three ARAIM availability requirements (95% and 99.99999% accuracy requirements and EMT requirement) follow the results of the requirement $VPL<VAL$. Table 3 show in a form of figures the time series of *VPL* and absolute values of *VPE* at the three stations CUT0, ZIM3, and ABMF,

respectively. The *VAL* value of 35 m, used in LPV-200, is also shown. Recall that for ARAIM to be available, the condition *VPL* ≤ *VAL* should be met.

Table 2. Percentage of ARAIM Availability

Mode/station	CUT0	ZIM3	ABMF
GPS	74.50	85.16	83.16
GPS+GLN	99.61	100.0	98.70
GPS+ BDS	100.0	100.0	90.92
GPS+ GAL	89.55	99.20	87.65
GPS+GLN+GAL	100.0	100.0	100.0
GPS+GLN+BDS	100.0	100.0	99.18
GPS+GAL+BDS	100.0	100.0	94.35
GPS+GLN+GAL +BDS	100.0	100.0	100.0

Table 3. Mean and standard deviations of ARAIM availability metrics at CUT0

GNSS	VPL < VAL (35m) (mean/stdv)	%95 acc. < 4m (mean/stdv)	%99.99999 acc. < 10m (mean/stdv)
GPS only	29.81/12.20	2.71/0.65	7.21/1.82
GPS+GLN	22.40/3.68	1.96/0.22	5.30/0.71
GPS+ BDS	18.70/2.30	1.76/0.18	4.80/0.48
GPS+ GAL	24.22/5.91	2.41/0.41	6.34/1.08
GPS+GLN+GAL	21.84/3.00	1.84/0.23	5.01/0.62
GPS+GLN+BDS	18.23/1.83	1.53/0.15	4.20/0.40
GPS+GAL+BDS	18.82/2.31	1.68/0.17	4.58/0.45
GPS+GLN+GAL+BDS	16.78/1.66	1.47/0.14	4.00/0.34

Table 4. Time series of *VPL* and *VPE* on 1st March 2015 (Mask 10°) – Part I

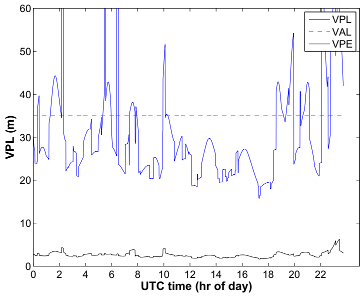
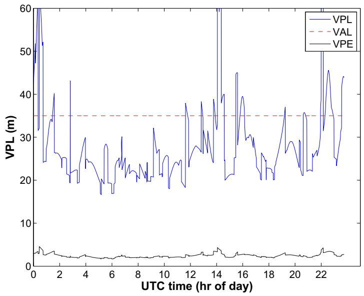
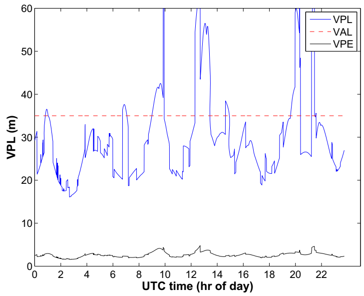
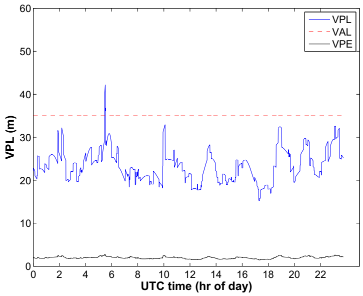
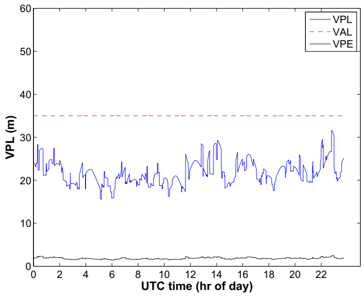
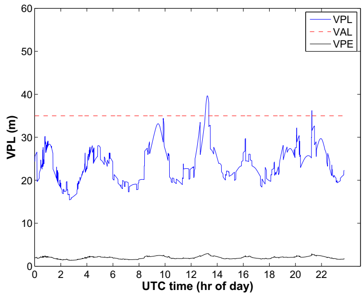
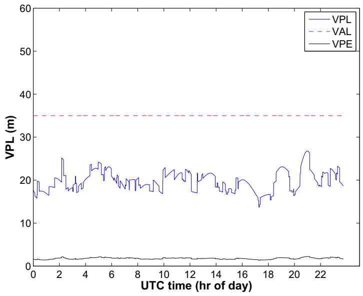
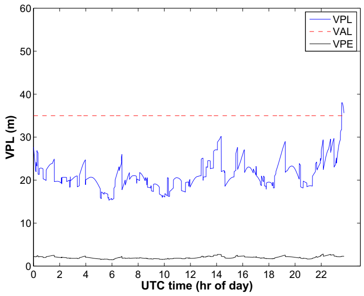
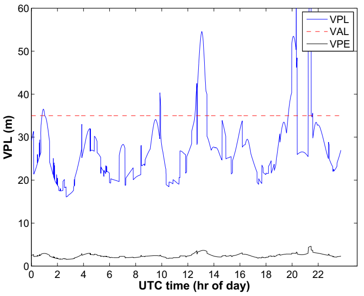
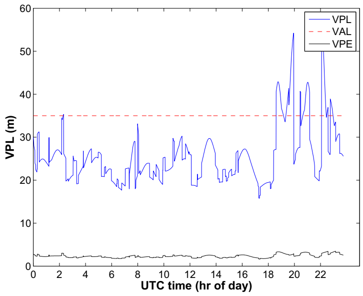
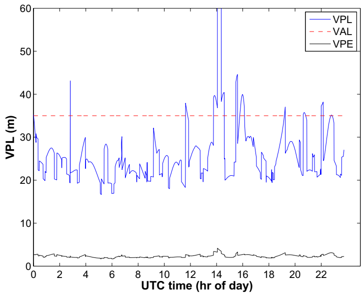
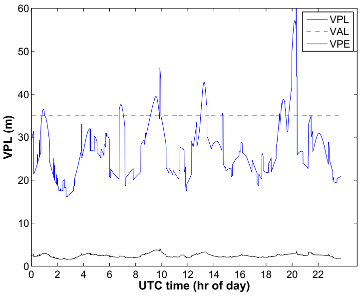
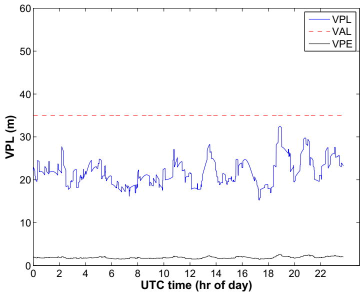
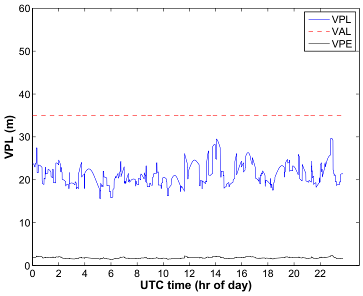
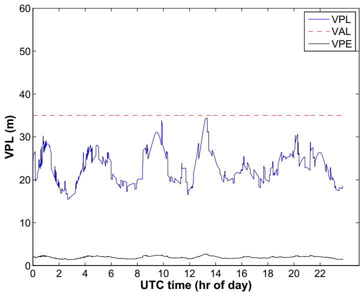
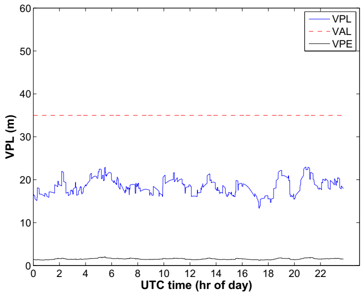
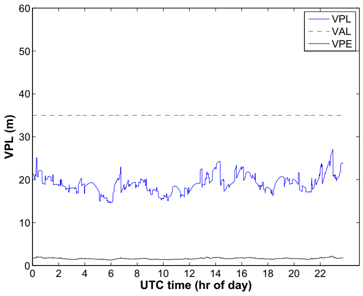
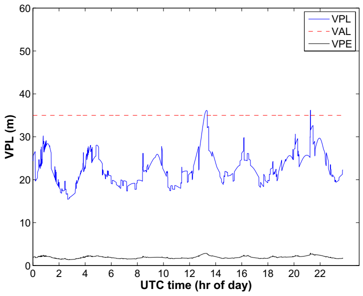
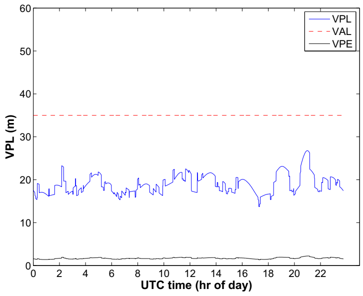
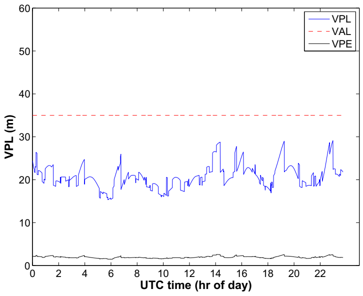
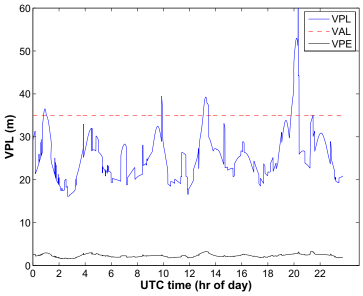
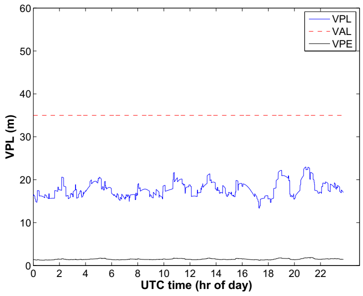
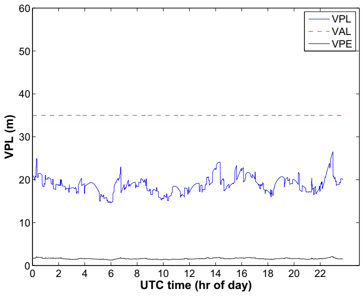
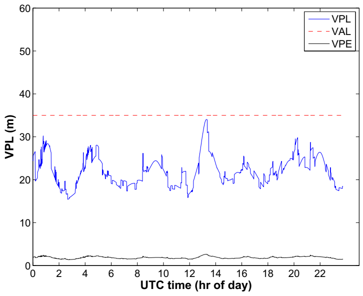
Mode	CUT0	ZIM3	AMBF
GPS only			
GPS+GLN			
GPS+ BDS			
GPS+ GAL			

Table 4. Time series of *VPL* and *VPE* on 1st March 2015 (Mask 10°) – Part II

Mode	CUT0	ZIM3	AMBF
GPS+GLN +GAL			
GPS+GLN +BDS			
GPS+GAL +BDS			
GPS+GLN +GAL +BDS			

Inference of the results of the tables 2 and 3 and their related figures show the following:

- The use of all current GNSS constellations during the tested period and under the assumptions made gave 100% ARAIM availability in all cases at the three regions, even though Galileo and BeiDou are incomplete and the error parameters are higher than the expected future values. The use of three systems was sufficient at CUT0 and ZIM3. This result demonstrates the promising future of ARAIM when the final signals are used on board of all satellites, the completion of all constellations, the implementation of the proposed Integrity Support Message (see EU-U.S. WG-C ARAIM, 2015), and the use of CNAV. Finalisation of the stochastic parameters and fault probabilities for each constellation is still a task that needs continuing research. The impact of integrating Galileo, compared with that of GLONASS or BeiDou is limited due to the limited availability of Galileo satellites at the time of the study (4 satellites). However, this still adds to the availability of ARAIM and will continue to improve the performance with time as more satellites are deployed.

- In our test, the computed *VPE* were always bounded by the *VPL*. For example, at station CUT0 the *VPE/VPL* ratio, depicted in Figure 2, was in general within ± 0.2. The standard deviations of the *VPE* using the integrated constellations were less than those for GPS mode, indicating better positioning results. The amount of improvement varied across the test sites according to the number and quality of the collected observations. Although this test covered only one month, it gives a good indication about the future performance of the method.

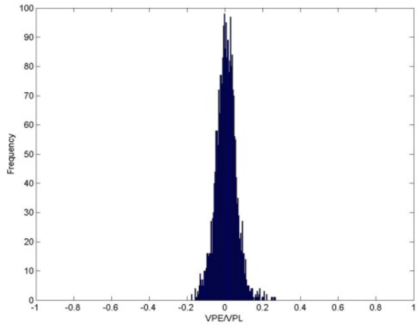


Fig. 2. VPE/VPL ratio using the GPS+Galileo+BeiDou at CUT0

6. CONCLUSION

To demonstrate the improvement gained when using various combinations of GNSS constellations, ARAIM availability was investigated in a limited study using real data (March 2015) at several IGS stations capable of tracking all GNSS constellations. Tested combinations of constellations included, GPS+GLONASS; GPS+Galileo; GPS+BeiDou; GPS+GLONASS+Galileo; GPS+GLONASS+BeiDou; GPS+Galileo+BeiDou; and finally all four constellations. Results showed that the use of all current constellations gave 100% ARAIM availability with the assumed values for error parameters (*URE*, $bias_{int}$ and $bias_{acc}$) and using an elevation mask angle of 10^o, even though Galileo and BeiDou are yet incomplete. In all cases, the *VPE* values were bounded by the *VPL* indicating validity of the ARAIM integrity approach during the test period and for the used data set. Similar performance is expected under similar test conditions.

Acknowledgment

The Institute for Geoscience Research (TIGeR), Curtin University, is acknowledged for partially funding this research.

REFERENCES

Blanch, J., Walter, T., Enge, P., Wallner, S., Fernandez, F.A., Dellago, R., Ioannides, R., Hernandez, I.F., Belabbas, B., Spletter, A., and Rippl, M. (2013). Critical Elements for a Multi-Constellation Advanced RAIM. *Navigation*, **60**(1), 53-69.

Blanch, J., Walter, T., and Enge, P. (2014). Optimal Positioning for Advanced RAIM. *Navigation*, **60**(4), 279-289.

China Satellite Navigation Office (CSNO). (2012). *BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B1 (Version 1.0),*" www.beidou.gov.cn, 2012.

China Satellite Navigation Office (CSNO). (2013a). *BeiDou Navigation Satellite System Open Service Performance Standard* (BDS-OS-PS-1.0)". www.beidou.gov.cn, 2013.

China Satellite Navigation Office (CSNO). (2013b). *BeiDou Navigation Satellite System Signal in Space Interface Control Document Open Service Signal* (BDS-OS-SIS-ICD-2.0)," www.beidou.gov.cn., 2013.

Choi, M., Blanch, J., Walter, T., Akos, D., and Enge, P. (2012). Evaluation of Multi-Constellation Advanced RAIM for Vertical Guidance using GPS and GLONASS Signals with Multiple Faults. *Proceedings 25th Interntional Technical Meeting, ION*, Nashville TN, Sept. 17-21, 2012, 884-892.

Ene, A., Blanch, J., and David, P.J. (2007). Fault detection and elimination for Galileo-GPS vertical guidance. *Proceedings of the 2007 National Technical Meeting of the Institute of Navigation*, San Diego, CA, 22-24 Jan., 2007, 1244–1254.

El-Mowafy, A. (2013). RAIM for Vertical Guidance Using GPS and Beidou," *Journal of Global Positioning System*. **12**(1), 28-37.

El-Mowafy, A. (2014a). ARAIM Using GPS, GLONASS and Beidou. *Proceedings of the European Navigation Conference (ENC-GNSS)*, Rotterdam, Netherlands, April 14 – 17, 2014, 1-11.

El-Mowafy, A. (2014b). GNSS Multi-frequency Receiver Single-Satellite Measurement Validation Method," *GPS Solutions*, **18**, 553-561.

El-Mowafy, A. (2014c). Quality Monitoring of BeiDou *GEO/IGSO/MEO* Satellite Observations", *IEEE Workshop on Asia-Pacific Satellite Navigation And Positioning,* 27 -28 February, 2014, Brisbane.

El-Mowafy, A. and C. Yang (2015). Limited sensitivity analysis of ARAIM availability for LPV-200 over Australia using real data. *Advances in Space Research,* doi:10.1016/j.asr.2015.10.046, 12pp.

El-Mowafy, A., and Hu, C. (2014). Validation of BeiDou Observations," *Journal of Applied Geodesy*. **8**(2), 155–168.

EU-US Cooperation on Satellite Navigation, WG C-ARAIM Technical Subgroup "*ARAIM Technical Subgroup Milestone 1 Report*. (2012). http://ec.europa.eu/enterprise/newsroom/cf/getdocument.cfm?doc_id=7793 Accessed July 2015.

EU-U.S. Cooperation on Satellite Navigation Working Group, C-ARAIM Technical Subgroup Milestone 2 Report (2015), http://www.gps.gov/policy/cooperation/europe/2015/working-group-c/ARAIM-milestone-2-report.pdf, [Accessed July 2015].

GNSS Evolutionary Architecture Study Phase II Report (GEAS) (2010). *http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/library/documents/media/GEASPhaseII_Final.pdf.* Accessed July 2015.

Heng, L. (2012). Safe Satellite Navigation with Multiple Constellations: Global Monitoring of GPS and GLONASS Signal-In-Space Anomalies. Ph.D. Dissertation, Stanford University, Available at http://waas.stanford.edu/~wwu/papers/gps/PDF/Thesis/LHengThesisFinalSignedSec.pdf.

ICAO, Annex 10 (2009). *GNSS standards and recommended practices (SARPs). Section 3.7, Appendix B, and Attachment D, Aeronautical Telecommunications,"* Vol. 1 (Radio Navigation Aids), Amendment 84.

IS-GPS-200H. (2013). *Interface Specification, NAVSTAR GPS Space Segment/ Navigation User Interfaces*," http://www.gps.gov/technical/icwg/IS-GPS-200H.pdf, 24 Sept 2013, Accessed July 2015.

Joerger, M., and Pervan, B. (2014). Solution Separation and Chi-Squared ARAIM for Fault Detection and Exclusion," *Proceedings of IEEE/ION PLANS 2014, Monterey, CA*, May 2014, 294-307.

Lee, C., and McLaughlin, M. (2007). Feasibility Analysis of RAIM to Provide LPV-200 Approaches with Future GPS. *Proceedings of the ION GNSS 2007, Fort Worth, TX,* Sept. 25-28, 2007, 2898-2910.

Lijun, P., Kai, J., Xiaojun, D., Yan, Z., and Wenqiang Y. (2012). Receiver Autonomous Integrity Monitoring Parameter Design and Analysis for Multi-Constellation Navigation. *Proceedings China Satellite Navigation Conference (CSNC)*, Vol. 2, *2012*, 15-28.

Liu, Y., and Zhu, Y. (2014). Design and Performance Evaluation of Airspace-Ground Cooperative GPS/BeiDou Dual-constellation RAIM Algorithm. *Proceedings of ION International Technical Meeting 2014*, San Diego, CA, 27-29 Jan. 2014, 127-136.

Montenbruck, O., Hauschild, A., Steigenberger, P., Hugentobler, U., Teunissen, P., Nakamura, S. (2013). Initial assessment of the COMPASS/BeiDou-2 regional navigation satellite system," *GPS Solutions.* **17**(2), 211-222.

Misra P. and P. Enge, (2006). *Global Position System: Signals, Measurements, and Performance.* Ganga-Jamuna Press.

Rippl, M., Spletter, A., and Günter, C. (2011). Parametric Performance Study of Advanced Receiver Autonomous Integrity Monitoring (ARAIM) for Combined GNSS Constellations. *Proceedings of the International Technical Meeting of The ION*, San Diego, California, 24-26 Jan. 2011, 285-295. .

Walter, T., Blanch, J., Choi, M.J., Reid, T., Enge, P. (2013). Incorporating GLONASS into Aviation RAIM Receivers. *Proceedings of the 2013 International Technical Meeting of the Institute of Navigation*, San Diego, CA, 27-29 January, 2013, 239-249.

Received: 2015-12-08,

Reviewed: 2015-01-19, by P. Wielgosz,

Accepted: 2015-01-22.