Advanced RAIM Demonstration using Four Months of Ground Data

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ABSTRACT

In the near future, many more navigation satellites with dual frequency L1 and L5 will be deployed. The increased number of satellites and the possibility of mitigating the ionospheric delay using dual frequency have opened the door to the possible use of RAIM for vertical guidance. For this purpose, several Advanced RAIM (ARAIM) algorithms have been proposed and extensive simulation studies have established that with two constellations it might be possible to achieve global coverage of LPV 200, which requires a 35 meter Vertical Alert Limit. However there have only been limited tests with actual receiver measurements. In order to build confidence in ARAIM for vertical guidance, which is dependent on the performance of the GNSS core constellations, an extensive validation effort on an ARAIM prototype will be necessary.

In this paper, we will test an ARAIM prototype using large datasets of L1 CA and L2 semi-codeless GPS measurements collected in ground stations located worldwide. Our specific goal for this paper is to test the ARAIM algorithm on a hundred ground receivers for four months. For each receiver, we will compute the Vertical Protection Level (VPL), the actual Vertical Position Error (VPE) etc every second. Then we will test the ability of ARAIM to bound VPEs under nominal conditions – the actual data - , data fault conditions – the faults that might have happened during the four months and are similar to the real fault condition-, and simulated fault conditions.

INTRODUCTION

In the next years, two major enhancements will be implemented in the GNSS environment and many studies suggest it will be possible to mitigate the vertical position error. Those two changes are: transmitting dual frequency L1, L5 from GPS satellites and the deployment of new GNSS constellations. The two enhancements will allow receivers to remove the ionsophere-induced errors and compute more accurate position fixes. More importantly, the redundancy can be exploited for the application of RAIM to vertical guidance. This possibility has been evaluated using Advanced RAIM (ARAIM) in several studies [1], [2], [3], [4], [5]. The fundamentals of an ARAIM prototype have been established from previous study [6], and the ARAIM algorithm has been applied successfully to data collected in flight tests [7]. The goal of this paper is to validate the capability of ARAIM to provide conservative error bounds on the vertical position error with a large amount of real ground data, which has not been done before.

This paper is organized as follows. In the first section , the details about acquiring real measurement data and the processing setup for the algorithm evaluation are presented. This explains the size, type, and period of the data, and the computing. Then, a brief description of the ARAIM algorithm as well as the error models will be given. In particular, the multipath error model and threat model are defined. Also, the conditions for choosing the measurements and the carrier smoothing method are presented. The fault detection methodology is illustrated briefly at the end of the section. In the second section, , the results of the validation under three types of conditions are shown and discussed, with a focus on the data anomalies that were found during the processing.

ARAIM VALIDATION SETUP

This section presents the processing of the ARAIM algorithm prototype using dual frequency measurements acquired from ground GPS receiver stations. The purpose of this section is to illustrate the processing setup of the data and the algorithm and to validate the ability of the ARAIM algorithm under three kinds of conditions: fault free conditions, simulated fault conditions, and data fault conditions which is similar to the real fault condition.

Data

The data was collected from eighty two Continuously Operating Reference Station (CORS) network for four months (9/1/2010 – 12/31/2010) in the U.S. territory and worldwide as shown in Table 1. The type of data file is RINEX. Instead of L5 which is not operating now in a sufficient number of satellites, L1 CA and L2 semi-codeless code and carrier phase measurements were used. The sample rate was 1 Hz. A total of 9,461 data files were

processed. Each data file has real measurements for twenty four hours of one receiver station.

Table 1. *GPS receiver stations*

ID	City	State	ID	City	State
al40	Alexander	AL	scun	Union	SC
al60	Montgomery	AL	scwt	Walterboro	SC
al70	Troy	AL	tn31	Nashville	TN
azkr	Kearny	AZ	tn32	Gallatin	TN
azpe	Peoria	AZ	tn33	Clarksville	TN
bjpa	Parakou	BG	tn34	Belfast	TN
brft	Fortaleza	BR	tn35	McEwen	TN
brw1	Barrow	AK	vtbe	Bennington	VT
cola	Columbia	SC	vtd2	Dummerston	VT
colb	Columbus	OH	vtd9	Derby	VT
gast	Gastonia	NC	vtda	Danby	VT
ict1	Wichita	KS	vtmi	Middlebury	VT
ict3	Wichita	KS	vtsp	Springfield	VT
ict4	Wichita	KS	yfb1	Iqaluit	NN
idss	Soda Springs	ID	yqx1	Gander	NF
inhc	Danville	IN	ywg1	Winnipeg	MB
jnu1	Juneau	AK	yyr1	Goose Bay	NF
kycp	Campbellsville	KY	zab1	Albuquerque	NM
kytd	Elizabethtown	KY	zab2	Albuquerque	NM
msjk	Jackson	MS	zan1	Anchorage	AK
msox	Oxford	MS	zau1	Aurora	IL
msyz	Yazoo City	MS	zbw1	Nashua	NH
mtdt	Helena	MT	zdc1	Leesburg	VA
mtum	Greenough	MT	zdv1	Denver	CO
ncca	Carthage	NC	zfw1	Fort Worth	TX
nccl	Cedar Island	NC	zhn1	Honolulu	HI
ncet	Elizabethtown	NC	zhu1	Houston	TX
neho	Holdrege	NE	zjx1	Jacksonville	FL
njoc	Toms River	NJ	zkc1	Kansas City	KS
nvbm	Las Vegas	NV	zla1	Los Angeles	CA
nvca	Las Vegas	NV	zlc1	Salt Lake City	UT
nvla	Laughlin	NV	zma1	Miami	FL
nvlm	Las Vegas	NV	zme1	Memphis	TN
nvpo	Las Vegas	NV	zmp1	Minneapolis	MN
nvsv	Near Ely	NV	zny1	New York	NY
nvtp	Las Vegas	NV	zoa1	Oakland	CA
ohco	Coshocton	OH	zoa2	Oakland	CA
ohli	Jackson Town	OH	zob1	Oberlin	OH
ohun	Marysville	OH	zse1	Seattle	WA
scha	Charleston	SC	zsu1	San Juan	PR
scsr	Sumter	SC	ztl4	Atlanta	GA

Figure 1. *GPS receiver stations distribution in the U.S. territory*

Processing

Validation and simulation were executed by MATLAB. In order to process the large amount of data files efficiently, 41 workstations were utilized in Stanford UNIX computing environment. Parallel processing was implemented using same MATLAB scripts with different receiver station data files in each workstation respectively. Average processing time was about thirty minutes for one data file. Twenty four hours were required to process the data corresponding to one month in forty one stations.

Error models

As was pointed out in [6], the ARAIM algorithm will be operating in an airborne receiver, however since we collected real measurements from ground receiver, the nominal error models must be adjusted, because the multipath environment is different. We used a ground multipath model that was described in [8] unlike the previous tests, which still used the airborne model [6]. For the URA, we used the value which was transmitted in the navigation message, whose most common value is 2.4 m.

Position Solution

With dual frequency ionosphere free smoothing method, the ionosphere-related delay was removed. . The carrier smoothing time of 100 s was applied, which is the maximum filter length. The filter is re-initialized after a cycle slip. Since the ARAIM assumed that the computing is executed by the receiver alone without any assistance from augmentations, we did not apply differential correction for the position calculation. Only measurements with a Signal to Noise ratio greater than 25dB were used. Mask elevation angle was 5 degree.

ARAIM algorithm

The ARAIM algorithm implemented in this study is presented in [3]. As in [3], the required Probability of Hazardously Misleading Information (*PHMI*) is 10^{-7} and the Prior Probability(P_{ap}) of satellite fault is 10^{-5}. We applied mode one error model, which specifies each subset includes only one failed satellite. For fault detection, a chi-square test [9] was used. After computing the position solution, we calculated the chi-square statistic defined as Weighted Sum of the Squared Errors such that:

$$WSSE = y^T \cdot W \cdot (I - P) \cdot y$$

$$P = G \cdot (G^T \cdot W \cdot G)^{-1} \cdot G^T \cdot W$$

where G is the observation matrix, W is weighting matrix, and y is an N dimensional position vector. Then we compared the each subset solution in WSSE and checked that it was below a given threshold, if the test passed, the measurements were deemed consistent. If the measurements were consistent, we computed the Vertical Protection Level (VPL) using the approach presented in [3] and [10]. If the measurements were not consistent, measurements were excluded until the remaining ones were consistent. Then we computed the VPL. If there are only four measurements in one epoch, we did not a compute position fix nor a VPL. The flow chart of the integrated version of the algorithm is presented in Figure 2.

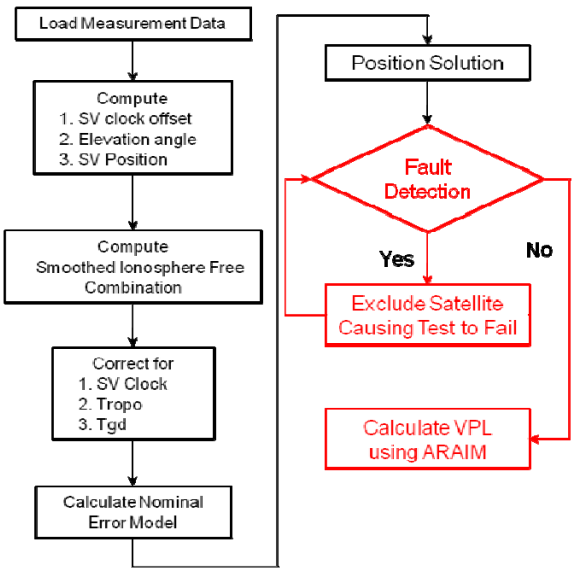

Figure 2. *Flow Chart of Algorithm*

VALIDATION RESULTS

Behavior under fault free condition

Figure 3 shows the Vertical Position Error and the Vertical Protection Level for 24 hours. This is the outcome of one receiver station located at Nashua, NH, on 1 September 2010. The standard deviation of the station is 2.75 meters. The histogram of the Vertical Position Error to the Vertical Protection Level ratio for four months from eighty two stations is illustrated in Figure 4. The histogram represents 687,881,782 points, which are 99.99% of position fixes out of total position fixes. The 0.01% of position fixes accounts for the situation that the ARAIM cannot bound the vertical position error. The underbounding cases had all a point in common they seemed to be related to very poor geometries. The poor geometries seem to have caused numerical issues in the matrix inversions. For example, several of this underbounding situations are have negative chi-square statistics, a sign of the unstability of the computation. Although only a .001% of the data, it is still a large number of anomalies, so it was not possible to go through all of them manually. Although this is not a source of concern for ARAIM, it will need to be investigated further.

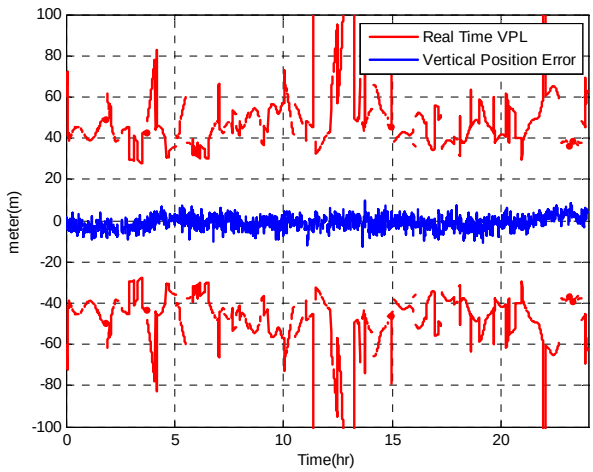

Figure 3. *VPE and VPL as a function of time in fault free condition*

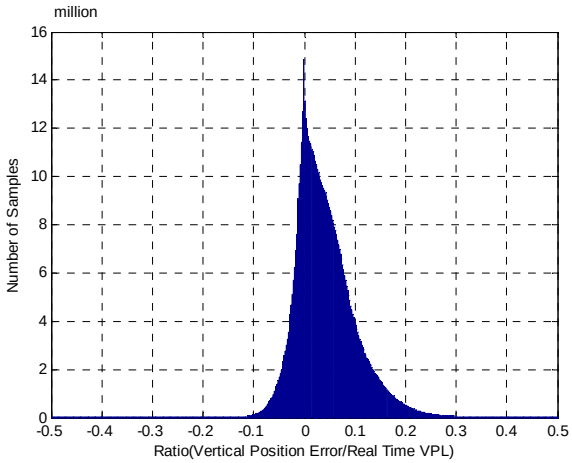

Figure 4. *Histogram of the VPE/VPL ratio in fault free condition*

Simulation of 1 failure

In this case we added a bias intentionally in order to simulate satellite failure on all measurements of PRN 2 at all times. We applied 20 meters bias which is chosen in [6]. Figure 5 shows the VPE and the VPL for 24 hours. The receiver station and date are the same as in the fault free condition. Due to the simulated satellite failure, the standard deviation of the position error increased to 6.87 meters. However, the VPE is always well bounded by the VPL. Figure 6 shows the histogram of the VPE to VPL ratio for one month and all eighty-two receivers. It is important to notice that the failure condition persists for much longer than assumed in the threat model, which shows that there is margin.. In this severe failure condition, we can see that the algorithm performed as we expected.

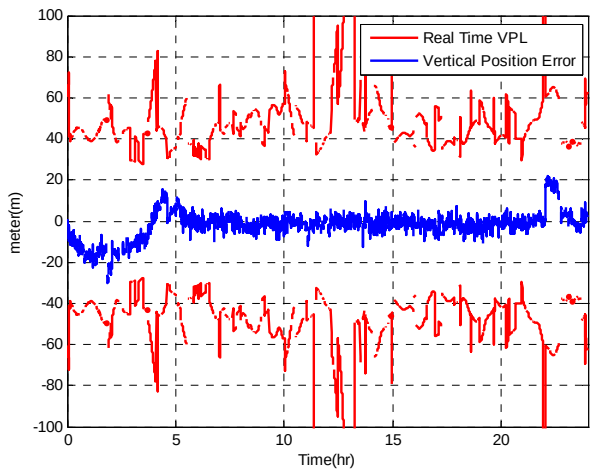

Figure 5. *VPE and VPL as a function of time with one simulated failure condition*

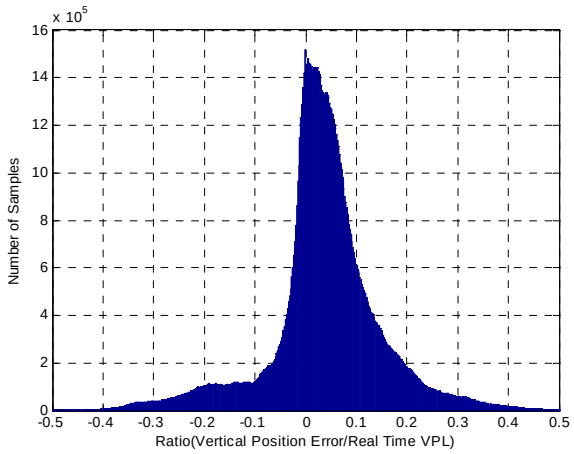

Figure 6. *Histogram of the VPE/VPL ratio in with simulated one failure condition*

Abnormal case in fault free conditions

However, not all the VPE are less than the VPL under fault free conditions. As you see in Figure 7, one of the VPE is greater than the VPL. The position error of vertical component reached 1,700 km. It happened 11 October 2010 at Leesburg, VA, near Washington D.C. According to the assumption of the ARAIM algorithm, VPE should be less than the VPL, however the characteristics associated with the outlier epoch do not show any abnormal indicators: the chi-square test passed and the solution separations were consistent. Elevation angles and signal to noise ratios were normal enough to compute a position fix. However, all the measurements had a large discontinuity between consecutive measurements (instead of affecting only one satellite failure, which would have been caught by the algorithm). The slant range of the position error was 2,782 km.

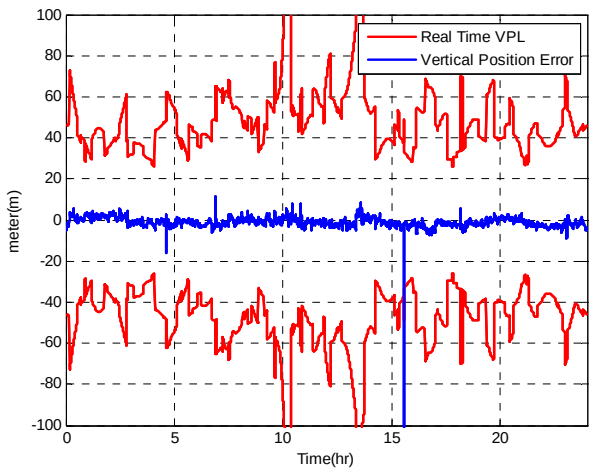

Figure 7. *VPE and VPL as a function of time with outlier*

Eventually, we found that the position pointed to another GPS receiver station located at Iqaluit in Canada as shown in Figure 8. Since both receiver stations are WAAS reference stations, we can infer that the measurements of Iqaluit station were inserted into (and replaced) the measurements of the Leesburg station for one epoch.. We observed this situation two times out of total position fixes. Another case happened at Memphis, TN, on 6 October 2010. The outlier position corresponded to the WAAS Reference station at San Juan in Puerto Rico. These two cases should not be taken into account for the validation of ARAIM, because it is not a failure mode in a real airborne situation, due to the fact that an airborne receiver processes the measurements in real time and does not use re-distributed data from other receivers. However, it is a point to keep in mind when processing large amounts of data for validation.

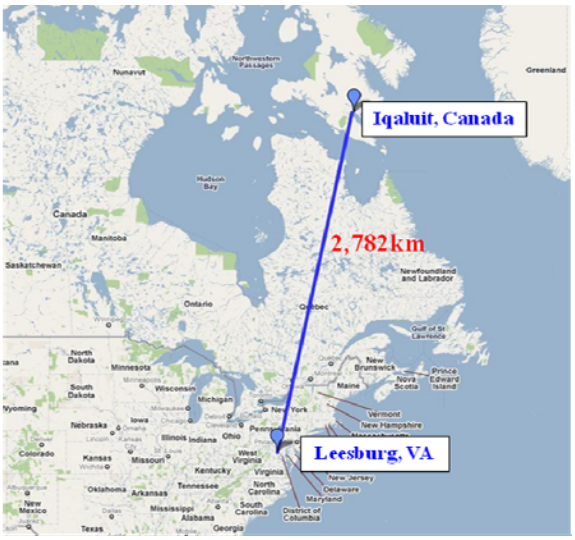

Figure 8. *The position of abnormal case in Leesburg receiver station pointed to the position of Iqaluit receiver station*

Behavior under data fault condition

In this paragraph, we show the ability of the ARAIM for fault detection and exclusion under a data fault condition which is similar to a real fault condition – and which could be a real satellite anomaly. . The reason why we used the term data fault is that the quality of RINEX file is not always good. This is not due to the fact that the measurement itself has a fault, but that the data have faults that can be derived from data collecting, also called data assembly. Because of this feature, we could observe fault situations similar to real fault conditions. In this case, we first recorded how many times exclusion occurred and which stations conducted exclusions in order to compare outputs from the algorithm without exclusion and the algorithm with exclusion. Figure 9 and 10 represent the VPE and the VPL without exclusion and with exclusion for 24 hours of one receiver station which included fault measurements in RINEX file. The receiver is located at Barrow, AK, and the fault measurements were observed on 30 September 2010. As you see in Figure 9, which is without exclusion, after 23 hours, the position error of vertical component increased rapidly up to 120 meters. Although the anomaly resulted in a large position error in the VPE was always bounded by the VPL. . Figure 10 shows that with the exclusion on, the anomaly was detected, so that the VPE becomes normal again. This shows that any faults that were considered in the threat model were detected and excluded successfully. Even without exclusion, they did not cause any loss of integrity. We also found that other receivers have performed its exclusion due to PRN30 on the same date so it will be necessary to investigate further to make sure it was not a true anomaly.

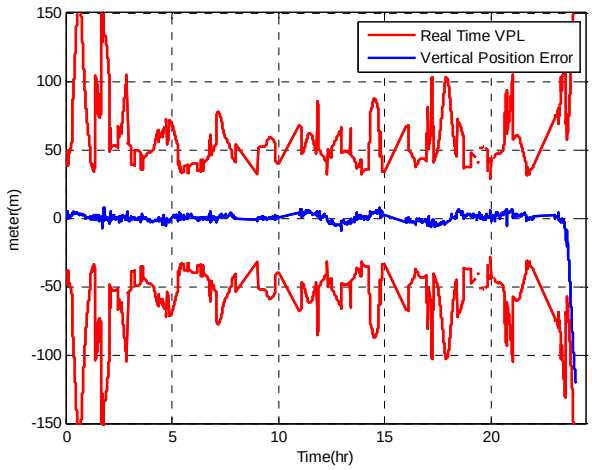

Figure 9. *VPE and VPL as a function of time without exclusion in data fault condition*

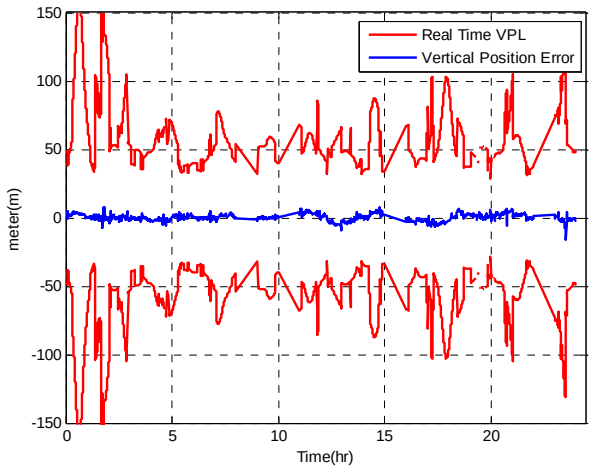

Figure 10. *VPE and VPL as a function of time with exclusion in data fault condition*

CONCLUSION

The ARAIM prototype which has been proposed in [6] went through extensive validation process in this study. We computed the VPEs and the VPLs using this algorithm for four months of data from eighty two stations. In order to certify the capability of the algorithm, we put three types of condition that would cover a range of possible situations in real airborne system. The result of evaluation shows that the algorithm performed, as we expected. In fault free conditions, simulated fault conditions and data fault condition, we observed the VPE was always less than the VPL, which did not break the integrity characteristics. We did detect a relatively large amount of situations where the computation of the VPL appears to be unreliable for numerical reasons. For VPLs below 100 m, even severe conditions and regardless of fault detection, the ARAIM algorithm shows reliable error bounding.

An immediate task will consist on ruling out and explaining completely the underbounding cases that seem to be due to numerical reasons. Later, we will expand this prototype to a test ARAIM with several constellations,, such as Galileo and GLONASS, in order to establish more credibility in terms of integrity and availability.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Federal Aviation Administration (FAA) CRDA 08-G-007 for supporting this research and Dr. Jiwon Seo, Stanford University, for his advice of network parallel computation. The opinions discussed here are those of the authors and do not necessarily represent those of the FAA or other affiliated agencies.

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