Development of a Real-time GNSS Software Receiver for Evaluating RAIM in Multi-constellation

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ABSTRACT

As Global Navigation Satellite System continues to upgrade, there will be an increasing number of satellites and signals. This offers users benefits such as increased availability and improved diversity of signal. For safety-of-life users like aviation, higher availability of integrity is the key goal. A technology providing integrity with little or no ground infrastructure overhead is receiver autonomous integrity monitoring (RAIM). As more satellites are visible to the receiver, the redundancies increase and RAIM availability for detecting faults improves. For evaluating RAIM in multi-constellation in a physical receiver, a real-time software receiver is developed using relative low-cost Commercial Off-The-Shelf (COTS) components. The receiver currently supports single frequency and three constellations with Code Division Multiple Access (CDMA) signals including GPS L1 C/A, Galileo E1 and BeiDou B1. An efficient software architecture are proposed for the real-time purpose. Some issues are addressed when integration multi-constellation. Using the outputs from the receiver, a developed RAIM script computes the protection levels for the receiver position. Several tests are conducted in

multiple locations worldwide and the results show the multi-constellation GNSS has improvement on the position solution and protection level. In the end, future path forward dual-frequency Advanced RAIM (ARAIM) is mentioned.

INTRODUCTION

Current autonomous integrity monitoring (RAIM) is only capable of providing integrity to support horizontal guidance. The next generation Advanced RAIM (ARAIM) is built on multi-constellation GNSS and is designed to provide vertical guidance for aircraft precision landing [1]. However, using signals from different constellation adds cost and complexity to receiver design. Currently, there is an existing opportunity on single frequency to capture at least 4 satellites in view for each constellation of GPS, BeiDou and Galileo. Over East Asian, typically we can see 9 BeiDou satellites in view. The BeiDou ICDs were released recently, B1 in Dec 2012 [2] and B2 in Dec 2013 [3]. Also, there is a chance to see four Galileo satellites in view. Moreover, it is easier to implement all Code Division Multiple Access (CDMA) signal on the same frequency for receiver design.

For the first step, we take this opportunity to implement a real-time software receiver which is single-frequency and supports GPS, BeiDou and Galileo. One Universal Software Radio Peripheral (USRP) [4] is used as RF front-end and the software is developed on a Personal Computer (PC). The receiver has total 36 tracking channels which is expected to have 12 channels for each constellation. Because the constellations do not coordinate their time reference, they will have different time biases relative to the receiver clock. Hence, the time biases for each constellation are estimated separately. The receiver currently supports a single frequency but is designed to be expandable to multiple frequencies as ARAIM requires dual frequency capability. A software architecture that accounts for real-time capability is described. Several issues are addressed for integrating multi-constellation GNSS. With the measurement and satellite ephemeris from all constellations, we can evaluate the RAIM algorithm [1] using the developed tool in the previous studies [5]. Using the developed software receiver and RAIM tool, tests are conducted in multiple locations worldwide. The position solution and protection levels result are provided for showing the improvement in the multi-constellation.

This paper is organized as follows. First, the development of receiver is described. Then, an overview of GNSS signal and current status is given. The software architecture and integration issues are addressed. We then explain what the data processing flow from receiver to RAIM tool. The testing setups and results are shown. Finally, the path forward ARAIM is detailed.

MULTI-CONSTELLATION GNSS SOFTWARE RECEIVER DEVELOPMENT

The developed GNSS receiver [6] is a PC-based software receiver [7][8][9]. The hardware architecture of receiver is depicted in figure 1 and its setup is in figure 2. The hardware contains one GNSS antenna, one USRP [4] and one host PC. Currently, the supporting USRP types are N210 and B210. The external clock is optional if B210 is used. The USRP is equipped with a programmable mixing and down-conversion daughter board. Current PC is equipped with Intel qual-core Core i7 CPU in which each core can run two threads. So, total 8 threads can be run in parallel. That gives us a lot of resource to distribute tasks to multiple cores. The USRP is controlled by the PC running the Ubuntu distribution of Linux. USRP hardware driver (UHD) [10] software is used to configure the USRP and daughter board settings such as sampling rate and RF center frequency. The radio frequency (RF) signal from each antenna element is converted to a near zero Intermediate Frequency (IF) and then digitized to 14-bit complex or in-phase and quadrature outputs (I & Q). The RF center frequency is set to 1568 MHz and the sampling rate is set to 20 Megasamples per second (MSPS). The digitalized IF data is then processed in real-time and stored into hard drive in the PC.

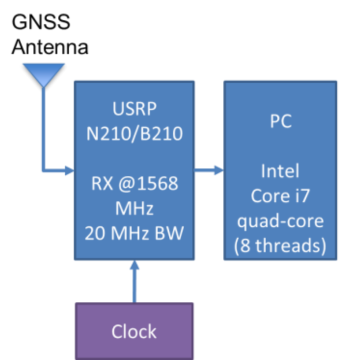

Figure 1. Block diagram of receiver

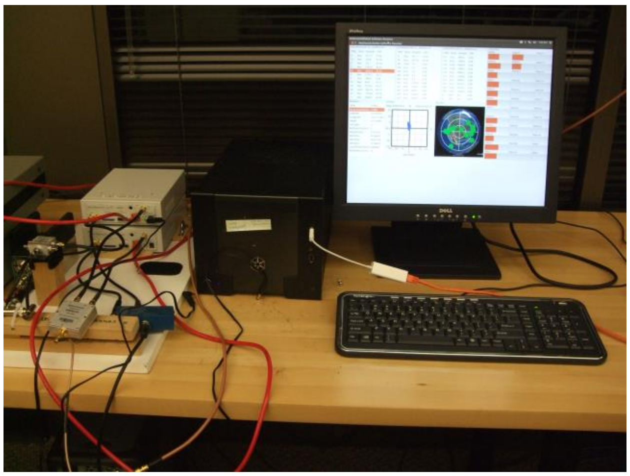

Figure 2. Receiver setup

GNSS SPECTRUM AND STATUS

With the frequency setting described in the previous section, the transmitted signal spectrum which can be received from the USRP is depicted in figure 3. The spectrum contains signals from three constellations, GPS, BeiDou and Galileo. GPS L1 C/A uses Binary Phase Shift Keying (BPSK) modulation on 1575.42 MHz and 1.023 MHz chipping rate [11]. BeiDou B1 uses Quadrature Phase Shift Keying (QPSK) modulation on 1561.098 MHz and has higher chipping rate 2.046 MHz [3]. Galileo uses the same chipping rate with GPS, but has Binary Offset Carrier (BOC) modulation on 1575.42 MHz [12]. The frequency bandwidth is 20MHz and includes the main lobes of all constellations.

Current status of GNSS constellations in Jan, 2014 is listed in table 1. The GPS PRN 30 is set as unhealthy, so total number of healthy GPS satellite is 31. The Japanese QZSS has one satellite which has the same modulation, frequency and chipping rate as GPS on L1 C/A. There are fourteen BeiDou satellites and four Galileo satellites.

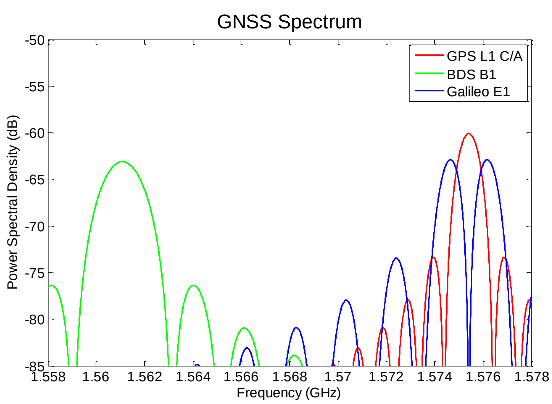

Figure 3. GNSS signal spectrum

Table 1. GNSS constellation status

Constellation	Satellite Number	Assigned PRN
GPS QZSS	31 1	1~29,31,32 193
BeiDou	14	201~214
Galileo	4	311,312, 319,320

SOFTWARE ARCHITECTURE

Because of high sampling rate 20 MSPS and high receiving channel requirement for multi-constellation, the software needs to be designed efficiently to achieve real-time capability [13]. The goals of software architecture are to run 8 threads in parallel and have 36 channels or 12 channels for each constellation. The software architecture of receiver is shown in figure 4. The software starts from requesting data from the UHD driver and then store the data into a 2-second-long queue. Every 1 millisecond data is processed in 6 working threads. Each thread serves for 6 channels in which executes functions including software correlator, signal acquisition/tracking and message decoding. These functions have the most computational complexity, so we distribute these channels to multiple threads for saving processing time. For every 100 millisecond, another thread makes measurement from all tracked channels and then solve the receiver position. As number of satellite increases, the computational load of matrix multiplication inside the positioning gets higher. Hence, a dedicated thread for positioning is needed. There is an additional thread reserved for future implementation of RAIM algorithm. By considering the complexity of RAIM algorithm, providing 1 Hz output rate should be enough for evaluating purpose.

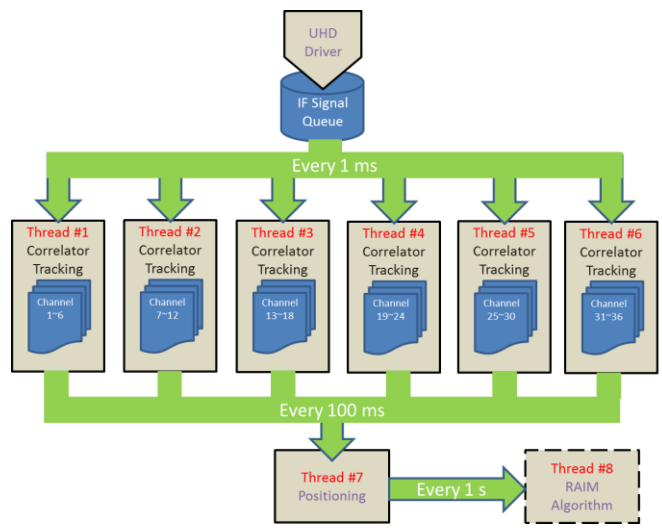

Figure 4. Software architecture

INTEGRATION ISSUES

When integrating the multi-constellation, several issues need to find solutions. For adding a constellation, an extra time unknown is added to G matrix [6] because time system is different. Currently, the time offset between GPS and Galileo is within 10ns [14]. This offset can be solved by adding extra time unknown. However, the time offset between GPS and BeiDou is around 14 seconds. This offset is too large to be solved using the G matrix. Hence, our solution is to firstly eliminate the 14 seconds and then let the positioning to solve the remaining time offset within 1 second.

In the RAIM algorithm, the User Range Accuracy (URA) from satellite ephemeris is used as weighting accounting for range accuracy difference. Currently, GPS and BeiDou provide the URA, but Galileo hasn't broadcasted the URA content yet due to not being in full operation. Hence, the URA of Galileo is assumed to be 2.4 meter according to the recent performance [14].

Because current implementation is only for single frequency, the ionospheric correction should be taken into account for range measurement. The correction is derived by the ionospheric model provided from messages of satellites. However, the ionospheric model of Galileo is NeQuick. It is different from the Klobuchar model used by GPS and BeiDou. It is better to use the same model for all constellation because different model may lead to different delay. Hence, the Klobuchar model is chosen for the ionospheric correction.

DATA PROCESSING FLOW

Current receiver has not implement RAIM algorithm in real time. The RAIM algorithm is evaluated in post-processing. The data processing flow from the receiver to RAIM algorithm is shown in figure 5. The flow starts from running multi-constellation receiver and logging required data at 1 Hz rate. The data include pseudorange, carrier phase, satellite position, ionosphere parameters, URA and clock correction. A MATLAB tool developed for multi-constellation ARAIM [5] is modified to process in the single-frequency mode. Originally, the tool was designed for the dual-frequency GPS/GLONASS. The modifications include 1) making ionospheric correction to pseudorange 2) adding the sigma of ionosphere delay to range model 3) adding one more constellation. The outputs of RAIM algorithm include Vertical Protection Level (VPL) and Horizontal Protection Level (HPL) [1][5]. VPL and HPL provide bounds of the Vertical Position Error (VPE) and Horizontal Position Error (HPE), respectively. As the number of satellite increases, the VPL and HPL are expected to decrease because of lower Dilution Of Precision (DOP).

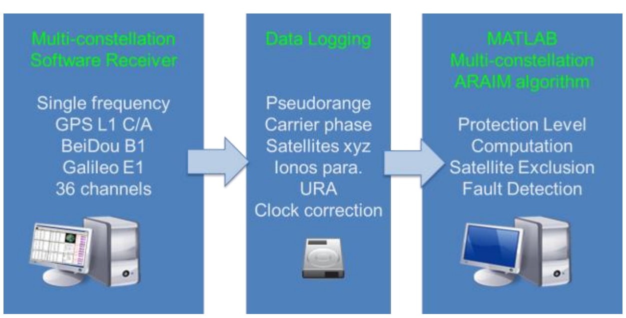

Figure 5. Data processing flow

TESTS AND RESULTS

Several tests are conducted using the data processing flow described in the previous section. Because BeiDou provides full operational regional service in Asia, the testing locations are chosen in Taiwan and Singapore for having more BeiDou satellites in view. In the initial test, a half-hour baseband data set was taken in Taiwan. The testing result includes the position solution comparison between different constellation as well as protection levels. In the second test, only logging data were taken in the worldwide locations. The testing results show 4-hour-long HPL for all locations.

A. Initial Test

In the initial test, the antenna is located on the roof of National Cheng Kung University EE building shown in figure 6. Before testing, an online GNSS planning tool provided by Trimble is used to select the specific time which the satellite geometry is interesting. The test was conducted on Dec 14, 2013 and figure 7 shows the number of satellites on that day. The maximum number of satellites is up to 28. However, we are interested in a half-hour period which has at least 4 satellites in view for each constellation. Figure 8 shows the satellites geometry in this period. Figure 9 shows the GUI of our multi-constellation software receiver when processing the data set. The receiver keeps tracking 22 satellites including 8 GPS, 9 BeiDou, 4 Galileo and 1 QZSS. The channel status, Doppler and C/No are provided. Also, the positioning result, Earth-North (EN) plot and sky plot are shown in GUI.

Figure 6. Left: testing location Right: antenna

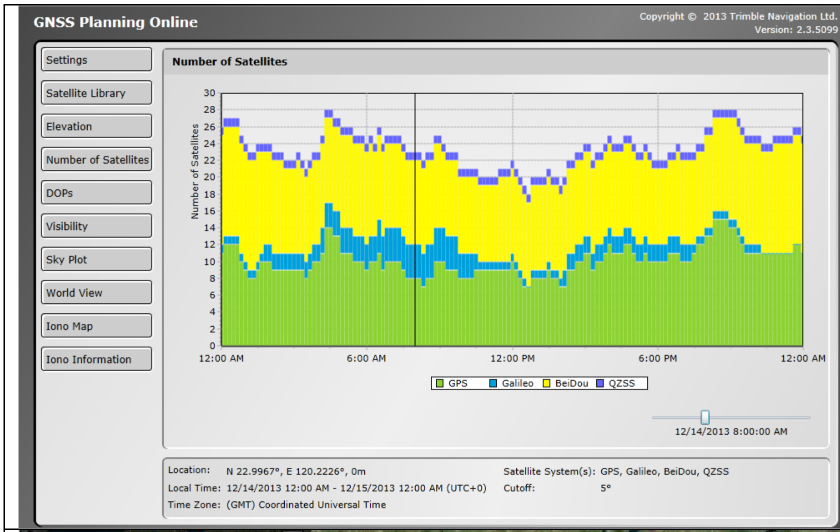

Figure 7. Prediction of number of satellite for a day long using GNSS Planning Online

Figure 8. Prediction of satellite geometry at a specific time using GNSS Planning Online

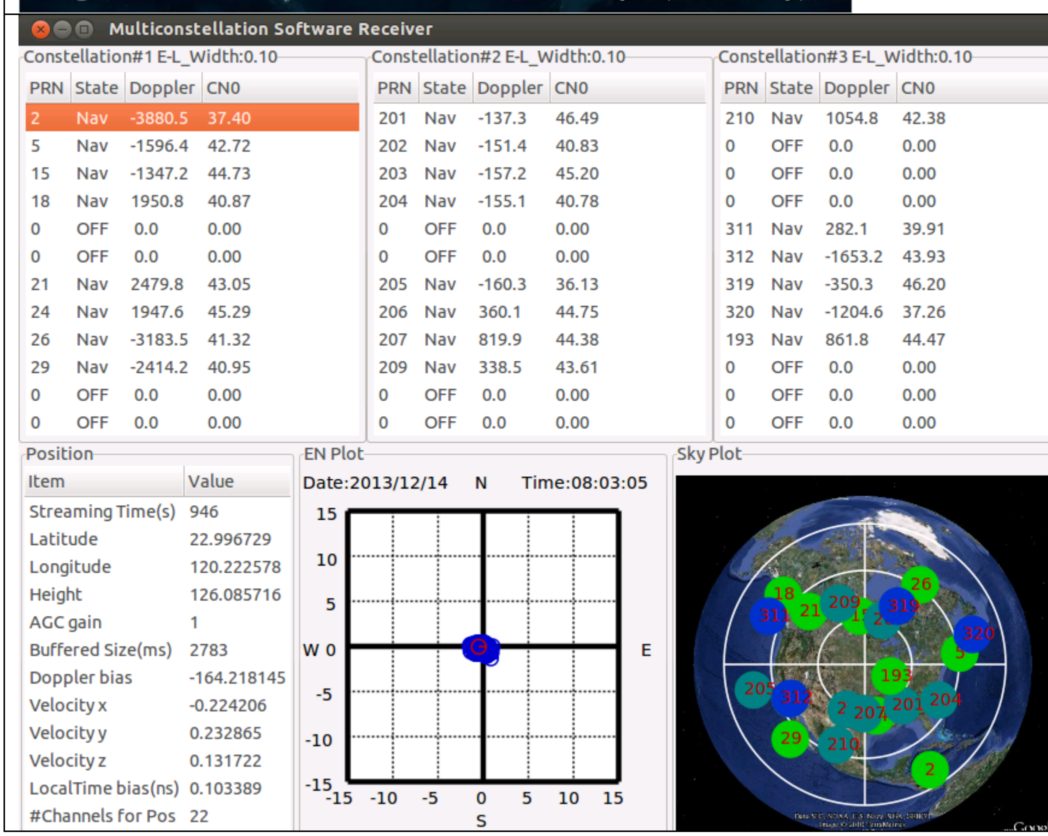

Figure 9. GUI of software receiver when processing the data set

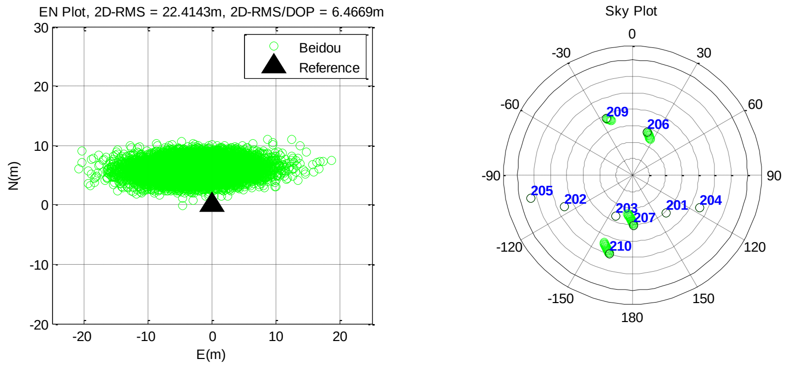

Figure 10. Left: EN plot for BeiDou Right: Sky plot for BeiDou

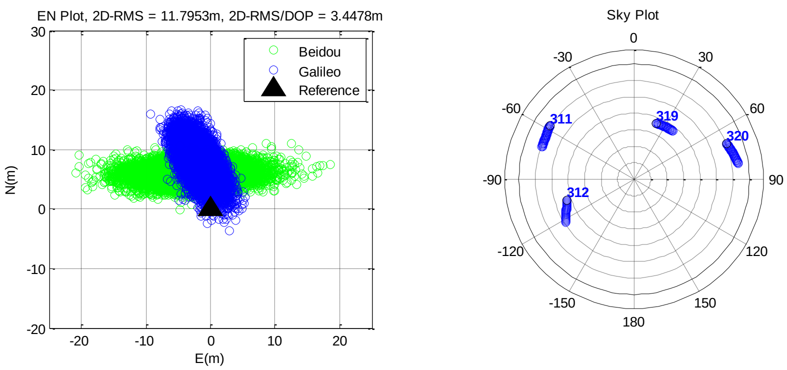

Figure 11. Left: EN plot for Galileo Right: Sky plot for Galileo

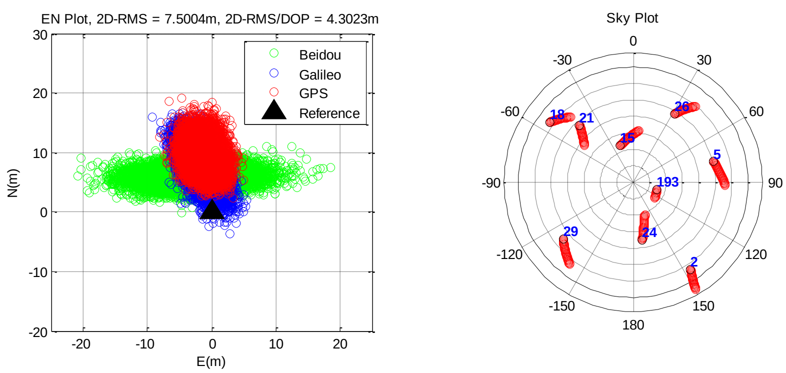

Figure 12. Left: EN plot for GPS Right: Sky plot for GPS

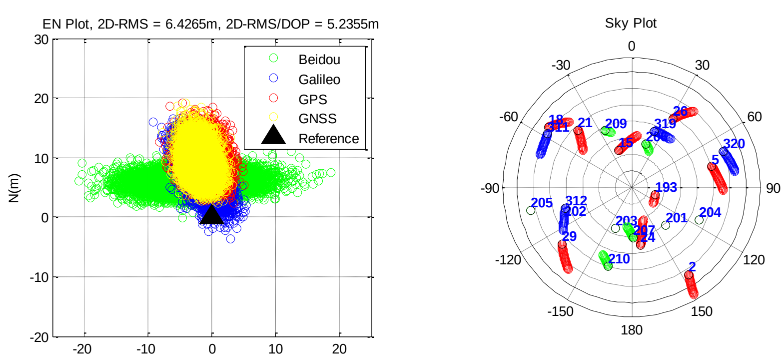

Figure 13. Left: EN plot for GNSS Right: Sky plot for GNSS

Figure 10,11,12,13 show the position results for BeiDou, Galileo, GPS and GNSS, respectively. These solutions are solved without ionospheric correction and all satellites are equally weighted. The position accuracy is provided by 2D-RMS. Also, the range accuracy is provided by 2D-RMS/DOP. For single constellation only, GPS has the best position accuracy because of better satellite geometry and more mature system. Galileo has the best range accuracy because of its signal characteristic. For multi-constellation GNSS, the position accuracy has improvement because low DOP. However, the range accuracy does not have improvement because it is an average result of all constellation.

The results of RAIM algorithm, VPL and HPE, are shown in figure 14 and 15. These preliminary protection levels are computed using single frequency only. Real protection levels should wait for dual frequency. Three cases are compared 1) GPS only – one constellation 2) GPS and BeiDou – two constellations 3) GPS, BeiDou and Galileo – three constellations. Because of single frequency only, the range sigma includes the sigma from ionospheric delay and induces the high protection levels. However, the protection levels have improvement as number of satellites increases. Also, the protection levels do provide bounds of the position errors. In the 1850 seconds, there is one GPS satellite losing lock. The VPL for GPS has dramatic change about 70 meters higher. However, the VPL for multi-constellation only has 10 meters higher. That shows the benefit of multi-constellation. The DOP does not have dramatic change if one of satellite in view loses lock.

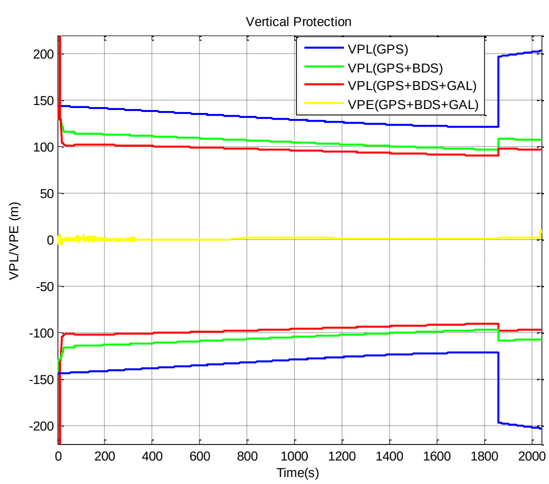

Figure 14. Preliminary VPL results for single frequency

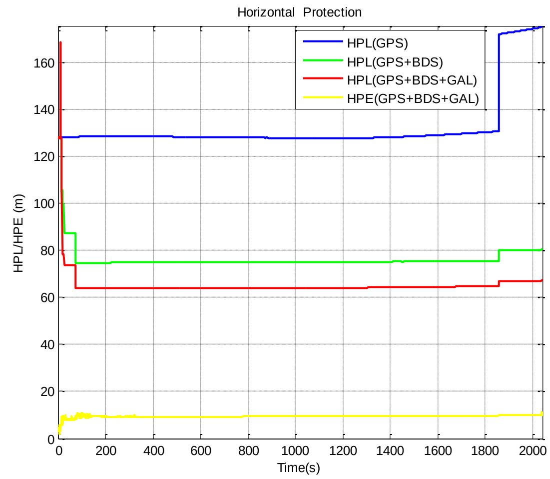

Figure 15. Preliminary HPL results for single frequency

B. Second Test

The second test is conducted in three locations on the same day. The locations are chosen in 1) Stanford University (SU), USA 2) National Cheng Kung University (NCKU), Taiwan 3) Nanyang Technological University (NTU), Singapore shown in figure 16. Figure 17 shows antenna locations at SU and NTU. Preliminary HPL results for GPS only and multi-constellation GNSS are shown for all locations in figure 18, 19 and 20. At SU, currently the maximum number of BeiDou satellites in view is only 2, so sometimes there is not much improvement with multi-constellation. However, the HPL of GNSS is always lower than GPS only. At NCKU, the improvement of HPL for multi-constellation is more than 20 meters. NTU, Singapore is in the equatorial region and the center of BeiDou five GEOs. Hence, the geometry of BeiDou in NTU is the best among three locations. Good geometry results the 40 meters improvement for multi-constellation HPL.

Figure 16. Locations in the second test

Figure 17. Antenna locations
Left: Stanford U Right: Nanyang Tech U

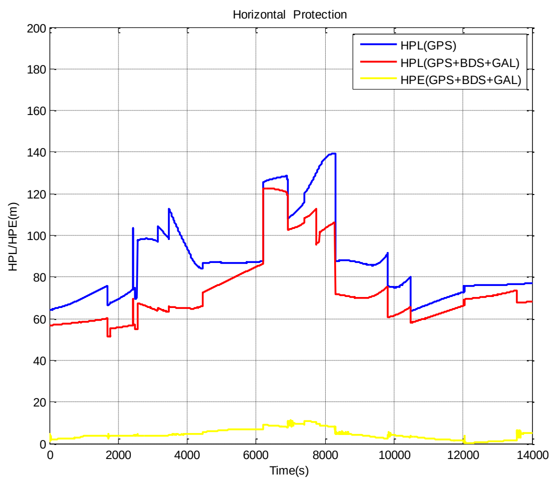

Figure 18. Preliminary HPL results at Stanford

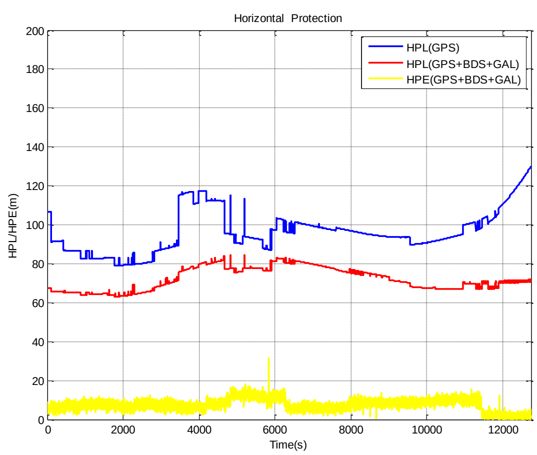

Figure 19. Preliminary HPL results at NCKU

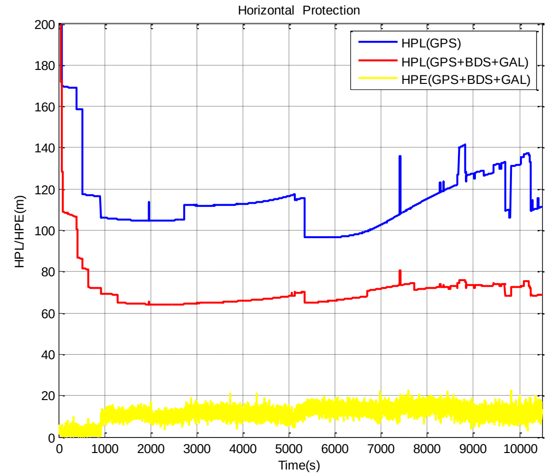

Figure 20. Preliminary HPL results at NTU

CONCLUSIONS AND PATH FORWARD

Our receiver demonstrated an implementation of software radio for multi-constellation GNSS using the COTS components. This software receiver has the repeatable advantage. Hence, everyone with the USRP and a PC can easily repeat the same setup and conduct the same test. Hence, we can test in the worldwide locations without in-person appearance. The preliminary results show that multi-constellation GNSS has improvement on position solution and protection results compared to single constellation.

For path forward ARAIM, the hardware should support dual frequency and multi-constellation. Figure 21 shows the hardware plan. We plan to have 2nd USRP for GPS L5 and Galileo E5a, 3rd USRP for BeiDou B2 and Galileo E5b and 4th USRP for GLONASS on L1 or L2. However, four USRP should be synchronized. Our previous antenna array works [15][16][17] have the similar setup, but we need to set different center frequency for each USRP. For the software part, we have a previous work on dual frequency for GPS L1/L5 [18] which can be applied on this platform. The BeiDou B2 has the same ranging code and navigation message as B1 according to latest ICD [3]. Hopefully, this software can be implemented based on all of our past experience.

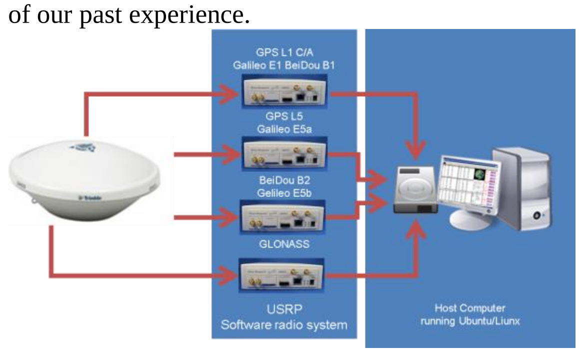

Figure 21. Hardware plan for ARAIM

ACKNOWLEDGMENTS

The authors gratefully acknowledge the FAA CRDA 12-G-003 for supporting this research. They acknowledge Professor Jyh-Ching Juang from National Cheng Kung University, Taiwan for providing the testing equipment, and I-Wen Chu also from NCKU for setting up the equipment. They also acknowledge Dr. Yung-Fu Tsai from Nanyang Technological University, Singapore for providing and setting up the equipment.

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