Direct Comparison of the Multipath Performance of L1 BOC and C/A using On-Air Galileo and QZSS Transmissions

Yu Hsuan Chen, Sherman Lo, Per Enge
Department of Aeronautics & Astronautics
Stanford University
Stanford, CA, USA

Dennis Akos
Department of Aerospace Engineering Sciences
University of Colorado, Boulder
Boulder, CO, USA

***Abstract*—New Global Navigation Satellite System (GNSS) satellites will bring common, interoperable GNSS signals on L1. These new signals, L1C Global Positioning System (GPS)/Quasi-Zenith Satellite System (QZSS) L1C and Galileo E1 Open Service (OS), promise performance improvements in many areas. One key area is that these signals, which use binary offset carrier (BOC) and multiplexed BOC (MBOC), will provide better multipath performance over the binary phase shift keyed (BPSK) GPS L1 C/A. This paper evaluates the benefit of difference using on-air measurements of these signals. The evaluation will utilize signals from to-be operational Galileo and QZSS satellites. The assessment conducts BPSK and BOC processing using signals from the same satellite to eliminate the effects of geometry.**

Keywords—multipath; BOC; MBOC

I. INTRODUCTION

Currently most consumer Global Navigation Satellite System (GNSS) receiver use only Global Positioning System (GPS) L1 coarse acquisition (C/A) to support a myriad of location based applications. In the future, Binary Offset Carrier (BOC) modulated signals promise to allow receivers to access multiple satellite navigation systems including Galileo (E1 Open Service (OS)), GPS (L1C), and Quasi-Zenith Satellite System (QZSS) (L1C) using on a common, interoperable channel. In addition to interoperability, a key benefit of BOC(1,1) over the current GPS Binary Phase Shifted Keyed (BPSK) L1 C/A signal is that the BOC modulated signal allows for improved multipath performance by narrowing the autocorrelation function. Multipath effects can be further reduced through the use of composite BOC (CBOC) or time-multiplexed BOC (TMBOC) modulation used by Galileo and GPS, respectively.

While the multipath and other benefits of the BOC over the BPSK used in L1 C/A has been theoretically assessed, few on-air, operational assessments have been published. The ideal way to make a direct comparison of multipath performance is to use BOC and BPSK signals emanating from the same satellite. Using the same satellite rather than two close by satellites is key to an accurate comparison as multipath is sensitive to even the slightest differences in geometry. The research in this paper develops methods to make direct comparison of the multipath performance of L1 C/A and BOC from Galileo and the Japanese Quasi-Zenith Satellite System (QZSS).

The paper provides several direct comparisons of common BOC based signals vs L1 C/A BPSK performance using on-air, operational signals. Range and position domain evaluation are presented. Measurements made in multipath environments highlight the potential benefits of the BOC and composite BOC signals. The paper is organized as follows. Section II presents background on the BOC vs. BPSK multipath performance and previous research using on-air signals. It discusses the advantages and disadvantages of using Galileo and QZSS for direct comparison of BOC versus L1 C/A BPSK performance using on-air signals. Section III examines the analysis and results with QZSS. Section IV examines the analysis and results with Galileo. It shows both range and position domain evaluation of operational Galileo BOC E1 OS compared to BPSK performance in multipath environments.

II. BACKGROUND

A. BOC and BPSK

A Binary Offset Carrier signal modulates an additional square wave onto a BPSK signal. Whereas BPSK(m) uses BPSK with a m*1.023 MegaHertz (MHz) chipping rate, a BOC(n,m) signal takes an underlying BPSK(m) and further modulates it with a rectangular square wave subcarrier with a frequency of n*1.023 MHz. The result is that BOC modulation spreads the main lobe of signal n*1.023 MHz away from the nominal BPSK carrier. A consequence of the spreading is that the signal has a null at the BPSK carrier and hence it does not greatly affect the existing BPSK(1).

The spread bandwidth of BOC(1,1) also results in improved multipath performance over BPSK(1). Further multipath mitigation has been introduced with the multiplexing of a BOC(1,1) signal with a BOC(6,1) signal. This multiplexed BOC (MBOC) signal is implemented via time multiplexing

(TMBOC) in L1C or through a composite BOC (CBOC) in E1 OS [1].

B. *Prior & Current Work*

Significant analysis and design went into creation of the common BOC(1,1) based transmissions. BOC(1,1) was shown to theoretically provide improved multipath performance over L1 C/A[2][3][4][5]. Analysis of the MBOC signals indicated further improvement [2][3]. Figure 1 shows the autocorrelation function for BOC(1,1), BPSK(1) and MBOC signals. Also shown is BOC processed CBOC signal, labeled CBOC-BOC, and Mock BPSK, which is the BOC signal processed as BPSK. CBOC-BOC essentially follows the BOC autocorrelation function. Mock BPSK, which is discussed later, has an autocorrelation function similar to but not the same as BPSK. The MBOC autocorrelation functions have steeper slopes than the BPSK(1) autocorrelation function resulting in improved multipath performance. However, as noted in our previous effort [6] and seen the figure, care must be taken in choosing the correlator spacing when employing MBOC processing as their autocorrelation functions do not have constant slope. Some choices, as will be seen later, result in worse multipath rejection than BPSK.

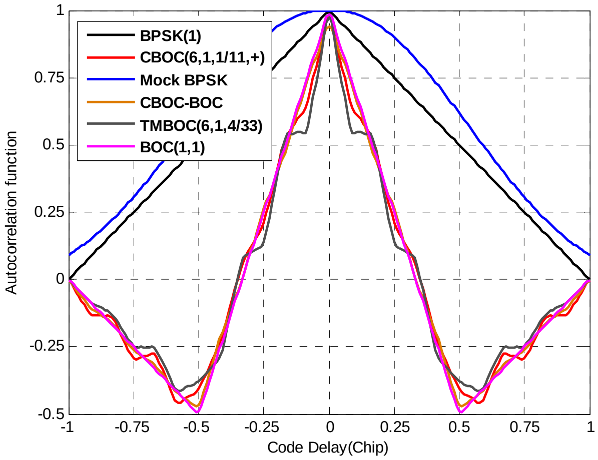

Figure 1. Normalized Correlation Function for MBOC signals on Common L1

Our previous effort assessed the multipath benefits by comparing signals from GPS (BPSK) and Galileo (BOC, CBOC) with similar geometry. Pseudorange estimate is derived from early minus late correlators. Figure 2 captures this idea with example early late correlators equidistant from the center of the correlation function. The figure shows the correlator spacings used in this paper. As the code tracking output (essentially pseudo range) is ambiguous, a differential range assessment was performed using an ultra-narrow correlator spacing using a technique developed in [9]. The reference spacing used was 0.01 chips between the early and late correlator. The Galileo CBOC signals, whether processed as BOC or CBOC, seem to have lower errors, the results are inconclusive as multipath sensitive to geometry and even small differences could have a significant difference. The experiments did reveal the importance of correlator spacing and, as well be illustrated later, using MBOC with a poorly chosen correlator spacing (for early minus late) can result in worse multipath performance. The result is seen in the correlation in Figure 2 where one can imagine correlator spacing (e.g., 0.25 chip spacing) where the autocorrelation function has a slope that is smaller than that with BPSK. This would imply worse multipath performance.

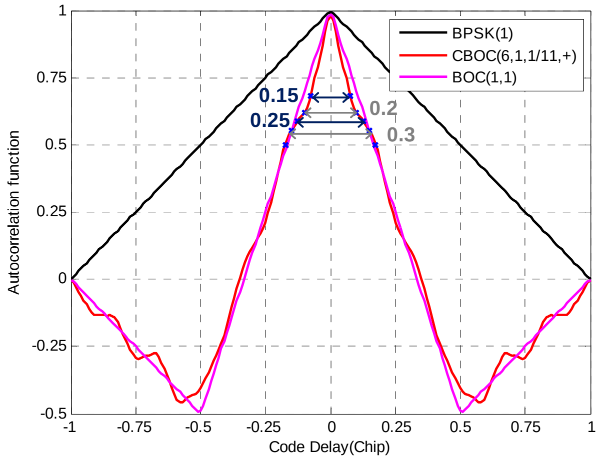

Figure 2. Autocorrelation Function Using Data from Galileo PFM OS signal

In this effort, the effect of geometry is eliminated by using signals from the satellite for the assessment. The direct comparison of the BOC and BPSK extends the previously developed assessment technique to also examine position domain effects. Two satellite constellations currently transmit a BOC(1,1) signal: Galileo and QZSS. The QZSS L1C signal is should be similar to the L1C that will first appear on GPS Block III satellites. Both systems are used for the assessment.

In this effort, the previously developed processing is used to analyze multipath performance. The correlator spacings shown in as well as the ultra-narrow 0.01 chip correlator spacing is processed by the Stanford GNSS Software Defined Radio (SDR). We then examine differences in the code tracking or pseudo range outputs for the more conventional, correlator spacings relative to the reference, ultra-narrow correlator output. Furthermore, the multipath rich locations from the previous effort are also used for this assessment. These sites are shown later in Figure 11 and Figure 13.

C. *BOC/BPSK with QZSS*

QZSS provides the most direct means of doing an on-air comparison of the performance of L1 C/A and L1C BOC(1,1) as it currently transmits both L1 signals. It transmits a signal that should be very similar to GPS L1C[1] with the exception that QZSS has L1C$_d$ (L1C data) and L1C$_p$ (L1C pilot) in quadrature [8] instead of interplexed. On QZSS, L1C$_d$ is in phase with L1 C/A and while the signals are generated off the same oscillator, the modulation for L1C and L1 C/A is separate.

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[1] GPS L1C signal has defined to be TMBOC with 25% power on data (L1C$_d$) and 75% on the pilot channel (L1C$_p$) in the same phase [8].

There is only one Quazi-Zenith Satellite (QZS), QZS-1, operational which makes it suitable for range domain evaluation of the future L1C. It uses BOC(1,1), instead of MBOC, for L1C[8]. Position domain benefits can also be made with the use of range measurements from other constellations. As QZSS is only visible briefly and at low elevation angles from Stanford, California (CA), we gathered measurements from Tainan, Taiwan to supplement the analysis.

D. BOC/BPSK with Galileo

There are currently four Galileo satellites in orbit with all four satellites visible simultaneously at different times and locations around the world. As a result, the Galileo system provides the opportunity to evaluate multipath benefits in the position domain when using only BOC(1,1) based signals. Of course, range domain analysis can also be conducted.

The comparison is more difficult as Galileo does not transmit an L1 C/A signal. However, the BOC(1,1) can be processed in a BPSK(1) manner. The result of the processing, as discussed later, does not exactly replicate L1 C/A but the multipath performance is similar for short delays.

E. Stanford Software Receiver & Analysis

The Stanford GNSS SDR provides real-time GNSS processing capabilities [10]. It can support several signals about L1 including BeiDou (B1I), Galileo (E1), WAAS, and GPS L1 C/A and L1C as well as GPS/WAAS L5 [11][12]. It has also been modified to support precise signal measurements through the use of ultra-narrow correlator spacing [9]. In the previous work [6], the SDR was modified to process both L1C TMBOC and Galileo E1 OS CBOC. The code replicas are designed with multiple bits accounting for CBOC modulation.

The SDR can simultaneous track a given satellite signal at five multiple correlator spacings in real time. Each correlator spacing is tracked individually and outputs separated range measurement. For the range domain analysis, the baseline 0.01 correlator chip spacing is tracked and used as reference. The difference in range between the tracking output and this baseline is used to assess the multipath error. The SDR outputs code phase or pseudorange at a 10 Hertz (Hz) rate. The pseudorange for positioning can be chosen from one of five correlation spacings. An extra time state is added into positioning calculation when adding one more GNSS constellation.

For this evaluation, the data is collected using a Universal Software Receiver Peripheral (USRP). The typical USRP data set is collected at 20 Megasamples per second (Msps) with 14 bits I/Q samples. The high sampling rate is needed to support the ultra-narrow correlators. Generally, the SDR processes the data at full bandwidth without filtering. While the BPSK processed Galileo data ("mock BPSK") is not filtered, spectral energy from the two main BOC lobes are combined to maintain the same amount of energy in the BPSK processed signal as in the BOC.

III. QUAZI-ZENITH SATELLITE SYSTEM (QZSS)

A. QZSS Visibility

QZSS is ideal for a direct range domain comparison of BOC with BPSK as it currently transmits both L1 C/A and L1C signals. QZS-1 L1C signals, data and pilot, are in phase quadrature and are solely BOC(1,1) rather than MBOC. QZSS satellites have elliptical geosynchronous orbit which allows them to spend a significant portion of their orbital period visible to East Asia. While that makes their use difficult in North America, they provide ever present high elevation GNSS signals for places such as China, Korea, Taiwan or Japan. Figure 3 shows the sky plot for a user in Tainan, Taiwan of the QZSS orbit over its 24 hour period. At Tainan, the satellite is always visible and always significantly above 10 degree elevation. In fact, most of the dwell time is at high elevation at greater than 45 degrees (~ 15 hours) whereas at Stanford, CA, the satellite gets barely above 5 degrees and is visible for about one hour per day. Due to the low elevation, the multipath rich environments used in [6] would result in signal blockage. Data was collected from National Cheng Kung University (NCKU) in Tainan for the evaluation.

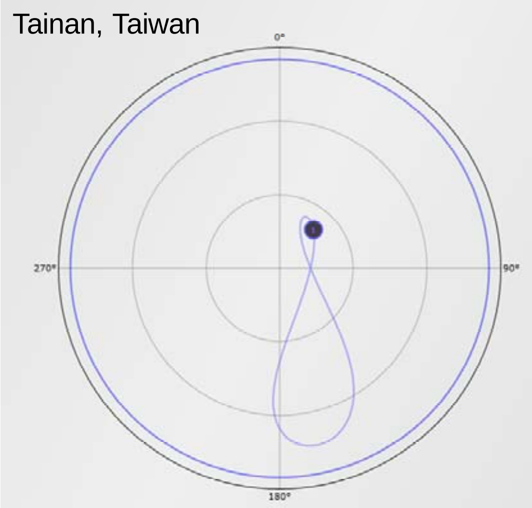

Figure 3. Sky plot of QZS-1 from NCKU, Tainan, Taiwan

B. Data Collection

Two locations at the electrical engineering (EE) building at NCKU were used for the data collection. The first location is the roof top of the building located on the thirteenth floor. The site serves as a low multipath location and provides reference results. The second location is on an 8th floor balcony. The balcony located about 20 meters away from another tall building (Chi Mei Building). The proximity and height of the building relative to the data collection location should result in multipath, even from the high elevation QZSS satellite. These locations are shown in Figure 4. A sky plot of the satellites visible in the data collection is shown in Figure 5. As seen in the sky plot, QZSS (PRN 193), is at high elevation and its direct signal should be visible at the balcony location. For the balcony location, it is anticipated that multipath signals are receivable with the one-reflection multipath delay being 40 meters or less given the proximity of the adjacent building as the presumed multipath source.

Figure 4. Data Collection Sites at NCKU

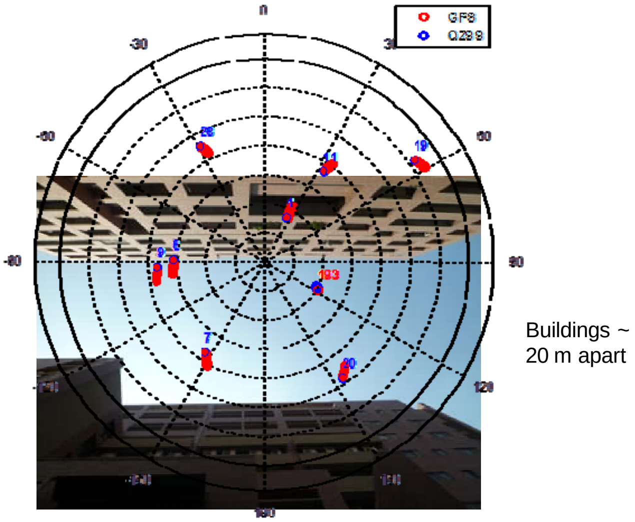

Figure 5. Sky plot of satellites in view during QZSS Data Collection (PRN number shown)

C. Processing

Signal data was collected and later post-processed using the Stanford SDR. The anticipated multipath performance of the SDR is shown in Figure 6 which shows simulated results code tracking (range) error from multipath for the L1 C/A BPSK(1) signal. The multipath signal strength is attenuated by 3 decibel (dB) from the direct signal. Figure 7 shows the results for BOC(1,1) at different correlator spacings.

With the collected data, a 0.8m (2.7 ns) bias between the BOC and BPSK results was found. The cause of the bias is unknown and could be due to misaligned in the Stanford SDR code replica table or bias from the signal generation on the satellite.

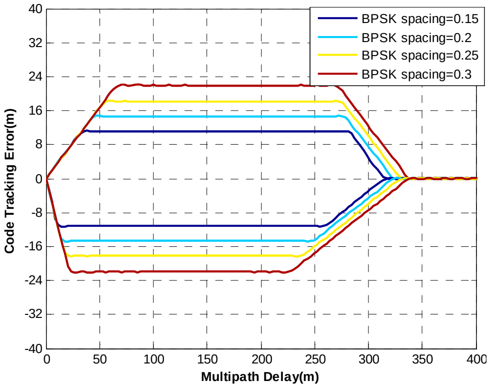

Figure 6. Code Tracking Error Envelope as function of Multipath Delay for BPSK(1) at different correlator spacings (3 dB multipath, 20 MHz Bandwidth)

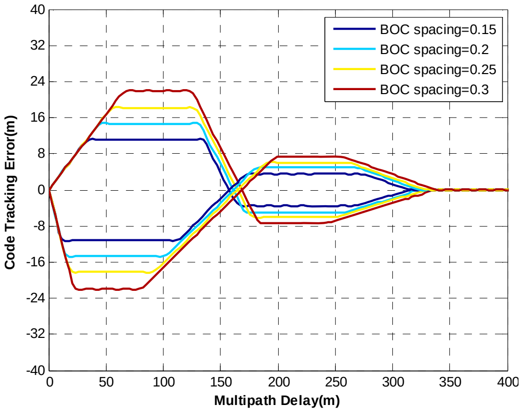

Figure 7. Code Tracking Error Envelope as function of Multipath Delay for BOC(1,1) at different correlator spacings (3 dB multipath, 20 MHz Bandwidth)

D. Results

Figure 8 shows the range differences (from 0.01 chip correlator spacing) of the QZS-1 L1 C/A (BPSK) and L1C (processed as BOC) for the roof top measurements for several correlator spacings. The analysis uses a 200 pseudo range sample (20 second at 10 Hz) running average. The range difference for BOC and BPSK are very similar, especially for the same correlator spacing. The range differences do not vary significantly for different correlator spacings which suggest a low multipath environment. The difference in range difference increases with increasing correlator spacing.

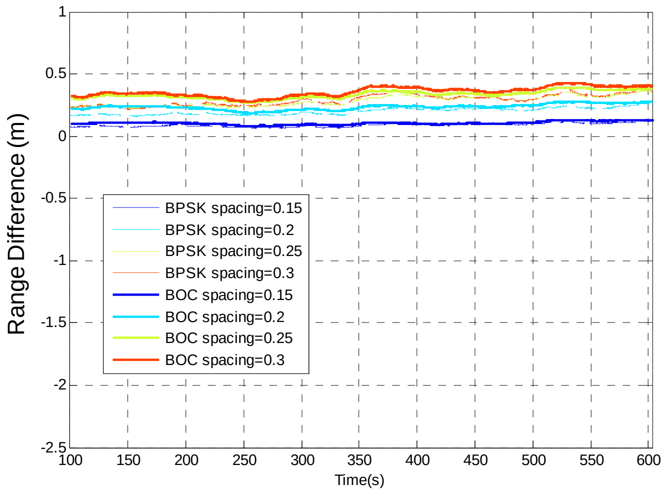

Figure 8. Range differences from reference 0.01 chip spacing for QZS-1 from NCKU EE rooftop

Figure 9 shows the range difference from QZS-1 for the balcony measurements. There are some significant differences for different correlator spacing which suggests the presence of multipath. For the most part, the BOC and BPSK results are very similar given the same correlator spacing. For larger range differences, which imply greater multipath effect, the results differ more. The BOC range differences are always smaller than that seen with BPSK with the same correlator spacing. The improvement with BOC is most clearly seen around 400 seconds.

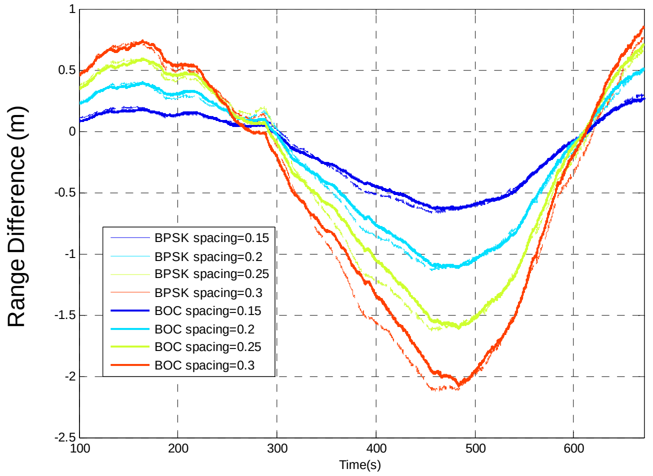

Figure 9. Range differences from reference 0.01 chip spacing for QZS-1 from NCKU EE 8th floor balcony

Position is calculated using either the QZSS L1 C/A BPSK or L1C BOC signal along with GPS pseudorange measurements. The result for the EE balcony location when processed with a correlator spacing of 0.15 chips is shown in Figure 10. The position errors are large as many of signals received in the balcony location should experience multipath. The differences between BOC and BPSK are muted as most satellite measurements are the same. But there is a noticeable difference, especially around 400-500 seconds. As a result of the 0.8 m bias, the difference between BOC and BPSK position error is non-zero even at times when Figure 9 indicates the range differences are zero.

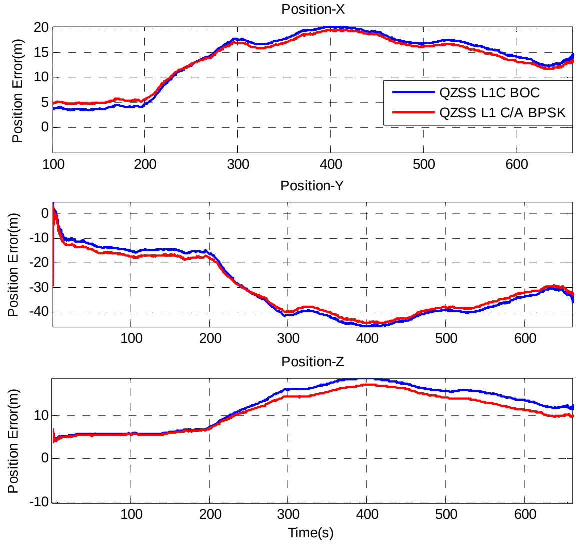

Figure 10. Position Error from QZSS & GPS (EE Balcony, 0.15 chip correlator spacing)

IV. GALILEO

A. *Galileo Visibility*

The Galileo system currently has four In-Orbit Validation (IOV) satellites operating. While these satellites are in test mode, they are planned to be part of the operational system. The orbital placement of these satellites allows all four satellites to be simultaneously visible on occasion. At Stanford, all four satellites are simultaneously visible roughly every two to three days.

B. *Data Collection*

Data collection was made at two different field sites - an enclosed rooftop courtyard and light urban canyon as shown in Figure 11 and Figure 13. The previous described processing is used to assess and compare multipath performance for these collected field measurements to compare environmental effects on the BOC versus BPSK performance.

The courtyard is located on the roof (fourth floor) of the Durand building. The sight lines available at the Durand building roof courtyard should result in good visibility to most satellites. Because the location is enclosed and contains four tall ventilation towers, there are several surfaces that can generate multipath. The multipath should have a short delay (less than 20 m) relative to the direct signal. Figure 12 shows the sky plot for the data collection in the courtyard. The outline provides a rough approximation of the orientation of the courtyard roof. The roof results in blockage of signals from low elevation satellite. The locations of satellites whose signals were not received are indicated with “x”.

Figure 11. Durand Building Roof Courtyard (4th Floor)

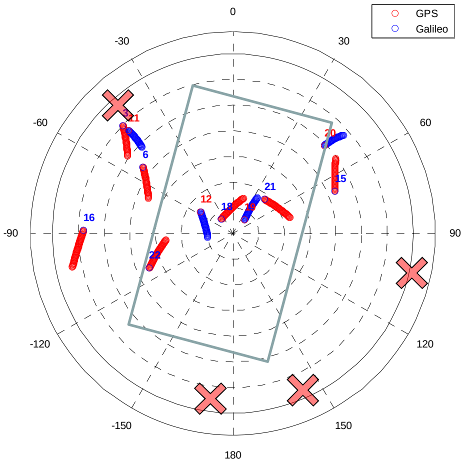

Figure 12. Sky plot of satellites in view during Durand Roof Courtyard Data Collection (PRN number shown)

Figure 13. Light Urban Canyon (between Huang and Yang-Yamazaki Engineering Buildings)

The light urban canyon scenario is located on the walkway between two four-story buildings separated by about 20 m. The buildings obstruct more GNSS signals and should yield multipath with longer delays than in the Durand courtyard. However, given the spacing between buildings, the maximum one-reflection multipath delay should be limited to about 40 m.

C. *Processing*

The BOC/BPSK multipath comparison using Galileo required developing software processing techniques to use the Galileo CBOC as BPSK signal in a manner that retains the same signal and noise power. The combination is done by first shifting the carrier frequency plus and minus 1.023 MHz. Then correlator outputs are generated for each resulting carrier replicas using the same BPSK code replica. The correlator outputs are combined non-coherently on early/late correlators. The code discriminator uses these combined outputs to generate unfiltered code phase error while maintaining the full energy of the BOC main lobes. Figure 14 shows the basic flow of this calculation. For this paper, this CBOC processed BPSK is termed “mock BPSK”.

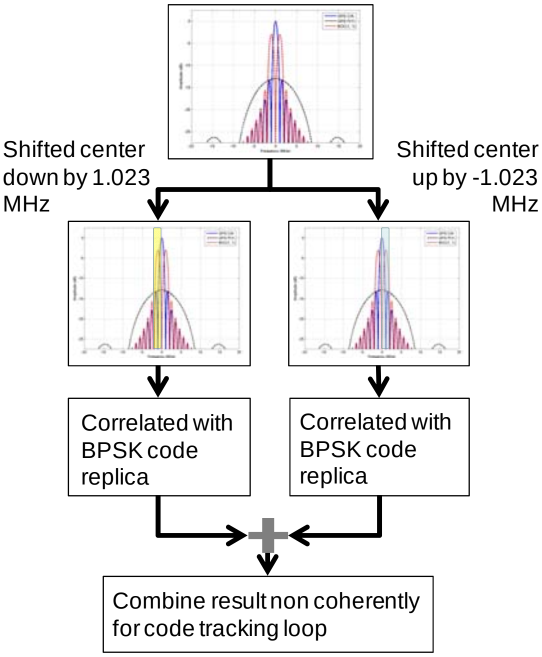

Figure 14. Flowchart for processing CBOC as BPSK (“Mock BPSK”)

Figure 15 and Figure 16 show the simulated code tracking error envelope from 3 dB (strength) multipath for CBOC and mock BPSK, respectively using the same methodology as previously discussed for QZSS. The mock BPSK code error envelope looks quite different from that of BPSK. Also, the envelope does not differ greatly for different correlator spacings. This is due to the rounding of the correlation envelope due to the processing which weakens the benefit of narrower correlator chip spacings. However, as will be noted later, the region of interest is for delays of less than 40 m. For the courtyard, the delays are likely less than 20 m. In this case, mock BPSK is similar to BPSK for the correlator spacings tested, particularly for at larger correlator spacing (0.3 chips or greater).

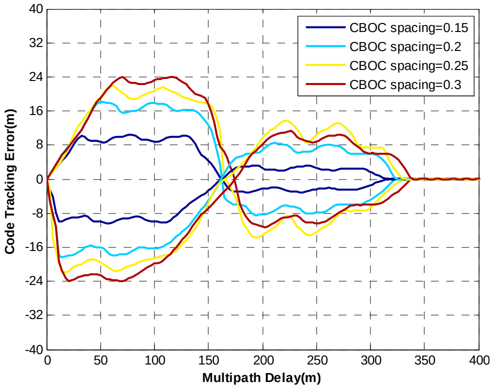

Figure 15. Code Tracking Error Envelope as function of Multipath Delay for CBOC at different correlator spacings (3 dB multipath, 20 MHz Bandwidth)

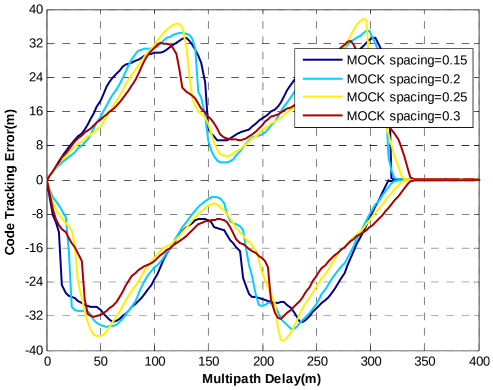

Figure 16. Code Tracking Error Envelope as function of Multipath Delay for BPSK processed BOCK (Mock BPSK(1)) at different correlator spacings (3 dB multipath, 20 MHz Bandwidth)

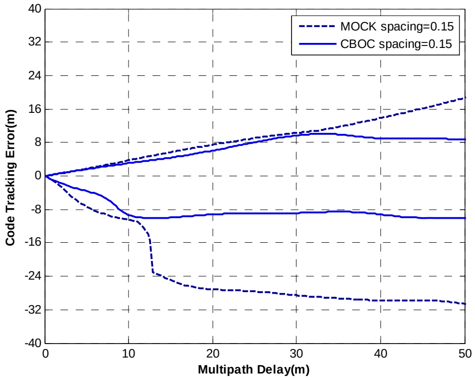

Figure 17. Zoomed Code Tracking Error Envelope as function of Multipath Delay for Mock BPSK(1) and CBOC at 0.15 chip spacing (3 dB multipath, 20 MHz Bandwidth)

As the multipath delay is expected to be less than 40 m, the portion of multipath error envelope for delays from 0 to 50 m is of greatest interest. Figure 17 shows the code tracking error envelope for CBOC and mock BPSK for multipath delays of 50 m or less when using 0.15 chip correlator spacing. The important observation is that even at these short delays, there are some differences between CBOC and mock BPSK, with CBOC generally having lower error. Hence, one would expect to see different results for CBOC and BPSK for both sites.

D. Results

The Durand building courtyard yielded the most consistent results as all four satellites are visible for a significant time. Multipath has been found to be present likely due to the vertical surfaces of the ventilation towers. The mock BPSK BOC, and CBOC results for PRN 11 are shown in Figure 18 to Figure 20, respectively. Multipath has its largest effect about 1050 seconds into the data set. As expected, the mock BPSK results have similar range differences for the different correlator spacing used. BOC consistently performs better than mock BPSK. In the case of CBOC, there can be a significant difference between results from different correlator spacings. This suggests that there is multipath at play. Looking closely, the worst CBOC (0.25 correlator spacing) performs worse than the corresponding result from mock BPSK. It also should not be surprising that CBOC at 0.3 chip correlator spacing performs better than CBOC at 0.25 chip correlator spacing. This tendency is repeated in other results.

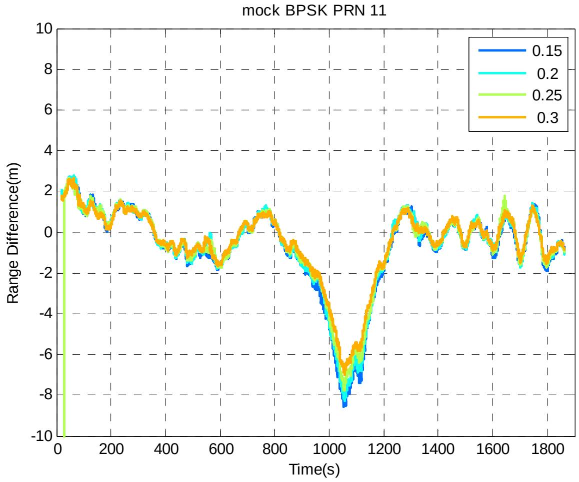

Figure 18. Courtyard Data Processed Using Mock BPSK on Galileo PRN 11

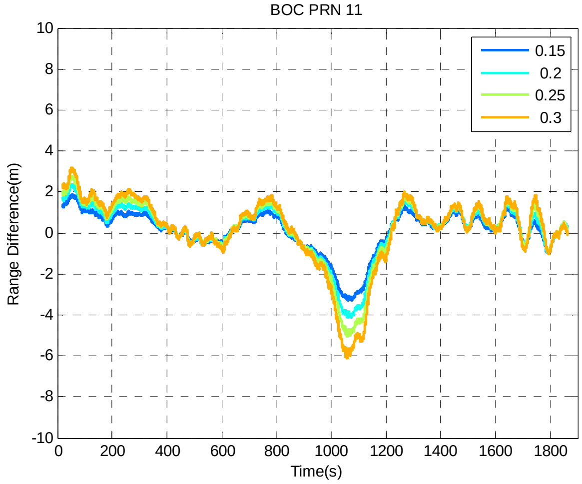

Figure 19. Courtyard Data Processed Using BOC on Galileo PRN 11

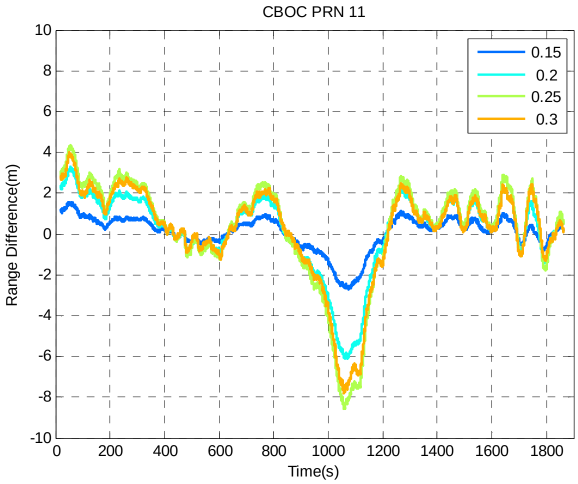

Figure 20. Courtyard Data Processed Using CBOC on Galileo PRN 11

Figure 21 to Figure 23 show the courtyard data processed for Galileo PRN 12. It does not have as large an excursion as seen in PRN 11 but it seems like it also has some multipath related errors. In this case, the BOC results are generally better than mock BPSK. Again, CBOC shows noticeable difference for different correlator spacings. Again, CBOC at 0.25 chip spacing performed worst than other CBOC and mock BPSK. Conclusions similar to that drawn from PRN 11 can be made.

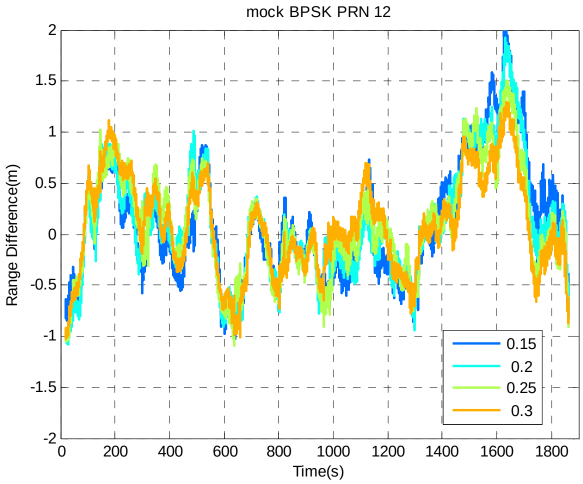

Figure 21. Courtyard Data Processed Using Mock BPSK on Galileo PRN 12

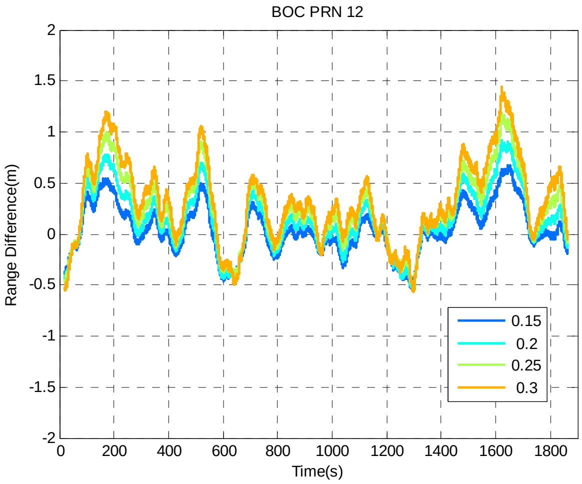

Figure 22. Courtyard Data Processed Using BOC on Galileo PRN 12

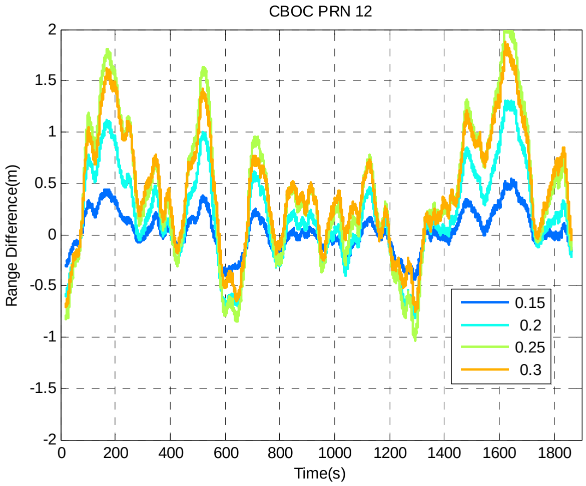

Figure 23. Courtyard Data Processed Using CBOC on Galileo PRN 12

The effect of multipath on position estimates is presented in Figure 24 shows the position error in three dimensions for an all Galileo solution processed as mock BPSK and CBOC. The initial error is very large due to poor geometry – a consequence of having the current satellite orbit configuration. The effect of multipath at 1050 seconds into the data set is visible in the position error, especially in the vertical (*z*) dimension. However, these errors are shadowed by geometry effects. To reduce the impact of geometry, the position calculations are also conducted with the addition of GPS ranging measurements. Figure 25 shows the position error when the GPS constellation is added. The initial geometry problem is no longer an issue and the effect of BOC multipath mitigation, albeit reduced, is clearly visible around 1050 seconds into the data set.

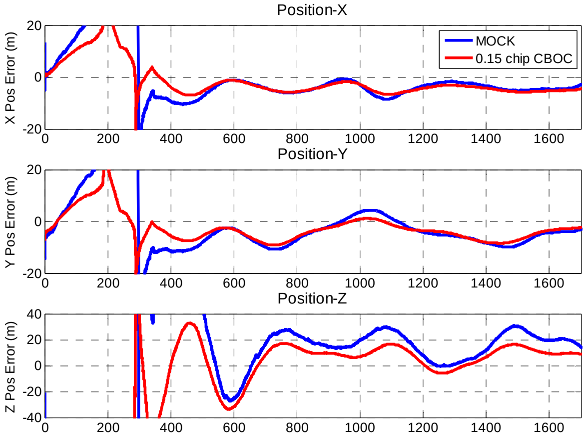

Figure 24. Position Error from Galileo Only (Courtyard)

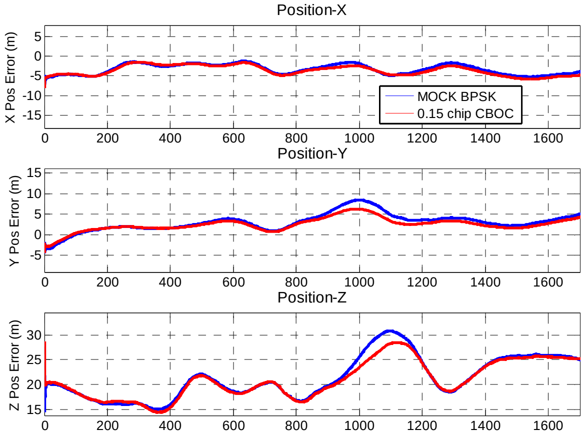

Figure 25. Position Error from Galileo + GPS (Courtyard)

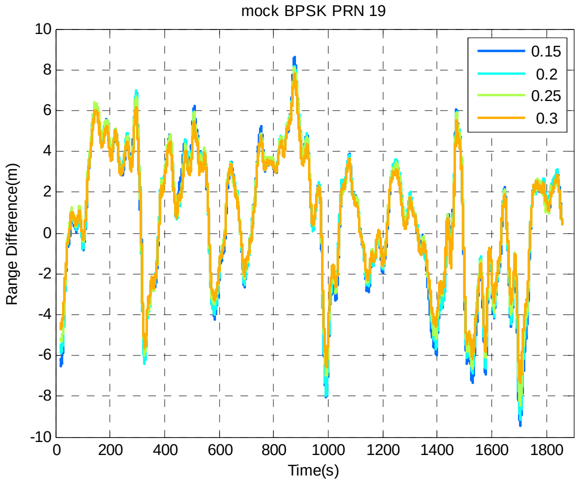

Figure 26. Light Urban Canyon Data Processed Using Mock BPSK on Galileo PRN 19

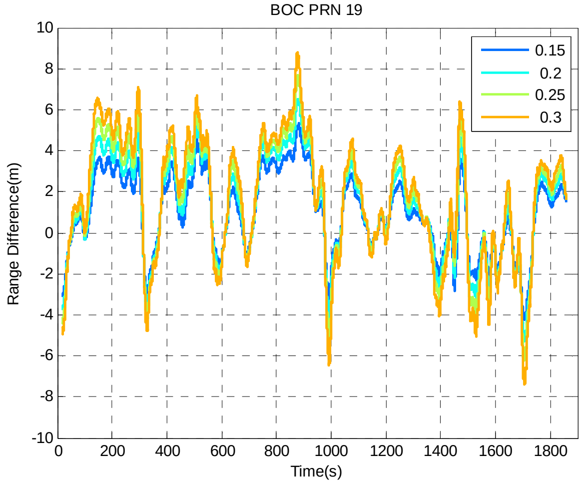

Figure 27. Light Urban Canyon Data Processed Using BOC on Galileo PRN 19

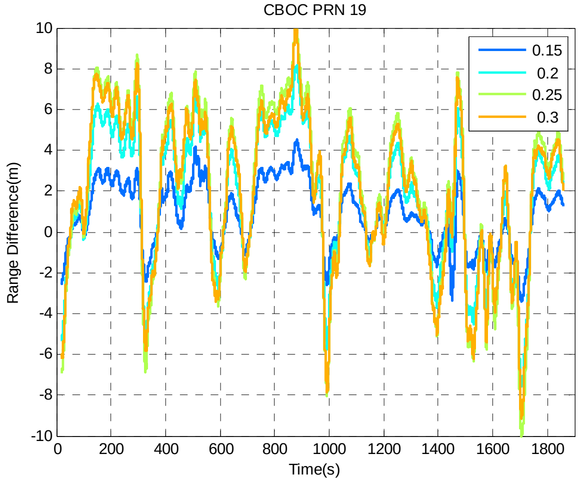

Figure 28. Light Urban Canyon Data Processed Using CBOC on Galileo PRN 19

The multipath experienced at the light urban canyon site is generally stronger than that measured in the courtyard. Figure Figure 26 to Figure 28 show the mock BPSK, BOC and CBOC results for PRN 19, respectively. The range differences are larger and fluctuate more than in the courtyard. Figure 29 show the light urban canyon results for mock BPSK and CBOC from PRN 12. No Galileo only position results are available as at least one Galileo satellite was blocked during the data collection. Solution using GPS and Galileo is possible but the buildings shadow much of the sky often resulting in poor geometry for the solution.

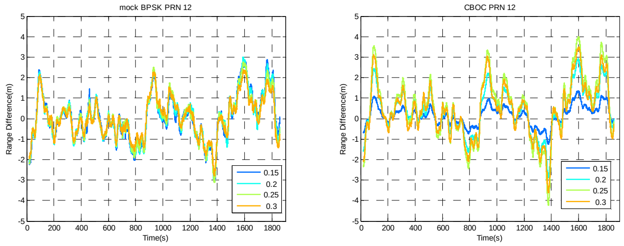

Figure 29. Light Urban Canyon Data Processed Using Mock BPSK (Left) & CBOC (Right) on Galileo PRN 12

V. SUMMARY & CONCLUSIONS

This paper provides one of the first on-air direct comparison of BOC(1,1) vs L1 C/A BPSK performance in multipath. Analysis was conducted both in the range and position domain evaluation using both QZSS L1C and L1C/A and Galileo E1 OS signals.

The results from both Galileo and QZSS give a clear demonstration of the benefits of BOC and MBOC (CBOC or TMBOC). Multiplexed BOC techniques do perform better than basic BOC but care needs to be taken with correlator spacing when using these signals. The results demonstrate that poor choice of correlator spacing for CBOC can result in worse (more error) multipath performance than BOC and even C/A.

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DISCLAIMER

REFERENCES

[1] G. W. Hein, J.-A. Avila-Rodriguez, S. Wallner, A. R. Pratt, J. Owen, J.-L. Issler, J. W. Betz, C. J. Hegarty, S. Lenahan, J. J. Rushanan, A. L. Kraay, T. A. Stansell, "MBOC: The New Optimized Spreading Modulation Recommended for GALILEO L1 OS and GPS L1C," Proceedings of IEEE/ION PLANS 2006, San Diego, CA, April 2006, pp. 883-892.

[2] J. Betz, M.A. Blanco, C.R. Cahn, P.A. Dafesh, C.J. Hegarty, K.W. Hudnut, V. Kasemsri, R. Keegan, K. Kovach, L.S. Lenahan, H.H. Ma, J.J. Rushanan, D. Sklar, T.A. Stansell, C.C. Wang, S.K. Yi, "Description of the L1C Signal," Proceedings of the 19th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2006), Fort Worth, TX, September 2006, pp. 2080-2091.

[3] J. Betz, M.A. Blanco, C.R. Cahn, P.A. Dafesh, C.J. Hegarty, K.W. Hudnut, V. Kasemsri, R. Keegan, K. Kovach, L.S. Lenahan, H.H. Ma, J.J. Rushanan, D. Sklar, T.A. Stansell, C.C. Wang, S.K. Yi, “Enhancing the Future of Civil GPS: Overview of the L1C Signal,” *InsideGNSS*, Spring 2007

[4] J. J. Floc'H, M. Soellner, "Comparison Between BOC CBOC and TMBOC Tracking," Proceedings of the 2007 National Technical Meeting of The Institute of Navigation, San Diego, CA, January 2007, pp. 964-973.

[5] O. Julien, C. Macabiau, J.-L. Issler, L. Ries, "1-Bit Processing of Composite BOC (CBOC) Signals and Extension to Time-Multiplexed BOC (TMBOC) Signals," Proceedings of the 2007 National Technical Meeting of The Institute of Navigation, San Diego, CA, January 2007, pp. 227-239.

[6] C. Lee, Y.-H. Chen, G. Wong, S. Lo, and P. Enge, “Multipath Benefits of BOC vs. BPSK Modulated Signals Using On-Air Measurements,” Proceedings of the Institute of Navigation ITM Conference, San Diego, CA, January 2013, pp. 742–751.

[7] G. Wong, Y.H. Chen, R.E. Phelts, T. Walter, P. Enge, “Measuring Code-Phase Differences due to Inter-Satellite Hardware Differences”, Proceedings of the 25th International Technical Meeting of The Satellite

[8] Japan Aerospace Exploration Agency (JAXA), “Quasi-Zenith Satellite System Navigation Service Interface Specification for QZSS (IS-QZSS),” Version 1.5, March 27, 2013

[9] Division of the Institute of Navigation (ION GNSS 2012), Nashville, TN, September 2012. Wong, Gabriel, Chen, Yu-Hsuan, Phelts, R. Eric, Walter, Todd, Enge, Per, "Measuring Code-Phase Differences due to Inter-Satellite Hardware Differences," Proceedings of the 25th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2012), Nashville, TN, September 2012, pp. 2150-2158.

[10] Y.-H. Chen, S. Lo, D. M. Akos, D. S. De Lorenzo, P. Enge, "Validation of a Controlled Reception Pattern Antenna (CRPA) Receiver Built From Inexpensive General-purpose Elements During Several Live-jamming Test Campaigns," Proceedings of the 2013 International Technical Meeting of The Institute of Navigation, San Diego, California, January 2013, pp. 154-163.

[11] Y.-H. Chen, S. Lo, D.M. Akos, M. Choi, J. Blanch, T. Walter, P. Enge, “Development of a Real-time GNSS Software Receiver for Evaluating RAIM in Multi-constellation,” Proceedings of the 2014 International Technical Meeting of The Institute of Navigation, San Diego, California, January 2014, pp. 525-533.

[12] Y.-H. Chen, J.-C.Juang, D. S. De Lorenzo, J. Seo, S. Lo, P. Enge, D. M. Akos, "Real-Time Dual-Frequency (L1/L5) GPS/WAAS Software Receiver," Proceedings of the 24th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2011), Portland, OR, September 2011, pp. 767-774.

[13] T. Sakai, S. Fukushima, N. Takeichi, K. Ito, "Augmentation Performance of QZSS L1-SAIF Signal," Proceedings of the 2007 National Technical Meeting of The Institute of Navigation, San Diego, CA, January 2007, pp. 411-421.