Real-Time Dual-Frequency (L1/L5) GPS/WAAS Software Receiver

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ABSTRACT

This paper demonstrates a real-time software receiver supporting GPS/WAAS dual-frequency (L1/L5) processing. The software receiver is implemented on a widely-available recent generation multi-core processor and is capable of post-processing datasets from collection hardware. Key contributions of this software receiver are that 1) it is perhaps the first receiver capable positioning solely on L5 ranging despite there being only one operational GPS L5 signal and 2) it estimates ionosphere delay using L1-L5 measurements

The architecture of such a software receiver needs to be carefully developed so that it can process signals from each individual frequency. Multitasking and synchronization mechanisms were developed to support the tracking of multiple channels in real time. To achieve real-time capability, parallel operations are necessary to reduce computation complexity. Bit-wise operations are exploited and implemented by Single Instruction Multiple Data (SIMD) instructions in the software correlator. An assistance mechanism between L1 and L5 is built for

shortening the acquisition time and increasing the sensitivity of tracking L5 data-free channel.

Currently, positioning using GPS/WAAS L5 signal needs assistance from L1 signal because the ephemeris on GPS L5 is currently not provided. However, using the L1 GPS ephemeris from L1 should consider the time offset or interfrequency bias (IFB) between L1 and L5 which results from the difference of antenna phase center and other hardware on the satellite. Besides, a time offset exists between WAAS and GPS time. These time offsets are solved by adding another unknown into position solution. The solutions of the time offset are used to correct the pseudorange of L5 and then perform positioning by three methods 1) L1 only 2) L5 only 3) iono-free combination. The results of positioning by the dual-frequency software receiver are illustrated and the positioning accuracy is analyzed in this paper.

INTRODUCTION

GPS is executing a modernization program to provide civil L5 signal. The spreading code on L5 signal has a ten times higher chipping rate than L1 C/A code. The signal decreases both tracking error and multipath-induced error. Future, using an iono-free combination of L1/L5 pseduoranges, positioning accuracy would improve under severe ionospheric conditions. Before May 6th 2011, there were two GPS satellites (PRN1/SVN49 and PRN25/SVN62) broadcasting the L5 signal. Additionally, the L5 signal payload will be included in all future GPS satellites. Wide Area Augmentation System (WAAS) geostationary earth orbit (GEO) satellites also provide user ranging information. Presently, all of WAAS GEO satellites (PRN133, PRN135, and PRN138) broadcast the L5 signal. In total, there were currently five GPS/WAAS satellites broadcasting L1 and L5 simultaneously. Hence, we believe it is time to evaluate the positioning performance using L5 signal rather than only to assess signal tracking performance. The objective of this paper is to implement a real-time software receiver capable of dual-frequency (L1/L5) processing for GPS/WAAS. To enable L5 positioning we will provide the solutions for time offset problem. Finally, we can then use dual-frequency measurements to examine positioning methods including L1, L5, iono-free combination and analyze the resulting position.

The paper is organized as follows. First, the signal specification and status of L5 signal are introduced. Then, the issues and solutions of positioning using L5 signal are listed. The signal collection hardware and the architecture of the software receiver are described in detail. The solutions of time offset between L1 and L5 as well as WAAS and GPS time are provided. The positioning results of dual-frequency software receiver are shown and its positioning accuracy is analyzed. Finally, some concluding remarks are made.

SIGNAL SPECIFICATION AND CURRENT STATUS OF GPS/WAAS L5 SIGNAL

The GPS L5 signal is designed with two channels (I & Q) [1]. The chipping rate of the spreading code of both channels is 10.23 Mcps with 10230 code length. I channel is the data channel with 50 bit per second (bps). Forward error correction (FEC) code with rate ½ convolution is encoded on I channel at 100 symbol per second (sps). It is further encoded by 10-bit Neuman-Hoffman (NH) code at 1 KHz. The Q channel is the data-free channel which is only encoded by 20-bit NH code at 1 KHz. The WAAS L5 signal has only one data channel with 250 bps which is encoded by the same FEC at 500 sps. It is further encoded by a 2-bit NH code (1,0) at 1000 sps [2]. Table 1 lists the signal specification of GPS/WAAS L5.

Table 1. Signal specification of GPS/WAAS L5

Signal Specification		GPS L5	WAAS L5
Spreading Code	Chipping rate	10.23 Mcps	10.23 Mcps
	Code length	10230	10230
Channel		I (data) Q (data-free)	I (data)
Neuman-Hoffman code		I (10-bit) Q (20-bit)	I (2-bit)
Forward error correction code		Rate ½ convolution	Rate ½ convolution
Data rate		50 bps on I	250 bps

Before May 6th 2011, the GPS PRN1/SVN49 was only broadcasting L5Q data-free channel and was currently set unhealthy. The SVN49 has internal multipath problem. To mitigate the multipath, one option proposed is to shift the antenna phase center of satellite 152 m above satellite [3], so there is about 517 nanoseconds time offset between L1 and L5. And, the L5 signal power of SVN49 is about -173.5 dBW corresponding to an average C/No 30dB-Hz resulting in a very weak that is hard to track. The PRN25/SVN62 is broadcasting on both L5 channels. The data message on I channel of PRN25/SVN62 only contains preamble, time of week (TOW), PRN, and cyclic redundancy check (CRC). The other fields of message are filled with zeros. The data on L5 signal of WAAS GEO satellites are the same as L1 signal. But, timing information like TOW is not included in any available message type broadcasting by the WAAS GEO. Table 2 lists the current status of GPS/WAAS L5.

Table 2. Status of GPS/WAAS L5 before May 6th, 2011

Status	GPS		WAAS GEO
PRN/SVN	PRN1 /SVN49	PRN25 /SVN62	PRN133 PRN135 PRN138
Channel	Q	I & Q	I
Time offset b/w L1 and L5	517 ns delay*	103ns adv.*	233ns 255ns 185ns adv. *
NAV Data	None	CNAV on I w/ limited content	WAAS Message
Signal Power	-173.5 dBW**	-157.9 dBW [1]	-158.5 dBW [4]

*The time offset between L1 and L5 is estimated by developed dual-frequency software receiver one time and may include ionosphere delay.

**The power is calculated by subtracting C/No difference between L1 and L5 which is received by Trimble Net-R9 receiver.

THE STRATEGY OF POSITIONING USING L5 SIGNAL

To position using today's L5 signals, it is necessary to get assistance from the L1 broadcast. The ephemeris of GPS satellite is unavailable on the L5 signal and is obtained from L1. The acquisition of the L5 signal will take longer than the L1 signal as we need to search a code phase space that is ten times bigger. The code phase synchronization of two frequencies can be used to provide code phase assistance from L1 to shorten the acquisition time of the L5 signal. Another issue is that timing information like TOW is not included in any available message type broadcasted by WAAS GEO satellites. According to [4], the start of every other 24-bit preamble (provided as 8 bits every second) of WAAS message is synchronized with a 6-second GPS sub-frame epoch. Because the altitude of the WAAS GEO satellite is roughly 15,000 kilometer more than that of the GPS satellites, the preamble of WAAS message is delayed by approximately 50 milliseconds relative to the preamble of GPS signals. Therefore, the TOW obtained from GPS signal can be used to align WAAS signal with millisecond-level accuracy once its preamble is found. Further, the WAAS time has a time offset to GPS time [4]. This time offset should be taken in account when using the WAAS GEO satellites ranging information. Moreover, there exists another time offset between L1 and L5. If one would like to use the ephemeris of L1 to serve for L5, the time offset should be considered. The time offset for two cases can be estimated by adding an unknown when positioning. However, we need better geometry in order to have higher confidence in the solution.

Table 3. Issues and solutions of positioning using L5

Issues	Solutions
The ephemeris of GPS satellite is unavailable on L5.	Use ephemeris of GPS satellite from L1 signal.
It takes longer to acquire L5 signal.	Take assistance from L1 to assign code phase.
The timing information like TOW is not included in any available message type broadcasted by WAAS GEO satellites.	Use the TOW obtained from GPS signal to align WAAS signal with millisecond-level accuracy once the preamble is found.
Time offset exists between WAAS and GPS time.	Add an unknown into positioning to solve it.
Time offset exists between L1 and L5.	

THE DESCRIPTION OF SIGNAL COLLECTION HARDWARE

The hardware used to collect dual-frequency dataset is depicted in figure 1. The detail description of hardware is described in [5]. The hardware contains two signal collection systems including the USRP2 software radio system [6] and host computer. The Trimble L-band Zephyr antenna is used to receive the dual-frequency signal. The signal is divided into two branches by a 1-to-2 power splitter. Each one signal passes to a USRP2 board equipped with a DBSRX programmable mixing and down-conversion daughterboard. Individual USRP2 boards are synchronized by a 10 MHz external common clock generator. The USRP2 is controlled by host computer running Ubuntu distribution of Linux. The open-source GNU Radio software-defined radio block is used to configure USRP2 and collect dataset. One of USRP2 is configured to collect L1 (1575 MHz) signal and the other one is for L5 (1176 MHz). The signals are converted to near zero intermediate frequency (IF) and digitized to 14-bit complex outputs (I & Q). Its sampling rate is set as 20 MHz with given 24 MHz bandwidth for L5 and limitations due to the communication rate of Gigabit Ethernet from USRP2 to host computer. The host computer uses a solid state drive to store the dataset because of high data streaming rate (80 Megabyte/s).

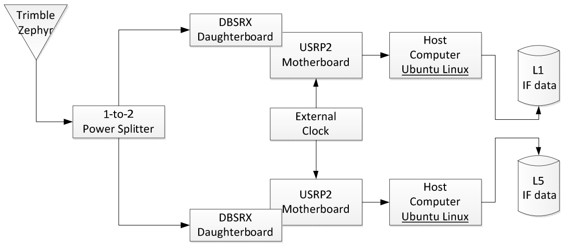

Figure 1. Block diagram of the signal collection hardware

SOFTWARE ARCHITECTURE

The software is developed with Visual Studio under Windows. Most of source code is programmed using C++. Inline assembly is used to program the functions with high computational complexity such as correlation operations. The software architecture [7][8][9][10] of dual-frequency software receiver is depicted in figure 2.

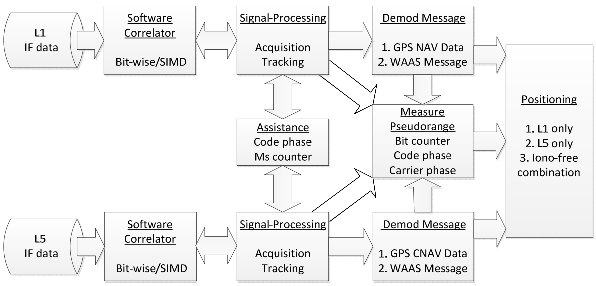

Figure 2. Block diagram of the software architecture

Basically, this architecture exploits two sets of parallel signal-processing engines to process L1/L5 signal and combine measurements in positioning. The individual IF data is read from disk, quantized into 2-bit resolution, and stored in a queue buffer in terms of millisecond length. The data is processed by software correlator which adopts bit-wise parallel algorithm [7] and is implemented by signal instruction multiple data (SIMD) instructions [9]. The software correlator is controlled by signal-processing function for setting PRN, code phase, and Doppler frequency. The signal-processing uses the correlator outputs to decide the state of signal-processing from acquisition to tracking. The details of the signal-processing for the software receiver are described in [8]. An assistant mechanism between L1 and L5 for shortening acquisition time and increase sensitivity of tracking L5Q was developed. It is described in the next section. The tracking state of signal-processing would find the data transition point and decode the NH code. Signal-processing function outputs the navigation data sequence to demodulate messages. Several message formats are possible including GPS NAV, GPS CNAV, and WAAS Message. After demodulating the messages, the TOW is obtained and provides second-level accuracy. The preamble of message is used to find the header of message and provides millisecond-level accuracy. The bit counter, code phase, and carrier phase are measured in the tracking state of signal-processing function to calculate the pseudorange with carrier smoothing (where bit counter represents the number of navigation data bit from the start of week). In the end, the positioning function combines ephemeris and pseudoranges from previous stage to calculate position by three methods in table 4. Figure 3 shows the GUI of dual-frequency software receiver including channel status of L1 and L5, sky plot, C/No plot and positioning results for three methods. The software receiver with 12 channels for individual frequency is tracking five satellites with L1 and L5 in the post-processing mode. The processing time represents for the execution time of software receiver. The data streaming time represents for how long IF dataset has processed. The status bar of GUI shows that the processing time is less than data streaming time. This demonstrates that the developed dual-frequency software receiver can operate in real-time.

Table 4. Methods of calculating position

Method	**Description**
L1 only	Use ephemeris and pseudoranges from L1
L5 only	Use ephemeris from L1 and pseudoranges from L5
Iono-free combination	Use ephemeris from L1 and L1/L5 iono-free combined pseudoranges [11] by $\frac{f_{L1}^2 PR_{L1} - f_{L5}^2 PR_{L5}}{f_{L1}^2 - f_{L5}^2}$

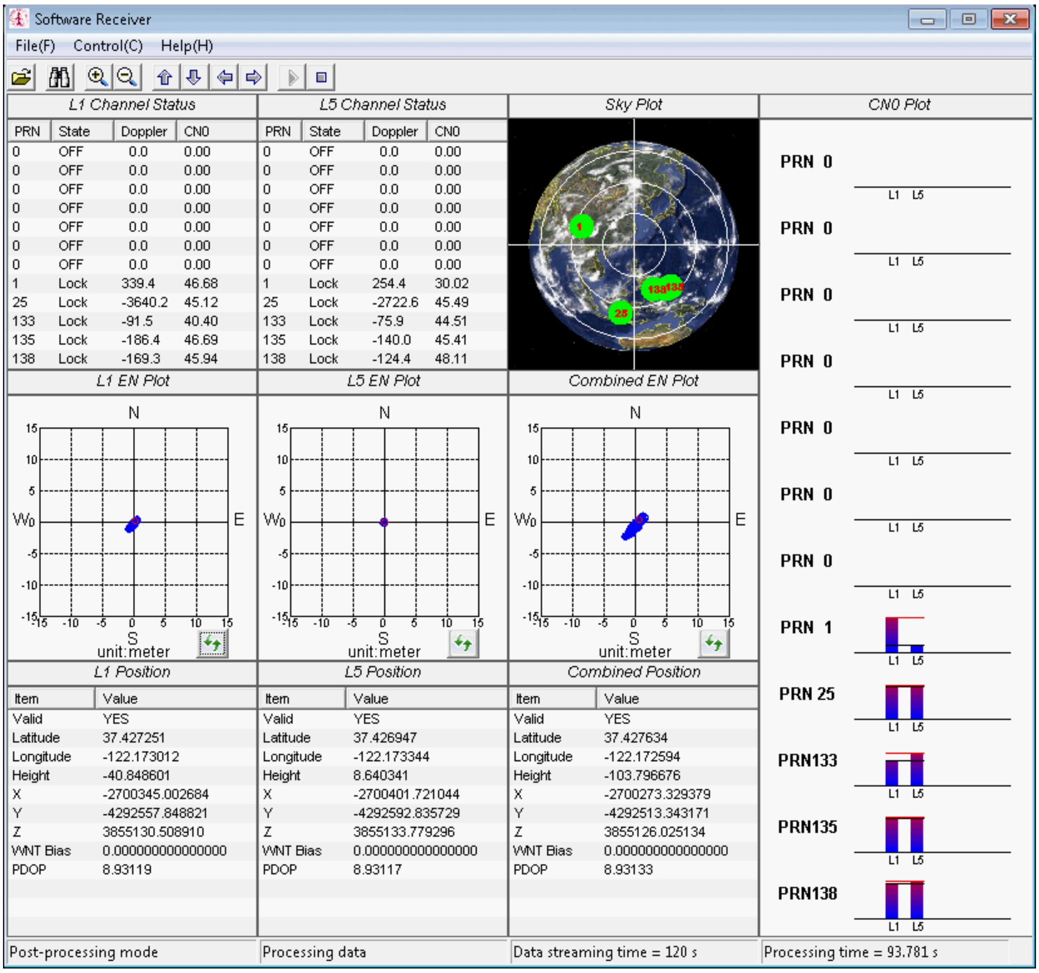

Figure 3. Screenshot of dual-frequency software receiver GUI

THE ASSISTANCE MECHANISM BETWEEN L1 AND L5

There are two assistance mechanisms between L1 and L5. First one is to shorten acquisition time. Once signal-processing function of one frequency enters tracking state, the assistance mechanism assigns its code phase to the other frequency which is still in the acquisition state. Typically, the L1 channel goes into tracking faster than L5 due to its smaller code phase search space. In case the L5 signal is weak as with SVN49, it needs to integrate several code periods to detect the signal. This would take significant time to search whole code space and frequency space. With this mechanism, the code phase obtained from L1 is fixed and it only needs to search frequency space. Moreover, frequency step for searching can be narrow down for increasing signal sensitivity.

The other assistance mechanism is to increase signal sensitivity for tracking L5Q data-free channel. The millisecond (MS) counter is used to indicate the index of millisecond in one navigation data period. For L1 and L5Q, a MS counter counts from 0 to 19. The assistance mechanism is made by sending the MS counter from L1 to L5Q for getting the NH_{20} code. With known NH_{20} code, one could perform coherent integration for whole period of NH_{20} code. The NH_{20} code can combine the L5Q spreading code to make 20 times longer length code. The coherent integration will benefit when L5 signal is weak like SVN49. However, it also increases the size of code table by 20 times. Alternatively, one can use the original one-millisecond code table to perform correlation, multiply the output by NH code sequence, and then sum over the NH_{20} code period. This approach is easy to implement using hardware correlator. But, for software correlator, the carrier table is made by starting from zero phase [8]. So, each correlator output should be rotated by a phase which is function of carrier frequency and integrated phase. The coherent integration for software correlator is written as follows.

$$\begin{bmatrix} I_S \\ Q_S \end{bmatrix} = \sum_{i=0}^{M} \begin{bmatrix} I_R^i \\ Q_R^i \end{bmatrix} = \sum_{i=0}^{M} NH_i \begin{bmatrix} \cos(\Delta\theta^i) & \sin(\Delta\theta^i) \\ -\sin(\Delta\theta^i) & \cos(\Delta\theta^i) \end{bmatrix} \begin{bmatrix} I_Z^i \\ Q_Z^i \end{bmatrix}$$

$$\Delta\theta^i = \frac{(\omega_R - \omega)T_I}{2} + \sum_{j=0}^{i-1} \omega T_I \quad (1)$$

where I_S , Q_S denotes integrated correlator output. i is index of integration period. M is the number of integration. I_R^i, Q_R^i, denotes rotated correlator output of ith period. NH_i is ith code of NH_{20} sequence. $\Delta\theta^i$ is phase shift of ith integration. I_Z^i, Q_Z^i denote original zero-phase correlator output of ith period. ω is carrier frequency. ω_R is the frequency after rounding the ω . T_I is the time of code period.

SOLVING THE TIME OFFSET BETWEEN GPS TIME AND WAAS TIME

In order to measure the time offset between GPS time and WAAS Time, a surveying-level receiver (NovAtel ProPak-G2) is used to calculate the precise location of a fixed antenna. Using the same antenna, IF data is then logged by our collection hardware for three minutes. Our software receiver then post-processes the data and collects the results of the pseudoranges and positions of the satellite. The time offset is calculated by following equation without subtracting other error sources such as ionosphere delay.

$$t_{os} = \frac{\left\| \mathbf{x}^{(k)} - \mathbf{x}_r \right\| - \rho_r^{(k)}}{c} \quad (2)$$

where $\mathbf{x}^{(k)}$ is the position of kth satellite, $\mathbf{x}_r$ is the precise position of antenna, $\rho_r^{(k)}$ is the pseudorange from kth satellite to antenna, and c is speed of light. Figure 4 shows the results of estimated time offset. The constellation geometry is shown in the upper left. The result corresponds to URA of satellites as table 5. The WAAS GEO satellites have a greater time offset than GPS satellites with most of value resulting from the difference between GPS time and WAAS Time.

For solving the time offset, one unknown is added to observation equation as follows [12].

$$\begin{bmatrix} \delta\rho^{(1)} \\ \delta\rho^{(2)} \\ \vdots \\ \delta\rho^{(k)} \\ \delta\rho^{(k+1)} \\ \vdots \\ \delta\rho^{(k+n)} \end{bmatrix} = \begin{bmatrix} \left(-1^{(1)}\right)^T & 1 & 0 \\ \left(-1^{(2)}\right)^T & 1 & 0 \\ \vdots & \vdots & \vdots \\ \left(-1^{(k)}\right)^T & 1 & 0 \\ \left(-1^{(k+1)}\right)^T & 1 & 1 \\ \vdots & \vdots & \vdots \\ \left(-1^{(k+n)}\right)^T & 1 & 1 \end{bmatrix} \begin{bmatrix} \delta x \\ \delta b \\ \delta w \end{bmatrix} + \tilde{\varepsilon} \quad (3)$$

where $1^{(k)}$ is the unit vector from satellite to antenna, δx , δb ,and δw are the unknown corrections for position, receiver clock bias and time offset between WAAS and GPS time. k, n is the number of GPS satellite and WAAS GEO. Figure 5 shows the positioning result using L1 on the ENU coordination respect to precise position. The positioning results where we do not solve for the GPS/WAAS time offset are divided into four groups which are resulted from using different number of WAAS GEOs into positioning. As expected for this case, if we use more WAAS GEOs for positioning, we generally have greater the position bias. However, positioning results that solve for the GPS/WAAS time offset have smaller position bias and are less affected by the number of WAAS GEOs. The solution of WAAS time offset is about 52 nanoseconds.

Table 5. User range accuracy (URA) of satellites on collection day

PRN	URA(m)	PRN	URA(m)	PRN	URA(m)
5	2	**21**	2	**30**	2
15	2	**25**	2	**133**	4096
16	2	**26**	2	**135**	4096
18	2	**29**	2	**138**	2

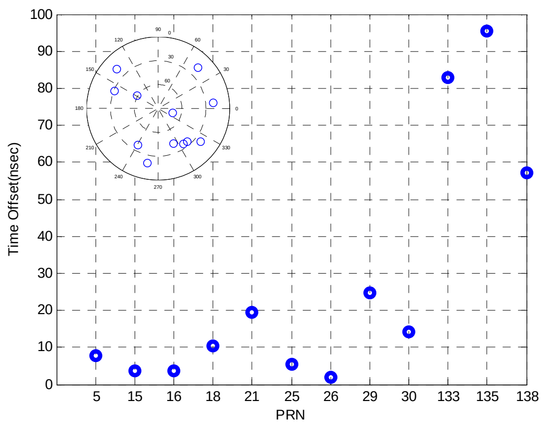

Figure 4. Results of time offset calculated by difference between true range and pseudorange (PDOP = 1.827)

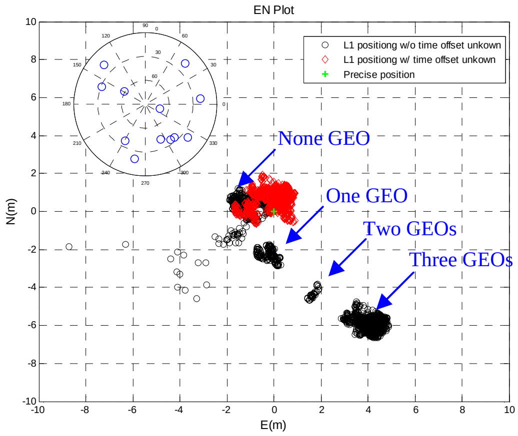

Figure 5. EN plot of L1 positioning w/ and w/o WAAS time offset unknown respect to precise position (PDOP = 1.827)

SOLVING THE TIME OFFSET BETWEEN L1 AND L5

The ephemeris of GPS L1 is used to serve as the ephemeris of GPS L5 for positioning. But, a time offset between L1 and L5 which is resulted from IFB is needed to subtract from L5 pseudorange. For solving this time offset, one unknown is added to observation equation and uses L5 pseudorange of target satellite instead of L1 pseudorange as follows [12].

$$\begin{bmatrix} \delta\rho_{L1}^{(1)} \\ \delta\rho_{L1}^{(2)} \\ \vdots \\ \delta\rho_{L1}^{(k-1)} \\ \delta\rho_{L5}^{(k)} \end{bmatrix} = \begin{bmatrix} \left(-1^{(1)}\right)^T & 1 & 0 \\ \left(-1^{(2)}\right)^T & 1 & 0 \\ \vdots & \vdots & \vdots \\ \left(-1^{(k-1)}\right)^T & 1 & 0 \\ \left(-1^{(k)}\right)^T & 1 & 1 \end{bmatrix} \begin{bmatrix} \delta x \\ \delta b \\ \delta v \end{bmatrix} + \tilde{\varepsilon} \qquad (4)$$

where $1^{(k)}$ is the unit vector from satellite to antenna, δx, δb ,and δv are the unknown corrections for position, receiver clock bias and time offset between L1 and L5. Each satellite with the L5 signal goes through this process. The solutions are averaged with time and listed in the table 6. The time offset of PRN1/ SVN49 is 517 nanoseconds (155 meters). This result corresponds to the current configuration for PRN1/SVN49 which places antenna phase center above 152 meters above the satellite [3]. However, this result is only one time estimation and one would present more statistical result in the future.

Table 6. Time offset and antenna phase center difference between L1 and L5

PRN	L1/L5 Time offset (nsec)	L1/L5 Antenna Phase Center Difference (m)
1	517.219	155.058
25	-103.214	-30.942
133	-233.096	-69.881
135	-255.516	-76.602
138	-185.551	-55.718

THE POSITIONING RESULT OF DUAL FREQUECY SOFTWARE RECEIVER

After solving time offset from previous two sections, some corrections can be made by adding the time offset between WAAS and GPS time to satellite time correction. Moreover, subtracting the time offset between L1 and L5 from L5 pseudorange allows us to align the L5 antenna phase center with L1. Applying the three positioning methods mentioned in table 4, we generate the results on seen in the figure 6. Table 7 compares the positioning accuracy of three methods. The PDOP = 8.876 is poor due to the limited number of satellites with L1 and L5. The positioning results have some biases respect to precise position and distribute in a line shape with 45 degree because of no satellite available in the upper right side. The (L5 only) method has smallest bias (1.311 m) and 2-D RMS error (0.711 m) which is much better than SPS service. There is no ionosphere activity on the collection day, so the iono-free combination method which combines the errors from the L1 and L5 has worst performance [11].

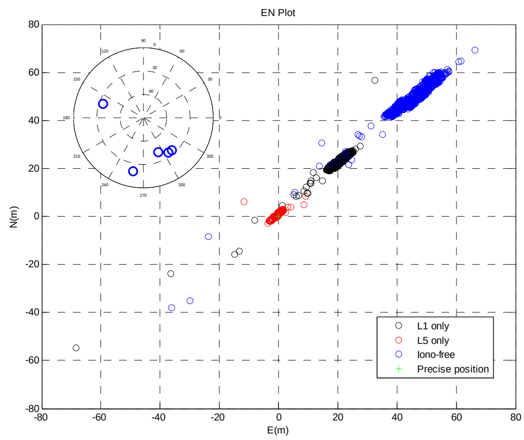

Figure 6. EN plot of positioning by L1 only, L5 only, and iono-free respect to precise position (PDOP = 8.876)

Table 7. Positioning accuracy

Method	Bias(m)	1-sigma 2D-RMS(m)
L1 only	30.804	3.103
L5 only	1.311	0.771
Iono-free combination	68.312	7.572

CONCLUSIONS

A real-time software receiver is implemented for dual-frequency (L1/L5) GPS/WAAS in a PC with a modern processor to demonstrate positioning using L5 signal and dual-frequency combination. This work is potentially the first GPS receiver capable of L5-only positioning, and solves some significant issues with using the current non-homogeneous L5 constellation and signal broadcast. The solutions of time offset between L1 and L5 as well as WAAS and GPS time are developed. The results show positioning accuracy of software receiver. While more and more GPS satellites with an L5 payload are planned for the future, the software receiver can be used to test new satellite and positioning accuracy will improve with better geometry. The paper also proposes an assistance mechanism between L1 and L5 for shortening acquisition time and increasing signal sensitivity of L5Q signal. For integrating correlation results using combination code consisting of spreading code and NH code in the software receiver, a method which rotates the each output of correlator and sums over NH code period without increasing code table size is addressed in the paper.

Future work includes developing a dual-frequency (L1/L5/E1/E5) multi-constellation (GPS/Galileo/QZSS) software receiver. We are also interested in reducing ionosphere error in the severe ionosphere activities condition.

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