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High Accuracy Real-Time Precise Point Positioning using the Japanese Quasi-Zenith Satellite System LEX Signal

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Abstract

The Quasi-Zenith Satellite System (QZSS) is a regional navigation satellite system transmitting navigation signals that are compatible and interoperable with GPS, as well as transmitting augmentation signals that carry bias correction messages. The L-band Experimental (LEX) signal on the E6b frequency delivers correction messages – such as orbits and clock information, which enable Precise Point Positioning (PPP). Since March 2013, Australian and Japanese researchers have conducted collaborative investigations in order to evaluate the QZSS LEX signal and the quality of the broadcast correction messages for real-time PPP. The QZSS LEX has been tested in both static and kinematic positioning modes in Australia. The results have been compared to positioning solutions derived from conventional positioning techniques such as Real-Time Kinematic (RTK), as well as those derived from the International GNSS Service's (IGS) real-time service. Decimetre level positioning accuracies in real-time have been obtained in both static and kinematic tests. Furthermore, a prototype system of an 'Australian-generated LEX corrections' has been developed. This paper presents the results of investigations into the feasibility of using the QZSS LEX signal to deliver a high accuracy real-time positioning service to Australian GNSS users. This is a collaborative research project between the Australian Cooperative Research Centre for Spatial Information and Japan Aerospace Exploration Agency (JAXA).

Keywords

Quasi-Zenith Satellite System (QZSS), LEX, Global Navigation Satellite Systems (GNSS), Global Positioning System (GPS), Precise Point Positioning (PPP)

Introduction

Global Navigation Satellite Systems (GNSS) have long been recognized as an invaluable technology providing accurate Position, Navigation and Timing (PNT) information on a global scale. 'GNSS' is a standard term for global satellite-based navigation systems, which include US' GPS, Russia's GLONASS and several other new and emerging constellations such as Europe's Galileo and China's BeiDou systems. There are also Regional Navigation Satellite Systems (RNSS) and Satellite Based Augmentation Systems (SBAS) that will be operational in the coming years, particularly from Japan and India, which will augment the performance of GNSS.

The Quasi-Zenith Satellite System (QZSS) is a Japanese satellite navigation system developed by Japan Aerospace Exploration Agency (JAXA). The objective of QZSS is to enhance the current availability and performance of GNSS typically over Japan and neighbouring Asia Oceania countries. Besides transmitting conventional positioning signals, QZSS also transmit augmentation signals to enhance the performance of GNSS

(JAXA, 2014). One of the QZSS augmentation signals is the L-band experimental (LEX) signal, which is sometimes referred to as the L6 signal. This signal is designed to enable high accuracy positioning in real-time and time transfers through transmission of precise corrections. RTK-like performance (3 cm horizontal and 6 cm vertical RMS errors with time to first fix of 35 seconds) has been reported in Japan utilising regional corrections that are only valid in Japan and also include atmospheric corrections (Saito et al., 2011). Another type of correction messages that are transmitted on the LEX signal has wide-area validity and is currently in testing phase for high accuracy point positioning. These messages are known as ‘MADOCA-LEX’ messages.

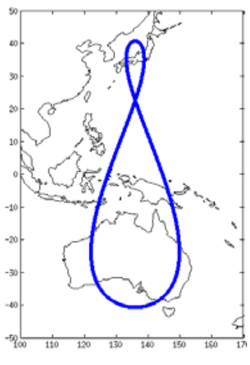
In this paper, we present an analysis of the quality of the real-time Precise Point Positioning (PPP) solutions using corrections broadcasted on the LEX signal. The aim is to evaluate the capability of the QZSS LEX signal and messages to deliver high accuracy real-time PPP solutions in both static and kinematic modes. The theoretical aspect of PPP including the functional model is assumed known and hence will not be discussed. Interested readers are recommended to refer to (Kouba, 2009, Kouba and Hèroux, 2001, Zumberge et al., 1997). In addition, we will also describe the performance of an ‘Australian-generated LEX corrections’ prototype system that were developed to package and transmit augmentation corrections for real-time PPP.

First, a description of the Japanese QZSS system is given in Section 2. The structure of the LEX signal and messages are presented in Section 3. Section 4 describes the positioning results of the real-time PPP processing using the LEX correction messages. In Section 5, the prototype ‘Australian-generated LEX Corrections’ system is described with results being presented. Finally, a summary and conclusions are given in Section 5.

Quasi-Zenith Satellite System

QZSS is a Japanese Regional Satellite Navigation System (RNSS). When fully deployed in 2018, it will consist of three QZSS satellites placed in Highly Inclined Elliptical Orbits (HEO) and one Geostationary (GEO) satellite (QSS, 2014). The HEO satellites have similar orbital period as equatorial geostationary satellites. However, they have a large orbital inclination angle from the equatorial plane, so that the satellites spend most of the time in the apogee area (over Japan). The orbit configuration of these inclined QZSS satellites provides continuous coverage at a high elevation angle, thus improving the performance of satellite navigation in areas of Japan that challenge traditional satellite positioning capabilities, e.g., natural and urban canyons. While built primarily for users in Japan, the orbit design of QZSS offers significant advantages to neighbouring East Asian and Oceania countries centred along the 135° E meridian line. The first QZSS satellite, QZS-1 or nicknamed ‘Michibiki’, was launched on 11 September 2010. JAXA declared QZS-1 user-ready in June 2011 (JAXA, 2014). The orbit parameters and ground track of the QZS-1 satellite are presented in Table 1.

Table 1. QZS-1 HEO parameters.



Parameter	Nominal
Semi-major axis	42164.16945 km
Eccentricity	0.075
Inclination	43º
Argument of perigee	270º
Central longitude	135º E

QZSS is intended as a regional augmentation system for GNSS, aimed at enhancing the availability and the performance of GNSS based Positioning, Navigation and Timing (PNT). In addition to transmitting navigation signals similar in structure, frequency and spreading codes to GPS, i.e., L1C/A, L1C, L2C, L5, QZSS also transmits two augmentation signals, i.e., L1-SAIF (Sub-metre Augmentation with Integrity Function) and LEX. The L1-SAIF signal provides wide-area differential corrections, allowing sub-metre positioning accuracy, coupled with integrity data for safety-of-life services. This system is similar to the U.S. Wide-Area Augmentation System (WAAS). The LEX signal, on the other hand, is unique to QZSS. It delivers correction messages, such as precise orbit and clock corrections, that will augment the current performance of single receiver point positioning.

The L-band Experimental Signal

The QZSS-LEX signal is an experimental performance enhancement signal transmitted on 1278.5 MHz carrier, which has the same frequency as Galileo E6b signal. Numerous organisations in Japan, e.g., JAXA, Spatial Positioning Research and Application Centre (SPAC), National Institute of Information and Communications Technology (NICT), and Geospatial Information Authority of Japan (GSI), are currently investigating and evaluating the signal to support their own PNT applications.

Figure 1 illustrates the navigation message modulation for the LEX signal. The LEX signal uses a Kasami series short code (2.5575 Mcps) with a chip length of 10230 and a 4 ms period, and a Kasami series long code (2.5575 Mcps) with a chip length of 1048575 and a 410 ms period. The short code is modulated by the navigation message using a 256-ary Code Shift Keying (CSK), which involves replacing the short code with a left circle shifted version of it, the number of steps to be shifted representing the symbol value (JAXA, 2014).

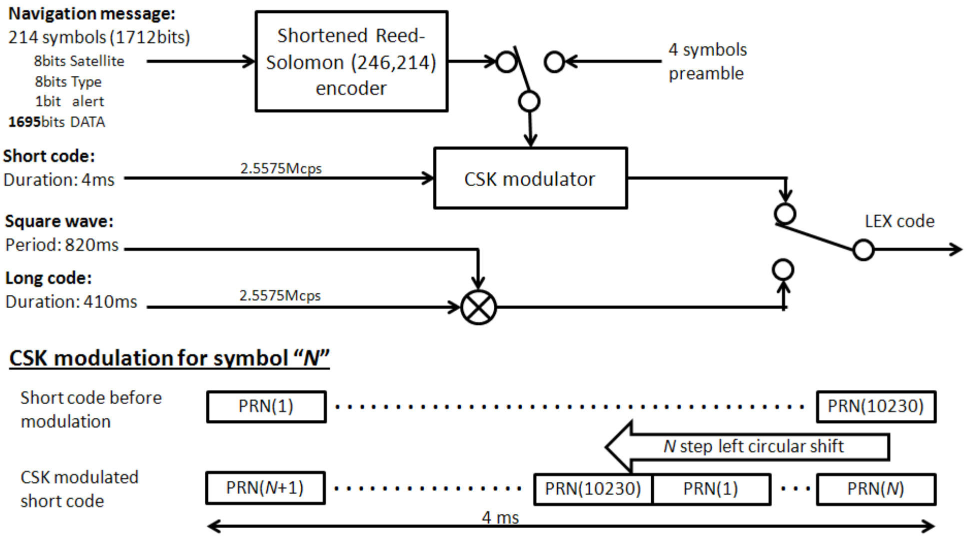


Figure 1. LEX signal code modulation (JAXA, 2013).

The LEX navigation message is grouped in frames of 250 symbols. 8 bits indicating the satellite transmitting the message (193 for the QZS-1 and 194 to 196 for the next three QZSS satellites), 8 bits indicating the type of message and an alert flag of 1 bit are added to 1695 bits of data to form 214 symbols of 8 bits each. The 214 symbols are encoded into 246 symbols using a shortened Reed-Solomon code. Finally 4 preamble symbols i.e. "1A, CF, FC, 1D" are added. One frame is transmitted every second.

The LEX signal is an augmentation signal transmitted using the 1278.75 MHz (L6) carrier and is designed to transmit GPS and multi-GNSS satellite orbits and clock corrections to enable real-time PPP for high accuracy point positioning. The key advantage of the LEX signal is the relatively large data capacity, which could support high accuracy positioning such as PPP. Table 2 shows the data rates for the GNSS navigation messages transmitted using different signals. The LEX signal, with its 2000 bps capacity is capable of transmitting eight times the information of traditional satellite based augmentation signals.

Table 2. Data transmission rate of the different navigation messages.

Message	Constellation	Carrier (MHz)	Data Rate (bps)
NAV	GPS	1575.42	50
SBAS	WAAS/MSAS/EGNOS	1575.42	250
C/NAV	Galileo	1278.75	500
LEX	QZSS	1278.75	2000

Several types of LEX messages are being tested to provide precise positioning using the LEX signal. The messages being tested by JAXA from April 2013 are generated by the Multi- GNSS Advanced Demonstration tool for Orbit-and-Clock Analysis (MADOCA) software. The MADOCA software outputs State Space Representation (SSR) messages for satellite orbits and clocks that follow the Radio Technical Commission for Maritime Services (RTCM) version 3.2 protocol (RTCM, 2013), hereon as RTCM messages for simplicity.

In the case of the current MADOCA streams, the RTCM-SSR messages are packed within the LEX messages as shown in Figure 2. The LEX message stream consists of 2000 bit frames which are transmitted every second. The first 49 bit header is transmitted first, followed by 1695 bits of data, and finally a 256 bits complete a shortened Reed-Solomon (250,218) code (JAXA, 2014).

The data part of the MADOCA based LEX messages contain the GPS time of transmission (time of week and GPS week number) followed by the data part of RTCM messages, which are obtained by discarding the preamble, message length and the 24 parity bits from the standard RTCM messages. It is also worthy to note that the MADOCA-LEX messages uses the high-rate clock corrections of the RTCM messages thereby reducing the required data rate. This is preferred because no high order component of the clock corrections needs to be transmitted as satellite clocks errors are difficult to predict with a polynomial model (Hadas and Bosy, 2014). Table 3 shows the RTCM messages contained in the MADOCA-LEX stream for PPP applications.

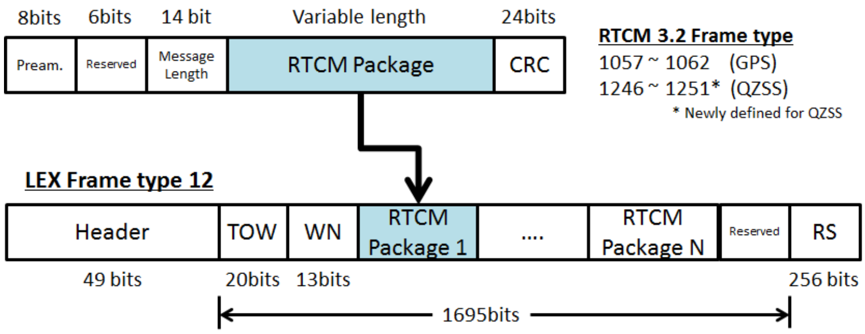


Figure 2. Packaging of RTCM messages on QZSS LEX signal. 1695 bit data part of MADOCA-LEX messages are includes the GPS time of transmission and the data part of RTCM messages.

Table 3. MADOCA based LEX messages.

Message type	Update Interval (s)	System
Orbits	30	GPS, GLONASS QZSS
High Rate Clock	2	
Code Bias	30	
URA	30	

The MADOCA-LEX messages for PPP have been tested and verified in both Japan and Australia. From a series of evaluations performed in Australia from 2013 to 2014, it was found that the LEX signal can be reliably decoded when the QZS-1 satellite elevation angle is above 40° and when using a patch antenna, that is a G5Ant-2A4MNS1 from ANTCOM (Choy et al., 2013). The ground track of the QZSS satellites and its coverage area are shown in Figure 3. The left plot shows the number of hours a day the QZS-1 is above 40°of elevation. As it can be seen from the figure, QZS-1 is available for more than 12 hours a day in most of the Asia-Pacific region. The right figure shows the number of hours a day in which at least one QZSS satellite is above 40°of elevation. The coverage area of the QZSS under these conditions will include Japan, Korea, Australia and Papua New Guinea, most of Southeast Asia, and large parts of China.

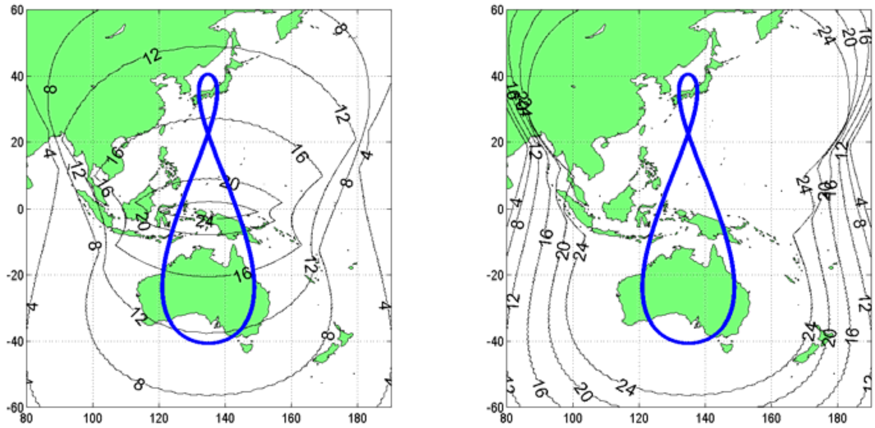


Figure 3. Coverage area of QZSS. Left: Number of hours a day QZS-1 satellite is above 40° of elevation. Right: Number of hours a day at least one satellite will be above 40° of elevation once the four satellites constellations are active in 2018.

Real-Time PPP Performance Using LEX Corrections

The MADOCA-LEX products have been evaluated in terms of real-time PPP solutions in static and kinematic processing modes (Harima et al., 2014a). No phase ambiguities were resolved in this analysis and the solutions presented herein were based on ambiguity-float ionosphere-free PPP solutions or hereon known as standard-PPP. We present two tests, one at a fixed-point (static) and a moving vehicle (kinematic) test. Real-time PPP solutions based on the International GNSS Service (IGS) Real-Time Service (IGS-RT) products were also presented for comparison. All processing was done in RTKLIB software version 2.4.2 (Takasu, 2013) and the results were GPS-only solutions. It is worth noting that the MADOCA-LEX products contain GPS, GLONASS, and QZSS corrections since January 2014. Dual frequency geodetic grade GNSS receivers were used and the MADOCA-LEX corrections were collected using an independent LEX receiver. The PPP solutions from the IGS-RT corrections were streamed through an NTRIP caster using a mobile data router connected to a cellular network.

Figure 4 shows the positioning errors of the fixed-point test that was conducted on 1 August 2013. The fixed-point data were collected at a permanent GNSS station located at the RMIT Bundoora campus in Melbourne, Australia. The known coordinates of the reference station with RMS errors of 2 cm were used as ‘ground-truth’ to evaluate the quality of the PPP estimates. The 3D RMS error using MADOCA-LEX corrections after 2-hour of solution convergence is 4.1 cm. The RMS error is approximately 25% larger than those of the IGS-RT solutions.

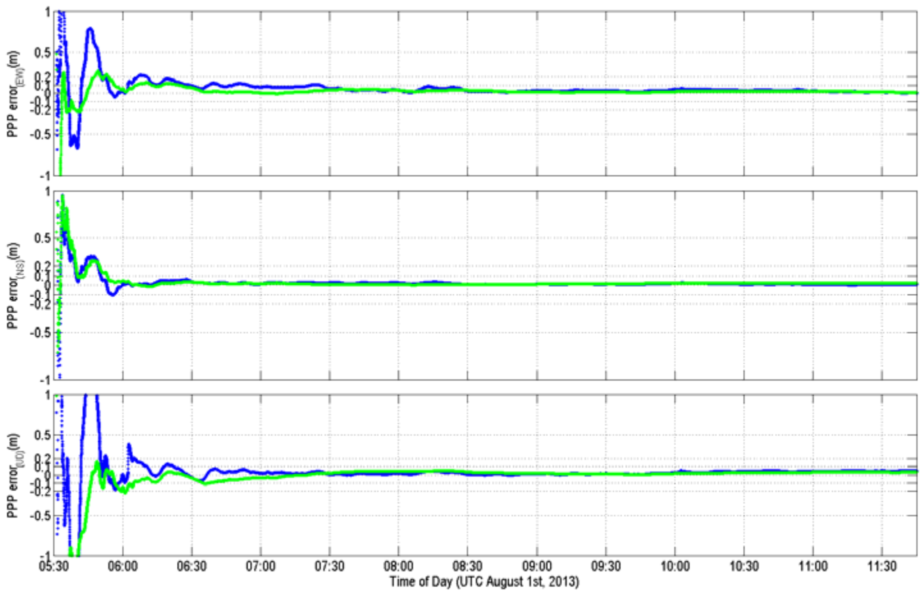


Figure 4. Real-time static PPP position (East, North and Up components) errors from using the MADOCA-LEX (blue) and the IGS-RT corrections (green).

The moving vehicle test was carried out on 22 October 2013 from 21:15 UTC to 22:20 UTC in Centennial Park, Sydney, Australia. Figure 5 shows the time series of the car's positioning errors based on the real-time MADOCA-LEX in blue, IGS-RT corrections in green, and post-processed PPP solutions from NRCan PPP service in black. The positioning errors are the differences between the estimated PPP solutions with network-RTK solutions. The network-RTK solutions are expected to be accurate to 2 cm horizontally and 5 cm vertically. The 3D position RMS errors of the real-time kinematic PPP using MADOCA-LEX solutions were 11.3 cm, and 12.1 cm using the IGS-RT products. The 3D RMS errors of the post-processed PPP solutions were 10.2 cm.

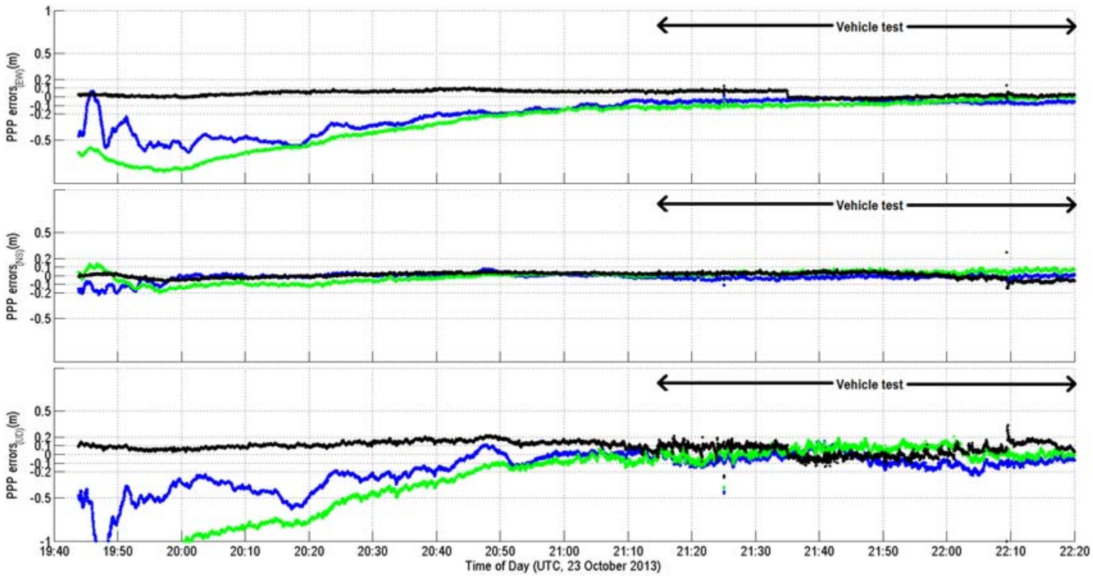


Figure 5. Real-time kinematic PPP position (East, North and Up components) errors of the moving vehicle using MADOCA-LEX (blue) and IGS-RT (green) corrections. Post-processed NRCan PPP solutions (black) are shown for comparison.

A Prototype Australian-generated LEX Corrections

A major component of the CRCSI and JAXA joint research is to augment the current correction messages to include satellite phase biases. This is to enable PPP Ambiguity Resolution (PPP-AR) (Collins et al., 2010, Ge et al., 2007, Laurichesse et al., 2009). Existing correction messages for PPP from the IGS-RT streams and the CLK9B stream from the French Government Space Agency (CNES) PPP-Wizard project were received in RTCM format and packaged as LEX messages for transmission by QZS-1. These messages were packaged at RMIT University using a format similar to that of the MADOCA-LEX messages and transmitted to the QZSS Master Control Station (MCS) in Japan for broadcast by QZS-1.

As part of the effort to evaluate the LEX signal and messages to support standard-PPP and PPP-AR applications in Australia, the outage rate and latency for the messages transmission and broadcasting process were measured. The packaged LEX messages were decoded in Australia and used for PPP positioning. The IGS-RT corrections stream, which consists of precise satellite orbits and clock corrections, were used to compute standard-PPP solutions; while the corrections from the CNES CLK9B stream, which contains uncalibrated phase delays, were used for PPP-AR.

It is necessary to emphasize that although the messages for PPP-AR were based on CLK9B, the messages used in our study contains only a fraction of the information contained in the original stream (so it can be fitted into the LEX messages). For this reason it is possible that we may be limiting the full potential of the CLK9B messages. For these reasons, we call these CLK9B based messages RMIT messages in order to distinguish them from the full CLK9B corrections provided by CNES.

For these tests, the generated correction messages were broadcasted using two methods. In the first method, the messages were sent to the QZSS MCS and broadcasted using the LEX signal. In the second method, the messages were broadcasted through the Internet using an NTRIP caster.

Figure 6 shows the positioning errors obtained using IGS-RT RTCM messages directly from the NTRIP caster (Blue), and using messages transmitted via the LEX signal (Cyan). As it can be seen from the figure, the two solutions are very similar to each other with RMS difference of 1.9 cm after 2 hours of convergence. Figure 7 shows the positioning errors obtained using RMIT messages directly from the NTRIP caster (Blue and Dark Green), and using messages transmitted via the LEX signal (Cyan and Light Green).

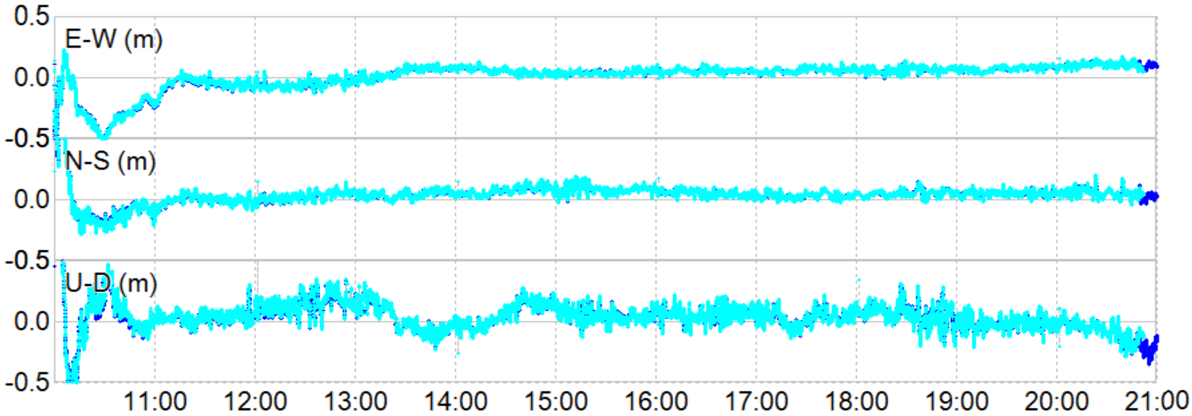


Figure 6. PPP solutions calculated using IGS-RT corrections streamed from NTRIP caster (blue) and from LEX signal (cyan).

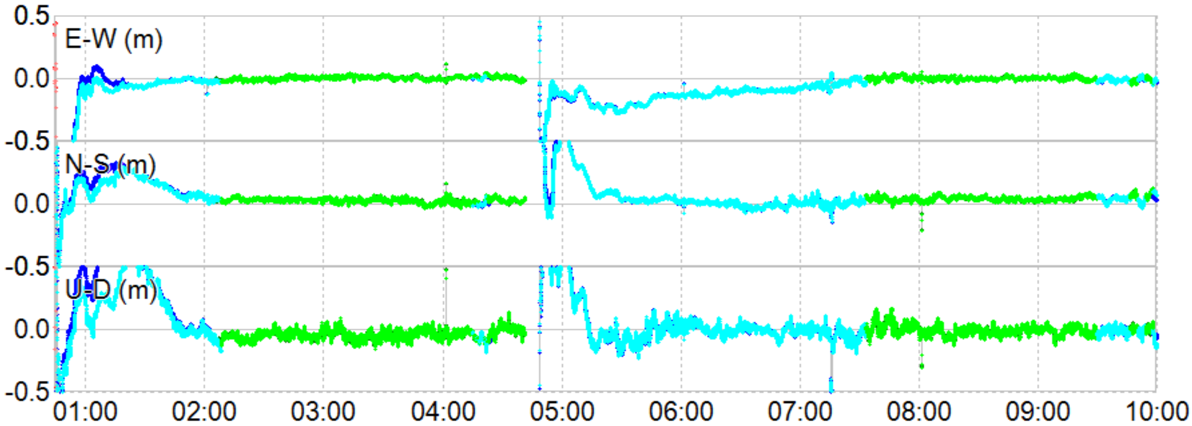


Figure 7. PPP-AR solutions calculated using CLK9B based corrections streamed from NTRIP caster (dark green & blue) and from LEX signal (light green and blue). The green points are solutions with fixed ambiguities.

The findings from the research also demonstrated that real-time PPP-AR solutions based on the generated RMIT corrections delivered using the LEX signal, achieved accuracies of 3 cm for horizontal positioning and 7 cm for 3D positioning (Harima et al., 2014b). However long convergence times ranging from 90 minutes to more than 3 hours was needed to obtain these solutions. The transmission of correction messages using the LEX signal was found to add an average of 5.67 seconds of latency. For times when the QZS-1 satellite is above 40˚ of elevation, the message outages were below 0.8%. Since the majority of the outages occurred when the satellite elevation was relatively low, it is suspected that most of the outages are caused by the receiver's configuration settings and antenna. The reliability of the message decoding may be improved by using a survey grade antenna.

Conclusions

The Japanese QZSS system is a regional augmentation system that aims to improve GNSS satellites availability in the East Asia and Oceania region as well as to enhance performance of GNSS-satellite-based PNT applications. One of the augmentation signals transmitted by the QZS-1 is the LEX signal. The LEX signal is designed to provide enhanced accuracy of GNSS-based PNT applications such as real-time PPP and timing. The services provided by the LEX signal are expected to cover most of the East Asia and Oceania region by 2018 when the system reaches full operational capability with three HEO and one GEO satellites.

A joint project between the Australian CRCSI and JAXA aims to assess the feasibility of using the LEX signal to potentially deliver a real-time precise positioning service in Australia. The capabilities of the QZSS LEX signal to deliver a standard-PPP service with decimeter-level accuracy through the transmission of MADOCA-

LEX type messages have been demonstrated in Japan and Australia. In addition, a prototype system of an 'Australian-generated LEX corrections' has been developed. The overall effect of the outages and added latencies on the PPP solutions was found to be less than 2 cm in 3D RMS difference and less than 1 cm of RMS in horizontal positioning difference. No significant effect on the PPP solution convergence time and ambiguity resolution rate was found.

The next phase of the research is to further develop a new augmentation message to enhance the performance of real-time precise positioning. This message will incorporate a global ionospheric model as a first step toward including a regional ionospheric model to ultimately facilitate PPP-RTK.

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