Technical Working Group Report to the U.S.-Japan GPS Plenary

-----GPS-QZSS compatibility and interoperability-----

GPS-QZSS Technical Working Group

January 18, 2012

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Table of Contents

1. Scope

The Global Positioning System (GPS)-Quasi-Zenith Satellite System (QZSS) Technical Working Group (TWG) was established according to a decision made by the 2nd U.S.-Japan GPS Plenary meeting held on October 16, 2002 in Tokyo, under the auspices of the 1998 U.S.-Japan Joint Statement on Cooperation in the use of GPS. The purpose of the TWG is to exchange information and share concepts in an effort to achieve compatibility and technical interoperability between QZSS and current and future configurations of GPS.

During the TWG discussions, both parties (U.S. and Japanese Government representatives) identified the basic technical concepts for GPS-QZSS compatibility and interoperability. The purpose of this document is to provide results of investigations that demonstrate the compatibility and interoperability between both systems and which were adopted into the actual system design for the QZSS.

The first satellite of the QZSS, named as “Michibiki,” which means the “Guiding light” or “Showing the way” in English, was launched successfully on September 11, 2010. The Operations Team for Michibiki has celebrated one year of successful operations on orbit. The recent achievements of the technical demonstrations showing secure compatibility and the effect of high interoperability between QZSS and GPS are described in this report which was compiled as of the end of November 2011.

Both parties identified the importance of continuous cooperation at International Telecommunication Union (ITU) proceedings in order to secure the safe and reliable operation for Radio Navigation Satellite Service (RNSS) systems. This document describes collaborative activities among the U.S., Japan and other RNSS providers and the results of those activities at the ITU as well.

2. GPS-QZSS TWG/EWG

2.1 Goal, Structure, Work plan

The Quasi-Zenith Satellite System (QZSS) is a regional GPS augmentation system which covers the East Asia and Oceania region. It was designed to enhance GPS capability and performance by transmitting navigation signals and augmentation messages with the same radio frequency (RF) properties as GPS.

Compatibility between GPS and QZSS signals was an essential and mandatory requirement for both systems. Additionally, high interoperability between both systems was to be satisfied to secure improvement of GPS capability without any huge modifications on current GPS receiver’s design.

The goal of the TWG was defined as follows:

1) To secure the compatibility between both systems as a mandatory requirement.
2) To maximize the interoperability between both systems for obtaining better performance from combining use of GPS and QZSS rather than GPS stand-alone usage.
3) To collaborate with each other to maintain allocated frequency bands to RNSS in good condition without harmful interference with other services with regard to ITU regulation.
4) To support establishment of the ground control segment of the QZSS, especially Monitoring Stations in U.S.-owned facilities.

The TWG was established at the second U.S.-Japan GPS Plenary meeting on October 16, 2002 in Tokyo under the auspices of the 1998 U.S.-Japan Joint Statement on Cooperation in the use of GPS. The QZSS was a Research and Development program in Japan, and the related ministries such as Ministry of Education, Culture, Sports, Science and Technology (MEXT), Ministry of Internal Affairs and Communications (MIC), Ministry of Economy Trade and Industry (METI) and Ministry of Land, Infrastructure Transport and Tourism (MLIT) participated in the TWG with their research institute members. On the U.S. side, the GPS Joint Program Office (JPO) co-led the TWG, and United States Naval Observatory (USNO), National Aeronautics and Space Administration (NASA) and Federal Aviation Administration (FAA) with their technical support contractors also participated in the TWG. The lead office for the U.S. for the TWG has now transferred to the office of the Assistant Secretary of the Air Force, Directorate of Space Programs, GPS Cell (SAF/AQSL)

The first TWG meeting was held in Los Angeles, on December 4 to 5, 2002.

The Expert Working Group (EWG) was formed under the TWG activity to discuss more detailed technical topics, inviting specialists from the TWG members according to discussed topics based on mutual agreement at the second TWG meeting on May 2 to 3, 2003. The first EWG was held in Tokyo on January 20 to 21, 2004. Separate meetings for two sub-groups: Timing; and Signal structure; were convened at the first opportunity of the EWG, however, no separate sub-group meetings have been conducted since then.

The work plan of the TWG is briefly summarized as follows:

1: Securing compatibility between GPS and QZSS

- 1-1: ITU operator-operator coordination between N-SAT-HEO2/QZSS-1 and NAVSTAR GPS/NAVSTAR GPS-IIRF
- 1-2: ITU operator-operator coordination between N-SAT-HEO2/QZSS-1 and USRSR
- 1-3: Compatibility study for Indoor Messaging System (IMES)

2: Maximizing interoperability between GPS and QZSS

- 2-1: QZSS GPS interoperable signal
- 2-2: Joint study for new L1C signal design
- 2-3: Timing
- 2-4: Geodetic reference

3: Collaboration in ITU information exchange and making joint strategy in advance of ITU meeting.

- 3-1: ITU-R Recommendation describing RNSS technical characteristics
- 3-2: RNSS operating band protection

4: Cooperation for QZSS ground control segment

- 4-1: Feasibility study and site survey
- 4-2: Establishment agreement

2.2 Meeting History

As of January 18, 2012, nine meetings of TWG and twelve meetings of the EWG have been held as shown in the Table 1.

Table 1: Meeting History of TWG and EWG

Meeting	Date	Place	Note
#1 TWG	December 4-5, 2002	Los Angeles	
#2 TWG	May 28-29, 2003	Los Angeles	
#1 EWG	January 20-21, 2004	Tokyo	Signal structure
#2 EWG	January 20, 2004	Tokyo	Timing
#3 TWG	January 21-22, 2004	Tokyo	
#3 EWG	November 19, 2004	Washington, D.C.	
#4 EWG/TWG	July 19, 2005	Hawaii	
#5 EWG	January 24-25, 2006	Tokyo	
#5 TWG	January 26, 2006	Tokyo	
#6 EWG	August 4, 2006	Kauai, Hawaii	
#7 EWG	May 23, 2007	Washington, D.C.	
#6 TWG	May 23, 2007	Washington, D.C.	
#8 EWG	November 8, 2008	Tsukuba Space Center	
#9 EWG	August 25, 2009	NOAA Weather Forecasting Station in Guam	Ribbon Cutting Ceremony for Guam MS
#10 EWG	December 21, 2009	Tokyo	
#7 TWG	December 21, 2009	Tokyo	
#11 EWG	January 11-12, 2011	Tsukuba Space Center	
#8 TWG	January 12, 2011	Tokyo	
#12 EWG	September 9, 2011	Tokyo	Just after ICG #6 in Tokyo
#9 TWG	January 17, 2012	Washington, D.C.	

Several technical video conferences and small group interim meetings were also held between the 10th, 11th and 12th EWG meetings.

3. Achievements of TWG/EWG

3.1 Interoperability between GPS and QZSS

3.1.1 Signal Structure and data format

Technical concepts for GPS-QZSS interoperability were discussed and investigated through the TWG. The outcome of the discussions was introduced into the QZSS signal design and is defined in "Interface Specification for QZSS (IS-QZSS)" which is available on the following web site:

http://qz-vision.jaxa.jp/USE/is-qzss/index_e.html

3.1.1.1 Signal structure

The QZSS signal structure design for the L1, L2 and L5 bands was introduced and discussed with respect to their compatibility and interoperability with GPS signals. At the 5th TWG and EWG meetings which were held on January 24 to 26, 2006, both parties agreed that the QZSS signals are fully compatible and interoperable with GPS, based on the assumption documents at that time. The GPS L1C signal specification, IS-GPS-800, was released as a draft document to the public in April 2006. The QZSS signal specifications were released to the public as the first draft documents in January 2007.

The following items were confirmed and agreed upon by both parties:

(1) Signal structure and characteristics

Through the entire orbit of each satellite, QZSS transmits positioning signals on L1, L2, L5 and E6 bands.

Signals transmitted on L2 and L5 have the same structure and characteristics as the GPS L2C and L5 signals, except for small differences in the data messages, as described in a later section.

As for L1 band, QZSS transmits the following three signals simultaneously:

1) L1C
2) L1 C/A
3) L1-SAIF

The L1C signal is a brand-new civil signal for GPS and will be transmitted from Block III satellites, scheduled for first launch in 2014.

The L1C cooperative signal design effort has incorporated many U.S. and Japanese L1C survey contributions, as well as joint U.S./Japan participation in L1C Technical Meetings, which led to maximum interoperability between the GPS and QZSS L1C signals. Both parties agreed that they would like to develop cooperative L1C Interface Specifications (IS) and to extend signal design cooperation to the L1 C/A, L2C and L5 signals at the 5th TWG meeting. Based on discussion at the 6th EWG and a follow-on U.S.-Japan technical meeting, the U.S. and Japan agreed that the control of L1C signal specifications, IS-GPS-800 and IS-QZSS, would be implemented separately by both parties. The EWG, TWG and close cooperation between U.S. and Japanese experts through the GPS Interface Control Working Group (ICWG) secured consistency between both documents in order to maintain full interoperability with both systems.

Japanese experts determined that the minimum received signal powers for all QZSS signals have been set to the same values as defined in IS-GPS-200D, IS-GPS-705, and IS-GPS-800. Maximum powers for all QZSS signals have been determined so that Radio Frequency Compatibility with GPS is successfully achieved.

(2) Code assignment

The PRN assignment process was updated and the U.S. has created an expanded set of PRN codes with good correlation properties. Japan agreed to use the U.S. PRN codes and requested code sets for L1, L2 and L5 QZSS signals, preferably numbers in a sequential order. Japan submitted a PRN code application per the GPS Wing’s updated PRN code assignment process after the 5th TWG meeting. The official PRN assignment process for QZSS PRN requests is complete. PRN number 193 is assigned to the first QZS satellite for the L1C, L1 C/A, L2C and L5 signals. Also, PRN number 183 is assigned to the first QZS satellite for the L1-SAIF signal. Finally, 9 additional PRN code sets for each signal were granted to Japan for future QZS expansion.

The assignment tables for L1C, L1C/A, L2C and L5 are available on the following web site:

http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=8618

The design for the QZSS LEX was introduced and discussed. The LEX uses a 40MHz bandwidth with a center frequency of 1278.75MHz. This LEX is not expected to have any impact on compatibility with GPS services.

3.1.1.2. Data format

Since QZSS uses elliptical orbits, some modifications are required in the navigation message that make it different from the GPS format. The differences relate to their operation and require a slightly different data message definition. The differences between the QZSS and GPS navigation messages were introduced and discussed. The following items were confirmed by and agreed upon by both parties:

(1) Ephemeris & Almanac

Orbit ephemeris and almanac data for QZS can be expressed in the existing data structure and format for GPS, changing their definitions from the ones used for GPS. QZSS broadcasts both the QZSS and GPS almanacs.

(2) Timing data

QZSS provides the difference between GPS time and QZS SV time, including GQTO that is to be transmitted as coefficients af0, af1 and af2. GQTO characterizes the difference between QZSS time and GPS time.

(3) Pseudo-Random Noise Identification (PRN ID)

In response to a Japanese request, the U.S. agreed to determine whether its CNAV2 message structure allocates 8 data bits to the PRN ID, otherwise CNAV message uses 6 data bit.

3.1.2 Time Offset

The time offset between GPS time and QZSS time is defined by the GPS-QZSS Time Offset (GQTO).

3.1.2.1 Coordination

To verify the measurement performed by USNO and NICT, GPS time is desired to have a certain level of stability, and this stability is coordinated and agreed on between the GPS and QZSS programs through appropriate channels.

3.1.2.2 Performance

3.1.2.2.1 Obtainable Time Accuracy

The accuracy aim of the GQTO is less than 3 ns rms over any 24-hour period, even with calibration biases.

3.1.2.2.2 Frequency Stability

The stability of the GQTO, expressed as an Allan deviation, has to be less than 4×10^{-14} over any one day to achieve the 3 ns accuracy stated above.

3.1.2.2.3 Update Interval

The update interval of the GQTO coefficients is at least once every 24 hours.

3.1.2.3 Implementation

3.1.2.3.1 Open Availability

The GQTO is openly available to all users.

3.1.2.3.2 QZSS Navigation Message

In case the NICE message format is available, the clock correction message accommodates a range of ± 1 μs with a resolution of 0.03 ns, and a rate of change of the GQTO $\pm 1 \times 10^{-12}$ s/s with a resolution of 4×10^{-16} s/s. If the NICE format is not available, the message has the same resolution and range as those of the legacy C/A message.

3.1.2.3.3 GQTO Estimation Techniques

The GQTO measurement can be measured and estimated using the QZSS ground receiver network and/or the TWSTFT combined with the USNO measurement of the GPS-to-UTC (USNO) time offset.

3.1.2.4 Output document

Both parties agreed to establish and maintain the following document:

1) GPS-QZSS Time offset (GQTO) ICD

This document describes the outline of the key specifications, and it defines the interfaces between GPS and QZSS for the provision of this functionality.

3.1.3 Geodesy

QZSS uses the ITRF geodetic reference system, while GPS uses WGS 84. The two reference frames are almost equivalent, thus negating the need for any translation of positions derived from QZSS to GPS.

3.2 Radio Frequency Compatibility

Both parties conducted the frequency coordination discussion and agreed that the each system can accept the interference from the other system.

In case any technical parameters of either system are updated or a new system for either side is introduced in accordance with its system evolution, both parties also recognize the need for additional frequency coordination discussions.

Additionally, compatibility studies between GPS/QZSS and IMES, which Japan proposed to enhance seamless positioning at the 7th EWG meeting, were conducted as a task of TWG. The result of this discussion is summarized in this section as well.

3.2.1 Coordination between N-SAT-HEO2/QZSS-1 and NAVSTAR GPS/NAVSTAR GPS-IIRF

The following documents have been established in order to investigate the study for the radio frequency compatibility analyses between GPS and QZSS:

1) Models and Methodology for GPS-QZSS Radio Frequency Compatibility Analysis, dated 27 January 2006
2) Reference Assumptions for GPS/QZSS Compatibility Analyses, dated 27 January 2006

The Models and Methodology document defines the methodologies and models to be used for the interference calculations and also shows the results of analyses. The assumptions document describes RNSS system parameters for both GPS and QZSS, which are to be used for the compatibility analyses. These parameters have been continuously updated based on the progress of the system design process.

Both parties fully agreed on all of the calculations in the Assumptions and Radio Frequency Compatibility (RFC) documents and that GPS and QZSS are fully compatible in all L1, L2 and L5 signals.

Both parties agreed that the completed coordination agreement can be applied to both the "N-SAT-HEO2" and "QZSS-1" ITU filings for the L1, L2 and L5 signals of QZSS and both the "NAVSTAR GPS" and "NAVSTAR GPS-IIRF" ITU filings for the L1, L2 and L5 signals of GPS.

3.2.2 Coordination between N-SAT-HEO2/QZSS-1 and USRSR

After the completion of the coordination between N-SAT-HEO2/QZSS-1 and NAVSTAR GPS/NAVSTAR GPS-IIRF, the U.S. submitted a new ITU filing, "USRSR", as a corresponding filing for GPSIII, so as to cover the technical parameters of GPSIII.

Both parties confirmed that the existing coordination agreement between N-SAT-HEO2/QZSS-1 and NAVSTAR GPS/NAVSTAR GPS-IIRF continues to be applicable as long as the GPS satellites of older blocks than GPSIII are operational.

For the frequency coordination between GPSIII and QZSS, the following documents have been established in order to investigate the interference studies between these systems:

3) QZSS System Assumption Document For Radio Frequency Compatibility Analyses, dated February 25, 2011

4) Reference GPS/WAAS Assumptions For GPS/QZSS/MTSAT Radio Frequency Compatibility Analyses, dated September 30, 2010

The Models and Methodology document referred as 1) in 3.2.1 is also used for the interference calculations.

Based on the interference analyses between GPS and QZSS in all L1, L2 and L5 signals, both parties fully agreed that the interference between GPS and QZSS in all L1, L2 and L5 signals can be acceptable.

Based on the above, both parties agreed that the frequency coordination for L1, L2 and L5 signals between N-SAT-HEO2/QZSS-1 and USRSR is complete.

3.2.3 Compatibility between GPS/QZSS and Indoor Messaging System (IMES)

The development of QZSS is aiming to provide enhanced PNT service to users, especially in Japan, and improvement of availability for seamless positioning is expected even in urban canyons where enough number of satellite signals cannot received. To accomplish the goal of realizing seamless positioning, IMES was proposed. The basic concept of the IMES is to transmit position data and/or unique ID and/or other user defined data from the transmitter to users indoors while keeping the similar signal structure as of QZSS/GPS signal.

In the 7th EWG meeting, Japan requested 10 L1 C/A and L1C code sets for future ground use in the proposed IMES. The result of interference analysis showed enough feasibility that the IMES can operate with other GNSS without harmful interference if it is used appropriately. The U.S. agreed to assign 10 PRN codes from 173 to 182 for IMES in Japan under appropriate conditions in November, 2007.

After the code assignment, the method of interference mitigation for high sensitivity receivers was discussed in the 11th EWG and the frequency offset method was adopted.

3.3 Cooperation on QZSS Monitoring Stations (MS)

Since Japan requested permission to host Japanese equipment in the Hawaii area and Mariana Islands, both parties attempted to find a solution through bilateral coordination. After strong efforts by both countries, the U.S. and Japan agreed that the QZSS MSs should be hosted at the Kokee Park Geophysical Observatory (KPGO) on the island of Kauai, which is run by NASA and USNO as well as at the Weather Forecast Station in Guam which is run by NOAA. Additionally, the U.S. and Japan agreed to co-locate a Two Way Time and Frequency Transfer (TWSTFT) station with the QZSS MS at KPGO. The TWSTFT coordinates Universal Time Coordinated (UTC) between the United States Naval Observatory (USNO) and Japan's National Institute of Information and Communications Technology (NICT). NASA and JAXA signed up a Letter of Agreement (LoA) for the cooperation of QZSS Monitoring Station and TWSTFT station in KPGO on October 10, 2008. The agreement between NOAA and JAXA for Guam was established on September 30, 2008.

The ribbon cutting ceremony at Guam was held on August 25, 2009. According to NASA, although the extension of a communications link for broader bandwidth for real time VLBI observations, which is included in the NASA-JAXA agreement, has not yet been completed; NASA established an alternative communication link which has enough capacity for the QZSS and TWSTFT operation at KPGO at this time.

Both MSs have been operated remotely from the Master Control Station (MCS) located in Tsukuba, and collected observation data of GPS and QZSS are used for orbit and clock offset estimation for both systems.

3.4 Cooperation on Spectrum Protection for Radio Navigation Satellite Service (RNSS) in ITU-R

Cooperation at the WRCs, ITU-R Study Group (SG)/Working Party (WP) meetings and Resolution 609 (Rev. WRC-07) Consultation Meetings has continued. In addition, both parties acknowledged the importance of continuous cooperation at future ITU activities.

3.4.1 Cooperation at WRC-03

At WRC-2000, frequency bands 1164-1215 MHz, 1215-1300 MHz and 5010-5030 MHz were allocated for Radio Navigation Satellite Service (RNSS). At WRC-03, agenda item 1.15 was set up to discuss sharing conditions with other services such as Aeronautical Radio Navigation Service (ARNS) in these frequency bands.

Both sides exchanged relevant information and confirmed that the U.S. and Japan were in almost full alignment on agenda item 1.15. Strategies for the WRC-03 were also discussed and coordinated to ensure cooperation at WRC-03.

3.4.2 Cooperation at WRC-07

At WRC-07, adding AM(R)S allocations in the bands 5000-5010 MHz and 5010-5030 MHz to support surface applications at airports was discussed under agenda item 1.6. Both parties discussed strategies for the WRC-07 and coordinated to ensure cooperation at WRC-07.

AM(R)S allocations in the bands 5000-5010 MHz and 5010-5030 MHz were successfully avoided at WRC-07 and the protection of the RNSS allocation in these bands was ensured at WRC-07.

3.4.3 Cooperation towards WRC-12

In preparations for WRC-12, the concept of adding AM(R)S allocations in the band 5000-5010 MHz to support surface applications at airports has been frequently discussed under agenda item 1.4. Furthermore, adding AM(R)S allocations in the band 5000-5010 MHz to support the Unmanned Aircraft System (UAS) also has been discussed under agenda item 1.3.

Both parties have been discussing and coordinating the strategies for WRC-12 to ensure cooperation for the protection of RNSS spectrum.

3.4.4 Cooperation at ITU-R SG/WP meetings

Because both parties understand the need to protect RNSS systems from the interference caused by other services and systems, both parties cooperated to develop the technical and operational characteristics of RNSS systems to be used in sharing and compatibility studies with other services or systems. With this regard, Draft New Recommendations

ITU-R [RNSS_GUIDE], [1477_NEW], [1088_NEW], [CHAR-RX3], [1479_NEW] and [E-S TX+RX] were adopted at the SG4 meeting in September 2011 and Recommendation ITU-R M.1787 was developed in 2009. Both parties also recognized the need for continued cooperation to develop the technical and operational characteristics of RNSS systems to be used in sharing and compatibility studies with other services or systems in the band 5,010-5,030 MHz, which would be contained in Preliminary Draft New Recommendation ITU-R M.[S-E RX+TX].

Because both parties recognize that the development of a single methodology for coordination of RNSS systems and networks would facilitate the successful conduct of necessary coordination, both parties cooperated to develop the ITU-R Recommendation to identify the methodology to be used for the coordination between RNSS systems and networks. With this regard, Recommendation ITU-R M.1831 was developed in 2009.

3.4.5 Cooperation at Resolution 609 (Rev. WRC-07) Consultation Meetings

WRC-03 adopted Resolution 609, whereby Consultation Meetings should be held on a regular basis to ensure an adequate level of protection for ARNS systems.

Because the aggregated equivalent flux power density (epfd) of all operational/planned RNSS systems is approaching the limit (the result of the latest Consultation Meeting showed the margin of 0.52 dB), both parties agreed on the importance of the continued exchange of views on possible ways to avoid the excess of the aggregate epfd limit.

3.4.6 Cooperation at Future ITU Activities

Because both parties understand the need to protect RNSS systems from interference caused by other services and systems, both parties will continue activities to maintain the technical and operational characteristics of RNSS systems to be used in sharing and compatibility studies with other services or systems. With this regard, Recommendation ITU-R M.1787 will be continuously reviewed.

There are several issues that merit an exchange of information between the U.S. and Japan, and both sides recognize the importance of the continuous cooperation at future ITU meetings.

3.4.7 Cooperation at UN-COPUOS ICG Activities

The International Committee on GNSS (ICG), established under the United Nations Committee on Peaceful Uses of Outer Space (UN-COPUOS), has been discussing the compatibility and interoperability of GNSS.

Both parties recognize that the achievement of compatibility and interoperability between GPS and QZSS contributes to this ICG discussion and also recognize the importance of continuous cooperation at future ICG meetings, in particular, for multilateral compatibility discussions.

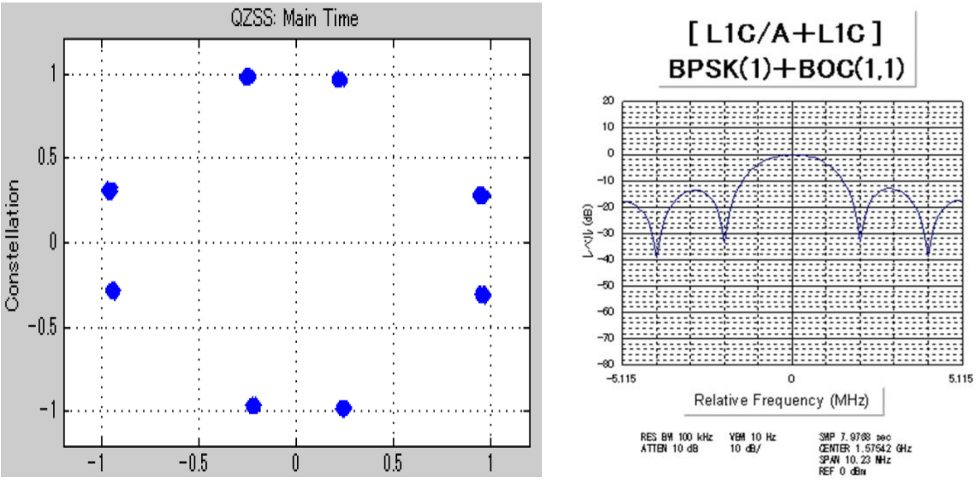
4. Evaluation Results for interoperability between GPS and QZSS

In this section, the evaluation results, such as for the L1C signal and positioning accuracy of GPS and QZSS, and so on, are described.

4.1. QZSS L1C signal

The L1C signal was designed in cooperation with experts from the GPS and QZSS teams. GPS developed IS-GPS-800 as the L1C baseline document, and QZSS also developed the IS-QZSS (Interface Specification for QZSS).

QZS-1 transmits L1C and L1-C/A signals from an L-band helical array antenna using the IPM (interplex modulation) technique. Figure 4.1-1 shows the constellation and the spectrum of QZS-1 L1C and L1-C/A signals, respectively.



(a) Signal Constellation (b) Signal Spectrum

Figure 4.1-1: QZS-1 Constellation and Spectrum of L1C + L1-C/A signals

From the evaluation of these figures and receiver information, QZS-1 transmits a good L1C signal regularly.

The L1C signal, as the modernized signal, is well-known for signal merits such as interference degradation, multipath degradation, and so on. Figure 4.1-2 shows an example of the user received power of the L1-C/A, L1CP and L1CD signals. From this figure, some interference was found at 12:07:28. Figure 4.1-3, 4.1-4 and 4.1-5 show the pseudorange acceleration at the same time. From these figures, only the L1-C/A signal suffered the interference, but the L1C signal (L1CD+L1CP) was not affected by the interference.

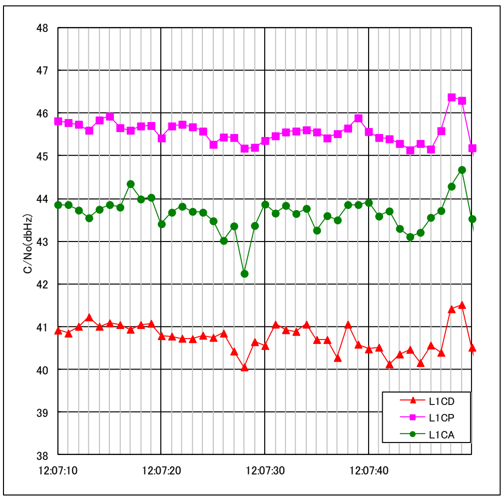


Figure 4.1-2: User Received Power of L1-C/A, L1CD and L1CP signals

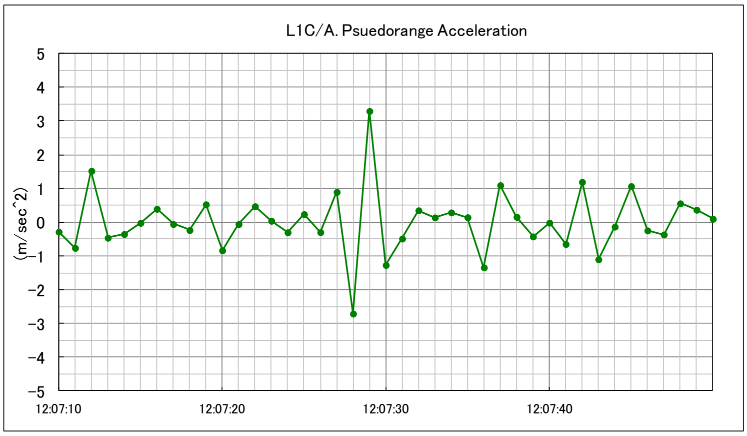


Figure 4.1-3: L1-C/A Pseudorange Acceleration

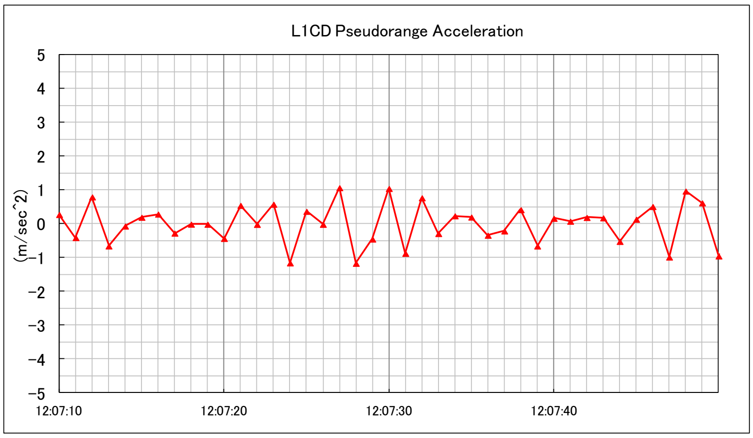


Figure 4.1-4: L1CD Pseudorange Acceleration

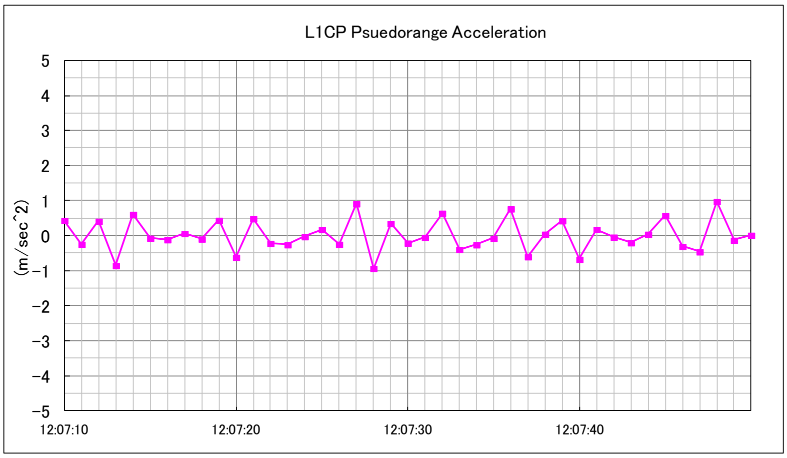


Figure 4.1-5: L1CP Pseudorange Acceleration

Next, figure 4.1-6 shows the elevation vs. multipath at Koganei MS. Figure 4.1-7 also shows the statistical results of the figure 4.1-6.

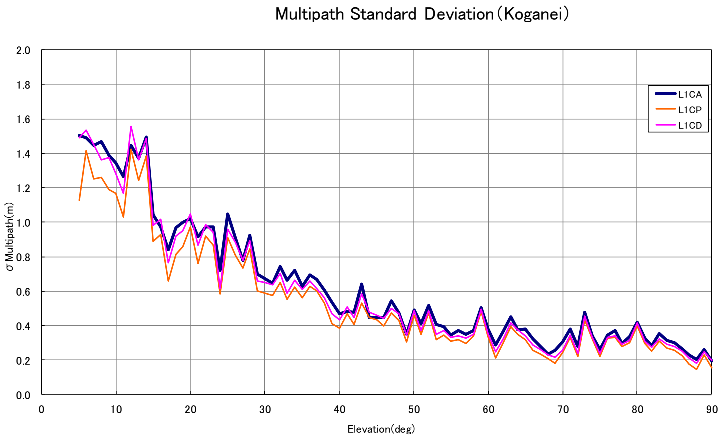


Figure 4.1-6: Multipath at Koganei MS

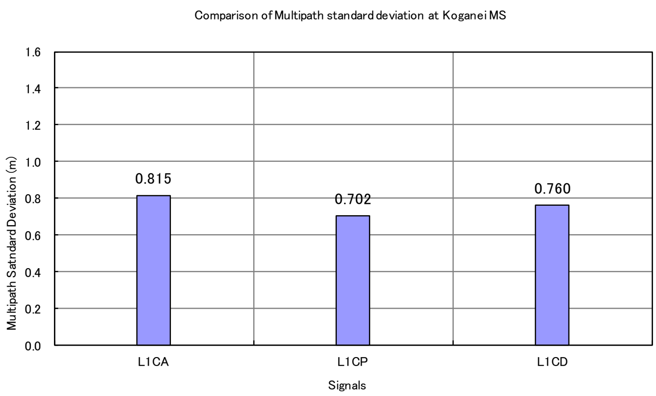
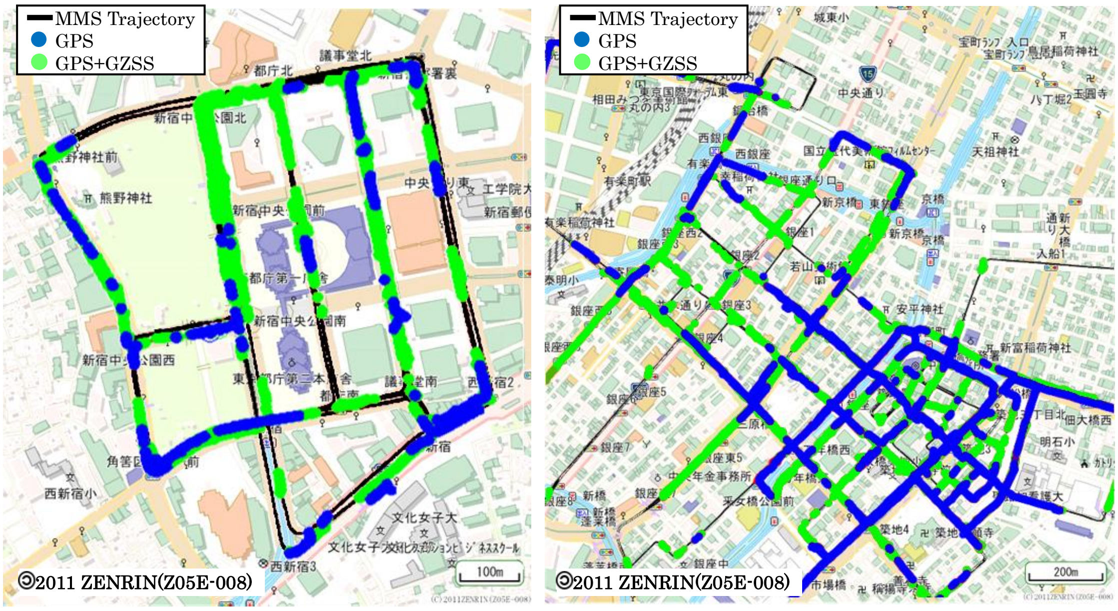


Figure 4.1-7: Comparison of multipath between L1-C/A, L1CP and L1CD

From these figures, QZS-1 proved that the L1C signal has good characteristics and effectiveness of the multipath degradation as the modernized signal.

4.2. Availability Improvement

To verify the effectiveness of availability improvement by QZSS, some experiments were conducted in representative urban canyons in Japan. The differences of the positioning availability between GPS only and GPS + QZSS were evaluated. Figure 4.2-1 shows the user positioning availability in Shinjuku and Ginza areas, respectively.



(a) Availability in Shinjuku (b) Availability in Ginza

Figure 4.2-1: User Positioning Availability between GPS only and GPS + QZSS

Shinjuku is famous as a high-rise building area, and Ginza is also well known as a maze full of back alleys. Both areas are used as the benchmark course for car navigation system. Table 4.2-1 shows the comparison of availability in Shinjuku and Ginza areas.

Table 4.2-1: Availability between GPS only and GPS + QZSS

Area	Availability	
	GPS only	GPS + QZSS
Shinjuku	28.5 %	70.0 %
Ginza	39.5 %	69.1 %

These results show that the signals from QZS-1 with a high elevation angle effectively benefit users to improve their positioning availability in urban areas.

4.3. Positioning Accuracy of GPS and QZSS

4.3.1 QZSS SIS-URE accuracy

The QZSS team has put intensive work into improving accuracy, especially SIS-URE, in the following process: 1) system dynamics model (i.e., solar radiation pressure model) improvement, 2) screening the bad observation data from MSs, 3) parameter tuning on Kalman Filter and identification (bias between the receivers, etc.), 4) identification of TGD (Time Group Delay) of navigation signals.

Starting on June 3, 2011, the QZSS team conducted an accuracy monitoring campaign for 12 days and confirmed that SIS-URE was stable and met the specification in the user interface document (2.6 m, 95%) (Figure 4.3.1-1).

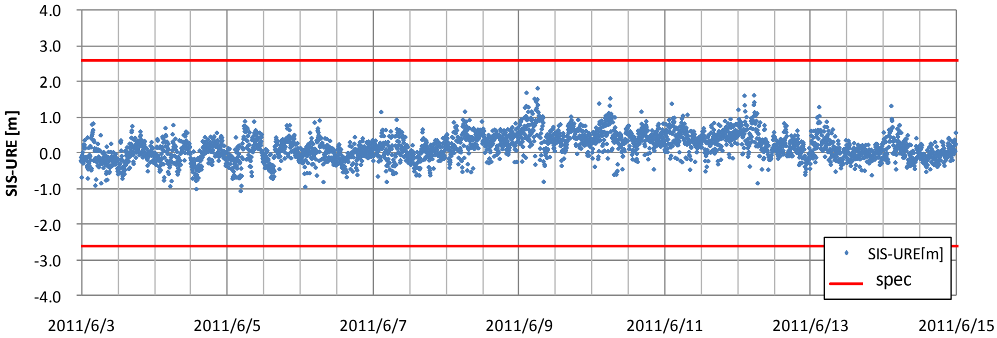


Figure 4.3.1-1: SIS-URE Variation

4.3.2 User Positioning Accuracy of GPS and QZSS

The QZSS team also investigated user positioning accuracy using Tokyo Koganei MS data on June 3. The horizontal user positioning error (X-Y plot) is shown in Figure 4.3.2-1, and the time variation of horizontal and vertical errors are shown in Figure 4.3.2-2 respectively, comparing between GPS-only-positioning and GPS + QZSS positioning. The summary of the user positioning error is shown in Table 4.3.2-1.

From Figure 4.3.2-1, 4.3.2-2 and Table 4.3.2-1, the user positioning accuracy improves greatly by adding QZSS, due to DOP (Dilution of Precision) and ionospheric correction improvement. These results prove the high interoperability between GPS and QZSS from the view of users.

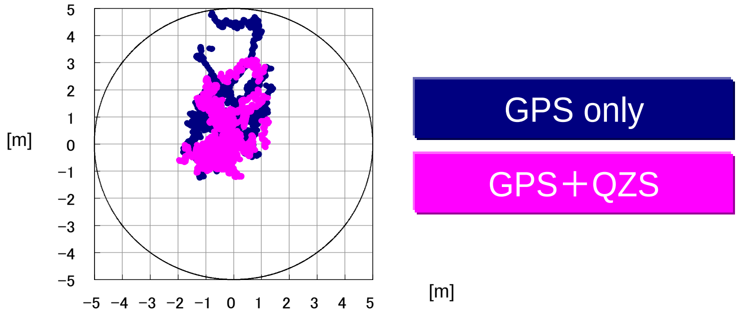


Figure 4.3.2-1: Accuracy of User Positioning in Horizontal

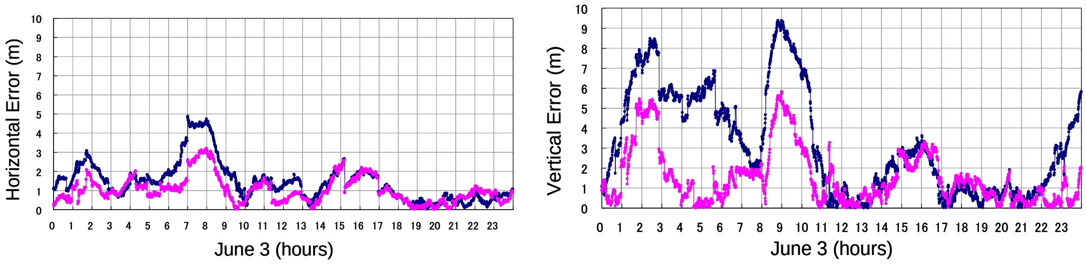


Figure 4.3.2-2: Time Variation of Horizontal Error Figure and Vertical Error

Table 4.3.2-1: Comparison of Positioning Accuracy

Positioning accuracy (m)		GPS only	GPS+QZS
Horizontal	Average	1.451	1.027
	RMS	1.773	1.232
	Max	4.885	3.209
Vertical	Average	3.204	1.540
	RMS	4.122	2.080
	Max	9.388	5.828

The accuracy has been maintained after the campaign. The QZSS team set the L1-C/A and L2C signals as "healthy" in the navigation message on June 22, followed by L5 and L1C on July 14. Figure 4.3.2-3 shows the SIS-URE after June 22, 2011. QZSS performance has met the IS-QZSS standard continuously after being set healthy.

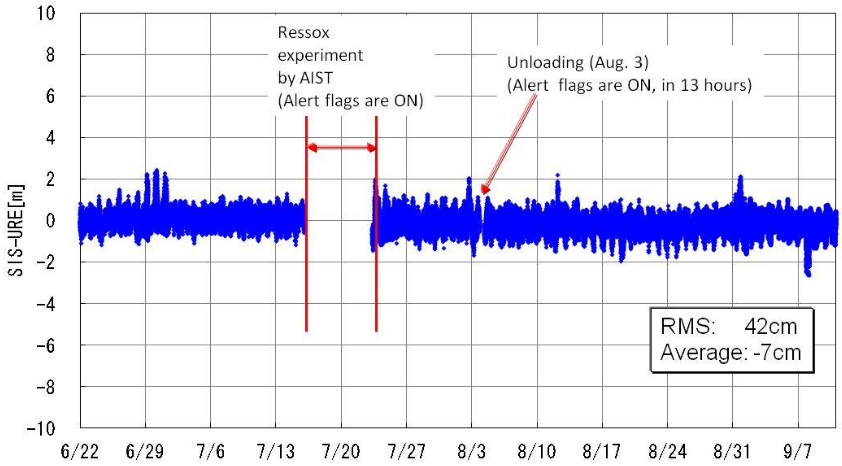


Figure 4.3.2-3: QZS-1 SIS-URE after June 22, 2011

Full interoperability between GPS and QZSS provides the people in the East Asia and Pacific region both the higher availability improvement and user positioning accuracy improvement. QZSS would like to maintain and pursue the high interoperability with GPS from now and in the future.

4.4. Confirmation of Compatibility between GPS and QZSS

After the launch of Michibiki, the transmission of the navigation signal started when it was confirmed that harmful interference was not observed. There have been no harmful effects on GPS signal reception since Michibiki started signal transmission.

5. Conclusion

This report reviewed and summarized all activities implemented by the GPS-QZSS Technical Working Group (TWG) and its sub-working group, EWG since 2002. The technical discussions through TWG/EWG contributed to realization of compatibility and interoperability between GPS and QZSS.

Japan has decided to accelerate the deployment of the operational QZSS as expeditiously as possible. More specifically, a four satellite constellation shall be established by the late 2010s. In the future, a seven satellite constellation shall be completed to enable sustainable positioning. The QZSS and the results of the TWG are expected to take a more important role in maximizing GNSS user benefits in the Asia Oceania region as a result of this decision.

Appendix Acronyms

epfd	equivalent power flux density
EWG	Expert Working Group
GQTO	GPS / QZSS Time Offset
GPS	Global Positioning System (U.S.)
QZS	Quasi-Zenith Satellite
QZSS	Quasi-Zenith Satellite System
NICE	New and Improved Clock and Ephemeris
NICT	National Institute of Information and Communications Technology
ICD	Interface Control Document
ITU	International Telecommunications Union
JAXA	Japan Aerospace Exploration Agency
KPGO	Kokee Park Geophysical Observatory
SBAS	Satellite Based Augmentation Service
SAIF	Sub-meter class Augmentation with Integrity Function
PRN	Pseudo Random Noise
QPSK	Quadrature Phase Shift Keying
TWG	Technical Working Group (in the context of U.S./Japan GPS/QZSS cooperation)
TWSTFT	Two-Way Satellite Time and Frequency Transfer
U.S.	United States of America
USNO	U.S. Naval Observatory
UTC	Universal Time Coordinated
VLBI	Very Long Baseline Interferometry

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