Highly-Accurate Positioning Experiment Using QZSS at ENRI

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1. INTRODUCTION

Positioning with GPS is widely used in Japan in the area of car navigation, man navigation and survey. GPS is said to have some difficulties. The first one is that users in mountainous or urban area cannot receive signals from sufficient number of GPS satellites for positioning because of shadowing by mountains or tall buildings. This cannot allow users provided with positioning service at any time and any place. The second one is that positioning accuracy with GPS may not be sufficient for high-speed mobile users such as trains or cars. These difficulties require the development of new satellite positioning technology. QZSS (Quasi-Zenith Satellite System) is considered to be a possible candidate to solve these difficulties.

QZSS [1] is the constellation consisted of several satellites orbiting in inclined orbital planes with GEO-synchronous period. Each satellite is allocated on a different orbit so as to pass over the same ground track with constant interval. (Figure 1) Eccentricity and inclination are selected so that the minimum elevation angle is higher than about 70 degrees through 24 hours in service areas. One of satellites in QZSS is visible near zenith any time. Users can always receive a signal from that satellite in QZSS near zenith. This means that users in mountainous or urban area can receive a signal from one of satellites in QZSS although a signal from a geostationary satellite (GEO) may be shadowed by mountains or tall buildings. (Figure 2)

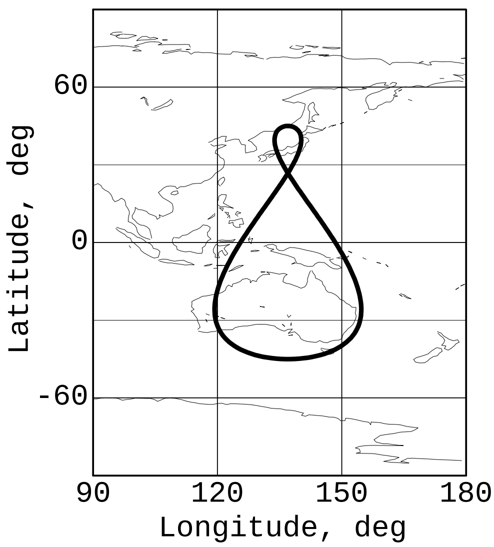

Figure 1 Ground track of a Quasi Zenith Satellite (QZS)

In 2003, the development of QZSS started under collaboration between the Japanese government and private sectors in Japan. In contrast to the global systems such as GPS, GLONASS and the Galileo systems, QZSS has a more focused and regional objective, which is to complement and augment GPS coverage in Japan by continuously providing an additional satellite at a high elevation angle. The design policies for QZSS are to: a) preserve and improve existing GPS user benefit and convenience, and b) to develop and demonstrate highly accurate and reliable satellite positioning technology. [2]

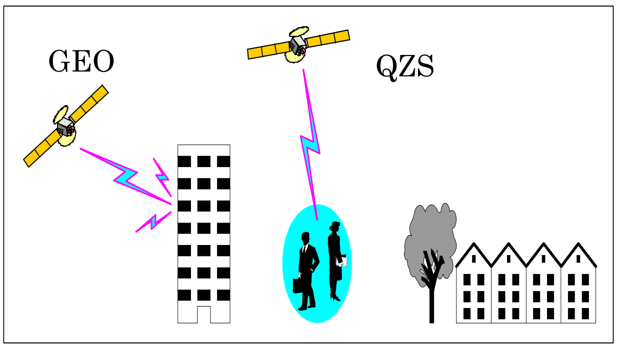

Figure 2 Characteristics of a QZS

ENRI (Electronic Navigation Research Institute) has started an experiment plan to study on correction technology for highly accurate positioning with a high-elevation satellite, QZS, combined with GPS since 2003. An ENRI experiment system is developed in cooperation with Japan Aerospace Exploration Agency (JAXA), Geospatial Information Authority of Japan (GSI) and related institutes. This paper gives the ENRI experiment system [3], [4].

2. QZSS PROGRAM

As the service area of QZSS is regional, QZS will be launched into 24-hour geosynchronous elliptic orbit and kept within a certain longitude range. At least three satellites are necessary to provide continuous navigation service from high elevation angle.

QZSS broadcasts both complement and augmentation signals. The former consists of GPS civilian signals, i.e., L1C/A, L2C, L5, and L1C with the minimum modifications. In QZSS, GPS augmentation messages will be broadcast on the GPS L1 frequency. For this purpose L1-SAIF (sub-meter-class augmentation with integrity function) signal has been developed based on SBAS standard [5] because both QZSS and SBAS will offer similar function to much the same service area. The target of user position accuracy is set to 1 meter RMS. As QZSS provide the integrity function necessary for safety of mobile users, integrity algorithm developed for SBAS is also adopted in QZSS. The frequency plan of QZSS is summarized in Table 1. The detail specification is defined by IS-QZSS document [6].

Table 1 Frequency plan of QZS

Signal	Frequency
QZS-L1C	1575.42 MHz
QZS-L1-C/A	
QZS-L1-SAIF	
QZS-L2C	1227.6 MHz
QZS-L5	1176.45 MHz
QZS-LEX	1278.75 MHz

3. ENRI EXPERIMENT SYSTEM

The ENRI experiment system has the function of GPS augmentation and integrity monitoring. Figure 3 shows the configuration of the ENRI experiment system.

In the ENRI experiment system, satellite data is collected at GPS reference stations such as ‘GPS continuous observation stations’ in GEONET (GPS Earth Observation Network System) of GSI located throughout Japan. This data is sent to L1SMS (L1-SAIF Master Station) and processed to generate differential GPS corrections and integrity information. As shown in Figure 3, messages including this information are uploaded to QZS via QZSS MCS (Master Control Station) of JAXA, then modulated and broadcast to users in an experimental area. Users can use these differential GPS corrections and integrity information to improve positioning error and carry out integrity monitoring. A signal including differential GPS corrections and integrity information is named as L1-SAIF by ENRI.

JAXA is in charge of developing the QZSS space segment (i.e., QZS) and deploying ground facilities including MCS and regional tracking stations.

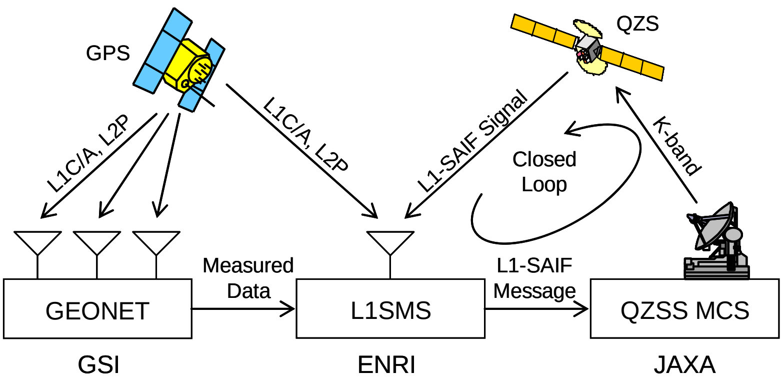

Figure 3 Experimental system configuration of QZSS L1-SAIF augmentation

3.1 Overview of QZSS L1-SAIF signal

The structure of QZSS L1-SAIF signal is defined to have full compatibility to the SBAS L1 signal. The signal frequency is equal to GPS/SBAS L1 (1575.42 MHz). The generator of pseudorandom noise code for spreading spectrum is the same as the one for the GPS gold code; PRN numbers from 183 to 187 are allocated to QZSS L1-SAIF signal.

The data rate for the L1-SAIF signal is 250 bits per second with 1/2 rate FEC (forward error correction) encoding, and a message consists of 250 bits, so QZS will transmit one message per second. The message contents are upper compatible to the SBAS. The only difference from SBAS signals except for message type definitions is Doppler and power variation due to elliptic orbit. Correction to the relativistic effects should be also applied.

Each L1-SAIF message (a message included in the L1-SAIF signal) consists of 250 bits, which are divided into (1) 8 bits preamble pattern; (2) 6 bits message type ID; (3) 212 bits data field; (4) 24 bits CRC parity, like the SBAS message. Figure 4 summarizes L1-SAIF message format. The MSB is transmitted first in each field. Note that FEC encoding is applied to the 250 bits raw message so that a preamble pattern could not be used to capture the beginning of a message unless FEC is decoded.

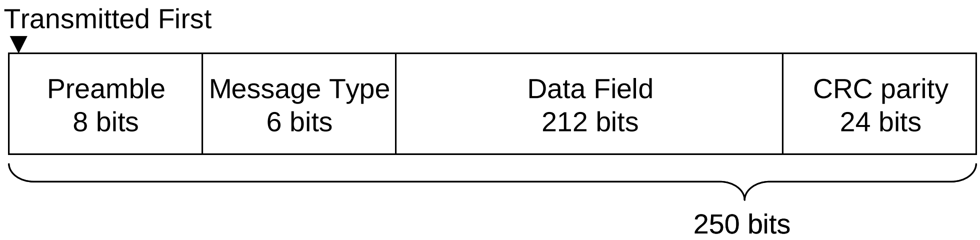

Figure 4 L1-SAIF message structure

Some of message types are assigned compatible with SBAS. QZS will not transmit message types which contain information dependent upon GEO orbit. Message types for SBAS network time and service message are also not used. Other SBAS-compatible messages are formatted to be identical with SBAS specification. There is no change of message format for these messages.

Extended messages are assigned to message types not used in SBAS. Some of extended messages are used for atmospheric corrections, intersignal bias corrections, QZS ephemeris and almanac.

3.2 L1-SAIF Master Station

The ENRI has been developing an L1SMS (L1-SAIF master station) system. This system consists of several subsystems operating in parallel. The configuration of the system is described in this section.

3.2.1 Function and Requirements

QZSS is a program supported by several agencies and laboratories in Japan. The satellite will be launched and operated by JAXA, and experiments will be conducted by program member agencies and laboratories. The master control station for QZSS is placed at Tsukuba Space Center of JAXA with communication lines to/from program members at remote sites. The GEONET realtime receiver network is available as monitor stations for QZSS. GEONET is operated by GSI. L1SMS receives measurement data stream from GEONET stations and generates L1-SAIF messages using received measurements.

The primary mission of L1SMS is to generate a L1-SAIF message stream and deliver it to MCS in realtime. L1SMS is developed by and set up at ENRI (Chofu City, Tokyo) 90 km away from QZSS MCS. L1SMS and MCS are connected to each other by ISDN and other communication lines.

In the worst case, it possibly takes 10 seconds from transmission of a message from L1SMS to reception of the message by a user receiver. This latency is caused by buffering at each step because an L1-SAIF signal is not broadcast via a bent-pipe transponder.

3.2.2 System Configuration

The L1SMS consists of several subsystems as shown in Figure 5. They are connected to each other via Ethernet LAN and work on Linux OS.

- GEONET Server
- Interface Processor (I/F)

- Message Generator
- Ionosphere Processor
- Troposphere Processor

The function of each subsystem is explained below. All subsystems are operated in realtime.

The GEONET Server receives data in dual frequency measurement from GEONET real-time stations. Currently most stations equip Trimble receivers and output a measurement data stream in RT17 format. This server consists of five independent processors and the number of monitor stations to be processed is limited to 200 for each processor. The output rate of a receiver in GEONET real-time stations is 1 sample per second (1 Hz), so transfer rate between GSI and ENRI reaches about 0.5 MB (Mega Bytes) per second for 1000 stations or 0.1 MB per second for 200 stations.

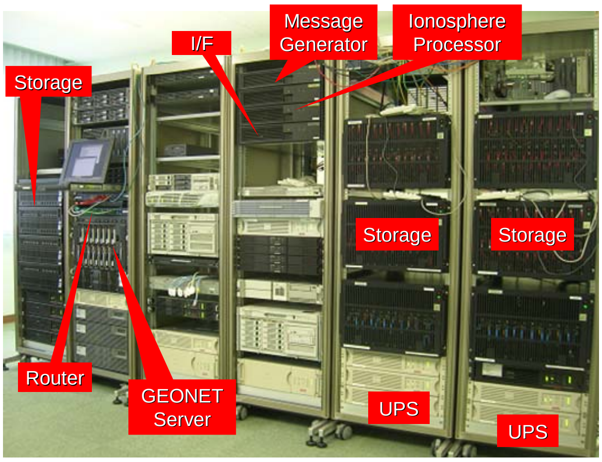

Figure 5 L1-SAIF Master Station (L1SMS)

The Interface Processor distributes measurement data stream received from the GEONET Server. Other subsystems obtain necessary measurements from this processor. The Interface Processor also relays L1-SAIF message packets from the Message Generator to QZSS MCS. All interfaces are based on TCP/IP socket connection.

L1SMG (L1-SAIF Message Generator) is the most important subsystem of L1SMS and explained based on WADGPS (wide-area differential GPS) [7]. The WADGPS basically needs 6-10 monitor stations for clock and orbit corrections over the L1-SAIF experimental area. Additional stations might help not only to generate better estimation of clock and orbit errors but also to enhance ionospheric correction and integrity performance. The L1SMG is developed for the experiment purposes. Therefore, the number of monitor stations for generation of correction information is not limited. The only limitation is caused by processor speed and memory capacity.

The Message Generator receives measurement data stream from the Interface Processor and generates L1-SAIF messages every second. It is capable of handling input data stream in the form of RINEX and format used in NovAtel, Trimble, and JAVAD receivers. Generated messages are in NovAtel OEM-3 FRMA record format.

The Ionosphere Processor is specialized to generate ionospheric correction and/or augmentation information based on vast number of monitor stations. The processor is capable of receiving and processing real-time measurement from at least 200 stations. Ionospheric information is delivered to the Message Generator to be integrated with clock and orbit corrections. This processor is optional. In case that this processor is not used, standard ionospheric augmentation algorithm implemented in the Message Generator is employed for message generation.

The Troposphere Processor is also an optional processor for tropospheric correction. This processor receives real-time GPS observations from the GEONET Server and estimates atmospheric condition over Japan with a latency less than 1 hour. Tropospheric delay estimates are formatted into L1-SAIF message by the Message Generator. In case that this processor is not used, a tropospheric correction message is not broadcast, and standard tropospheric delay model is used in both the Message Generator and user receivers.

3.2.3 Real-time Monitor Stations

A GPS augmentation system need monitor stations distributed uniformly over its service area. Each station should equip one or several dual-frequency and survey-grade GPS receivers and a communication line to transmit measurements to a master station.

Currently three networks are available for L1SMS as monitor stations; (i) GEONET real-time stations, (ii) ENRI real-time sites, and (iii) JAXA monitor stations. Each network has different properties as described below. The L1SMS Interface Processor is capable of handling any set of receivers of these three networks.

(i) GEONET real-time stations

GEONET consists of 1200 reference stations in Japan for surveying purposes. All of reference stations output real-time data streams to GSI and several surveying companies provide real-time surveying services. This national resource is available for the QZSS program.

L1SMS has its own GEONET Server and a communication link to GSI. The GEONET Server is capable of receiving measurement data streams from all 1200 stations. Each GEONET station equips a dual-frequency and survey-grade receiver without an atomic clock. Each station transmits measurement data every second in the format intrinsic to its receiver. We can try a large variety of monitor station configurations. A disadvantage of this network is data transmission latency of a few seconds, up to 2 seconds measured in the current environment.

(ii) ENRI realtime sites

ENRI has been operating its own realtime observation sites. Currently 9 domestic stations are available; Sapporo, Sendai, Tokyo, Toyama, Shigaraki, Kochi, Fukuoka, Naha, and Yonaguni. All sites have no atomic clocks. The great advantage of this network is less latency. Most stations are connected to ENRI directly via ISDN line. Especially the L1SMS has direct LAN access to Tokyo site receivers.

(iii) JAXA monitor stations

JAXA set up several monitor stations for QZSS operation. Four domestic stations are located at Wakkanai, Koganei (near Tokyo), Chichijima, and Okinawa. Each station will equip a specialized triple frequency receiver which can receive L1-SAIF, L1C and L2C signals and synchronize to an atomic clock. L1SMS will receive measurements at these stations via QZSS MCS.

4. PRTOTYPE RECEIVER

A prototype receiver can receive a L1-SAIF signal from a QZS and decode augmentation messages contained in the signal to carry out highly accurate positioning. The development of a prototype receiver completed in 2007. The prototype receiver was tested combined with L1SMS at ENRI. Figure 6 shows the outside of the prototype receiver. The prototype receiver consists of a main part and monitoring PC. The main part of the prototype receiver has the following functions:

(1) To receive L1-C/A signals from GPS satellites and an L1-SAIF signal from QZS
(2) to measure pseudo-ranges and decode navigation messages and augmentation messages
(3) to calculate a position of a prototype receiver

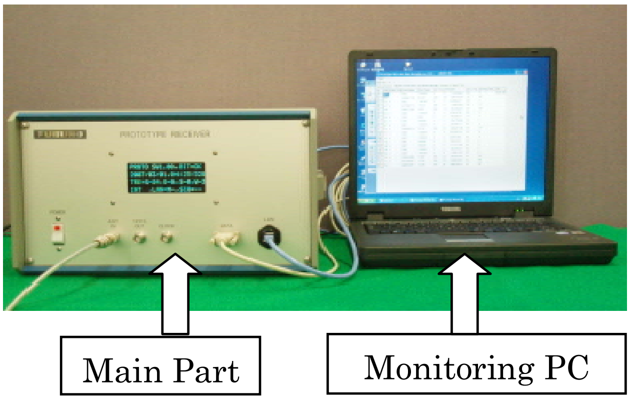

Figure 6 Prototype receiver

A monitoring PC displays measured data and calculated positions. The size and weight of the prototype receiver is 40 (width) x 40 (depth) x 20 (height) cm and 11 kg.

5. SCHEDULE

In 2003 and 2004, algorithm for generation of differential correction and integrity-related information adequate to QZSS was studied and validated using off-line data obtained at GPS reference stations in

GEONET. In 2005 through 2007, a real-time generation system of augmentation messages was developed. This real-time system was used to test that algorithm of generation of augmentation messages using on-line data obtained at GPS reference stations in GEONET. The procedure to broadcast augmentation messages to users was also estimated. During this period, the prototype receiver was developed.

A QZS was launched in September 2010. ENRI performed a ground test in 2008 and an interface test between JAXA and ENRI. A validation test using a QZS has started in December 2010. In the ground test, basic functions of the ENRI experiment system, that is, highly accurate positioning and integrity monitoring, were assured in detail by using online data obtained at GPS reference stations in GEONET. A ground test used a satellite simulator instead of a QZS and was carried out in ENRI.

An interface test was carried out to make sure data interface between MCS of JAXA and L1SMS of ENRI with real configuration of communication lines. The format of transmitted and received data packets was checked and compared with log files taken at both stations bit by bit. This interface test was successfully completed early in 2010.

A validation test is performed by using a QZS, GPS and online data from GPS reference stations in GEONET. The prototype receiver is set on an experiment vehicle in this test. The purpose of this test is to make sure that the ENRI experiment system has the expected performance when a real satellite (QZS) and GPS reference stations are used in real-time.

6. REALTIME OPERATION TEST

A real-time operation test was conducted to verify the initial performance of the L1SMG. In this test, all data used for message generation were obtained with reference stations in GEONET in real-time. Generated messages were stored and positioning errors at other stations in GEONET were evaluated by posterior processing.

6.1 Configuration of Monitor Stations

The performance of WADGPS largely depends on the configuration of monitor stations. For the test, several configurations of monitor stations were adopted. Note that GEONET was used for all configurations and only the number and combination of monitor stations were changed because we were investigating the performance of L1SMG not monitor stations.

(1) 4-Station Configuration: (Red Squares in Figure 7) JAXA monitor stations at Wakkanai, Koganei (near Tokyo), Chichijima and Naha.

(2) 6-Station Configuration: (Green Triangles) MSAS domestic ground monitor stations at Sapporo, Hitachi-Ota, Tokyo, Kobe, Fukuoka and Naha.

(3) 9-Station Configuration: (Blue Triangles) ENRI real-time sites at Sapporo, Sendai, Tokyo, Toyama, Shigaraki, Kochi, Fukuoka, Naha and Yonaguni

(4) 11-Station Configuration: JAXA monitor stations and ENRI real-time sites.

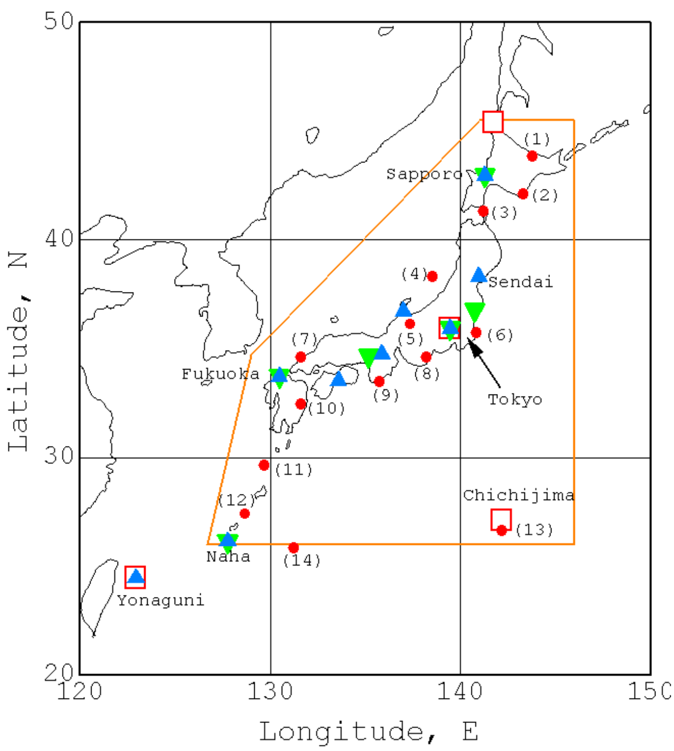

Figure 7 L1-SAIF experimental area (bordered by orange line); (Red Square) JAXA monitor stations; (Green Triangle) MSAS GMS; (Blue Triangle) ENRI real-time sites; (Red Circle) Real-time test user stations numbered with brackets

The operational parameters of L1SMG are fixed except for configuration of monitor stations. Only the minimum number of monitor stations required to generate correction information for a particular satellite was changed for 9 or more stations configuration. Other parameters are the same for all configurations. Ionospheric correction is performed with the standard planar fit algorithm and parameters used are identical to those for the MSAS.

6.2 Results

GEONET stations indicated as Green Circles in Figure 7 with brackets were regarded as user receivers in the evaluation of positioning error. User position accuracy was evaluated at these stations. Note that none of these user stations was used for generation of augmentation information.

Figure 8 is an example of horizontal position error at Site 940058 Takayama, indicated with (5) in Figure 7, for 5 days from Jan/19/08 to Jan/23/08. L1-SAIF messages were generated based on 6-station configuration. Most of position errors are less than 1 meter and the RMS accuracy was 0.292 m.

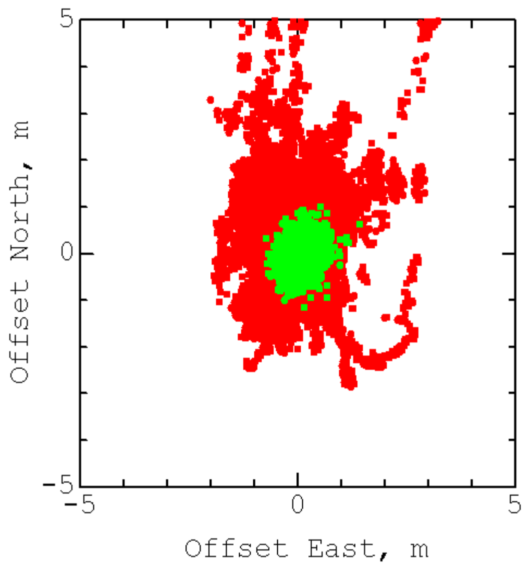

Figure 8 User position error at Site 940058 Takayama for Jan/19/08-Jan/23/08; (Green) Augmented by the L1-SAIF of 6-Station Config.; (Red) Standalone GPS

Figure 9 illustrates the statistics of user position accuracies with an augmentation at all evaluation sites for 4 configurations of monitor stations for 5 days from Jan/19/08. Solid and broken lines represent horizontal and vertical accuracy, respectively. In this figure, accuracy is shown in RMS value with respect to the evaluation station ID numbered from north to south as shown in Figure 8 with brackets. Figure 9 indicates that the target accuracy of 1 meter RMS is likely to be achievable. The number of monitor stations should be at least 6. Increase of the number of stations does not automatically ensure an improvement of accuracy. The results for 9 or more stations configurations seem best in terms of accuracy among all locations tested here. However, it must be notified that the ionospheric activity is relatively quiet for this test period. Much more stations would be necessary to prevent a large error caused by an ionospheric disturbance.

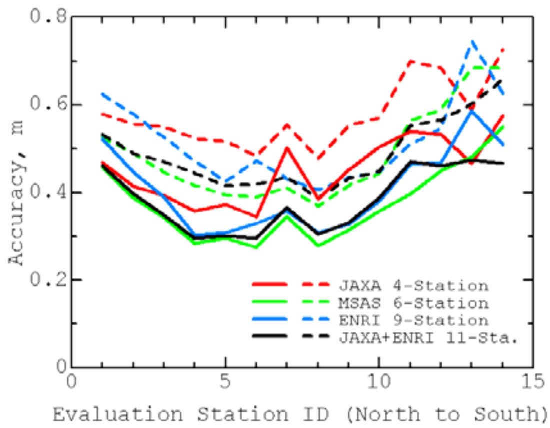

Figure 9 User position accuracies at evaluation sites for four configurations of monitor stations for 4 days; Solid and broken lines represent horizontal and vertical errors, respectively

7. CONCLUDING REMARKS

The ENRI experiment system was explained briefly. This experiment system generates information for differential GPS correction and integrity monitoring using data from GEONET. The L1-SAIF signal which contains this information will be broadcast users within a service area by QZS.

The ENRI has been developing L1-SAIF Master Station which consists of several subsystems including L1-SAIF Message Generator as the most important part. Configuration and fundamentals of L1-SAIF Message Generator were described in this paper. The initial results of real-time operation test on the ground demonstrate the target accuracy of 1 meter RMS is likely to be achievable during the normal ionospheric condition.

A validation test using a QZS has started in December 2010. It is expected that good results are obtained in this test.

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