Modernization of GEONET from GPS to GNSS

Hiromichi TSUJI, Kohei MIYAGAWA, Kazunori YAMAGUCHI, Toshihiro YAHAGI, Kenichi OSHIMA, Hiromi YAMAO and Tomoaki FURUYA

(Published online: 27 December 2013)

Abstract

Since 1994, the Geospatial Information Authority of Japan (GSI) has been operating a continuous GPS observation network system, later known as GEONET, for surveying and crustal deformation monitoring. On May 10, 2013, GSI started providing nationwide the observation data from the Quasi-Zenith Satellites System and GLONASS in addition to GPS, opening the multi GNSS era in Japan. This report provides the background and history behind this modernization of GEONET, the effect of the use of multi GNSS confirmed so far, and the plan for the future modernization.

1. Introduction

Currently, the Geospatial Information Authority of Japan (GSI) has Global Navigation Satellite System (GNSS) observation stations at approximately 1,300 locations nationwide to conduct continuous GNSS observations to realize the geodetic reference frame of Japan as well as to monitor crustal deformation. Observation data and analysis results are open to the public to support public surveys and precise positioning services using GNSS.

On May 10, 2013, GSI started providing nationwide the observation data received from the Quasi-Zenith Satellites System (QZSS) and GLONASS in addition to the existing GPS, opening the multi GNSS era in Japan. GNSS is a generic name of satellite positioning systems such as GPS and GLONASS, including QZSS.

The entire system comprised of the observation stations all over Japan and the central station in Tsukuba for collecting, analyzing and distributing its data is called GEONET. Formerly, GEONET was a GPS Earth Observation Network system that supported GPS only, but with the progress in GNSS implementations stated here, it has now evolved into a GNSS Earth Observation Network system.

In this report, the background and history of GNSS implementation in GEONET will be described. Although GEONET stations are now ready for GPS, QZSS, GLONASS, and Galileo, modernization of GEONET is probably a never ending process, and improvements to the analysis system and update of receivers for future GNSS will be mandatory. Therefore, the last chapter ends with the future plan.

2. Background

2.1 GEONET as Infrastructure

The deployment of the GPS continuous observation station as we know it today as GEONET goes back to 1993, and the operation of the initial observation network consisting of approximately 200 stations began in 1994. At that time, the geodetic reference frame of Japan was Tokyo Datum, and the coordinates in the World Geodetic System obtained from GPS could not be directly used for public surveys. Nevertheless, precise daily site coordinates of GEONET revolutionized the way to monitor crustal deformation, and contributed significantly in identifying the fault mechanisms of large earthquakes such as Hokkaido East Offshore Earthquake in 1994 and Southern Hyogo Earthquake in 1995. Since then, more GPS stations have been built, analysis systems have been integrated and modified, and there were 1,200 stations by 2003 (Geodetic Observation Center, GSI, 2004). During these years, they detected crustal deformation following various earthquakes and volcanic activities serving for disaster mitigation, and made academic discovery of slow slip events, i.e. earthquakes that are not accompanied by seismic emission (e.g. Sagiya, 2004; Nishimura et al., 2013).

Following the enforcement of the Survey Act Amendment 2002, the World Geodetic System was adopted for public surveys in Japan, and official site coordinates of GEONET stations became available. Observation data per 30 seconds were provided to the public in the receiver-independent exchange (RINEX) format, and were widely used as reference data of GPS surveys. In 2002, the real-time data with 1 second intervals were made open to the private sector, and location-based service providers started network-based RTK positioning services. As explained later, this method determines the position of a rover by cm level using the GPS data obtained at the rover and the correction data calculated from the surrounding GEONET stations, and has been used in public surveys, engineering surveys, and cadastral surveys.

Since GPS signals are affected by the atmosphere between satellites and receivers, they contain information on water vapor content in the air. Leveraging research results on such “GPS meteorology”, the Japan Meteorological Agency began using the perceptible water vapor computed from GEONET data in weather forecasting from October, 2009 (Japan Meteorological Agency and GSI, 2009). Moreover, since the state of ionosphere can be estimated from dual frequency GPS signals on L1 (1575.42MHz) and L2 (1227.60MHz) bands, GEONET is also utilized as a tool in ionosphere research (e.g., Saito et al., 2002).

Therefore, it is not an exaggeration to say that GEONET has become the infrastructure indispensable to support surveys, crustal deformation monitoring, location-based services, weather forecasting, earth sciences in Japan.

So far 1,240 GEONET stations had been deployed as survey control points (Fig.1). However, considering the need of survey users, official site coordinates of GNSS stations originally established for crustal deformation monitoring are also provided to the public in recent years. Including these, there are 1,273 GNSS-based control points as of April 1, 2013. The inclusion of other GNSS

Fig.1 Distribution of GEONET stations

stations at tide stations is under consideration, and the number of GNSS-based control points in a broad sense will increase by about 30 in 2014.

2.2 Expectations to GNSS

While GPS is a satellite positioning system developed by the U.S., the former Soviet Union followed suit and has developed GLONASS from the 1980s. Once the satellite positioning was recognized as socially important infrastructure with the success of GPS, Europe started developing their own satellite positioning system called Galileo from around 2000, followed by Japan starting the development of QZSS that compliments GPS. Through such efforts of countries, it was expected that we would usher in the era where numerous satellite positioning systems will become available (Tsuji, 2010).

If these GNSS are used in addition to the existing GPS, more satellites can be observed simultaneously, allowing us to survey areas in urban cities and mountains where receiving of satellite signals are difficult due to obstacles such as buildings and trees. Furthermore, as there will be new L5 (1176.45MHz) signals, it is expected that the time required for each survey can be shortened.

For these reasons, users had been requesting early implementation of GNSS in addition to GPS in GEONET, which are the survey infrastructure of Japan.

Promotion Council of Real Time Positioning using GPS-based Control Stations is a private organization established in 2001 for the promotion of use of GEONET real-time data and consists of survey companies, receiver manufacturers, location-based service providers, communication carriers, universities, and others. The Council's Request submitted to GSI in June 2010 stated their expectations as below by implementing GNSS in GEONET (Promotion Council of Real Time Positioning using GPS-based Control Stations, 2010).

1) There will be more areas and time that can be surveyed with satellites.
2) There will be more demand for purchasing GNSS receivers, stimulating the market.
3) The use in construction ICT is likely to be promoted especially at construction sites in the mountains.
4) Precise positioning with mobile devices will become possible in urban areas, enabling to create 3D maps easily by mobile mapping systems, which will facilitate the use of 3D maps.
5) Precise GNSS positioning becomes available in wide areas in Japan without setting up one's own GNSS stations, which will facilitate the use of GNSS positioning.

Since their main concern is on the application of GEONET, GNSS positioning here refers to kinematic positioning that has the precision level of cm class, not to point positioning for car navigation. Real Time Kinematic (RTK) positioning is a technique that performs this kinematic positioning of a rover in real-time. There are two methods of RTK: 1) A user places a reference station on the site and transfer the data to the rover by wireless transmission; and 2) A user calculates the rover position by receiving the correction data of the surrounding GEONET stations via cellular phones (Network-based RTK) (Fig.2).

To achieve the precision of cm level in real-time, at least five satellites should be observed simultaneously. Therefore, in the field of construction ICT (intelligent construction), which controls and guides construction site machines such as bulldozers, RTK with both GPS and GLONASS were already adopted to observe enough number of satellites in areas such as mountains where observation conditions are poor. If GLONASS data becomes available in GEONET, users will not have to set up reference stations themselves. That is why there was high demand from the ICT construction industry for GNSS implementation in GEONET, which was reflected in the Council's request.

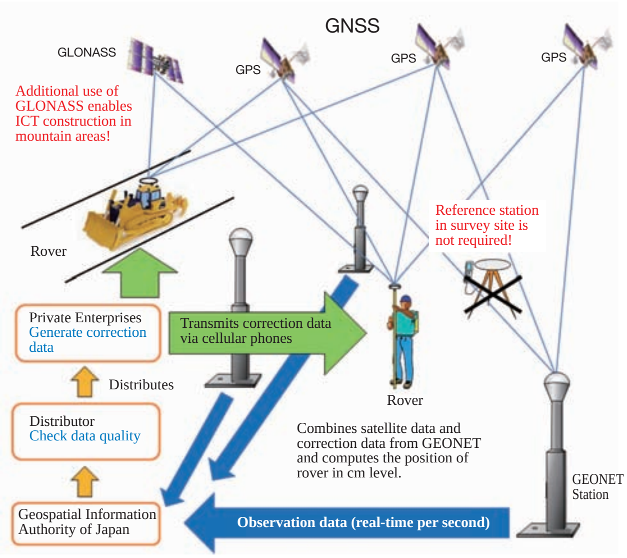

Fig.2 Schematic view of network-based RTK positioning

3. GNSS Implementation

3.1 Initial Plan

The GEONET renewal plan in 2009 targeted to install new receivers ready for GPS modernization by 2020 when the existing receivers of GEONET will not be able to track L2 signals after the US planned GPS modernization (Tsuji, 2009). Fortunately, the supplementary budget of FY2008 and the budget of FY2009 allowed renewal of aging receivers at 450 stations, so the plan was modified to renew 80 units annually for the following 10 years and to complete GNSS implementation at all GEONET stations by 2019. GPS modernization also required renewal of antennas to receive newly added L5 signals, but the schedule of the antenna renewal was not decided.

In September 2010, Japan's first QZSS "Michibiki" was launched successfully. In parallel, Russia's GLONASS completed satellite deployment. Confirming user needs, GSI decided to observe and provide QZSS and GLONASS data in addition to modernized GPS and Galileo, but the expected completion of GNSS implementation at all GEONET stations was not until 2019.

3.2 Early Renewal after the 2011 off the Pacific coast of Tohoku Earthquake

The 2011 off the Pacific coast of Tohoku Earthquake changed the whole situation. The crustal deformation caused by this unprecedentedly large M9.0 earthquake was recorded in detail by GEONET, which contributed to disaster mitigation after the quake, seismic research and restoration surveys (Nishimura et al., 2011; Suito et al, 2011; Yamagiwa et al., 2012).

Although backup communications by cellular phone and reinforced UPS systems at each station helped to prevent the operation shutdown of GEONET in Tohoku area immediately after the quake, the prolonged blackout and communication interruption destroyed some of the important observation data after the quake (Oshima et al., 2011).

This led to the renewal of GEONET receivers and antennas under the FY2011 supplementary budget, in order to recover GEONET stations damaged from the disaster and to secure the continuity of the crustal deformation monitoring that is critical in disaster mitigation. As a result, almost all GEONET station equipment would be renewed by the end of March 2012. However, since the development of the system for collecting / distributing GNSS data takes a certain period of time, it was to be done by 2013. At this point, GNSS implementation in GEONET was virtually pushed forward to 2014.

Later, to further assist in recovery from the disaster, it was decided to provide QZSS and GLONASS data from areas where equipment was renewed. In July 2012, GNSS data provision started in the Tohoku area, and in April 2013 data from 541 stations including East Japan, and from May 2013 data from all stations have been provided (Fig.3). Fig.4 illustrates this GEONET modernization process.

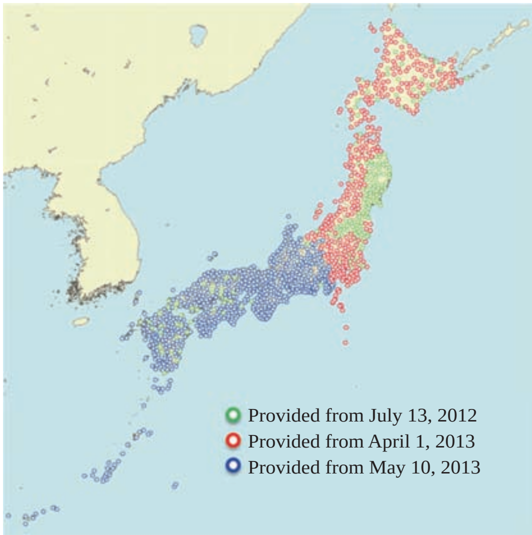

Fig.3 GNSS data provision from GEONET. In response to the 2011 Tohoku earthquake, Tohoku area was the first to be renewed and provide GNSS data.

3.3 Renewed Equipment

Receivers and antennas used as of April 2013 are shown in Table 1. Since renewal could not complete in the Okinotorishima island and in the vicinity of the Fukushima first nuclear power plant, the total for GEONET stations is different from the figure mentioned earlier. All receivers support signals of modernized GPS (except for L1C), QZSS, GLONASS and Galileo. TRM59800.80 is a triple-frequency choke ring antenna reworked from an old TRM29659.00 with a replacement amplifier (Fig.5). It has the same properties as L5-supporting choke ring antenna TRM59800.00.

3.4 RINEX Data

Standard operating procedure of the public surveys set into action on April 1, 2013 enables a combined use of GLONASS and QZSS together with GPS (Technical Management Division, Planning Department, GSI, 2013). GNSS data from GEONET stations are available for these public surveys from the GSI website (http://terras.gsi.go.jp/ja/index.html).

Assuming various users, 3 types of data files are provided (Table 2). All types contain observation data per 30 seconds and broadcast ephemerides in RINEX format. Recently, RINEX ver. 3.02 that officially supports QZSS was released, and we will provide the data with it from 2014.

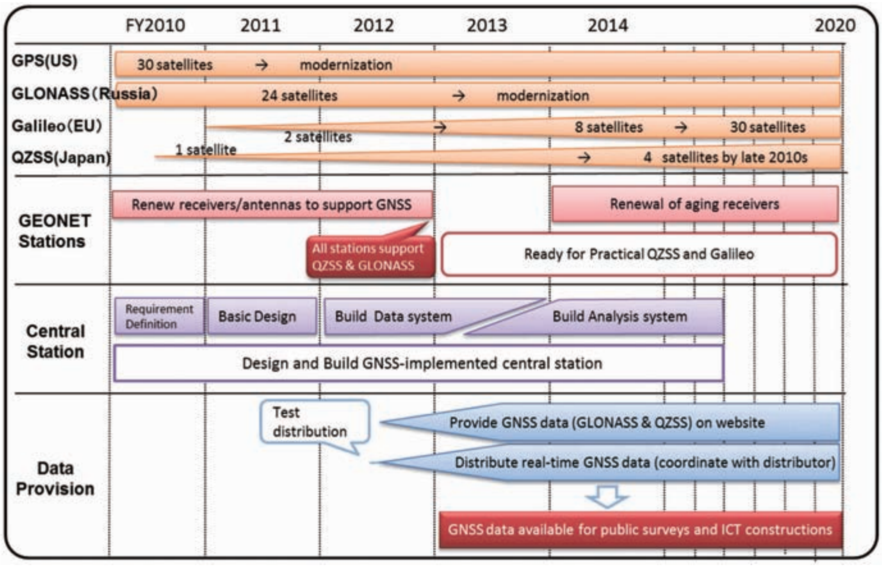

Fig.4 Time schedule of GEONET modernization

Table 1 Renewed GNSS Equipment (as of April 2013)

Receiver	Antenna	unit
Trimble NetR9	Trimble TRM59800.80	800
Trimble NetR9	Trimble TRM59800.00	3
Topcon NET-G3A	Trimble TRM59800.80	19
Topcon NET-G3	Topcon TPSCR.G5	448

Fig.5 Antenna being renewed (left) and GNSS receiver (right)

According to the web statistics on the access to RINEX data from June to September 2013, survey engineers downloaded a monthly average of 23,000 files in total, 3,000 with GLONASS, and 300 with QZSS from our http site. From our FTP site, researchers downloaded a monthly average of 7.85 million files in total, 40,000 with GLONASS, and 80,000 with QZSS. As provision of GNSS data has just started, their use is expected to grow in the future.

Table 2 Types of files provided on the GSI website

Satellite System	Format	Frequency
GPS	RINEX ver.2.10	L1, L2
GPS+GLONASS	RINEX ver.2.10	L1, L2
GPS+GLONASS +QZSS	RINEX ver.2.12 QZSS-supported	L1, L2, L5

3.5 Real-time Data

GSI started real-time data transfer with 1 second intervals from 200 stations to the central station in Tsukuba in May 2002, from 645 stations in June, and from 931 stations in October 2002. Today, 1,220 stations, excluding those in isolated islands and deep mountains, are transferring observation data per second in real-time. Such data are used for emergency analysis upon earthquakes and volcanic activities, as well as for the source of RINEX data of 30-second intervals. They are also provided via a distributor to private enterprises that generate correction data of network-based RTK for location-based services. For a few stations where IP-VPN (Virtual Private Network via wide area IP network) is not available, observation data per 30 seconds are collected in a batch every hour via ISDN, cellular phone, or satellite cellular phone lines.

Initially, receiver manufacturer's real-time data formats such as RT17 or JPS had been used, but from 2009 the standard real-time data format named BINEX developed by a U.S. non-profit university-governed consortium is being used (UNAVCO, 2011). In the area of navigation, RTCM SC104 is more popular, but because it does not support QZSS as of April 2013, and BINEX has more significant digits for observation data, we continue to use BINEX.

Now the final obstacle in pushing forward the start of GNSS data provision was the increased delay of real-time data. Real-time data are provided to private enterprises via distributor in BINEX streaming (Fig.6). For communication with each station, 64 kbps IP-VPN is dedicated. Since the GPS observation data size is 3 kbps or less, and about 7 kbps even with QZSS and GLONASS, we did not expect any problems at first. However, as we proceeded with the receiver renewal and data distribution, we gradually experienced increased delay of real-time data.

Signals observed every second at each receiver have exact time stamp as is the nature of GNSS, so by comparing to the arrival time of the signal packet at the distributor's server in the Shinjuku Data Center, the delay time between each station and Shinjuku can be measured. The distributor has a dedicated time server to correct the server time, keeping the precision of measured delay time better than 0.1 seconds.

When only with GPS, the delay time was about 0.3 seconds, as data size and observation stations with GNSS increased, delay time increased gradually up to near 1 second every several hours, and in some stations delay exceeded the limit of 1 second. Therefore, data transmission lines were carefully inspected, and bugs hidden in communication server transfer programs were found and fixed. We also modified the timing of data flow so as to reduce traffic around every second on the second. As a result, the average delay time was shortened to around 0.2 to 0.3 seconds, enabling GNSS data distribution from all stations by May 2013.

However, in some stations, delay of more than 1 second still occurs once in a while (Fig.7). Although this frequency of delay will not degrade the network-based RTK service, investigation is underway to find the cause. What is interesting is that delay time does not seem to depend on the distance between each station and the distributor server at Shinjuku so much. This is probably such that the delay time is sufficiently small within IP-VPN.

Real-time data are planned to be used for generation of centimeter-level augmentation signals to be distributed from full-scale QZSS (Cabinet Office, 2012), therefore the data delay time becomes the important quality factor of GEONET. In 2013, communication servers and lines in KDDI Shinjuku Data Center, where all GEONET data gathered from across the country, will be strengthened, aiming to provide more reliable real-

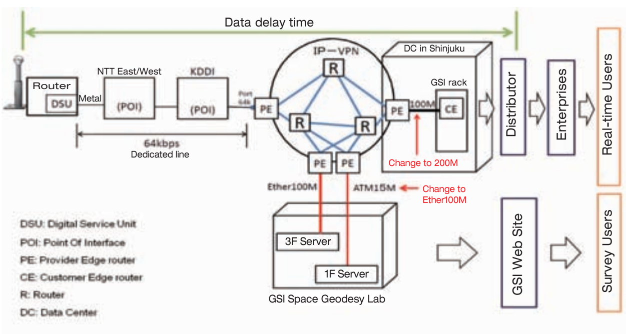

Fig.6 Data flow of GEONET from stations to users

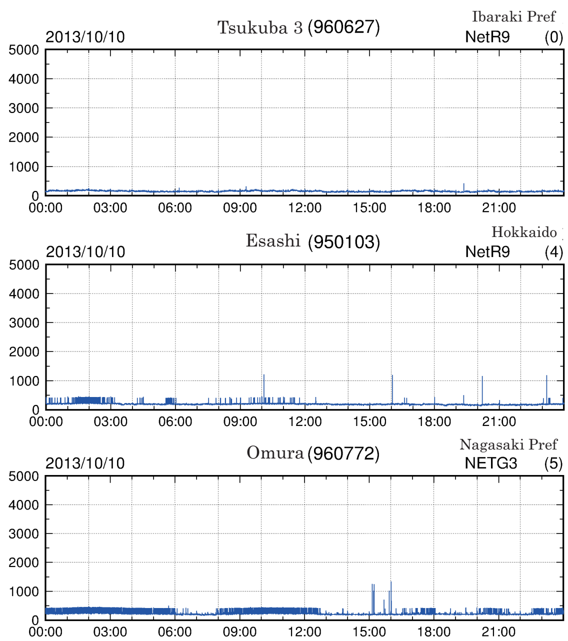

Fig.7 Examples of delays in real-time data on October 10, 2013. The horizontal axis is Universal Time, the vertical axis is delay time (ms). Normally, the delay time is about 0.2 seconds (top), it may sometimes be more than 1 second (middle and bottom).

time data.

4. Effect of GNSS Implementation

4.1 Precision of Baseline Analysis

Simple baseline analysis using GEONET data was conducted on the precision of surveys when QZSS or GLONASS was combined with GPS.

First, using the Tohoku area's data and broadcast ephemerides obtained on September 20, 2012, kinematic analysis of 30-second intervals by analysis software RTKLIB ver.2.4.1 (Takasu, 2011) was conducted for 16 baselines between the same types of receiver within 10 to 30km range (Furuya et al., 2012). When GLONASS was used together, the standard deviation of coordinates for one day decreased by 10 to 30 percent compared to GPS only (Table 3). This is considered to be the effect of having improved repeatability in time zone when the number of satellites is small (Fig.8). The effect of using QZSS together is not so significant since there is only one satellite, but as the minimum elevation angle for analysis is raised, i.e. as observation conditions become worse, the effect of combined use gets bigger (Fig.9).

The effect of combined use of QZSS was further analyzed using the data obtained at Tsukuba GNSS calibration baseline on November 26, 2012 and at GEONET stations on May 10, 2013. As analysis software, GSILIB prototype, modified by GSI based on RTKLIB ver.2.4.1, was used (Furuya et al., 2013a). Fig.10 shows an example of time series of kinematic analysis for 3 hours among different types of receivers in the calibration baseline (distance: 11km). Table 4 shows standard deviations of kinematic solutions of 36 baselines (10 to

Table 3 Results of kinematic baseline analysis between GEONET stations. Average standard deviation of 16baselines in Tohoku area on September 20, 2012. Minimum elevation angle is 15°.

Component	GPS only	GPS+ GLONASS	GPS+ QZSS
East-West	8.6 mm	7.7 mm	8.6 mm
North-South	12.2 mm	8.7 mm	11.4 mm
Up-Down	30.3 mm	25.7 mm	31.2 mm

Table 4 Results of kinematic baseline analysis between GEONET stations. Average standard deviation of 36 baselines on May 10, 2013 (14:00～20:00 UT).

Minimum Elevation Angle	Component	GPS only	GPS+ QZSS
15°	East-West	6.8 mm	6.7 mm
	North-South	8.8 mm	9.2 mm
	Up-Down	24.5 mm	25.4 mm
30°	East-West	7.8 mm	7.0 mm
	North-South	11.9 mm	11.5 mm
	Up-Down	45.6 mm	42.5 mm

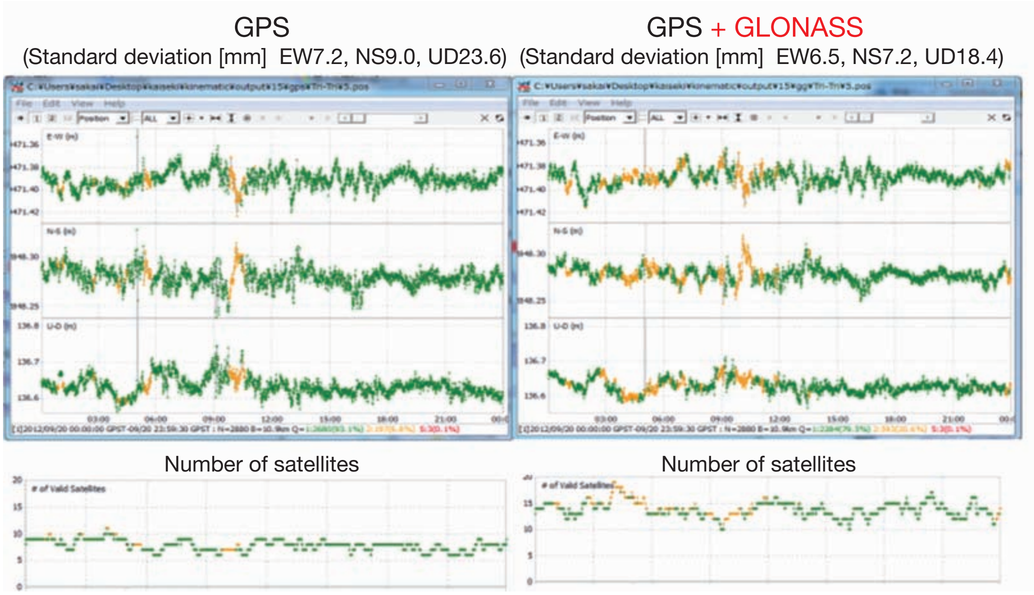

Fig.8 Time series of kinematic baseline analysis between GEONET stations (Onoda to Shikama, distance 11 km) for 1 day. Left: GPS only. Right: GLONASS is used together. Minimum elevation angle is 15°.

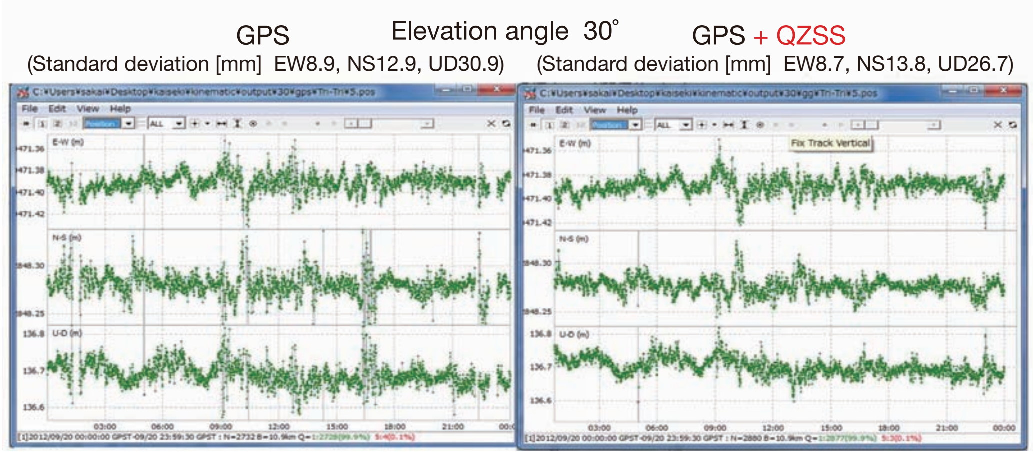

Fig.9 Time series of kinematic baseline analysis between GEONET stations (Onoda to Shikama, distance 11 km) for 1 day. Left: GPS only. Right: GLONASS is used together. Minimum elevation angle changed to 30°.

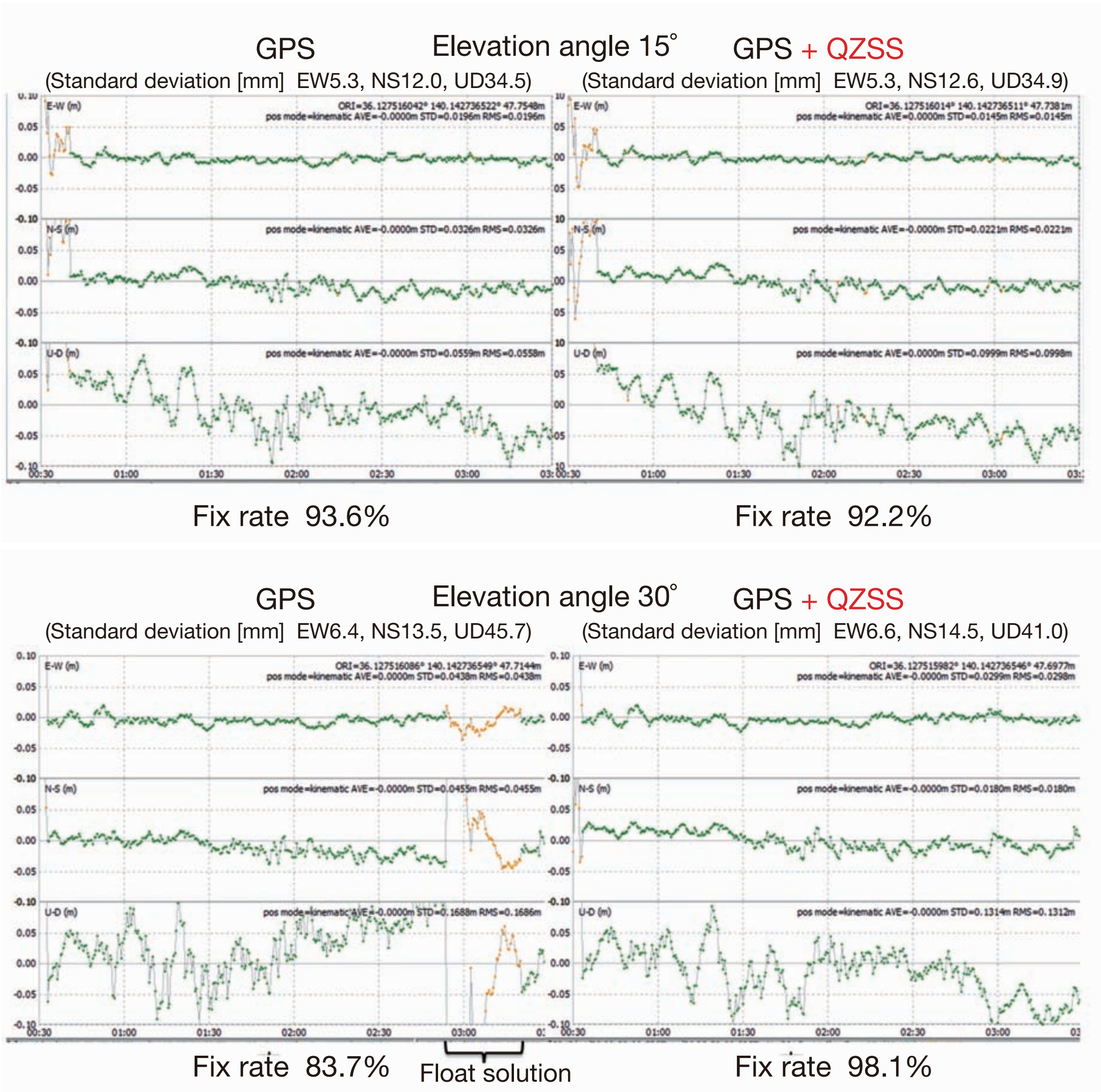

Fig.10 Time series of kinematic baseline analysis at the GNSS calibration baseline (distance: 11 km) for 3 hours. Left: GPS only. Right: QZSS used together. Top: Minimum elevation angle 15°. Bottom: Minimum elevation angle: 30°.

70 km) between GEONET stations with the same type of receivers in the vicinity of Wakkanai, Akita, Tsukuba, Osaka and Kochi. No systematic errors were found when QZSS was combined with GPS, and if the minimum elevation angle is 30°, the fix ratio of integer ambiguity and vertical repeatability improves with the use of QZSS (Furuya et al., 2013b).

To summarize, in places where observation conditions are good, GPS is enough to get sufficient precision, but in places where observation conditions are poor, combined use of GNSS enables the same level or higher precision. We will further examine the effect of shortening of observation time in static positioning with GNSS.

4.2 Network-based Multi-GNSS Experiments

The Council performed network-based RTK-GNSS experiments in Hokkaido, Tohoku and Kansai areas using GPS and GLONASS data from GEONET delivered in 2011 and 2012. It was confirmed that if GLONASS is used, more satellites can be observed at the same time, enabling stable positioning 24 hours a day (Promotion Council of Real Time Positioning using GPS-based Control Stations, 2013). Please note that stability of height improved by combined use of GLONASS in the actual network-based RTK (Fig.11).

4.3 Application to Intelligent Construction

In October 2012, the network-based RTK with GLONASS data from GEONET was utilized in intelligent construction at the construction site of the Sanriku Jukan Expressway in Miyagi Pref. for recovery from the aftermath of the Tohoku earthquake. It earned a reputation that said, “Thanks to GNSS implementation in GEONET, satellite reception restrictions were significantly reduced.” (Fukukawa, 2012).

According to the Intelligent Construction Strategic Plan compiled by the Ministry of Land, Infrastructure and Transport in March 2013, “Satellite positioning technique using the network-based RTK method is expected to expand the time and locations that can be positioned and to improve the stability by combined use of GNSS other

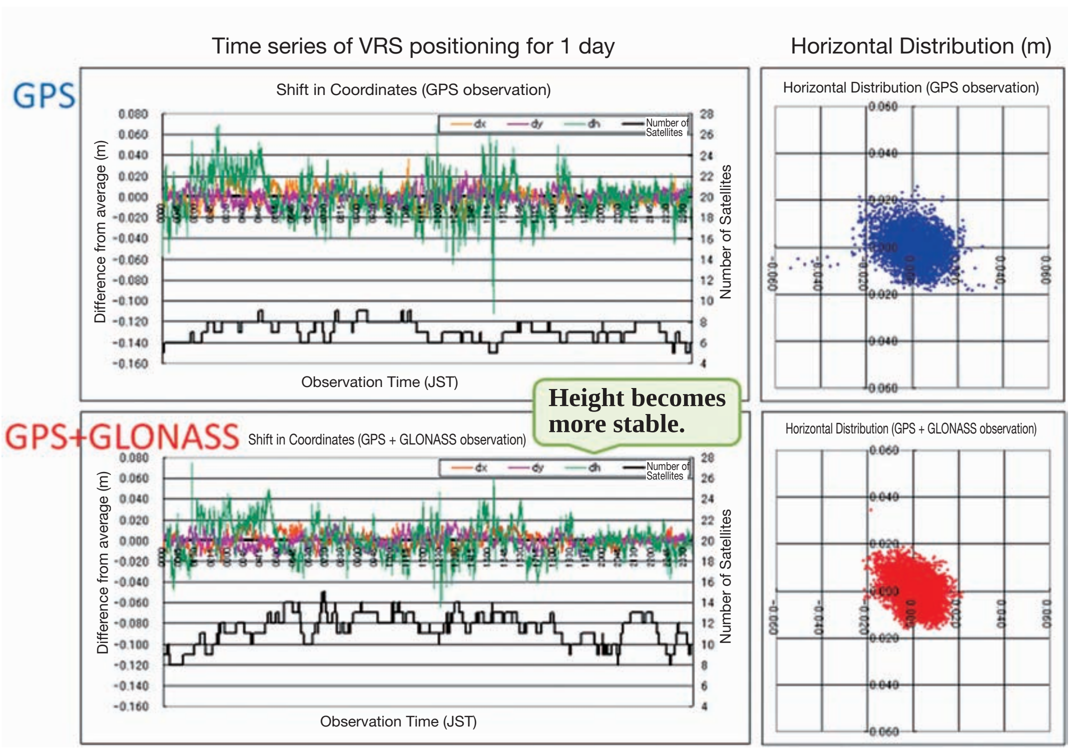

Fig.11 Example of network-based RTK performance with GLONASS. One day time series using Jenoba’s Virtual Reference Station method (VRS). Minimum elevation angle is 15°. (Promotion Council of Real Time Positioning using GPS-based Control Stations, 2013, p.24, modified)

than GPS in the future. Since the network-based RTK does not require setting up of a reference station in each construction site, this technology is expected to extend its use in intelligent construction" (Council for Intelligent Construction Strategy, 2013).

Today, there are two providers of network-based RTK services in Japan; Jenoba Co., Ltd. and Nippon GPS Data Service Corporation. Both companies have started network-based RTK using GLONASS data from GEONET since May 2013. According to them, about one third of users have already tested GLONASS data, and that the use of GNSS in the field of intelligent construction would expand further in the future. For contact information, please refer to the website of the Council (http://www.jsurvey.jp/pcrg/kyougikai.htm).

5. Future Plan

Although GEONET receivers are now ready for the current GNSS, implementation for future GNSS would be required. As for Galileo's L6 signal and CDMA signals of modernized GLONASS, user needs must be carefully confirmed. Since antennas have been upgraded for triple frequency to support L5 signals, no further upgrade will be required for the time being.

A new data collection system named GATE (Gather and Transfer Engine) that supports GNSS is being developed from 2012. In 2013, communication servers and bandwidth of lines in Shinjuku will be enhanced to secure high reliability as a source to generate augmentation data for full-scale QZSS in the future.

Regarding data analysis, the use of QZSS and GLONASS will be considered first in the real-time analysis of GEONET which are under development for tsunami early warning assistance following the Tohoku earthquake (Ohta et al., 2013). Regarding the routine analysis for crustal deformation monitoring that seeks maximum precision, the results from multi-GNSS analysis technology developed separately by the General Technology Development Project of the Ministry of Land, Infrastructure and Transport will be incorporated (GSI, 2013).

Come to think of it, when GPS was the only GNSS available, everything was simple including the receivers, antennas, analysis software and the GEONET operations. As GNSS other than GPS increases, there will be more size and types of data to be handled, and their increasing possible combinations will make users harder to make full use of them. However, there will be new developments expected in the era of multi GNSS when satellite positioning data from more than 100 satellites flourish. GSI will continue to enhance GEONET as the infrastructure as well as develop the environment in which multi GNSS can be fully used effectively for surveys and positioning in Japan.

Acknowledgements

Early provision of GNSS data from GEONET was the result of mutual collaboration with the Promotion Council of Real Time Positioning using GPS-based Control Stations, Japan Association of Surveyors, and Hitachi Zosen Corporation. We thank the contribution from Mr. Naohiro Abe in the evaluation of GSILIB prototype during his 6 month stay at GSI.

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