Outputs from the General Technical Development Project in 2011-2014 Towards the Realization of Multi-GNSS Surveying in Japan

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Abstract

The Geospatial Information Authority of Japan conducted a research and development project from 2011 to 2014 on the smart use of multi-GNSS signals for more efficient surveying and precise positioning essential in the management of national lands. The project aims to combine signals from various satellite positioning systems, such as GPS, QZSS, GLONASS, and Galileo, collectively called GNSS, to achieve centimeter-level positional accuracy in a short period of time, especially in urban or mountainous areas where satellite visibility is limited. Four years of effort on the smart use of multi-GNSS signals by the General Technical Development Funds of the Ministry of Land, Infrastructure, Transport and Tourism yielded technical outputs such as

1) Methods to handle between-receiver biases to combine multi-GNSS signals,

2) Open source software for multi-GNSS surveying named GSILIB,

3) A draft manual of multi-GNSS surveying applicable to public surveys in Japan.

This paper overviews the project and focuses on major technical outputs.

1. Introduction

Because of its efficiency and accuracy, since its introduction in the mid 1990s, GPS surveying has become an indispensable tool for many aspects of national land management in Japan, from geodetic, public, cadastral and construction surveys to disaster mitigation through crustal deformation monitoring. Nowadays more than two thirds of public surveys are conducted using GPS, and the nationwide network of GPS operated by the Geospatial Information Authority of Japan (GSI) monitors the crustal deformation of the entire Japanese archipelago's earthquakes and volcanic activities in near real-time (Tsuji et al., 2013).

However, as GPS's role has increased, demands from users to overcome the current limitations of GPS surveying have also increased. The first demand is to overcome the limitations on the use of GPS in urban and mountainous areas. Since GPS surveying requires good visibility of at least 4 satellites at both ends of a baseline, planners of control point surveys in both urban and natural canyons cannot choose efficient GPS surveying as the first choice, and have to prepare additional equipment, such as a total station and a targeting mirror, taking more time and human resources for their surveys.

The second demand to shorten the time required for satellite surveying comes mainly from the disaster mitigation sector. Although a real-time kinematic (RTK) GPS survey can achieve several cm horizontal accuracy in a few minutes, rigorous users depend on a static GPS survey with longer observation time of an hour or more, depending on a baseline length, to yield more accurate solutions. These long observation hours become serious for GSI's emergency analysis of GEONET at the time of large earthquakes and volcanic activities. As widely recognized by the disaster mitigation sector in Japan, crustal deformation information from GEONET plays a key role in understanding the geophysical nature of each earthquake or in predicting the process of volcanic activities. However, due to the relatively long baseline length of GEONET, which covers the whole of Japan with an average distance of 20 km, GSI needs at least 3 hours of GPS observation after earthquakes to achieve better than 1 cm horizontal accuracy on a regional scale of about 100 km. This long observation time delays the provision of coseismic deformation fields to the disaster mitigation sector. At the time of the 2011 Tohoku earthquake (magnitude 9.0), the deformation field was reported to the Earthquake Research Committee of the Government about 5 hours after the main shock. Since the main shock caused up to 1.2 m subsidence along the Pacific coast of the east north area of Japan (Nishimura et al., 2011), such information was critical for assuring people's safety from the tsunami and high waves. Thus a quicker response of GEONET is strongly desired. The same is true for volcanic activities, where crustal deformation is one of the few sources of information for detecting movements of underground magma.

These limitations of GPS surveying are expected to be solved or reduced by the recent rise of a multi-GNSS environment with more Global Navigation Satellite Systems (GNSS) and additional new codes and frequency signals (Langley, 2013). The United States is modernizing GPS by deploying a new generation of satellites: Block IIR-M with L2C code, Block IIF with L5 frequency, and Block III to come with L1C code. Russia maintains the full operational capability of GLONASS with 24 satellites. The European Union and China are in a push to deploy their GNSSs named Galileo and BeiDou. Japan successfully launched the first satellite of the Quasi Zenith Satellite System (QZSS) in September 11, 2010, which has interoperability with GPS.

Figure 1 shows an example of the multi-GNSS environment already realized over Japan. A total of 28

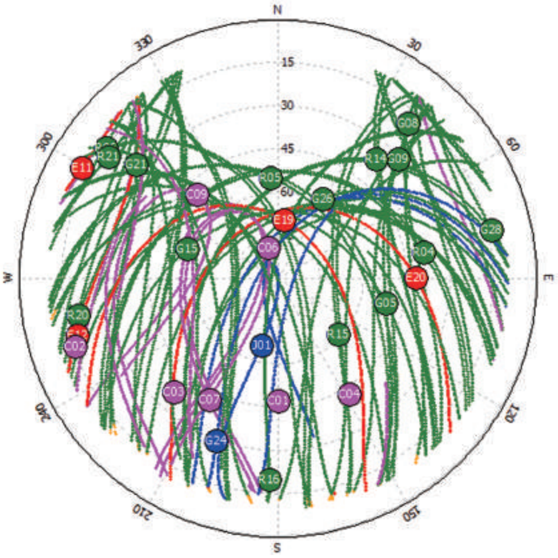

Fig. 1 Sky plot of GNSS data observed by modern GNSS receiver (Trimble NetR9) at Tsukuba from 5:25 to 23:15 UTC on July 17, 2013. G:GPS, E:Galileo, R:GLONASS, J:QZSS, C:BeiDou. The elevation cut off angle is 10 degrees.

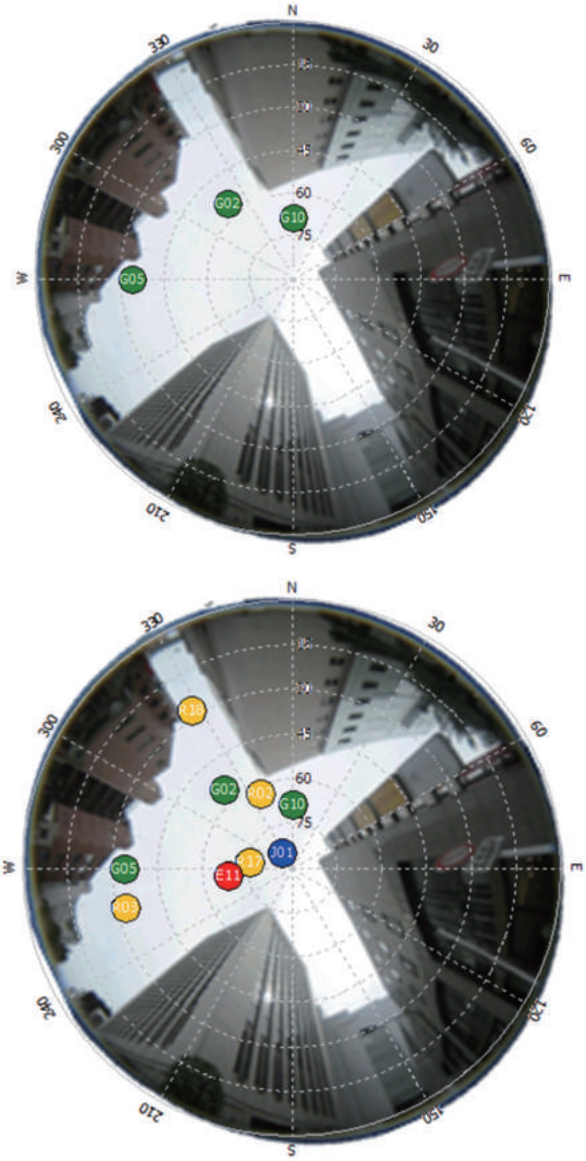

Fig. 2 An example of satellite visibility in an urban canyon of Ginza, Tokyo, at 15:00 UTC November 13, 2013. Above: No hope of positioning with only 3 GPS. Below: Positioning possible with additional 4 GLONASS, 1 QZSS, and 1 Galileo.

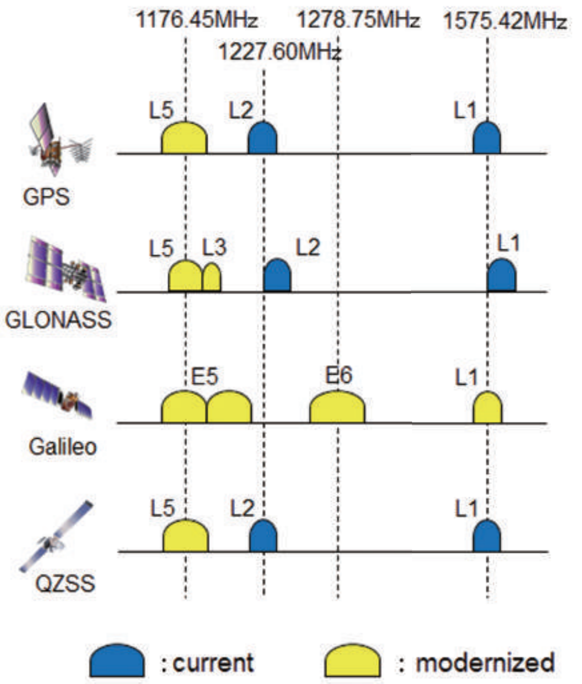

Fig. 3 Frequency bands of GNSS carrier phases in the near future

GNSS satellites were observed at 18:00 July 17, 2013, 8 GPS, 1 QZSS, 8 GLONASS, 4 Galileo, and 7 BeiDou.

It is expected that in the late 2010s, more than 100 multi-GNSS satellites will become available for satellite surveying in Asia and Oceania (Rizos, 2011), improving satellite visibility significantly, and the new L5 (1176.45MHz) signal will assist better and faster solutions when combined with the current L1 (1575.42 MHz) and L2 (1227.60Hz) signals.

Figure 2 illustrates how more GNSS satellites can help to resolve the urban canyon problem of GPS. Additional use of GLONASS, Galileo and QZSS will significantly improve the number of observable satellites.

Figure 3 illustrates the frequency bands of GNSS carrier phases in the near future applicable for surveying.

2. Project

A four year project named “Development of a precise positioning technique using multi-GNSS for advanced management of national lands” was funded as a general technical development project by the Ministry of Land, Infrastructure, Transport and Tourism in 2011, and conducted by GSI with collaborations from various contractors, including universities, under the technical advice of top GNSS experts and related organizations in Japan.

2.1 Objective

The project aims at technical development and standardization of smart use of multi-GNSS such as GPS, QZSS, GLONASS, and Galileo for national land management, to achieve cm level accuracy in a short period of time, especially in urban or mountainous areas where satellite visibility is limited.

The goals are set as follows:

1) Enabling satellite surveying at urban or mountainous areas where GPS surveying fails to work due to poor satellite visibility, by using multi-GNSS satellites, thus reducing costs of satellite surveys,
2) Shortening the observation time of GPS static surveys by using multi-GNSS satellites, thus reducing costs of satellite surveys,
3) Quicker provision of critical crustal deformation information of GEONET after large earthquakes or volcanic activities, and
4) Outreach of Japan’s multi-GNSS techniques including QZSS for Asia and the Pacific region.

2.2 Framework

The project was conducted by the Geodetic Observation Center with close collaboration with the Geography and Crustal Dynamics Research Center and Technical Management Division, Planning Department of GSI. The advisory committee was established by experts from universities, receiver manufacturers, survey companies, providers of network RTK services, and related government organizations in Japan. The committee of 11 members, headed by Prof. Teruyuki Kato of the University of Tokyo, was held 12 times in four years, overseeing the progress of technical developments. All the documents reviewed by the committee are open to the public at the project web site (http://www.gsi.go.jp/eiseisokuchi/gnss_main.html).

2.3 Implementation

The project was divided into three parts and implemented by several contractors.

1) Development of algorithms and software for multi-GNSS data processing. This is the core of the project and most of the resources were spent on software development over 4 years. Reports of algorithms and an open source software package named “GSILIB” with such algorithms are available at the project web site.
2) Field experiments and a simulation study to confirm the techniques developed in the project. Simulation is important as limited availability of actual L5 signals in orbit at an early stage of GNSS. Initial observation and data analysis of QZSS satellite leads to an early incorporation of QZSS into public surveys (Technical Management Division, 2013).
3) Standardization of multi-GNSS surveying for public surveys from 2013 to 2014. The final goal is a revision of the standard operating procedure of public surveys defined by the Minister of Land, Infrastructure, Transport and Tourism, which is the bible for all public surveys in Japan. During the project period, however, we aimed at producing a draft manual of multi-GNSS surveying applicable to some parts of public surveys in accordance with article 17 of the standard operating procedure that allows introduction of new techniques. Using the manuals confirmed by GSI, surveyors can use new techniques in their public surveys without taking time to prove their method is in accordance with the standard operating procedure.

3. Outcomes

Here we introduce major findings and outcomes of the project, which are described in detailed reports at the project web site in Japanese.

3.1 Methods to handle new frequency L5

First we observed L5 signals from GPS Block IIF with modern GNSS receivers, i.e. JAVAD DELTA, Trimble NetR9, Topcon NET-G3, and confirmed that an L5 signal with a high chip rate is less influenced by noise and multipath than an L1 signal (GSI, 2012a). However, in theory L5 alone is more sensitive to ionospheric disturbance than L1 because of its frequency.

Next we investigated algorithms to combine the new L5 signal of modernized GPS with L1 and L2 signals for better ambiguity resolution, which is a key element of GPS data processing, and chose the following two approaches for more studies with simulated L5 signal.

1) Three-Carrier Ambiguity Resolution (TCAR), which uses all L1, L2, and L5 signals to form an extra wide lane linear combination (Teunissen et al., 2002), and
2) Integer Least Squares (ILS) with ionosphere estimation (Takasu and Yasuda, 2010), which is based on the Lambda method (Teunissen, 1995).

RTKLIB: An open source program package for GNSS Positioning (Takasu, 2011) was modified to incorporate ILS analysis with L5 for the studies. A software signal simulator SPSS (Munekane et al., 2008) was also modified to output multi-GNSS signals including L5. By courtesy of JAXA, we collected GPS L5 signal from a hardware signal simulator GSS8000.

Simulation studies with the above GPS L5 data with modified RTKLIB show that

1) ILS with ionosphere estimation approach is better than TCAR from the point of time to fix, fix ratio, and precision for long baselines, but requires a longer analysis time.
2) Usage of 3 frequencies in the ILS method does not bring a dramatic improvement in fix ratio and precision compared to the 2 frequency analysis, but improvement in time to fix is confirmed. Figure 4 is an example of static GPS surveying for a 126 km baseline. The time to fix is reduced to 60 % by the additional use of L5 data in this case.

3.2 Methods to combine multi-GNSS signals

In dealing with signals from different GNSS, we have to consider several biases that originate from the different delays each signal experiences inside receivers, so as to get ambiguity fixed and obtain cm precision (GSI, 2012b; GSI, 2013; GSI, 2014a; GSI, 2015a).

3.2.1 Time and coordinate system

Modern GNSS receivers can track multiple frequency signals from multiple GNSS with

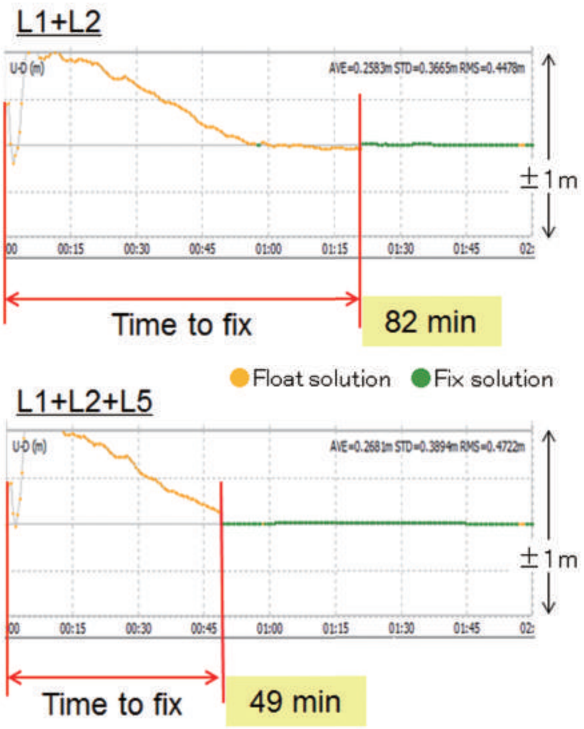

Fig. 4 Reduction of time to fix with L5 data for a static GPS survey of 126km baseline. Two hour observation data with L5 from 8 GPS satellites calculated from the software simulator SPSS and processed with the modified RTKLIB.

interoperability such as GPS, GLONASS, QZSS, Galileo and BeiDou. When we process signals from different GNSS, difference of time and coordinate systems should be corrected first. As is well known, GPS time and GLONASS time have a large discrepancy, as follows.

GPST = GLONAST + leap seconds + C0 + C1,

where C0: UTC - GPST (about 10 ns), C1: UTC - GLONAST (about a few hundred ns). C0 and C1 are available from the Circular T report of BIPM (ftp://ftp2.bipm.org/pub/tai//publication/cirt/cirt.???).

The coordinate systems of GPS (WGS84), Galileo (GTRF), and QZSS (JGS) are almost identical to ITRF, but GLONASS (PZ90.02) again should be corrected to WGS84 by adding -0.36 m in x, 0.08m in y, and 0.18m in the z component. Note that the precision of GLONASS broadcast ephemeris is about three times worse than that of GPS in 2011.

3.2.2 Inter frequency biases for GLONASS

Since present GLONASS distinguishes each satellite by frequency with frequency division multiple access (FDMA), ambiguity resolution of GLONASS needs care. In addition, when different kinds of GNSS receivers are mixed, between-receiver Inter Frequency Bias (IFB) should be corrected (Wanninger, 2011). IFB is also known as inter-channel bias. Estimation of IFB is possible from 12 to 24 hour field observation data at a zero or short baseline with different receivers at both ends by using ANTTOOL (Takasu, 2012). We have estimated the IFB of 4 four kinds of receivers, 6 in total, with respect to a reference one (Figure 5). We also changed

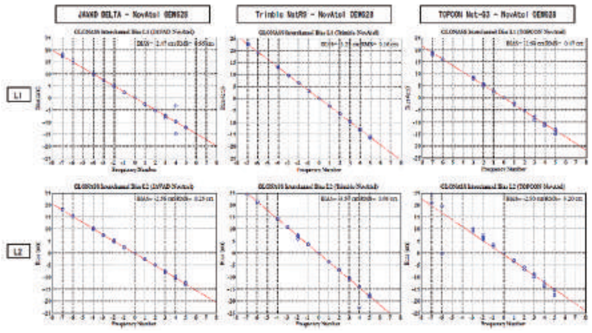

Fig. 5 Estimated IFB of receivers in test (JAVAD DELTA, Trimble NetR9, Topcon NET-G3) with respect to NovAtel OEM628. Note that IFB is well represented by a linear function.

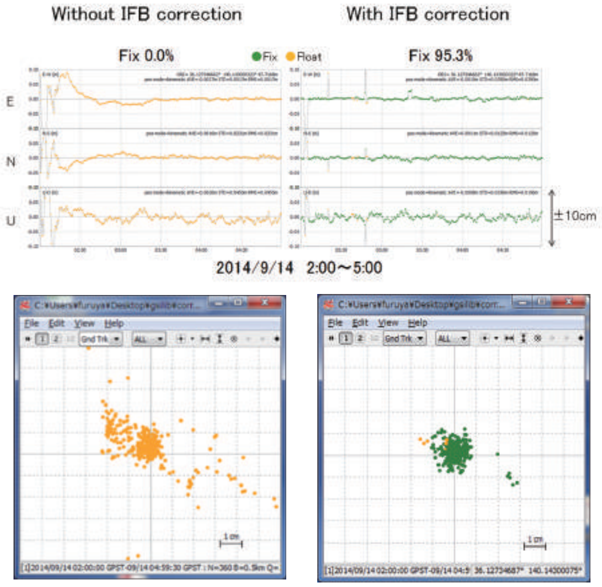

Fig. 6 GPS and GLONASS kinematic solutions of 500 m baseline at Tsukuba on September 14, 2014, between JAVAD DELTA and Leica GR25 receivers. IFB corrections are 53.4mm/MHz for L1 and 68.6mm/MHz for L2 from the zero baseline observation of 12 hours in August 27.

observation conditions such as temperature, antenna, firmware, and reboot of receivers. We found that IFB differs with manufactures but quite stable in time. Thus it is possible to correct IFB with pre-determined values from field observations, enabling GLONASS ambiguity fixing between different receiver types.

Figure 6 shows the effect of GLONASS IFB correction for GPS and GLONASS combination. IFB correction with pre-determined values significantly improves fix ratio and stability of solutions.

3.2.3 Quarter cycle shift in L2C for GPS and QZSS

GPS and QZSS carrier phase generated from new L2C code has a quarter cycle shift from that from existing L2P(Y) code by definition. The problem is that treatment of this shift depends on receiver manufacturers. This could be problematical for GPS and QZSS data processing between different types of receivers. We developed a method to check and correct the sign of quarter cycle shift in L2C. Figure 7 shows the effect of the quarter cycle shift correction for GPS and QZSS combination.

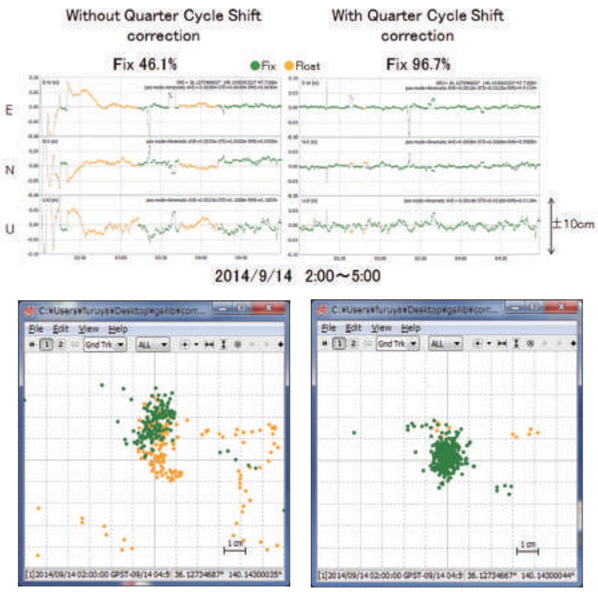

Fig. 7 GPS and QZSS kinematic solutions of 500 m baseline at Tsukuba on September 14, 2014, between JAVAD DELTA and Trimble NetR9 receivers. We previously confirmed that quarter cycle shift corrections for JAVAD as +1/4, and Trimble as 0.

3.2.4 Inter system biases between multi-GNSS

Forming "inter-system" double difference (DD) is a simple but straightforward way to make full use of multi-GNSS for surveying, especially in urban canyons where satellite visibility is limited. For example, if we can make DD observable between GPS and Galileo, we have a good chance to obtain ambiguity fixed solution from 3 GPS and 1 Galileo observations in theory. But to do so, we have to look into another bias named Inter System Bias (ISB) (Odijk and Teunissen, 2013).

Figure 8 illustrates ISB for multi-GNSS along

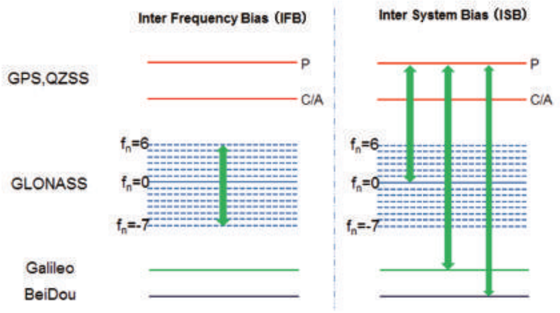

Fig. 8 Schematic view of GLONASS IFB and multi-GNSS ISB. Green arrows show each bias.

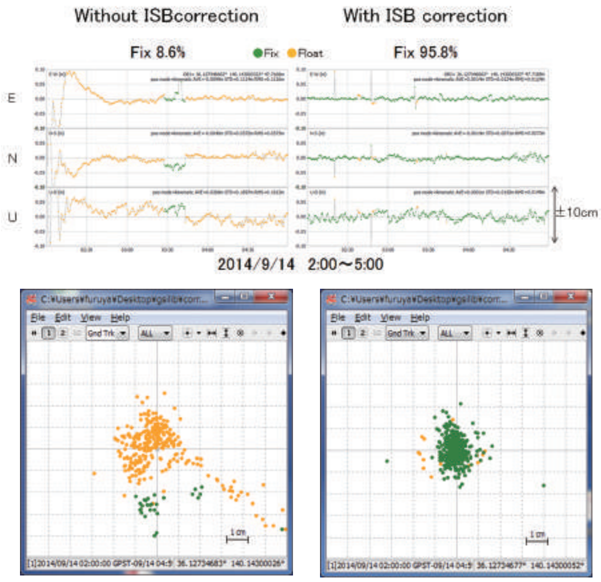

Fig. 9 GPS and Galileo kinematic solutions of 500 m baseline at Tsukuba city on September 14, 2014, between JAVAD DELTA and Trimble NetR9 receivers. Ambiguities between GPS and Galileo are successfully resolved with ISB correction of Code L1 -6.015 ns, Code L5 -20.210 ns, Phase L1 0.141 ns, and Phase L5 -0.002 ns, that are estimated from the zero baseline observation of 24 hours on August 27 and 28.

with the IFB for GLONASS mentioned at section 3.2.2. ISB originates from different delays of each GNSS signal experiences inside receiver hardware, therefore if different receivers are used at both ends of baseline, ISB should be estimated. We developed a method to estimate relative ISB using field observation data of a zero-baseline and examined the nature of ISB for modern GNSS receivers like IFB (Furuya et al., 2015).

As a result, we found that

1) ISB (phase) for GPS - GLONASS is not stable and changes with temperatures and reboot of receivers. So we cannot use pre-determined ISB related to GLONASS. This means inter-system DD with GLONASS is difficult to fix.
2) ISB (phase) for GPS - Galileo and GPS - QZSS is stable, so we can fix inter-system DD using pre-determined values for these combinations.
3) ISB (code) is not stable for most cases but we confirmed it has less effect in positioning.

Figure 9 shows the effect of ISB (phase) correction for GPS and Galileo combination.

3.2.5 Half cycle shift for BeiDou

We add tests of BeiDou after China released an official version of an interface control document on December 27, 2012. BeiDou transmits B1 (1561.098 MHz), B2 (1207.14 MHz), and B3 (1268.52 MHz) signals from GEO (Geostationary Earth Orbit), IGSO (Inclined Geosynchronous Orbit) and MEO (Medium Earth Orbit) satellites. BeiDou has a half cycle shift in carrier phase between GEO, IGSO, and MEO, and the treatment of the shift is dependent on receiver manufacture. Figure 10 shows the effect of half cycle shift correction of BeiDou.

Fig. 10 GPS and BeiDou kinematic solutions of zero baseline at Etchujima, Tokyo on August 9, 2014, between JAVAD DELTA and Trimble NetR9 receivers.

3.3 Open source multi-GNSS analysis software: GSILIB

By summing up improvements to RTKLIB in the project, we have developed a derivative open source software package named GSILIB (GNSS Surveying Implementation LIBrary), which runs on a Windows PC (Furuya et al., 2013). Following the open source license of RTKLIB ver.2.4.2, GSILIB is provided from the project web site under the BSD 2-clause license, which does not require open source code when revised by users. We also provide ANTapp which do the same work as ANTTOOL without Matlab under GPL v3 license.

There have been nearly 1000 downloads of GSILIB and ANTapp since January 2015. To promote multi-GNSS surveying using GSILIB, we had several seminars in Japan, as well as held a tutorial seminar at Phuket at the time of Asia Oceania Regional Workshop on GNSS in 2014.

Fig. 11 Interface and output view of GSILIB. GSILIB is a derivation from RTKLIB specialized in dealing with biases in multi-GNSS surveying.

3.4 Application of PPP for GEONET deformation monitoring

Since quicker provision of crustal deformation fields from GEONET at the time of earthquakes or volcanic activities is of high priority, we investigated the feasibility of using Precise Point Positioning (PPP) and PPP-AR (Ambiguity Resolution) techniques in addition to multi-GNSS option. From the point of CPU time, PPP/ PPP-AR is attractive compared to the time-consuming baseline analysis. However, PPP/ PPP-AR requires precise orbit and clock information, whose sources are currently limited. We have used real-time CNT data from CNES (http://www.ppp-wizard.net/index.html).

Figure 12 shows an example of whole GEONET analysis by baseline analysis and PPP/PPP-AR (GSI, 2014b). The CPU time by PPP/PPP-AR with RTKLIB is only 0.5 minutes to process about 1200 stations, whereas baseline processing with Bernese 5.2 took 12 to 15 minutes using 6 servers with 8 cores each. Note that 1 hour GPS baseline solutions are not so stable, but additional use of GLONASS stabilizes solutions. Currently CNES provide only GPS ephemeris for PPP/ PPP-AR.

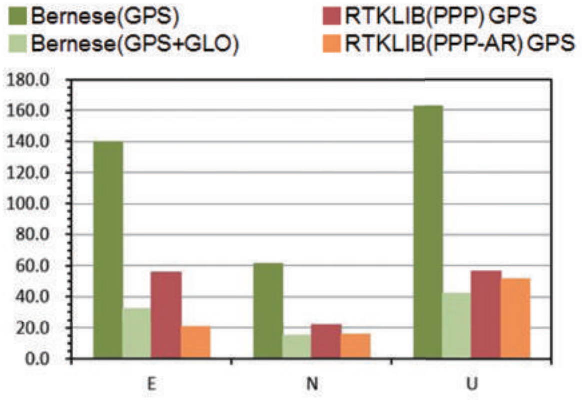

Fig. 12 Standard deviations of 1 hour static solutions of GEONET (median of whole stations) in mm on October 4, 2013 by 1) baseline analysis with GPS only and with GLONASS, and 2) PPP/PPP-AR with GPS. IGS ultra rapid orbit is used for the baseline analysis, and CNES's real-time CNT ephemeris is used for PPP/PPP-AR.

3.5 Draft manual of multi-GNSS surveying for public surveys

Based on several simulation studies and field observations of multi-GNSS with GSILIB processing, we made a draft manual of multi-GNSS surveying applicable to some part of public surveys, under the guidance of another advisory committee headed by Prof. Tatsunori Sada of Nihon University (GSI, 2015b). With this manual, usage of GPS, GLONASS, QZSS, and Galileo becomes possible in public surveys in Japan. A special method to combine inter-system DD of multi-GNSS is described for urban surveys.

4. Future works

Although the initial project ended in March 2015, we continue to work on the following items to promote multi-GNSS surveying in Japan.

1) Field evaluations of L5 data
2) Examination of new Code Division Multiple Access (CDMA) signal from GLONASS-K satellite
3) Improvement of multipath reduction for urban areas
4) Promotion of the draft manual and its revision
5) Maintenance of GSILIB

5. Conclusions

In response to the advent of a multi-GNSS environment, GSI conducted a four year technical development of a smart use of multiple frequency signals from multiple satellite systems for more efficient surveys and quicker crustal deformation monitoring in Japan. Although each GNSS is designed to have basic interoperability with other systems, combining carrier phase signals from different GNSS requires careful calibration of biases, such as the GLONASS IFB, ISB, the quarter cycle shift of L2C, and the BeiDou half cycle shift, in order to make full use of multi-GNSS. We modified the existing open source software RTKLIB to handle these biases and set up a package as GSILIB for precise surveying in multi-GNSS environment. Based on simulation studies and field observation analyses, we also set up a standard procedure of multi-GNSS surveying, forming a draft manual of multi-GNSS surveying for public surveys.

Looking back, everything was simple in the good old GPS days. With the rise of multi-GNSS, there are very many signal delay biases to be solved for their combinations. GSI will continue to assist surveying and disaster mitigation sectors through technical development to make full and smart use of a multi-GNSS environment.

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