Development of a Precise Positioning Technique Using Multi-GNSS

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Key words: GPS, multi-GNSS, IFB, ISB, surveying

SUMMARY

Multiple GNSS constellations such as GPS, QZSS, GLONASS, Galileo and BeiDou have been recently realized, and the number of available satellites for GNSS surveying is rapidly increasing. However, there are few analysis software for precise surveying that can handle multi-GNSS data. The Geospatial Information Authority of Japan (GSI) launched a 4-year project from 2011 to develop and standardize a precise positioning technique that can fully utilize the potential of multi-GNSS, especially at urban or mountainous areas where satellite visibility is limited. The project confirmed the effect of multi-GNSS surveying in severe observation conditions mentioned above, and yielded technical outputs such as

1) Methods to handle between-receiver biases for combination of multi-GNSS signals,
2) An open source software for multi-GNSS surveying named GSILIB, which can process GPS, QZSS, GLONSS, Galileo, BeiDou including L5 signal, with an additional option to form double differences between GPS and other GNSSs by correcting inter system biases,
3) Draft Manual of multi-GNSS surveying that are applicable to public surveys which are funded by public sectors in Japan.

Development of a New Gravitational Geoid Model for Japan

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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, which are funded by public sectors in Japan, are conducted using GPS, and the nationwide network of GPS operated by the Geospatial Information Authority of Japan (GSI) provides nationally authorized positional reference for the surveys and also 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 GNSS Earth Observation Network System (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 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 QZSS, GLONASS and Galileo will significantly improve the number of observable satellites.

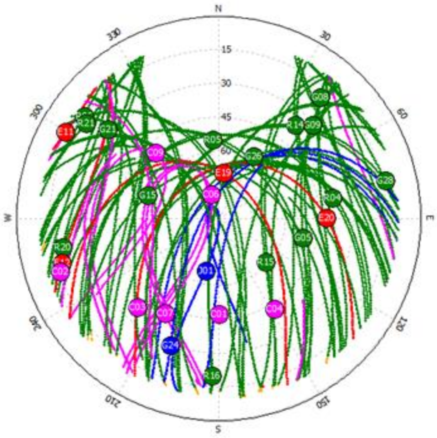

Fig.1: Sky plot of GNSS data observed by modern GNSS receiver (Trimble NetR9) at GSI headquarters in Tsukuba from 5:25 to 23:15 UTC on July 17, 2013. G: GPS, J: QZSS, R: GLONASS, E: Galileo, C: BeiDou.

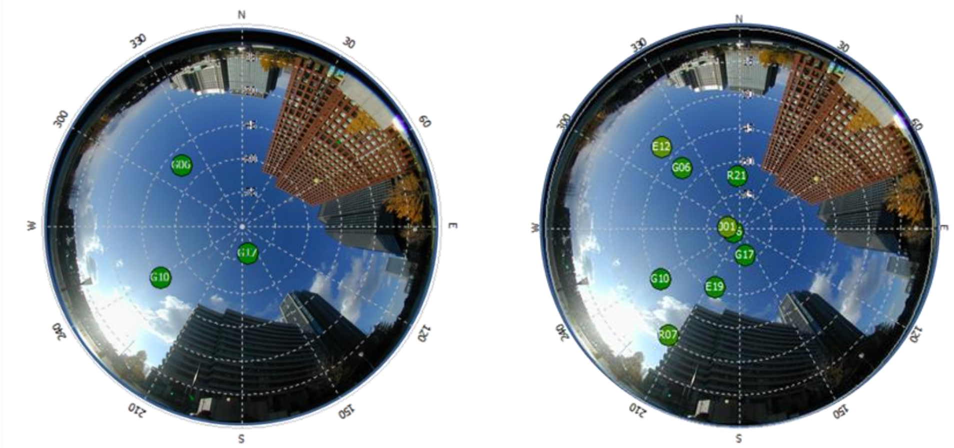

Fig.2: An example of satellite visibility in an urban canyon of Tokyo, at 1:00 UTC December 14, 2014. Left: No hope of positioning with only 3 GPS. Right: Positioning possible with additional 1 QZSS, 3 GLONASS, and 2 Galileo.

2. PROJECT DESCRIPTION

2.1 Objective

A four year project named "Development of a precise positioning technique using multi-GNSS for advanced management of national lands" was conducted by GSI with collaborations from various contractors, including universities. 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.

2.2 Implementation

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

1) Development of algorithms and software for multi-GNSS data processing.
2) Field experiments and a simulation study to confirm the techniques developed in the project. 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.

3. OUTCOMES OF THE PROJECT

3.1 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.

3.1.1 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 types 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 a very short baseline with different receivers at both ends by processing the data with ANTTOOL (Takasu, 2012). We have estimated the IFB of 4 kinds of receivers, 5 in total, with respect to a reference one (Table 1). We also changed observation conditions such as antenna, reboot, firmware and temperature of receivers. Figure 3 and 4 show the IFB on each conditions, the plots and lines are displaced every 1 cm/Freq for each GNSS 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.

Table 1: Averages of IFB with respect to JAVAD DELTA receiver in a zero baseline

Receivers	IFB (cm/Freq)	
	L1	L2
JAVAD SIGMA	-0.08	-0.10
LEICA GRX1200+ GNSS	2.71	2.77
TOPCON NET-G3	-0.48	-0.48
Trimble NetR9	-0.77	-0.92
Trimble NetR9	-0.77	-0.91

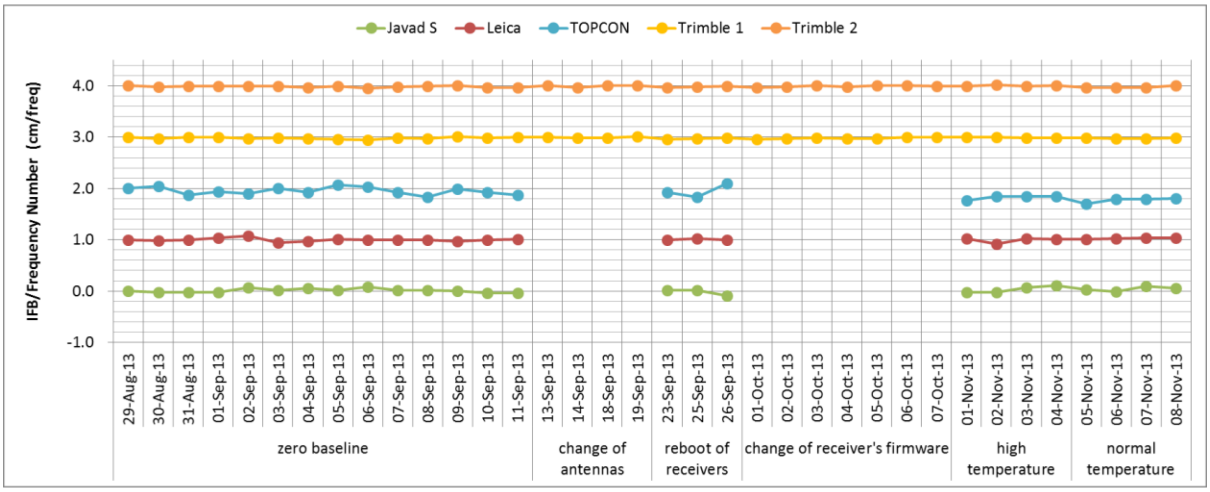

Fig.3: Variations of L1 IFB with respect to JAVAD DELTA receiver

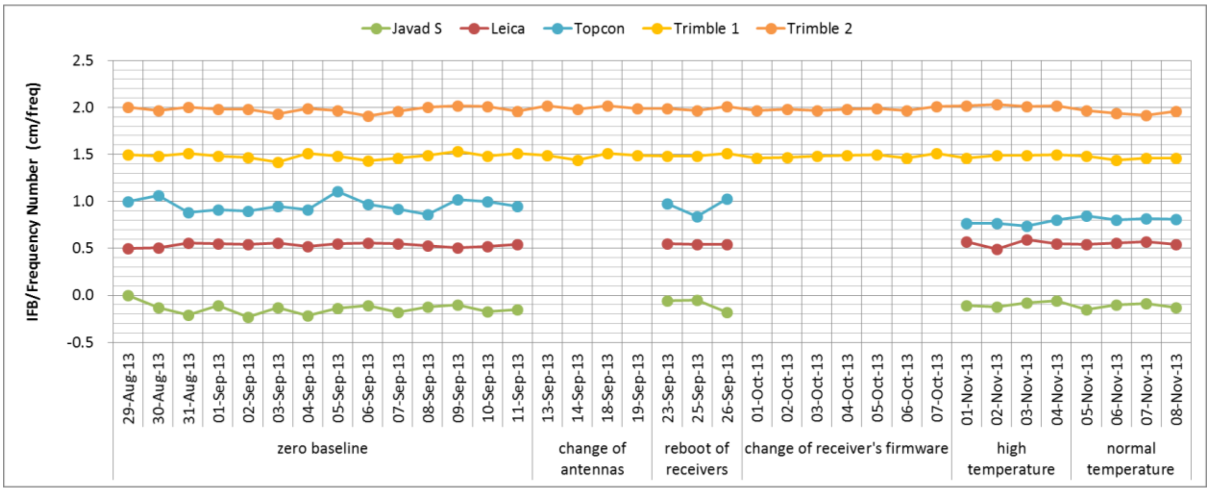

Fig.4: Variations of L2 IFB with respect to JAVAD DELTA receiver

Figure 5 shows the effect of GLONASS IFB correction for GPS and GLONASS combination. IFB correction with pre-determined values significantly improves ambiguity fix ratio and stabilizes the solutions.

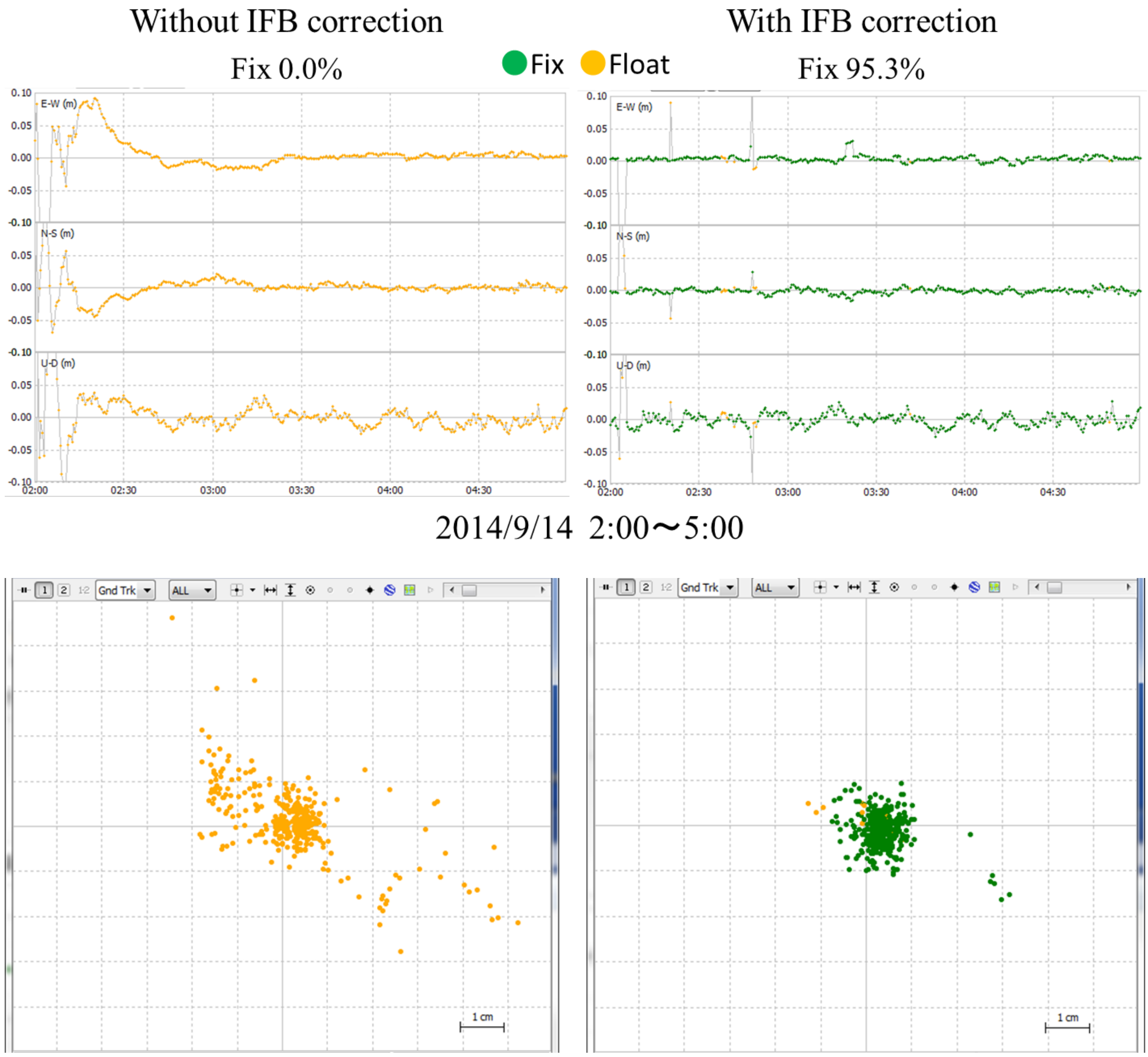

Fig.5: GPS and GLONASS kinematic solutions of 500 m baseline at GSI headquarters in Tsukuba on September 14, 2014, between JAVAD DELTA and Leica GR25 receivers. IFB corrections applied for the GSILIB proccessing are 3.00 cm/Freq for L1 and 3.00 cm/Freq for L2 which are estimated from the zero baseline observation of 12 hours on August 27, 2014. Unit for vertical axis of upper graphs is meter.

3.1.2 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 receivers of differenct manufacturers. We developed a method to check and correct the sign of quarter cycle shift in L2C. Figure 6 shows the effect of the quarter cycle shift correction for GPS and QZSS combination.

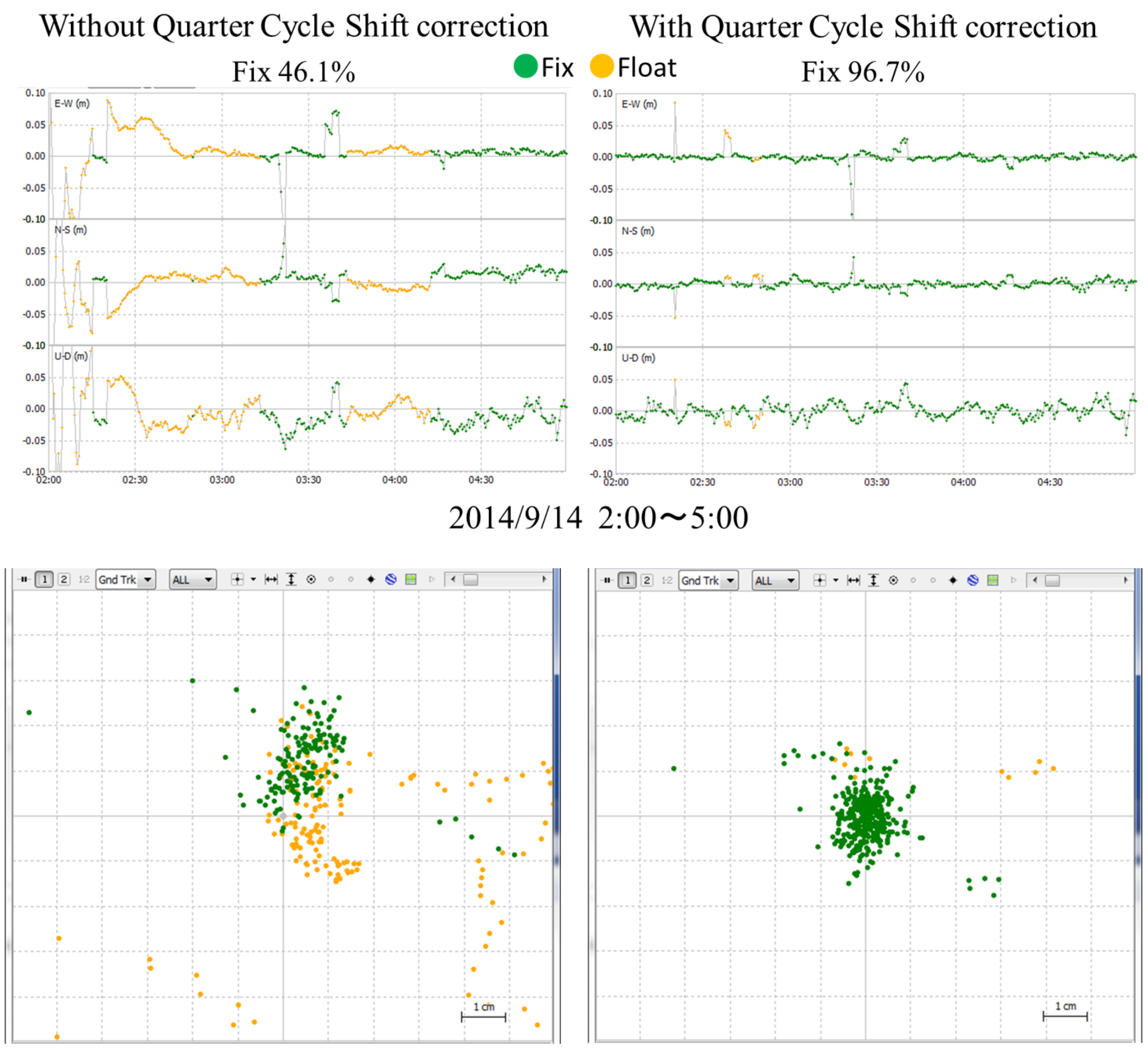

Fig.6: GPS and QZSS kinematic solutions of 500 m baseline at GSI headquarters in Tsukuba on September 14, 2014, between JAVAD DELTA and Trimble NetR9 receivers. We previously

confirmed that quarter cycle shift corrections for JAVAD as +1/4, and Trimble as 0. Unit for vertical axis of upper graphs is meter.

3.1.3 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).

ISB originates from different delays of each GNSS signal experiences inside receiver hardware, therefore if different receivers are used at both ends of a baseline, ISB should be estimated and corrected (Furuya et al., 2015). 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 (Table 2). Although ISB occurs in both code and phase measurements, we focused on the phase ISB that has directly impact on precise positioning. From Figure 7 to 13 show the variations of the phase ISB on each conditions, the plots and lines are displaced every 0.05 m for each GNSS receivers.

Table 2: Averages of phase ISB with respect to JAVAD DELTA receiver in a zero baseline

Receivers	QZSS			GLONASS		Galileo	
	L1 (m)	L2 (m)	L5 (m)	L1 (m)	L2 (m)	L1 (m)	L5 (m)
JAVAD SIGMA	0.002	0.005	0.002	-0.076	-0.037	—	—
LEICA GRX1200+ GNSS	—	—	—	0.118	0.142	0.093	0.133
TOPCON NET-G3	0.002	0.002	0.000	-0.200	-0.339	—	—
Trimble NetR9	0.002	0.005	0.002	0.025	-0.058	0.037	-0.002
Trimble NetR9	0.002	0.005	0.002	0.027	-0.058	0.037	-0.002

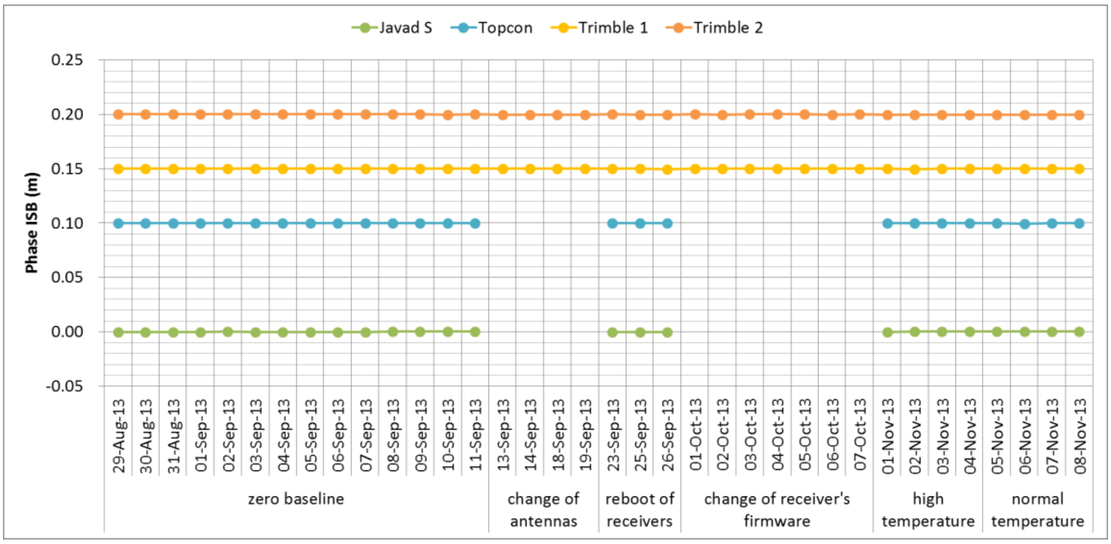

Fig.7: Variations of L1 ISB of GPS-QZSS with respect to JAVAD DELTA receiver

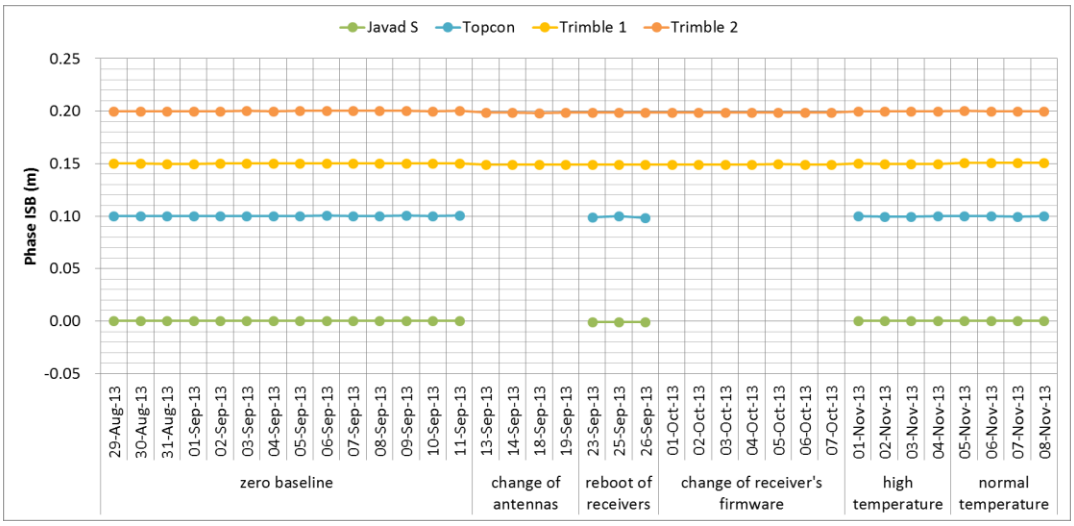

Fig.8: Variations of L2 ISB of GPS-QZSS with respect to JAVAD DELTA receiver

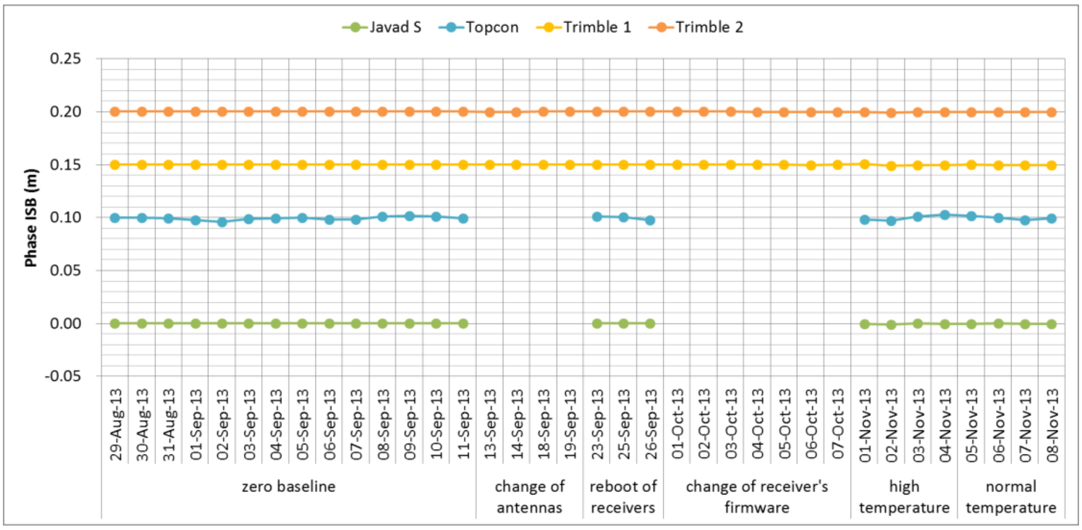

Fig.9: Variations of L5 ISB of GPS-QZSS with respect to JAVAD DELTA receiver

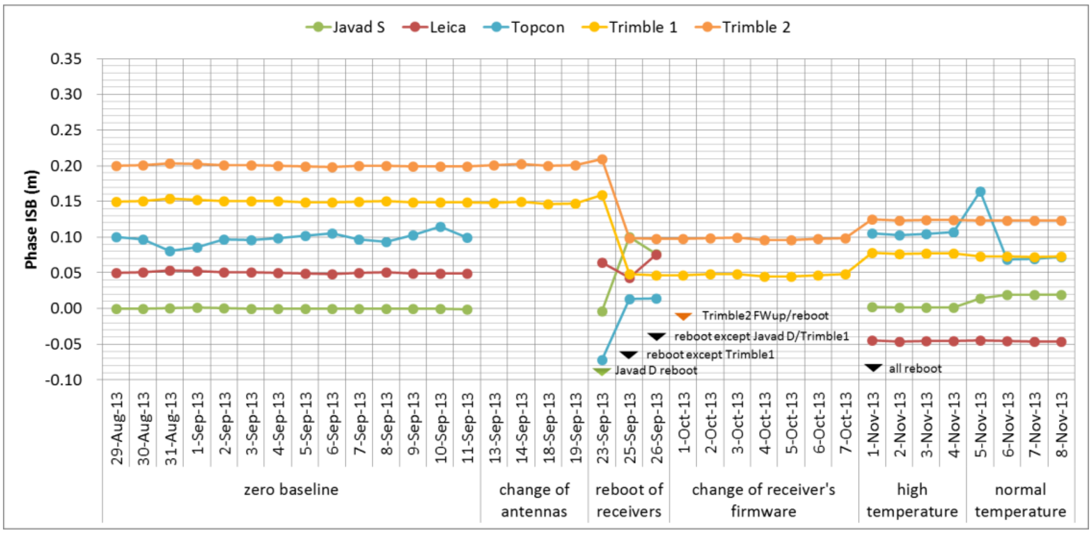

Fig.10: Variations of L1 ISB of GPS-GLONASS with respect to JAVAD DELTA receiver

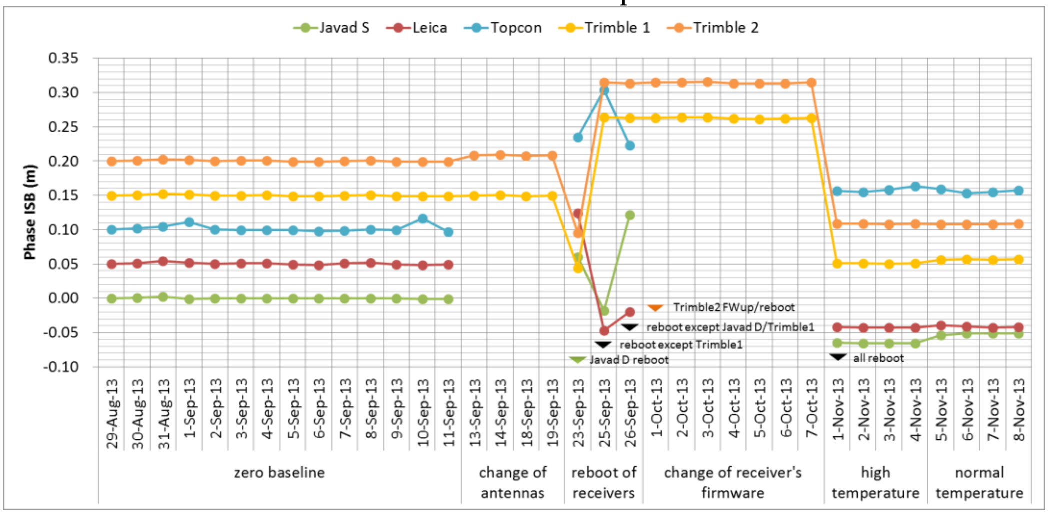

Fig.11: Variations of L2 ISB of GPS-GLONASS with respect to JAVAD DELTA receiver

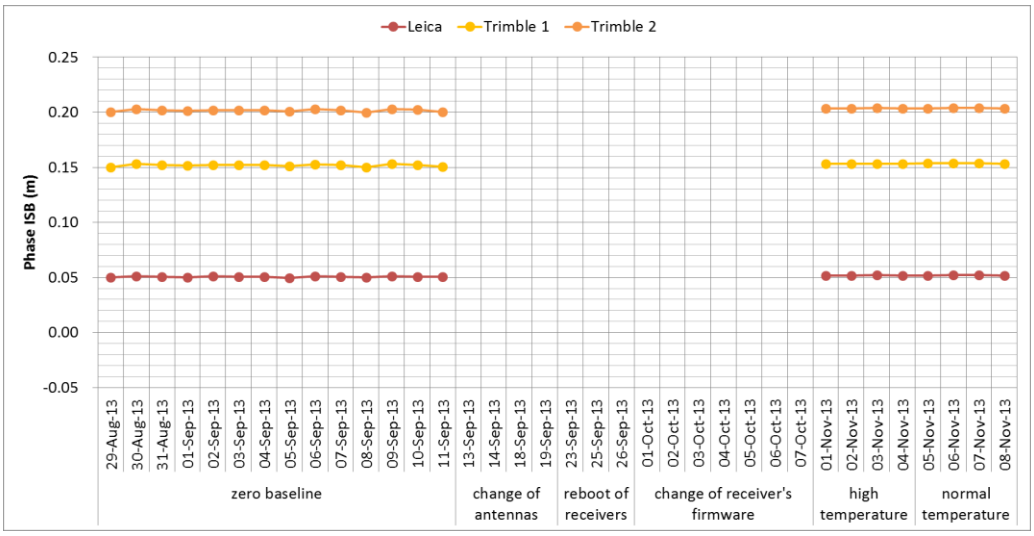

Fig.12: Variations of L1 ISB of GPS-Galileo with respect to JAVAD DELTA receiver

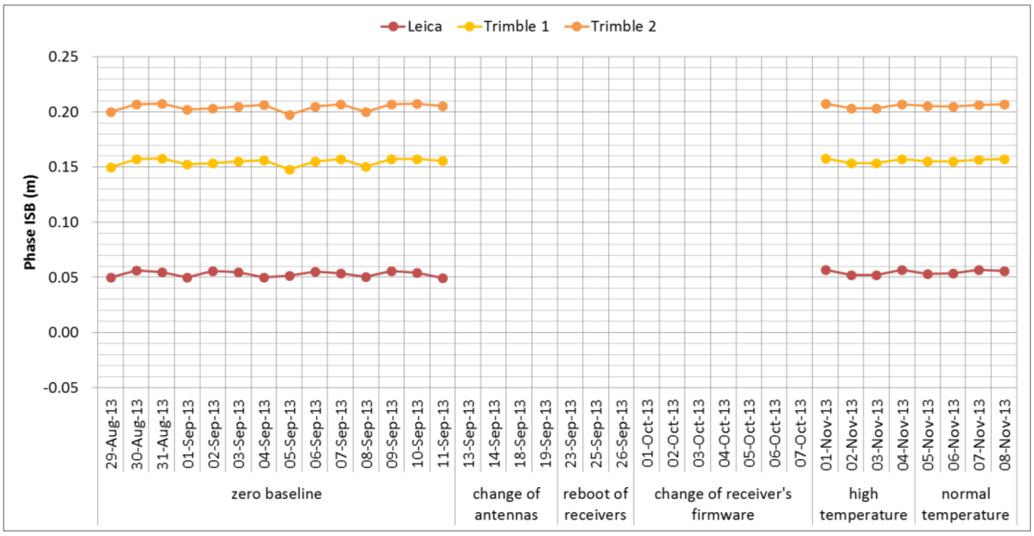

Fig.13: Variations of L5 ISB of GPS-Galileo with respect to JAVAD DELTA receiver

As a result, we found that

1) ISB (phase) for GPS-GLONASS is not stable and changes with temperatures and reboots 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-QZSS and GPS-Galileo is stable, so we can fix inter-system DD using pre-determined values for these combinations.

Figure 14 shows the effect of ISB correction for GPS and Galileo combination.

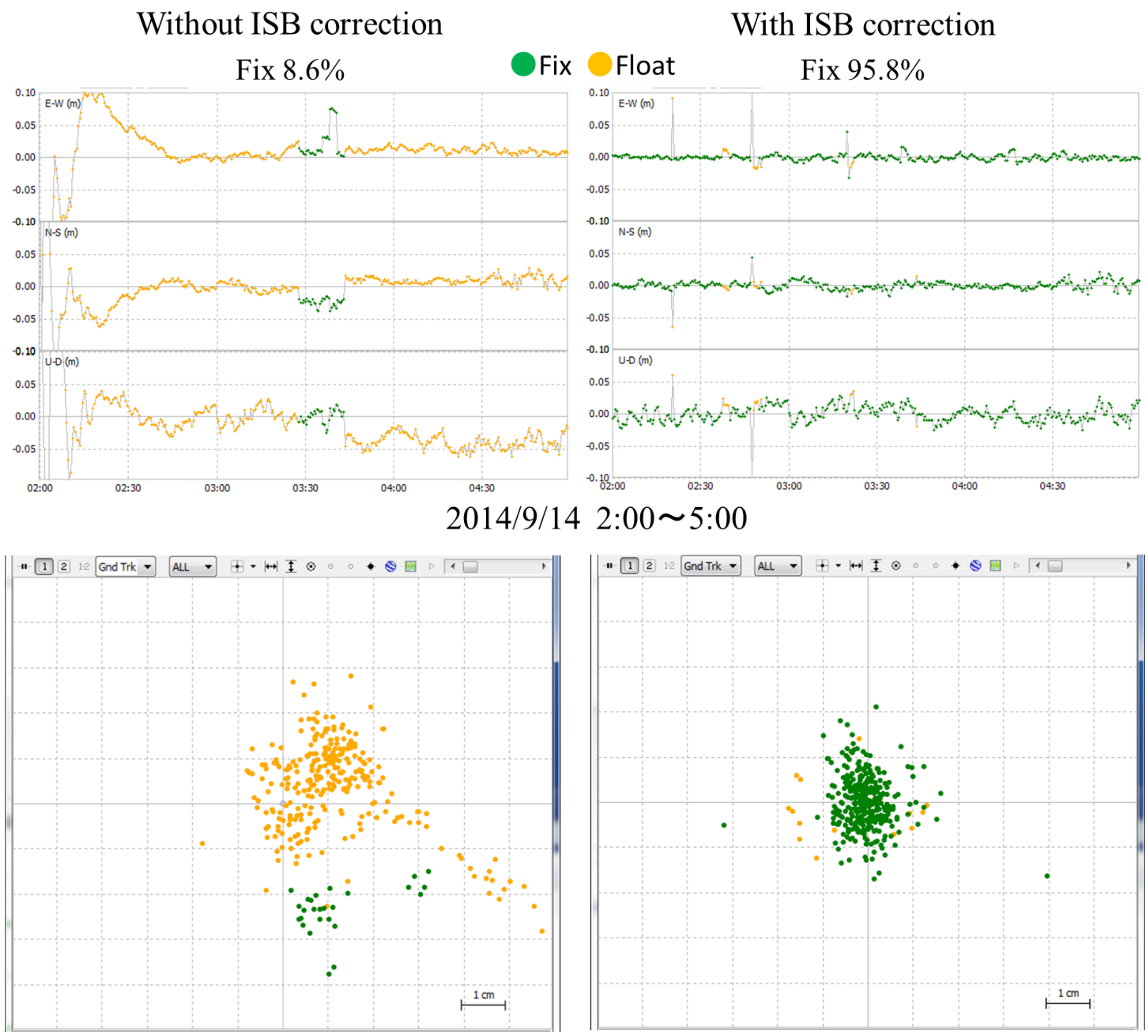

Fig.14: GPS and Galileo kinematic solutions of 500 m baseline at GSI in Tsukuba on September 14, 2014, between JAVAD DELTA and Trimble NetR9 receivers. Ambiguities between GPS and Galileo are successfully resolved with ISB correction of Phase L1 0.042m and Phase

L5 -0.001m, that are estimated from zero baseline observations of 24 hours on August 27 and 28, 2014. Unit for vertical axis of upper graphs is meter.

3.1.4 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 manufactures. Figure 15 shows the effect of half cycle shift correction of BeiDou.

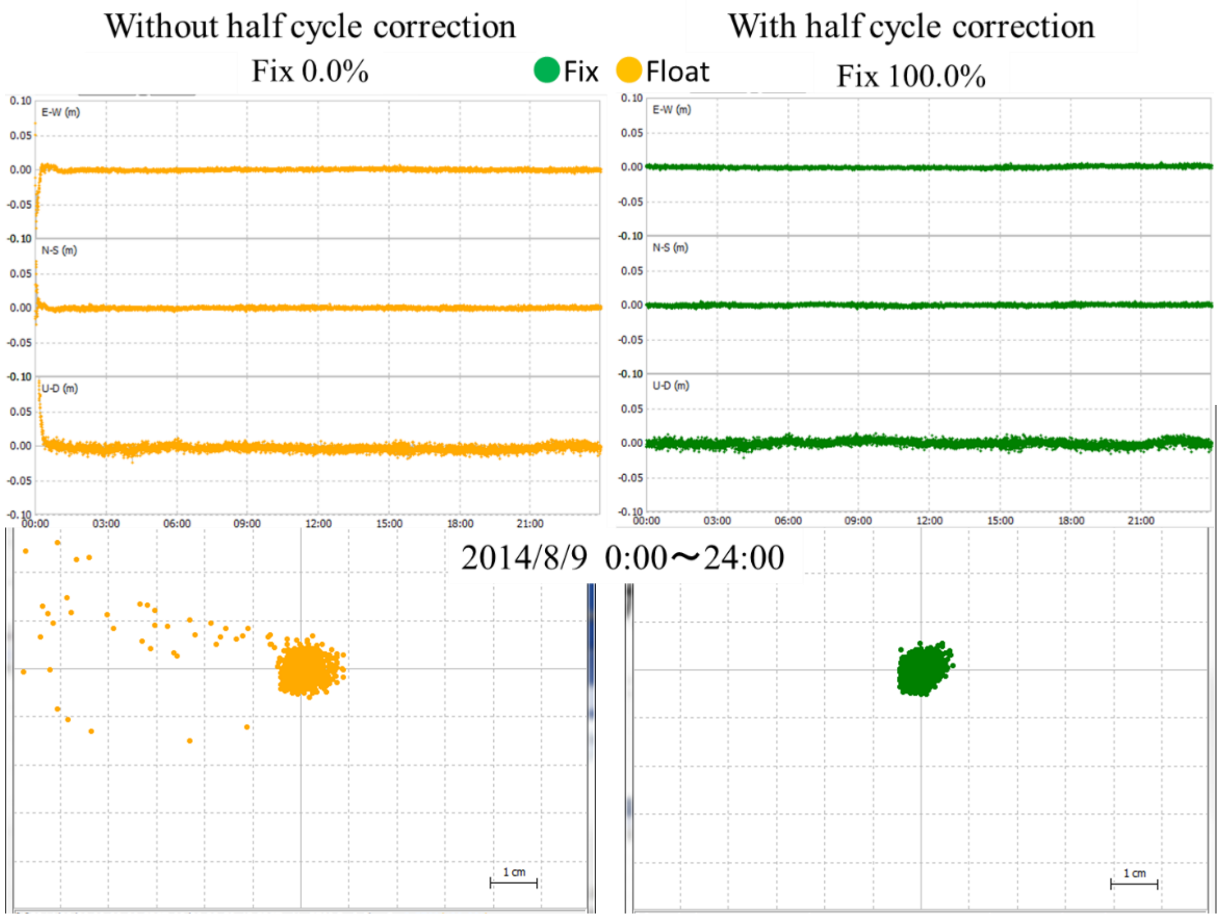

Fig.15: GPS and BeiDou kinematic solutions of a zero baseline at Etchujima, Tokyo on August 9, 2014, between JAVAD DELTA and Trimble NetR9 receivers. Unit for vertical axis of upper graphs is meter.

3.2 Open source multi-GNSS analysis software: GSILIB

By summing up improvements to RTKLIB: An open source program package for GNSS Positioning (Takasu, 2011) 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.

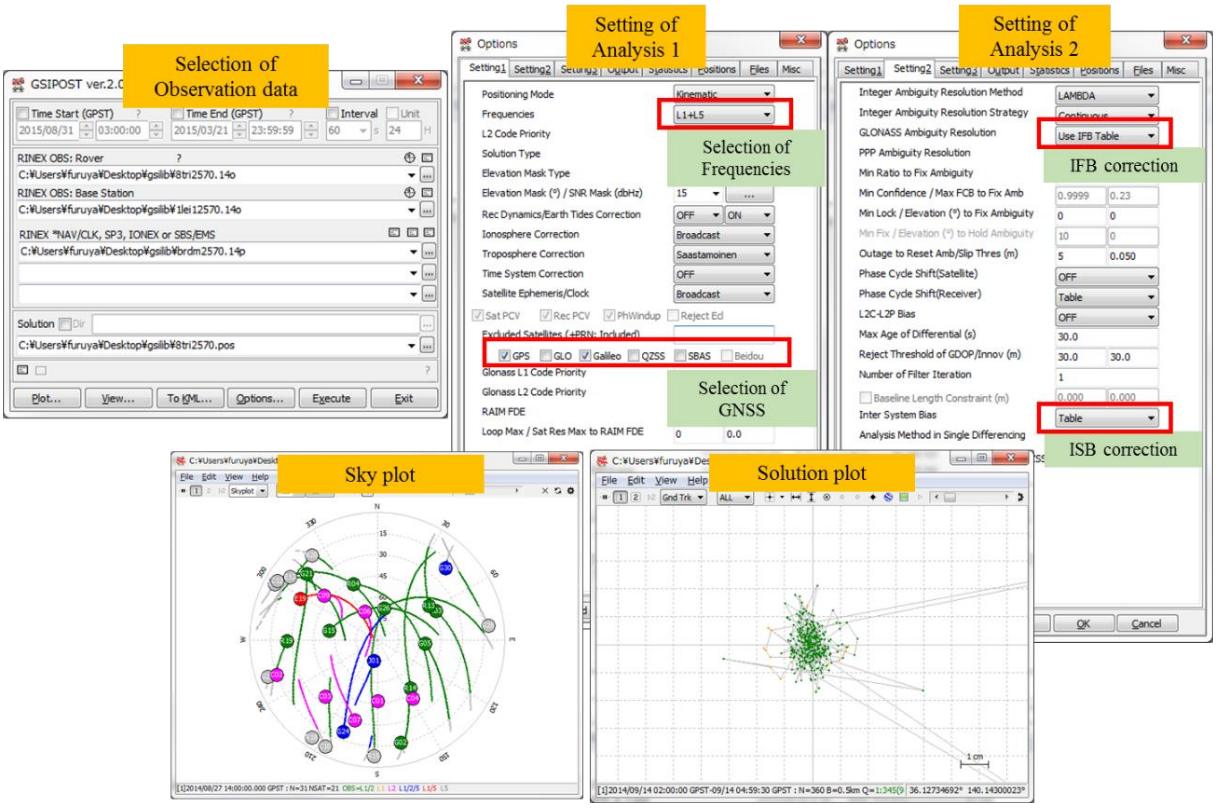

Fig.16: Interface and output view of GSILIB. GSILIB is a derivation from RTKLIB specialized in dealing with biases in multi-GNSS surveying.

3.3 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 parts of public surveys in accordance with article 17 of the standard operating procedure that allows introduction of new techniques to public surveys (GSI, 2015). With this manual, GPS, QZSS, GLONASS, and Galileo officially becomes available for the public surveys in Japan. A special method to combine inter-system DD of multi-GNSS is described for urban surveys.

4. 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 in Japan.

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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BIOGRAPHICAL NOTES

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