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Combined Processing of GPS & BeiDou Observations: An Investigation

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Abstract

Increasingly geodetic science applications require reliable, rapid, precise and, ideally, real time positioning capability. With GNSS positioning techniques today's geodesists can expect a positioning accuracy ranging from metre-level to mm, depending upon the receiver and measurement types, the sophistication of observation error modelling, and the data processing technique employed. The double-differenced observable approach and single- receiver Precise Point Positioning (PPP) are two classes of GNSS techniques for precise receiver positioning. In this master thesis the results of GNSS measurement processing are investigated, comparing the GPS-only measurement processing with combined GPS & BeiDou measurement processing. The GPS-only techniques may suffer due to poor satellite geometry. Hence, combined GPS & BeiDou measurement processing would lead to a better satellite geometry as well as improved positioning. Positioning accuracy and convergence time were investigated for PPP and Double Difference using the GPS-only, BeiDou-only and GPS & BeiDou measurement processing.

This GNSS investigation is based on the PPP processing for combined GPS & BeiDou observation data as well for BeiDou-only observations. A combined GPS & BeiDou PPP processing could be performed using GPS and BeiDou precise orbits and clock corrections.

Since 28 January 2014 the German GeoForschungsZentrum (GFZ) has provided satellite orbit and satellite clock correction information for the BeiDou constellation. In addition, the GNSS research group at the European Space Operations Centre (ESOC) provided orbit and clock corrections for BeiDou for GPS weeks 1783 and 1784. These precise BeiDou satellite orbit and clock products have been used to study the performance of PPP.

A closer look at the PPP solution indicates an improvement in PPP positioning accuracy when BeiDou observations are included in the analyses. The GNSS station CUTA0 (Australia) has been chosen for these analyses, and raw range data for 19 March 2014 were used. The Ocean Loading BLQ format file and ATX file were also used to enhance the positioning accuracy.

The SNAPP GNSS data processing software (a modified and upgraded version of the RTKLIB software developed at SNAP Lab, UNSW) was used for the PPP processing. The ionosphere-free linear combination of L1 and L2 for GPS and B1 and B2 for BeiDou were used. Zenith Tropospheric Delays were also estimated. The positioning accuracy is estimated from the difference between the PPP -derived results and the ground truth coordinate values.

For the positioning accuracy statistics orbit and clock files of ESA and GFZ were used to process the same data. The first 30 minutes of PPP solutions were excluded to ensure that only results after PPP convergence were considered. When introducing ESA products the GPS-only PPP solution bias and standard deviation for 24 hours data span is -10± 28mm, -5± 4mm and 30±42mm for the East, North and Up components, respectively. In contrast, the combined GPS & BeiDou PPP positioning solution accuracy is 32±31mm, -15±10mm and -31±43mm for East, North and Up components.

It was also observed that GPS-only analyses resulted in 5cm, 10cm, 20cm and 50cm deviations from the ground truth after 72, 51, 45.5 and 25.5 minutes, respectively, for the horizontal component. GPS & BeiDou results deviated smaller than 5cm, 10cm, 20cm and 50 cm from the ground truth after 60, 49, 30.5 and 21minutes. This is a slight improvement (20% less time) for the 20cm and 5cm convergence in the case of GPS & BeiDou compared to GPS-only solutions. However, other convergence criteria do not indicate any significant improvement.

For the vertical convergence GPS-only solutions converge to 5cm, 10cm, 20cm and 50cm after 124.5, 105.5, 49 and 4.5minutes, respectively, whereas GPS & BeiDou solutions converge after 24.5, 21.5, 11 and 5.5 minutes, respectively. This is a similar behaviour to the 2D horizontal results. Hence combined GPS & BeiDou processing has led to an improvement of about 80% in the case of 5cm and 10 cm convergence for this special test case.

The GPS-only PPP solution bias and standard deviation for 24 hours data span after convergence was 5±45mm, 3±6mm and 34±62mm for the East, North and Up components, respectively. The integrated GPS+ BeiDou PPP positioning solution bias and standard deviation is 1±24mm, -37±40mm and 80±235mm for East, North and Up components, respectively. It was also observed that GPS-only analyses resulted in accuracies better than 5cm, 10cm, 20cm and 50cm accuracy after 100, 69.5, 50.5 and 30minutes, respectively, in the case of horizontal positioning. GPS & BeiDou results deviate less than 5cm, 10cm, 20cm and 50cm after 190, 111, 60 and 30minutes. For the vertical convergence the GPS-only solutions converge to 10cm, 20cm and 50cm after 125, 95.5and 24.5 minutes, respectively, whereas the GPS & BeiDou solution provides only accuracies of 10 cm and 20 cm after 206, 155 minutes, respectively. It has been observed that GPS & BeiDou and GPS cannot produce coordinate with 5cm 2D accuracy.

Therefore, at least for the test period, it could be concluded that the ESA products provide higher quality than the GFZ products. However, this will need further analysis. In addition different station (same day and different days) data has to be analyzed to gain better insights.

Kurzfassung

Geodätische Anwendungen erfordern in zunehmendem Maße zuverlässiges, schnelles und präzises Positionierungsvermögen, das idealerweise in Echtzeit erfolgen sollte. Dank GNSS- Positionierungstechniken können Geodäten eine Positionierung in einem Spektrum von Meter- bis hin zur Millimetergenauigkeit erwarten, je nachdem welche Empfänger- und Beobachtungstypen vorliegen, wie hoch entwickelt die Modellierung der Fehlerterme der GNSS Beobachtungen ist und wie die eingesetzte Datenverarbeitungstechnik beschaffen ist. Der Double Difference und Single Receiver Beobachtungsansatz (Precise Point Positioning-PPP) sind zwei Klassen von GNSS Techniken zur präzisen Positionierung. In dieser Masterarbeit werden die Resultate der GNSS Datenverarbeitung von GPS-only und BeiDou-only basierten Messungen mit einer Kombination aus GPS und BeiDou Messungen verglichen. Die GPS-only basierten Techniken können durch schwache Satelliten-Geometrie beeinträchtigt werden. Es ist daher zu vermuten, dass eine Kombination aus GPS und BeiDou Messungen sowohl eine bessere Satellitengeometrie als auch eine optimierte Positionierung mit sich bringen. Positionierungsgenauigkeit und Konvergenzzeit wurden für PPP anhand GPS-only, BeiDou-only sowie kombinierte GPS und BeiDou Messungen untersucht.

Eine PPP Datenverarbeitung für kombinierte GPS und BeiDou Beobachtungen ist nur möglich, wenn GPS und BeiDou precise orbit and clock Produkte zur Verfügung stehen. Seit dem 28. Jänner 2014 stellt das GeoForschungsZentrum (GFZ) präzise Satellitenbahnen und Satellitenuhrkorrekturen für die BeiDou-Konstellation bereit. Zusätzlich stellte die GNSS Forschungsgruppe des European Space Operations Centre (ESOC) Precise Orbit und Uhr Korrekturen für BeiDou während der GPS Wochen 1783 und 1784 zur Verfügung. Die genannten Produkte wurden zur Untersuchung verwendet.

Die erzielten Ergebnisse weisen darauf hin, dass eine Verbesserung der PPP Positionierungsgenauigkeit vorliegt, wenn BeiDou-Beobachtungen die Analysen stützen. Die GNSS-Station CUTA0 (Australien) diente als Ausgangspunkt für diese Analysen, Rohdaten für den 11. März 2014 wurden verarbeitet. Um die Positionierungsgenauigkeit zu verbessern, wurden Ocean Loading Korrekturen sowie Antennenphasenmodelle angebracht.

Die SNAPP GNSS-Datenverarbeitungssoftware (eine modifizierte und verbesserte Version der RTKLIB Software die in den SNAP Laboratorien (UNSW- University of New South Wales) entwickelt wurde) kam bei der PPP Verarbeitung zum Einsatz. Es wurde von einer ionosphärfreien linearen Kombination von L1 und L2 für GPS und B1 und B2 für BeiDou Gebrauch gemacht. Des Weiteren erfolgte eine Schätzung der troposphärischen Zenit-Verzögerungen. Dennoch konnten die Phasen Ambiguitäten nicht auf Integer Werte fixiert werden. Eine Abschätzung der Positionierungsgenauigkeit erfolgte auf Basis des Unterschiedes zwischen den der PPP entnommenen Ergebnissen und den tatsächlichen Werten der Stationskoordinaten.

Auf Basis der ESA-Produkte konnten die folgenden Ergebnisse der PPP-Berechnungen abgeleitet werden. Aus der Statistik wurden die ersten dreißig Minuten der PPP Prozessierung herausgenommen um sicher zu gehen, dass einzig und allein die Resultate nach der PPP Koordinatenkonvergenz berücksichtigt sind. Das bedeutet, dass der Datensatz eines ganzen Tages (z.B. 2880 Epochen eines 24 Stunden-Datensatzes in 30 sekündigen Intervallen) zuerst verarbeitet wurde und die ersten 30 Minuten des PPP Processing von den Genauigkeitsstatistiken exkludiert wurden. Daraus folgt, dass die letzten 2820 Epochen der PPP Lösungen bei der Erhebung der Statistiken zum Einsatz kamen. Die GPS-only basierte PPP Genauigkeit lag bei -10± 28mm, -5± 4mm und 30±42mm für die Ost-, Nord- und Höhenkomponenten. Im Gegensatz dazu betrug die integrierte GPS & BeiDou PPP Positionierung-Genauigkeit jeweils 32±31mm, -15±10mm und -31±43mm für die Ost-, Nord- und Höhenkomponenten.

Es kann für die horizontale Komponente gezeigt werden, dass die GPS-only Analysen zu einer Koordinaten Konvergenz von 5cm, 10cm, 20cm und 50cm nach 72, 51, 45.5 und

25.5 Minuten führten. GPS & BeiDou Ergebnisse lieferten eine 5cm, 10cm, 20cm und 50cm Konvergenz nach 60, 49, 30.5 und 21 Minuten in der horizontalen Komponente. Das ist eine leichte Verbesserung (20% geringere Zeit) bei 20cm und 5cm Konvergenz im Falle von GPS & BeiDou verglichen mit GPS-only basierten Anwendungen. Dennoch weisen andere Konvergenzkriterien nicht auf irgendeine Art von signifikanter Verbesserung hin.

In der vertikalen Komponente erzielen rein GPS-basierte Anwendungen 5cm, 10cm, 20cm und 50cm Konvergenz nach jeweils 124.5, 49, 25.5 und 4.5 Minuten. Die GPS+ BeiDou Berechnung zeigt „ähnliche Ergebnisse“ wie für die horizontale Komponente. Folgerichtig hat eine Kombination aus GPS & BeiDou Beobachtungen zu einer Verbesserung der Konvergenz Zeit bei 10cm und 5cm von etwa 80% geführt.

Mit der Hilfe der GFZ Orbit- und Uhrenprodukte wurde eine Genauigkeit des GPS-only PPP Processing nach der Konvergenz von jeweils 5±45mm, -4±6mm und 3±62mm für die Ost-, Nord- und Höhenkomponenten erreicht. Die kombinierte GPS & BeiDou PPP Positionierung-Genauigkeit betrug jeweils 5±45mm, 3±6mm und 34±62mm für die Ost-, Nord- und Höhenkomponenten. Zudem konnte beobachtet werden, dass GPS-only basierte Analysen für die horizontale Komponente Ergebnisse im 5cm, 10cm, 20cm und 50cm Bereich nach 100, 69.5, 50.5 und 30 Minuten lieferten. GPS & BeiDou Resultate waren besser als 5cm, 10cm, 20cm und 50cm nach 190, 111, 60 und 30 Minuten für die horizontalen Komponenten. Bei der Untersuchung der vertikalen Konvergenz wies die GPS-only basierte Prozessierung eine Abweichung von kleiner als 10cm, 20cm und 50 cm nach jeweils 125, 95.5 und 24.5 Minuten auf, wohingegen die Positionierung mit Hilfe von GPS & BeiDou gleiche Abweichungen nach jeweils 206, 155 und 79.5 Minuten erzielte.

Es wurde somit ersichtlich, dass die ESA BeiDou Bahnprodukte für die untersuchte Zeitspanne qualitativ hochwertiger waren als jene des GFZ. Um dies zu bestätigen, bedarf es jedoch weiterer eingehenderer Analysen. Zudem wird man wesentlich längere Datensätze analysieren müssen, um statistisch fundierte Aussagen zu gewinnen.

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Chapter 1

1 Introduction

In the last few years tremendous changes in the development of Global Navigation Satellite Systems (GNSS)'s took place. Major improvements were made in modernization of the GNSS. Since ancient times, the navigation and positioning has been one of the essential tasks of human's common life, the traditional way of locating one's position or navigating was to make use of maps or compasses. Today people use the GNSS satellites for navigating and positioning. We have a start location to move towards the destination each day, usually both locations are known, and hence we can navigate ourselves by navigation systems. 20 years back this was definitely unthinkable that almost traffic participants can use the GNSS satellites for navigating from their known starting point to their known destination. Nowadays a lot of GNSS navigation applications are developed for different purposes of human life. These developments support pilots, policemen, mountaineers, seamen, soldiers as well as taxi drivers, etc. to locate their position.

Throughout the world, GNSS plays an important role in civilian use and in military use. Because of the increasing importance in civilian and in military use different nations have established and developed their own GNSS satellite systems. In this regard the most well-known GNSS is the NAVSTAR Global Positioning System (GPS) with about 32 satellites operated by the USA. The GLONASS is developed and established by Russians. GLONASS is the second GNSS satellite constellation which has achieved a fully operational status. The European nations will present their new GNSS constellation Galileo, which has currently 6 satellites in orbit. For several years the Chinese new GNSS constellation BeiDou was launched and this satellite system is capable of providing regional positioning, navigation and timing services and short message communication services to users in Asia- Pacific areas until now. BeiDou shall consist of 37 satellites by around 2020. In recognition of a rapid modernization of GNSS, the International GNSS Service has established the Multi-GNSS Experiment (MGEX) as a multi observation network for familiarization of all GNSS constellations. MGEX provides the highest quality data and products with all satellite navigation systems and this supports work with new signals and new constellations such as BeiDou. MGEX enables the extension from GPS towards full Multi-GNSS processing. The Double Difference GNSS technique bases on the carrier phase GNSS methods. Carrier phase methods use the short wavelength (19 cm for L1) of the carrier signal to achieve an accuracy range at mm level. Double Difference processing creates the baseline between base station and rover. The measurements at both stations are performed simultaneously. The baseline is the three- dimensional coordinate difference between two GNSS receivers. The base station is a receiver point with known coordinates. Precise Point Positioning (PPP) is an alternate GNSS technique and bases on GNSS measurements of a single rover and information about satellites from monitor stations around the world. Its most significant benefits are to enable users to produce geodetic positions without base station and without local networks. The quality of PPP GNSS processing heavily depends on the availability and accuracy of GNSS satellite orbits and satellite clock corrections which normally are provided by IGS.

This thesis investigates the Double Difference and the PPP positioning processing strategies with two different daily observation measurement data sets of the GNSS constellations GPS and BeiDou. Currently IGS research groups have provided BEIDOU precise orbit and clock corrections along with GPS. This investigation covers the idea to use the RINEX version 3 data sets of chosen MGEX ground station CUT0‘s, two receivers at the Curtin University in Australia and one ground station JFNG in China. The station coordinates and other parameters (e.g. the convergence time) are estimated in order to analyze 1) the positioning accuracy of ground station coordinate estimates with GPS-only and BeiDou- only, 2) the impact of adding BeiDou observations to simultaneous processing with GPS measurements. The used software is the free open source software package RTKLIB. For PPP processing the orbit and clock corrections for BeiDou from GFZ and ESA are used in order to compare the quality of the correction data for the investigated period.

Chapter 2

2 Global Navigation Satellite System (GNSS)

GNSS comprises all the available navigation satellites utilized used to provide the user's precise geographic location through their receivers anywhere in the world. The pinpointing with GNSS is based on a 3-D positioning solution by passive ranging. The radio signals are transmitted by orbiting satellites. Each satellite sends coded signals at precise intervals to receivers at ground tracking stations. The receiver converts signal information from satellites for calculating position, velocity, and time estimates. This information can be used by any receiver on or near the earth's surface for high precise positioning or calculating the distance between it and other close by receivers.

The visibility of four or more satellites enables the receiver to pinpoint its position. There is a number of satellite systems which cover the global world and transmit current signal data to ground stations. Navigation by Satellite Ranging and Timing (NAVSTAR), also known as GPS, from USA is the most well – known navigation satellite system. One of the alternatives to GPS is the global navigation system GLONASS from Russia. The navigation system Galileo was deployed by the European Space Agency (ESA), which provides a highly accurate global positioning service under civilian control. Galileo is inter-operable with GPS and GLONASS (www.esa.int/Our_Activities/Navigation/The_future__Galileo/What_is_Galileo). The global navigation satellite system BeiDou, formerly known as COMPASS, is the newest satellite system from China. Currently, it offers service for navigation and positioning in the Asia-Pacific region. The BeiDou constellation structure is similar to the Galileo network and it is inter-operable with GPS and GLONASS. In addition, there is a number of regional satellite navigation systems (e.g. QZSS from Japan) in operation. They enhance and ensure the highly accurate global service of GNSS.

2.1 Global Positioning System (GPS)

GPS is a navigation satellite system of 24 satellites made up by the U.S. government. At first, GPS was intended to be a military navigation system. The development of GPS started in 1973, the first operational prototype satellite was launched in 1978. Later in the 1980s, the U.S. government sets up the GPS system for civilian use. The Full operational capability (FOC) was achieved at the end of 1994. GPS consists of three segments-namely space segment, control segment and user segment. The nominal 24 satellites made up the GPS space segment and these are orbiting around the earth in about 20.200 km height. GPS satellites are located in six orbit planes, and these orbit planes have an approximately inclination of 55°. Each orbit plane is populated by about four to six satellites. The orbital period is one-half a sidereal day, i.e. 11 hours and 58 minutes. The GPS satellites will pass over the same location. At least six GPS satellites are located any time within the line of sight from almost everywhere on Earth's surface. The GPS satellites are powered by solar energy. They have backup batteries onboard to keep them running in the event of a solar eclipse, when there is no solar power available. Each GPS satellite has small rocket boosters to keep them flying on the correct path. The control segment of GPS consists of a network of a master control station, an alternate master control station, one or more control stations and a number of uplink stations. There are 16 global monitor stations, 12 uplink stations and two control stations.

The user segment of GPS offers two services for navigation and positioning: an open service for civilian use, also called Standard Positioning Service (SPS), and an authorized service for military use, also called Precise Positioning Service (PPS). The PPS is available to users who have been licensed by the U.S. government. In general, GPS receivers on the ground station consist of a tuned antenna, receiver-processor and a highly stable clock. The GPS satellites transmit the signals in three frequency bands: L1 (1575.42 MHz), L2 (1227.60 MHz) and L5 (1176.45 MHz). The C/A code and the L2C code transmit data at 1.023 chips per second and are freely available to the public. The P-code is used for military navigation and transmits 10.23 million chips per second. The

L1 carrier is modulated by the C/A code and P1-code, the L2 carrier by the L2C and the L2 P-code. The GPS signals contain three different sources of information – a pseudorandom code, ephemeris data and almanac data. Each GPS satellite has its own pseudorandom code, so it can be identified which satellite is transmitting the information to earth. The GPS satellites send ephemeris data directly to the user, and the data contains important orbit information of the satellites as well as exact clock corrections. For example, the current position of a satellite can be determined from the orbit elements. The ephemeris data contains the information about the visibility of GPS satellites. The almanac data is important for the GPS ground receiver. Each GPS satellite transmits almanac data showing the orbital information for all GPS satellites.

Table 1: Generations of GPS Satellites (as of August 2014)

GPS Satellite Block	Launch Dates	Number of Satellites	Currently in operation
Block I	1978-1985	10	0
Block IIA	1990-1997	9	6
Block IIR	1997-2004	12	12
Block IIR-M	2005-2009	8 (planned)	7
Block IIF	2010-2017	12 (planned)	6
Block III	2017-2024	24 (planned)	0

2.2 BeiDou

The Chinese BeiDou system is a new GNSS constellation, formerly known as COMPASS. This system is capable of providing regional positioning, navigation and timing services and short message communication services to users in Asia-Pacific areas until now. BeiDou will be developed in three distinct phases. The first phase started in 2007 and ended in 2012. The first test satellite of BeiDou was using GPS technology, and was launched in 2007. It is an experimental system of using three geosynchronous satellites. This phase provides a wide area of precise positioning and it offers navigation services in China for users. The second phase started in 2012 and BeiDou provides a regional GNSS-based service to China and surrounding countries. Until 2014 BeiDou has 14 active satellites in orbit. Five of them are in geosynchronous Earth orbit (GEO) satellites, five of them are inclined geosynchronous orbit (IGSO) satellites and four medium Earth orbit (MEO) satellites. The BeiDou satellites broadcast on three frequency bands. Phase three will be currently under development and we expect the full operational capability of the BeiDou constellation based on 5GEO, 3IGSO and 27MEO satellites which are orbiting the earth every 12 hours. The BeiDou constellation will provide a global coverage for GNSS users by 2020. Currently the BeiDou are mainly located above China and their neighboring countries. Therefore there is a need of eight satellites more for a geographic coverage of the Asia- pacific region, where BeiDou's PDOP value is as small as 2(elevation cutoff angle set five degrees). Many locations in the Oceania area can be covered with BeiDou. The constellation structure will be similar to the European Galileo system and GPS system and the ranging signals are based on the CDMA principle, like GPS and Galileo. China intends to market BeiDou receivers in competition with GPS, GLONASS and Galileo. There will be two levels of positioning service: open and authorized. BeiDou broadcasts on three frequencies, B1, B2 and B3. The B1 signal is opened for users at 1561.42 MHZ. BeiDou is transmitting the open and authorized signals at B2 (1207.14 MHz) and offers an authorized service at B3 (1268.52 MHz). BeiDou provides an active positioning technology and a passive positioning technology because of two satellite generations. The active positioning technology means that the receiver obtains the signal from satellites and gives self-information to satellites. Passive positioning technology means a one-way communication system. The receiver can only obtain the signal from the satellites. The positioning principle of BeiDou satellites is similar to GPS, GLONASS and Galileo. Each satellite has high precision clocks and orbital data provides passive receivers precise position information. BeiDou signals are interoperable with signals from multiple satellite constellations. Aside high-precise position BeiDou also offers users a service of communication messages. All antennas for BeiDou must be compatible with both generation satellites.

The Ground Segment consists of a Master Control Station, Upload Stations and Monitor Stations. The Master Control Station controls the satellite constellation and processes the observation measurements. There are 30 monitor stations which receive observation measurements to generate the navigation message. The monitor stations collect BeiDou orbit data for all satellites. The Upload Stations are responsible for uploading the orbital corrections and the navigation message to BeiDou satellites. The BeiDou User Segment consists of BeiDou user terminals, which receive satellite transmitted signals, pseudo ranges were determined and the navigation equations will be solved in order to obtain user coordinates. The receiver is a device capable of calculating the user's position, velocity and precise time (PVT) by processing the signal broadcasted by BeiDou satellites. The open service for civilian use will be free to all users with a BeiDou receiver and will have a positioning accuracy level of 10 meters, and it provides clock synchronization signals with an accuracy level of 20 ns.

2.3 BeiDou and GPS frequencies and wavelengths

The signal of the BeiDou satellites constellation will be transmitted at three frequencies, B1, B2 and B3, and includes a quadrature phase shift keying modulation. The BeiDou signals are based on Code Division Multiple Access. The GPS satellites constellation transmits at L1, L2 and L5 frequencies and the signals include the same QPSK modulation as BeiDou. The signals of GPS are based also on the CDMA. There is no overlap between GPS frequencies and BeiDou central frequencies. But there is some overlap due to the bandwidth of the individual signals.

Table 2: Central frequencies and wavelengths of GPS and BeiDou signals

	Name	Frequency [MHz]	Wavelength [cm]
BeiDou	B1	1561.098	19.20
	B2	1207.140	24.83
	B3	1268.520	23.63
GPS	L1	1575.42	19.03
	L2	1227.60	24.42
	L5	1176.45	25.48

2.4 Time References in GPS and BeiDou

Today BeiDou, GPS, GLONASS and Galileo navigation systems strongly depend on the time of arrival of radio signals transmitted by satellites at the receiver. Each system has its own time reference. The space, control and user segments are time synchronized. Most of the GNSS-based applications are based on this GNSS time reference except GLONASS (J. Sanz Subirana, 2011). All GNSS time scales differ at the ns-level from their corresponding UTC time.

GPS Time is a continuous atomic time scale and is defined by the GPS Control segment. It is based on the difference of a set of atomic clocks at the GPS ground control stations and atomic clocks in the satellites. GPS time is synchronized with UTC (Coordinated

Universal Time) and TAI (International Atomic Time) time, but GPS time is not corrected to match the rotation of the Earth, so it does not contain leap seconds or other corrections that are periodically added to UTC. GPS time started at 0:00:00 UTC time of January 6th 1980. At that epoch, the difference TAI −UTC was 19 seconds. Currently GPS-time differs from UTC by 16 seconds. GPS time is theoretically accurate to about 14 nanoseconds. However, most receivers references operate more cheap clocks and are therefore only accurate to 100 nanoseconds (http://en.wikipedia.org/wiki/Global_Positioning_System).

The time reference for BeiDou is the BeiDou Atomic Time. The BeiDou system time is an internal and continuous time scale without leap seconds. BeiDou Time started at 0^h UTC on January 1st, 2006 of UTC. BeiDou time is counted in weeks and seconds of weeks and is synchronized with UTC within 100 ns. The BeiDou time is counted within a week in seconds from 0 to 604799. BeiDou time is constructed by a clock ensemble at the Master Control station.

GPS time differs from BeiDou time by 14 seconds (i.e. GPS time = BeiDou time+ 14s). In addition to 14 seconds there are small variations at the few ns-level as shown in Figure1.

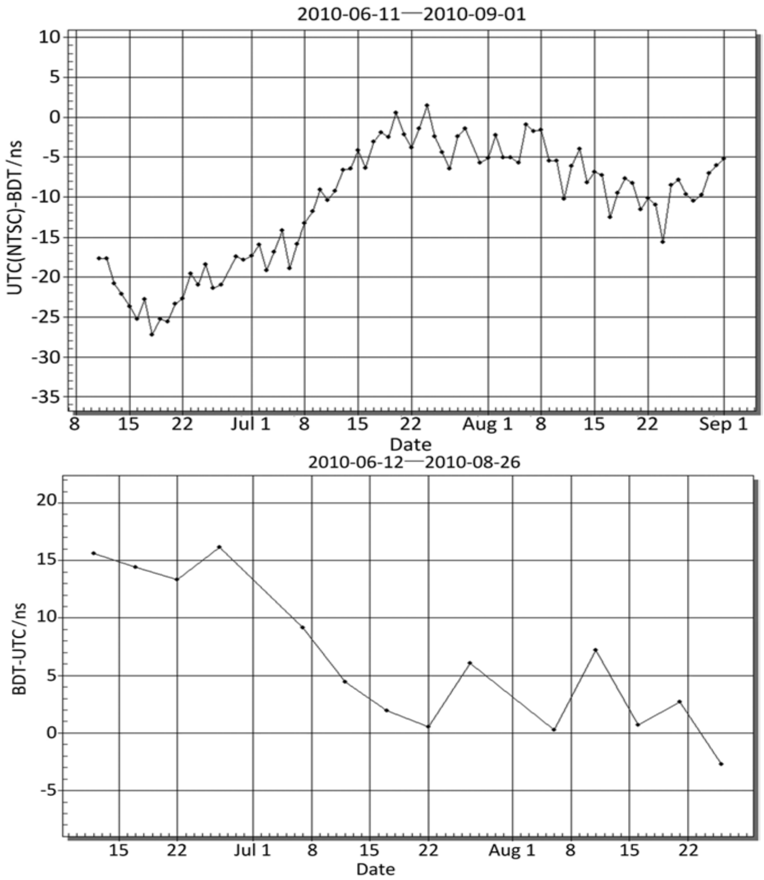


Figure 1: The plot on top shows the time difference between BDT and UTC obtained by GPS. The bottom plot shows the time offset between BDT and UTC calculated by UTC. (Chunhao Han, 2011)

2.5 GPS and BeiDou reference coordinate systems

The GPS satellite system bases on the coordinate system “World Geodetic System 1984“(WGS84). WGS 84 is an earth-centered and earth-fixed terrestrial reference system. WGS84 is associated with an earth ellipsoid and is aligned to ITRF2008 at the epoch of 2005.0. The BeiDou satellite system bases on the “China Geodetic Coordinate System 2000” (CGCS2000). This reference system has been adopted as the new national geodetic system since July 2008. This system is a geocentric coordinate system and there is only a small different between CGCS2000 and WGS84. The CGCS2000 is aligned to ITRF97 at the epoch of 2000.0.

2.6 International GNSS Service

The International GNSS Service (IGS) products base on a GNSS network of over 380 GNSS monitoring stations from more than 200 worldwide Agencies in 80 countries. IGS provides GNSS orbits products, tracking satellite data, analyzing data and other high-quality GNSS data and data products online. IGS was founded in 1994 by the International Association of Geodesy (IAG). In 1994 IGS only consisted of a global network with about 20 GPS station. At first, IGS provided the satellite data of two GNSS constellations, the GPS and the Russian GLONASS. In 2003 GLONASS was fully incorporated into IGS. Currently the IGS includes the data of other three GNSS constellations Galileo, BeiDou and Japanese QZSS. Approximately 100 IGS stations are equipped with combined multiple GNSS receivers and transmit their tracking data in near real time.

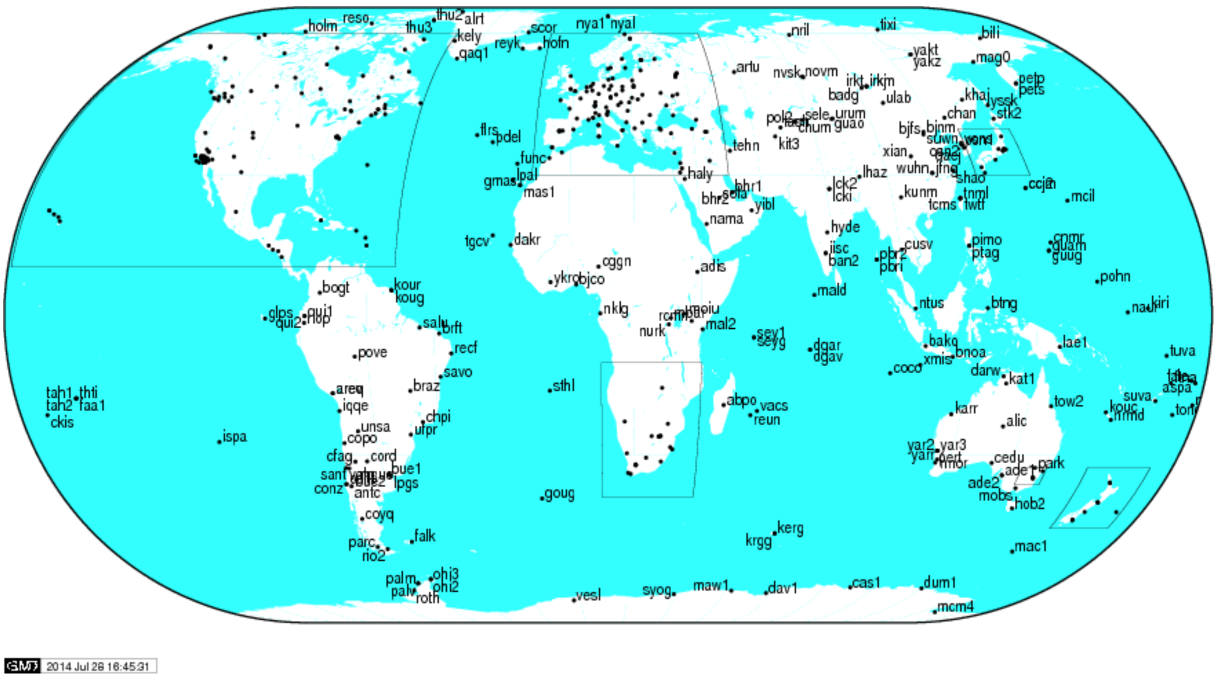


Figure 2: The GNSS tracking network (as of July 2014)

2.7 Mgex

MGEX is the abbreviation for Multi–GNSS Experiment. This project is a global initiative of multi– GNSS and is established by the International GNSS Service (IGS). Nowadays new GNSS, namely BeiDou, Galileo, QZSS and IRNSS have become available. The U.S GPS and Russia's GLONASS have already been modernized, the new generation of satellites (GPS III) will continue to launch, which provides additional signals to deliver better accuracy, reliability and availability of positioning, navigation and time services (Weber, 2012). The IGS has a global network of GNSS monitoring stations and gets support from more than 200 worldwide individual institutions. IGS plans a multi-GNSS observation network tracking these five GNSS systems, in order to establish the connection between all GNSS systems for the high – precision GNSS positioning. It ensures the expansion of tracking capabilities, and it supports in- depth analysis of new signals and equipment. The capabilities of GNSS data analysis will be improved. Almost 90 GNSS permanent stations participate in the IGS MGEX project, most stations can track, collate and analyze many (more than 3) GNSS signals including GPS as well as other new GNSS constellation except IRNSS. Among others, the institutions France's Centre National d'Etudes Spatiales (CNES), Deutsches Geoforschungszentrum, Bundesamt für Kartographie und Geodäsie (BKG) participate substantially in monitoring and contributing the MGEX stations. The MGEX observation data are hosted by data centers of many different GNSS organizations in new RINEX 3 standard format for users. The data centers at the Crustal Dynamics Data Information System (CDDIS), Institut Geographique National (IGN), and BKG archive and provide the observation data. Because of the structure of MGEX the network hosts many receivers of different types and antennas. Only geodetic-type receivers are used as they are capable of receiving the pseudo range and carrier phase observations. These receivers could track GPS or GPS+GLONASS signals and the signals of Galileo, BeiDou and also two frequencies of QZSS. Until now some MGEX GNSS experiments are performed.

From the CDDIS website precise orbit and clock products for GPS, Galileo and QZSS can be obtained, while the precise orbit and clock products for BeiDou and IRNSS are not available yet. For the MGEX project the broadcast ephemeris files of all GNSS constellations (except BeidDou and IRNSS) are generated. These data are used for the analysis of satellites visibility, quality control of observation data and relative navigation.

The aim of MGEX is to establish a global tracking network for all signals available from all GNSS satellites in parallel to the regular IGS operation.

Chapter 3

3 GNSS static positioning

This investigation performs GNSS Double Difference carrier phase positioning and PPP positioning with data from the GPS and BeiDou constellations.

3.1 Double Difference Approach

The pseudo range measurement is the distance measurement between satellite and receiver; it is used for estimating receiver coordinates and receiver clock bias. Unfortunately, there are several error terms in the measurements which have to be regarded for reaching the high precision positioning (Wieser, 2012). Until now the differential GNSS technique has been the dominant operational method for the highly-precise positioning in the geospatial community. We can perform Single Differences if two receivers and one satellite are used. Double Difference observables base on range measurement difference between two GNSS receivers and two satellites. Normally there are a rover receiver and a base receiver. At first, in differential positioning processing we can perform single differences to eliminate the satellite clock offset. The clock offset of the receiver cancel in Double Differences. The relative coordinates between two receivers is determined. In case the coordinates of the base receiver are known, the coordinates of the rover receiver can be determined. If the receivers are relatively close to each other, differential positioning can also eliminate a number of the further error terms. As we consider, most error terms from the mathematical model are cancelled or reduced by using difference positioning.

The error terms in the observation equation will be eliminated for short baselines. For longer baselines relative ionospheric- and tropospheric errors are usually estimated or mitigated by the ionospheric –free linear combination. Normally, in GNSS Double Difference processing we can achieve the Millimeter-level positioning accuracy.

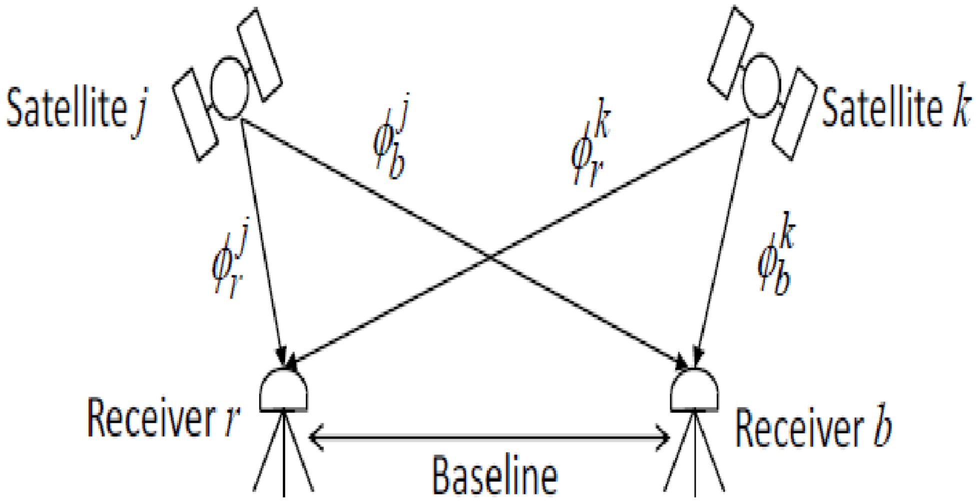


Figure 3: GNSS Double Difference approach

The GNSS observation equation for code measurements reads

$$Pi = \rho + c(dtr - dts) + T + Iono + b + \mathcal{E}p \qquad (1)$$

while for GNSS phase measurements equation(2) holds

$$Li = \rho + c(dtr - dts) + T - Iono + \lambda iNi + b + \mathcal{E}i \qquad (2)$$

where i equals the frequency index 1 and 2, Pi and Li denotes raw code and phase observations, ρ is the geometric distance between satellite and receiver, c is the speed of light in vacuum, dtr is the receiver clock error, dts is the satellite clock error, T is the tropospheric error, Iono is the ionospherice error, b denotes a sequence of error corrections including relativistic effects, earth tides and hardware delays , λi is the wavelength of the carrier Li, and lastly $\mathcal{E}p$ and $\mathcal{E}i$ are the noise, such as code/ phase noise, multipath errors.

We assume, that the observations of both receivers are taken at the same time and generate Double Difference observations.

$$\Delta_p = \Delta\rho + \Delta T + \Delta Iono + \Delta b + \Delta\mathcal{E}i \quad (3)$$

and

$$\Delta_L = \Delta\rho + \Delta T - \Delta Iono + \Delta\lambda iNi + \Delta b + \Delta\mathcal{E}i \quad (4)$$

The orbital and atmospheric errors are reduced and satellite and receiver clock errors are eliminated. This allows to fix the ambiguity term ΔN to an integer value for short baselines.

$$\Delta_L = \Delta\rho + \Delta\lambda iNi + \Delta\mathcal{E}i \quad (5)$$

3.2 Precise Point Positioning Approach

The Precise Point Positioning (PPP) is one of the evaluating GNSS technologies for precise positioning. This technology uses continuous dual -frequency phase and code observations. In PPP only observations of a single dual-frequency receiver are used for observation processing. The users are independent on observation data of other reference stations. On the other hand, there are several disadvantages of PPP like slow convergence time for the ambiguity float solution, currently no user equipment supports real time algorithms, real-time satellite orbit and clock data streams and uncertain coordinate datum(Rizos, 2012) . The long observation time currently restricts the processing of real- time PPP processing, it is still sufficient for static PPP processing though. The PPP positioning is tied to the reference frame of orbits and therefore to the International Terrestrial Reference Frame. As the accuracy of broadcast orbit and satellite clock corrections is about 100 cm or 5 ns (IGS 2013) more precise GNSS satellite orbit and satellite clock corrections are necessary for processing with PPP. We always use the precise orbit and clock products for GNSS positioning which we obtain from the Analysis Centers (AC) of the International GNSS Service (IGS). Additionally for more precise result we have to take into account also other corrections, such as phase wind-up corrections, satellite antenna phase centre corrections, solid earth tide corrections and ocean loading corrections. Thereby we expect results of carrier phase based positioning with PPP in the range of a few cm. Users can perform PPP in two ways. Either they upload the observation file to an online free service and will get back the positioning solution for the position of their station. Or they make use of a software like RTKlib, which is freely available to users to perform the GNSS positioning processing with PPP. The accuracy of a solution with PPP is dependent on the number of visible satellites. A lesser number of visible satellites is a problem for the accuracy of the GNSS positioning processing. Hence there are many problems in urban areas or mountain areas. Because of the new GLONASS, Galileo and BeiDou constellations IGS already has launched their new global multi GNSS project, the "the Multi-GNSS Experiment (MGEX) (see chapter 2.7)". This project will enhance the results of PPP processing.

3.3 Mathematical background of GNSS solution

The GNSS observation model was already presented in equation (1) and (2). The traditional PPP model makes use of ionospherefree code (P_{IF}) and phase (L_{IF}) observations to generate the float solution introducing precise orbit and clock corrections provided by the IGS and satellites.

$$P_{IF} = \alpha_{IF}P_1 + \beta_{IF}P_2 \qquad (6)$$

and

$$L_{IF} = \alpha_{IF}L_1 + \beta_{IF}L_2 \qquad (7)$$

where α_{IF} and β_{IF} are $(f_1)^2 / ((f_1)^2-(f_2)^2)$ and $-(f_2)^2 / ((f_1)^2-(f_2)^2)$, respectively.

In this investigation the inter system bias (i.e. b) is also estimated.

3.4 Least squares Adjustment

The Least squares adjustment employs the following measurement equation

$$y = H(x) + v \qquad (8)$$

x is the state vector of the parameter to be estimated (e.g. time, position and velocity). v is referred to as measurement noise with variance V (v) =R. y is the state vector of observations (e.g. GNSS pseudoranges); H(x) is a design matrix which consists of partial derivations of observations. It relates the measurements to the states.

$$y = H(x_o) + \frac{\partial H(x)}{\partial x} * \delta x + v \qquad (9)$$

$$y - H(x_o) = \frac{\partial H(x)}{\partial x} * \delta x + v \qquad (10)$$

$$\delta y = H * \delta x + v \qquad (11)$$

x_o is the current estimation of vector x, δy is the correction and H is the measurement model.

$$\delta x = (H^T R^{-1} H)^{-1} H^T R^{-1} \delta y \qquad (12)$$

R is the covariance matrix of the measurement errors v.

$$\delta x = (H^T R^{-1} H + P_o)^{-1} H^T R^{-1} \delta y \qquad (13)$$

P_o is the covariance matrix reflecting the uncertainty of the a priori state information.

$$P = (H^T R^{-1} H + P_o)^{-1} \qquad (14)$$

P is the covariance matrix of the estimated parameters. These upper equations base on the least-squares method. The least squares method is an iterative method. The estimated parameters are iterated until the corrections are sufficiently minor.

3.5 Kalman Filter

The Kalmen filter algorithm is over 50 years old, and it is still a very important method for parameter estimation. The Kalman filter has been developed in the 1960s and it is used for the optimal linear, discrete time, finite dimensional time varying system of dynamic and static parameter estimations (Wang, J 2011). The method bases on using its output as an input for the next calculation cycle. The future values of parameters can be predicted as well. The Kalmen filter is an optimal recursive algorithm for data processing (Marchbeck, 1979)

The difference between least squares estimation and Kalman filtering is very small. It depends on how the two estimators obtain their a priori information. The Least squares method obtains a priori information by occupying a known point. Kalman filtering uses the recent estimate of the state vector in order to create the prediction of the a priori information.

If traditional Kalman filter is used for position coordinate estimation, then we have to consider a simple linear equation.

$$y = H(x) + v \qquad (15)$$

Assuming a correct measurement model, we obtain some past estimated parameters und use it for this method. Prediction and update are two important steps for using Kalman Filtering estimation.

Prediction creates the state estimated vector at epoch k to epoch k+1, its covariance matrix bases on the estimate for the epoch k.

$$x_{k+1} = \Phi_{k,k+1} x_k \qquad (16)$$

Φ is the transition matrix and it usually defines the relationship between the preceding and current epoch. x is the estimated parameter.

$$P_{k+1=} \Phi_{k,k+1} P_k \Phi_{k,k+1}^T + Q_{k+1} \qquad (17)$$

Q is the process white noise covariance matrix, it causes the uncertainty in the assumptions for deriving the transformation matrix Φ.

The next step is updating the equation. In Kalman filtering, some past estimates are used. The equation is written as

$$\delta\bar{x}_k = P_{k-1} H_k^T (H_k P_{k-1} H_k^T + R_k)^{-1} \delta y_k \qquad (18)$$

k shows the k–th epoch, k-1 is the estimate at (k-1)-th epoch and it bases on measurements up to epoch k-1 like a priori information (Petovello,M)

$$K_k = P_{k-1} H_k^T (H_k P_{k-1} H_k^T + R_k)^{-1} \qquad (19)$$

K_k is the Kalman gain matrix which represents the weight of the actual measurement compared the accuracy of current parameters. R_k is the covariance matrix of the measurements.

Finally, the covariance matrix of the state vector is updated.

$$P_k = (I - K_k H_k) P_{k-1} \qquad (20)$$

P_k bases on the measurements up to epoch k.

Chapter 4

4 Applied GNSS processing steps

This chapter introduces the details about the different input data sets and several preparation steps for GNSS static post processing. The GNSS software packages e.g. RTKLIB, EOPS.P.V2, BERNESE and GAMIT/ GLOBK can handle these tasks and they are appropriate for precise GNSS post processing-based PPP and Double Difference applications. In this investigation we use the RTKLIB version 2.4.2 for GNSS processing.

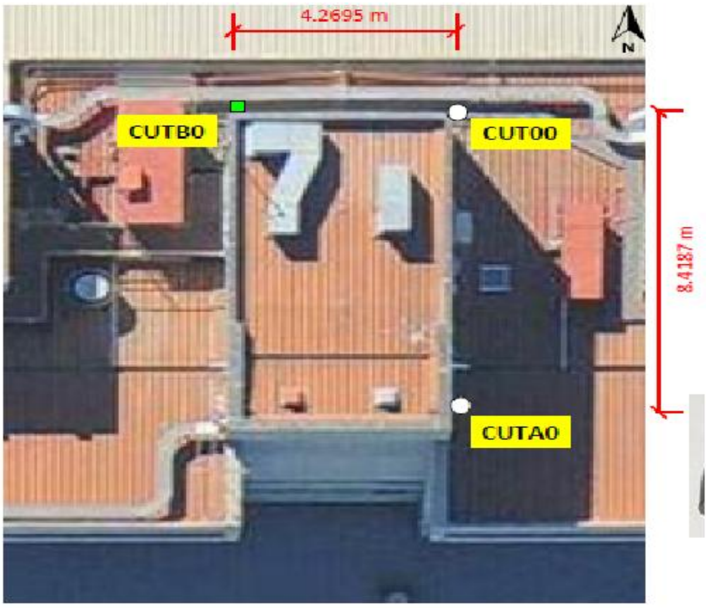
The following IGS Mgex stations have been chosen: Ground station CUT0 at the Curtin University in Australia and ground station JFNG in China. There are three Receivers connected to two antennas at station CUT0 for Double Difference processing in static mode which can track all GNSS satellite (GPS+GLO+GAL+CMP+QZSS) constellations. All stations provide observation data in the new RINEX (version 3) format. For PPP processing GNSS measurements of both stations are used in this investigation.

4.1 **Open source program package for GNSS: RTKLIB**

RTKLIB is an open source software for standard and precise positioning with GNSS. This software supports standard and precise positioning algorithms with GPS, GLONASS, Galileo, QZSS, BeiDou and SBAS. RTKLIB supports various GNSS positioning methods for real time and post static processing like Single Point Positioning, DGNSS, Kinematic, Static, Moving–Baseline, Fixed, PPP-Kinematic, PPP-Static and PPP-Fixed. RTKLIB has the ability to process many GNSS RINEX versions up to the new standard RINEX3. RINEX is a standard format for GNSS measurements to be further and analyzed in post-processing mode which is generated in the receiver.

4.2 Station CUT0 Receiver Setup

The station CUT0 is located in Bentley Campus at the Curtin University in Australia. This GNSS ground station consists of three IGS stations CUTB0, CUT00 and CUTA0. All three stations are also part of the APREF (Asia-Pacific Reference Frame) network. This station provides continuous data streams to the IGS and the data sets are available for GNSS user. The distance between these two antennas is about 8.5 meters. Three high quality geodetic type receivers (Trimble NetR9, Septentrio PolaRx4 PRO, and Javad Delta Q) connected to the antenna through a signal splitter. These receivers can track multi-frequency and multi- GNSS system data. The observation data sets are collected to support the IGS MGEX project. The receiver CUT0 (Trimble NetR9) is used as the main tracking receiver for antenna CUT00, while the other receivers (CUT1, Septentrio, CUT2 Trimble NetR9 and CUT3, Javad) provide a backup and can be used for research purposes. A receiver Trimble NetR9 is used as the main tracking receiver for antenna CUTA0, other receivers are CUTA (Trimble), CUAI (Septentrio) and CUAA (Javad) (Curtin GNSS receivers setup, GNSS research Centre Curtin university, 2012 March).



ECEF COORDINATES (METRES)

CUT00	-2364337.2971	4870285.5845	-3360809.8189
CUTA0	-2364335.2762	4870281.4185	-3360816.8489
CUTB0	-2364333.3776	4870287.2704	-3360809.6623

DATUM: IGS08
EPOCH: 2012-03-22 0:00:00

Figure 4: Location of station CUT00, CUTA0 and CUTB0

4.3 Details of the GNSS processing

1) Software used: RTKLIB version 2.4.2

2) Stations and equipment: IGS station CUTA0 (receiver CUAA) and CUT00 (CUT3) reside at the GNSS research centre at the Curtin University of Perth in Australia, Curtin University provides the continuous MGEX data to IGS. (http://gnss.curtin.edu.au/research/igs-mgex/index.cfm).

3) Positioning Mode:

1) Static Double Difference: basically, a baseline between two IGS Mgex stations is generated. The observation files of both stations and the navigation files are used for processing.

2) PPP static: SP3 files, CLK files, ERP files, ATX files and BLQ files are used in order to eliminate the error terms.

4) Downloading the dataset for processing

Primary input data sets are observation files. These files are based on the code and carrier observations from the GNSS ground observation stations. The measurements of the GNSS stations are available as 24 hours daily observation files converted to the newest receiver independent exchange format (RINEX 3).

I. Mode: Double Difference

1. Observation files: The observation data sets of the GNSS session March, 19th, 2014 are used. All data sets of stations CUAA and CUT3 were downloaded from the website: **http://saegnss2.curtin.edu/ldc/rinex3/daily/2014/**

2. Navigation files: The navigation datasets of the daily session March, 19th, 2014 (DOY 078, GPS week 17843) were downloaded from website: **ftp://cddis.gsfc.nasa.gov/pub/gps/data/campaign/mgex/daily/rinex3/2014.** The format rinex3 is required for GNSS processing with BeiDou and GPS.

II. Mode: PPP static

1. Observation files: The observation data sets of the GNSS sessions March, 11th and March, 19th, 2014are used. All data sets of stations JFNG and

CUTA were downloaded from the website: **http://saegnss2.curtin.edu/ldc/rinex3/daily/2014/**

2. SP3 files: download of the sp3 file for daily session on March, 11th and March, 19th (DOY: 070 , GPS week 17832 and DOY 078, GPS week 17843) from IGS website: **http://igscb.jpl.nasa.gov/igscb/product/**

3. CLK files: GPS and BeiDou satellite and receiver clock correction files at 30 second intervals were for downloaded from the CDDIS website: **ftp://cddis.gsfc.nasa.gov/pub/gps/products/**

4. ERP files: GNSS ERP (pole, UT1-UTC) solution. Download of the erp weekly files from the same website as for the sp3 files.
http://igscb.jpl.nasa.gov/igscb/product/

5. ATX files: Use of igs08_1771.atx format for Satellite Antenna PCV file and Receiver Antenna PCV file.
http://igscb.jpl.nasa.gov/igscb/station/general/

6. BLQ files: Ocean Loading BLQ format. This file contains the ocean tides coefficients. I could be obtained from **http://holt.oso.chalmers.se/.** The coordinates of station CUAA are required. The following settings for obtaining the BLQ format were required.

(1) Ocean tide model: **EOT11a**

(2) Type of loading: **vertical and horizontal displacements**

(3) Output format: **BLQ (normal)**

(4) Reference stations: **CUAA** -2364335.2762 4870281.4185 -3360816.8489

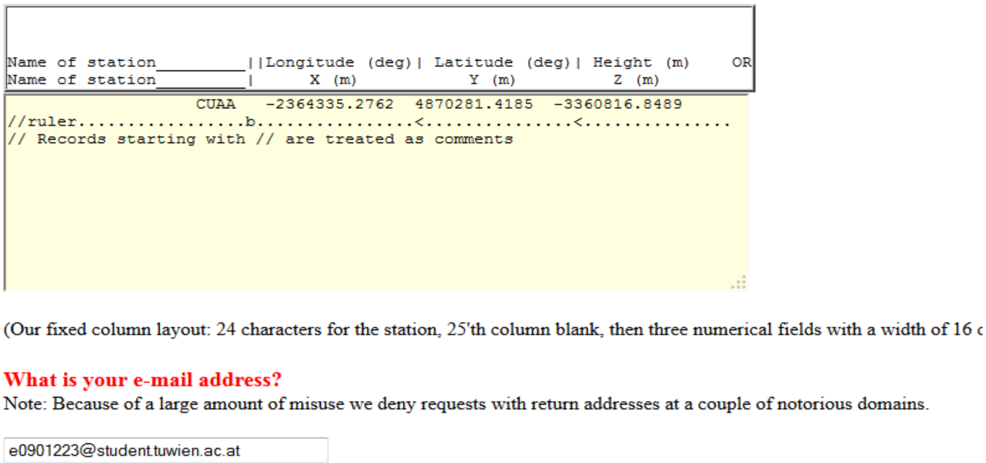


Figure 5: BLQ format from website http://holt.oso.chalmers.se/loading/

5) Settings for processing in RTKLIB

For mode: static

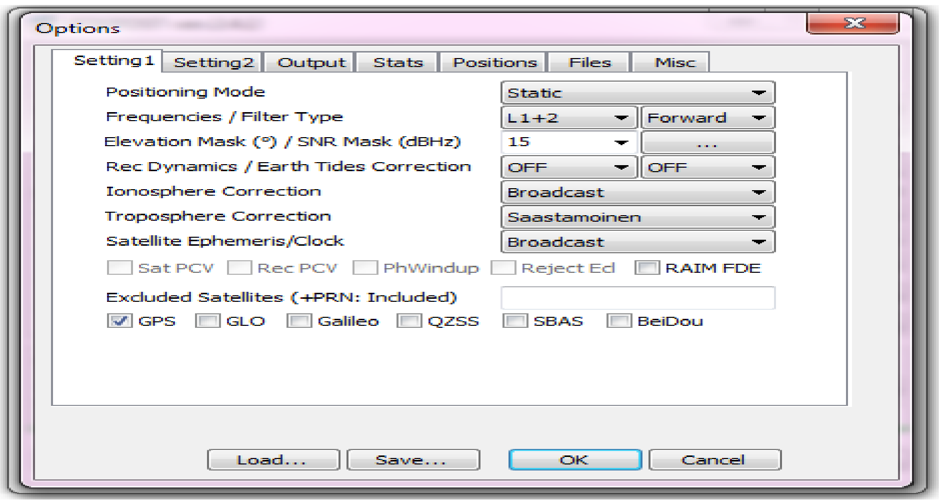


Figure 6: Setting for mode: static

For mode: PPP static

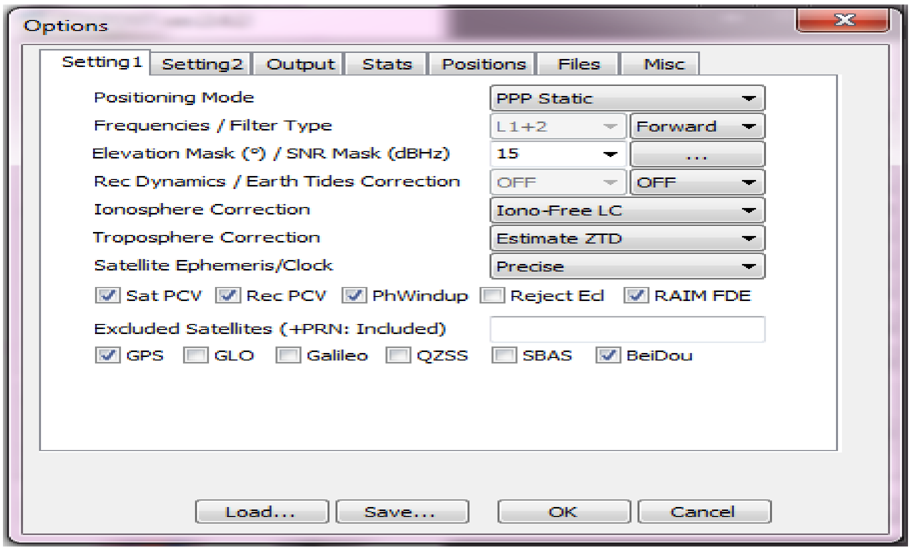


Figure 7: Setting for Mode: PPP static

For the baseline mode raw L1 and L2 observations are used, while the PPP processing utilizes the ionosphere-free linear combination.

4.4 AUSLIG's Online GPS Processing Service – AUSPOS

To investigate the positioning accuracy reference coordinates have to be established in advance. There are some free web-based positioning services such as OPUS, SCOUT, CSRS-PPP and AUSPOS. AUSPOS is one of the online free positioning services which ensure GNSS users the possibility to submit GPS global network data for calculating positions highly accurate anywhere in the world. This service bases on the Geocentric Datum of Australia (GDA) and ITRF and it supports GNSS static and dual frequency data. Some surveying and engineering methods as DGPS and GPS reference networks are used in AUSPOS, and this ensures the determination of long GPS baselines between two stations, establishment of geodetic connections to IGS and ARGN stations and performing GPS network quality control. The first step for using the service is to gather information about the antenna type. It is required to submit an email address and RINEX data. A number of the closest IGS reference stations establish a regional network and the double difference method is used for calculating the best set of coordinates. Then the remaining IGS stations are fixed for processing. Users send their observation data, usually in RINEX version2 format, to AUSPOS. The estimated coordinates are obtained in an email or can be picked from the AUSPOS anonymous ftp server.

Chapter 5

5 Site positioning

This chapter describes the results of the data computations with various GNSS processing methods and observation data of the different GNSS constellations. The GPS-only, BeiDou-only and the combined GPS & BeiDou observations were processed in baseline and the PPP method. Double Differencing is currently the primary method used for positioning. The PPP method is the secondary processing method in this thesis. The investigated examples are based on 24 hours daily observations of IGS station CUTA0 (receiver CUTA). Obtaining the precise orbit and clock corrections for 19th of March 2014 for BeiDou is an important prerequisite for PPP processing. The accuracy of station positioning and the standard deviation of coordinates and other parameters will be evaluated and analyzed.

5.1 Results of the Double Difference approach

When performing relative positioning the distance vector from any receiver to the base station is called a “base line”. The static Double Difference processing bases on 24 hours observations acquired at the base station CUT00 (receiver CUT3) and the rover station CUTA0 (receiver CUAA) from the APREF network at the Curtin University in Australia. The results were obtained with software RTKLIB. Aside from site coordinates the number of visible satellites and PDOP values for all three processings examples were subject to our analyses.

L1 & L2 dual frequency data for GPS and B1 & B2 dual frequency data for BeiDou data, GPS week 1784 has been processed. The solution distinguishes observed coordinates for receiver CUAA from GPS-only, BeiDou-only and combined GPS & BeiDou observations.

The brdm (Broadcast navigation files) products, which are provided in form of RINEX navigation files, for DOY 078, GPS week 17843 were downloaded from the IGS Mgex website. GPS-only, BeiDou and combined GPS & BeiDou Double Difference processing has been carried out in order to analyze the positioning accuracy and the impact of adding BeiDou observations. For ground truth the position of both stations calculated by the AUSPOS online GPS processing system is used as reference position. The Ionospheric Broadcast model and the Saastamoinen troposphere model are chosen for processing. The integer ambiguity resolution strategy „Fix and Hold" has been chosen to estimate the integer ambiguities in Double Difference mode.

More details about the Double Difference processing are given in table3.

Table 3: processing details of Double Difference processing on March 19 2014

Description	24 hours daily processing
Date of observation	19th of March 2014
Used processing Method	Double Difference
Used GNSS satellite constellations	GPS-only, BeiDou-only and combined GPS and BeiDou
Base station	CUT00 (receiver CUT3)
Rover station	CUTA0 (receiver CUAA)
Length of Baseline	8.4 m
Reference base station coordinate (CUT3) on 19th March 2014	X: -2364335.371 Y: 4870281.438 Z: -3360816.749

The main focus lies on the assessment of the site coordinate. Fig.8 shows the time series of ground station CUTA0 (receiver CUAA) from GPS-only (blue line), BeiDou-only (red line) and combined GPS & BeiDou observations in East, North and Up component. The

Cyan line stands for the results of the processing of the combined GPS & BeiDou data. In the post processing, the solution type was set to the combined filter. The solutions have been processed twice with forward and backward filters for smoothing the solution in the three components.

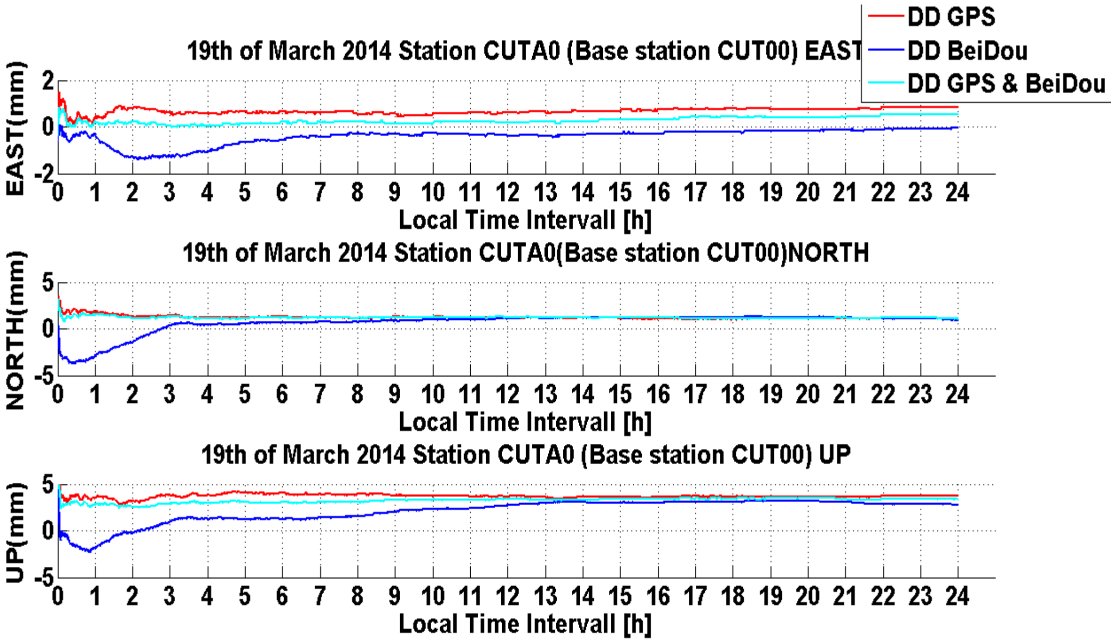


Figure 8: Calculated coordinates of station CUTA0. The red line is the result of using Double Difference of processing GPS observations, the blue line is the result of BeiDou observations, the cyan line shows the results of processing combined GPS & BeiDou observations.

A closer look at the calculated time series reveals that the positioning accuracy in the East component from combined GPS & BeiDou observations outperformed GPS-only and BeiDou-only for ground station CUTA0. It can be observed that the cyan line is close to the reference. In the North component the coordinate time series for GPS-only and combined GPS & BeiDou processing are at a quite similar level. The red line is overlapped by the cyan line from the GPS and BeiDou processing results. BeiDou-only shows worse results. In the Up component the blue line is closer to the zero line. The positioning accuracy from BeiDou-only observations outperformed GPS-only and combined GPS and BeiDou. But this might be an artifact due to an imperfect characterization of the antenna PCV. GPS-only and GPS & BeiDou solutions are more stable over the whole processing period. Obviously, the processing of combined GPS & BeiDou data provides the most stable result in all components. The time series of GPS-only looks similar to the result of the combined GPS & BeiDou. Fig.8 displays clearly that the BeiDou-only solution shows some jumps in all components. The processing of BeiDou-only data varies stronger than the other two cases. Across Fig.8 the three colored lines approach the zero line after a few hours. The difference between all three methods in all components is less than 2 mm. In addition, the BeiDou observations provide only a slight impact on the enhancement of the positioning accuracy.

Table 4: The Bias and STD of all three baseline processings methods on March 19 2014

Station CUAA on 19th March 2014		GPS-only (mm)	BeiDou-only (mm)	GPS & BeiDou (mm)
MEAN	East	1	-0,5	0.5
	North	1	1	1
	Up	4	2	3
STD	East	0.1	0.3	0.1
	North	0.2	1.1	0.1
	Up	0.3	1.3	0.3

For statistics all 2880 epochs of the calculated solutions were used. The formal errors for the GPS-only Double Difference solution are at the 0.1mm level with a bias of up to 1mm in horizontal component and 4mm in the vertical component. The formal errors for the combined GPS & BeiDou data are at 0.1mm level with a bias of 1mm in the horizontal component and 0.3mm level with a bias of 3 mm in the vertical component. The statistics indicates that adding BeiDou observations provides a slight improvement for positioning. The BeiDou-only solution delivers coordinates with a quality of -1± 1mm, 1± 1mm and 2±1mm.

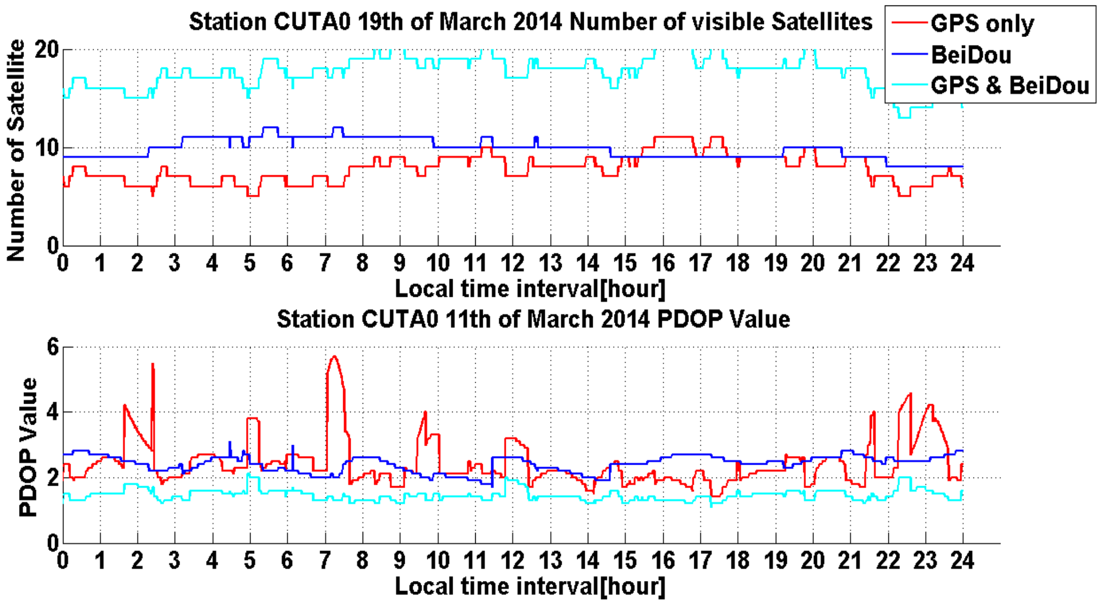


Figure 9 : Number of satellite visibility over 24 hours observation time and the corresponding PDOP on March 19 2014.

The accuracy, availability and reliability of Double Difference positioning is very dependent on the baseline length and number of visible satellites, which is often insufficient in urban areas and mountain areas. For each session, in addition to the positioning accuracy the number of used satellites was also shown on the graphic. Quite apart from these facts, the precision of the satellite-receiver geometry (PDOP) provides GNSS users the best initial and partial information of the expected positioning accuracy. Fig.9 shows the satellite visibility over 24 hours observation time and the PDOP values for all three processed cases. Most of the time it can be observed that processing combined GPS & BeiDou (cyan line) system data obtains the largest number of visible satellites(over 15 satellites). This improves the satellite signal availability and the positioning reliability. The difference of the number of visible satellites between BeiDou-only and GPS-only processing is very small. The number of visible satellites varies between 6 and 10. As seen from the other perspective, combining GPS and BeiDou satellites provides the best PDOP values with average PDOP value of 1,7. The average PDOP value for GPS-only is 2,8. The average PDOP value for BeiDou-only satellites is 2,9.

5.2 Results for positioning mode: PPP –static

For PPP processing the orbit and clock correction files, provided by ESA and GFZ, for GPS and BeiDou are downloaded from IGS data archives. The observation RINEX 3 data files acquired at the GNSS stations JFNG (China) and CUT0 (Australia) are used. GPS-only, BeiDou and combined GPS & BeiDou PPP processing has been carried out in order to analyze the positioning accuracy and the impact of adding BeiDou observations. For calculating the truth position of both ground stations again the AUSPOS online GPS processing system was used. Two different sessions and two different Mgex stations are used to verify the PPP solutions. For this data processing a 10° cut-off elevation angle is applied. Antenna PCV, phase wind up correction, earth rotation and solid earth tide correction models were also introduced. Elevation dependent weighting is applied according to $1/\sin(e)^2$, where e is the satellite elevation. In post processing the solution type was set to the combined filter. The solutions have been processed twice with forward and backward filters for smoothing the solution in East-North-Up directions.

Table 5: important details for the PPP processing on March 11 2014

Description	24 hours daily GNSS processing
Date of observation	11th of March 2014 and 19th of March 2014
Used processing Method	Precise Point Positioning (PPP)
GNSS satellite constellations	GPS-only , BeiDou-only and combined GPS and BeiDou
Base stations	CUTA0 (Receiver CUTA) and JFNG
Used IGS file NO.1	Precise orbit and clock correction
Used IGS file NO.2	ERP file
Used IGS file NO.3	ATX file
Used IGS file NO.4	BLQ file

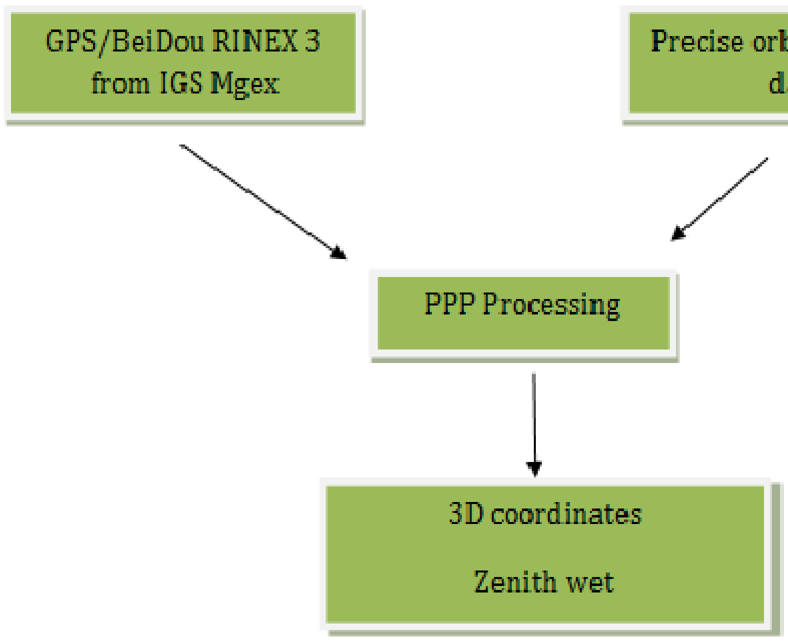


Figure 10: Principle of PPP processing for GPS and BeiDou investigation

5.2.1 March 11 at station CUTA0

In the first investigation a PPP positioning for station CUTA0 (Australia) has been performed. GNSS Observation data on March 11 2014 was chosen. This investigation also distinguishes between solutions using orbit and clock corrections produced by ESA and solutions produced by GFZ. A comparison of the results from different GNSS data sets were generated and analyzed.

Fig.11 displays the coordinate time series at station CUTA0 on the 11th of March 2014 in East, North and Up components for GPS only, BeiDou-only and GPS & BeiDou data processing. The utilized orbit and clock corrections were produced by ESA. Fig.12 shows the accompanying time series of the same day and same station by using corrections from GFZ. The cyan line stands for the results from combined GPS & BeiDou data. The red line stands for the results from GPS-only. The blue line stands for the BeiDou-only results.

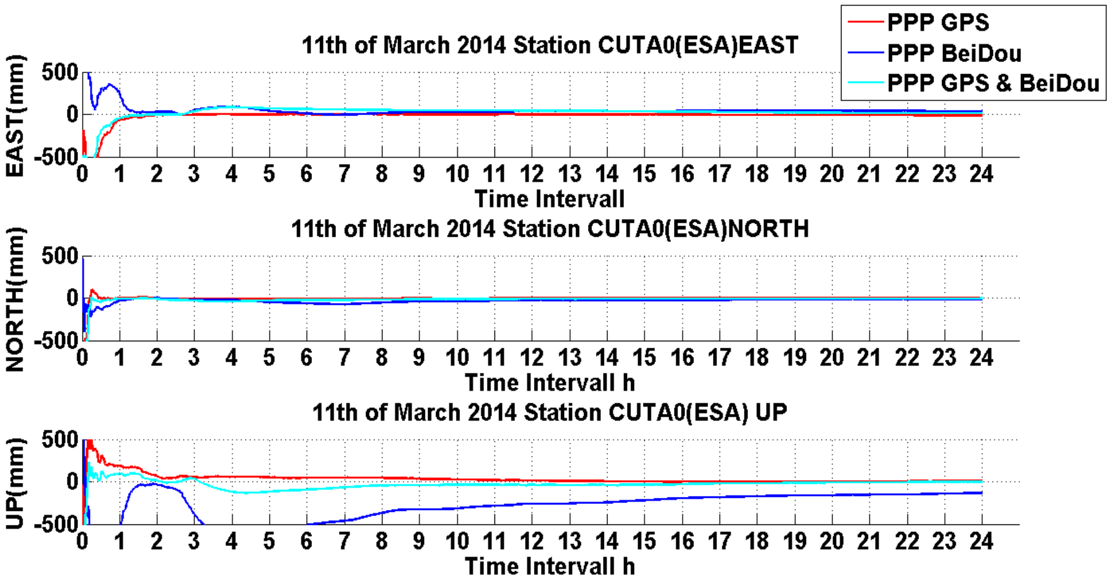


Figure 11: PPP positioning coordinate time series at station CUTA0 on 11 March 2014. The red line shows the results of GPS observation, the blue line is the results of BeiDou observations, the cyan line shows the results of processing combined GPS & BeiDou observations.

Across Fig.11 in East and in the North components all three processed cases are quite similar and show an accuracy level of about 10cm In the Up component it can be clearly observed that the BeiDou-only solution shows some jumps and provides unstable results. The cyan line and the red line approach to zero after 1 hour, the GPS-only processing provides the better and stable result though. The difference between GPS-only and combined GPS & BeiDou processings is very small. The BeiDou observation does not provide an improvement in positioning accuracy.

Table 6: The Bias, STD and RMS of PPP positioning at CUTA0 on 11 March 2014 are shown. The ESA corrections were used for this processing

		GPS-only [mm]	BeiDou-only [mm]	GPS & BeiDou [mm]
MEAN	East	-10	42	32
	North	-5	-31	-15
	Up	30	-291	-31
STD	East	28	44	31
	North	4	19	10
	Up	42	179	43
RMS	East	30	60	45
	North	7	36	18
	Up	51	341	53
3D Accuracy		35	297	60
3D RMS		60	348	71

Table 6 shows the bias values and standard deviation (sigma values) of the converged coordinate solutions for daily observations in the case of using the orbit and clock corrections produced by GFZ. There are 2880 epochs with 30 seconds interval. The first 30 minutes of PPP solutions were excluded from the statistics, overall 2820 epochs of PPP solutions were used for this determination. RMS values are also generated from the difference between the true coordinates and the estimated coordinates. The true coordinates of receiver CUTA0 are calculated by the Australian GNSS online service

AUSPOS. The standard deviation refers to the spread of the estimated positioning solutions from the mean estimated position.

The formal errors for the PPP GPS-only solution are at the 30mm level with a bias of 28mm in the East component, at the 7mm level with a bias of 4mm in the North component and at the 51mm level with a bias of 42mm in the Up component. In contrast, combined GPS & BeiDou PPP solutions are at the 45mm level with a bias of 31mm in the East component, at the 18mm level with a bias of 10mm in the North component and at the 53mm level with bias of up to 43mm in the Up component. The formal errors of the BeiDou-only processing is at the 60mm level with a bias of 44mm in the East component, at the 36mm level with a bias of 19mm in the North component and at the 341mm level with a bias of 179mm in the Up component. The GPS and BeiDou processing provides a 3D RMS of 71mm, whereas the GPS-only solution provides a smaller3D RMS of 60mm. BeiDou-only delivers a large 3D RMS of 348mm. Therefore adding BeiDou observations to GPS data does not improve the accuracy.

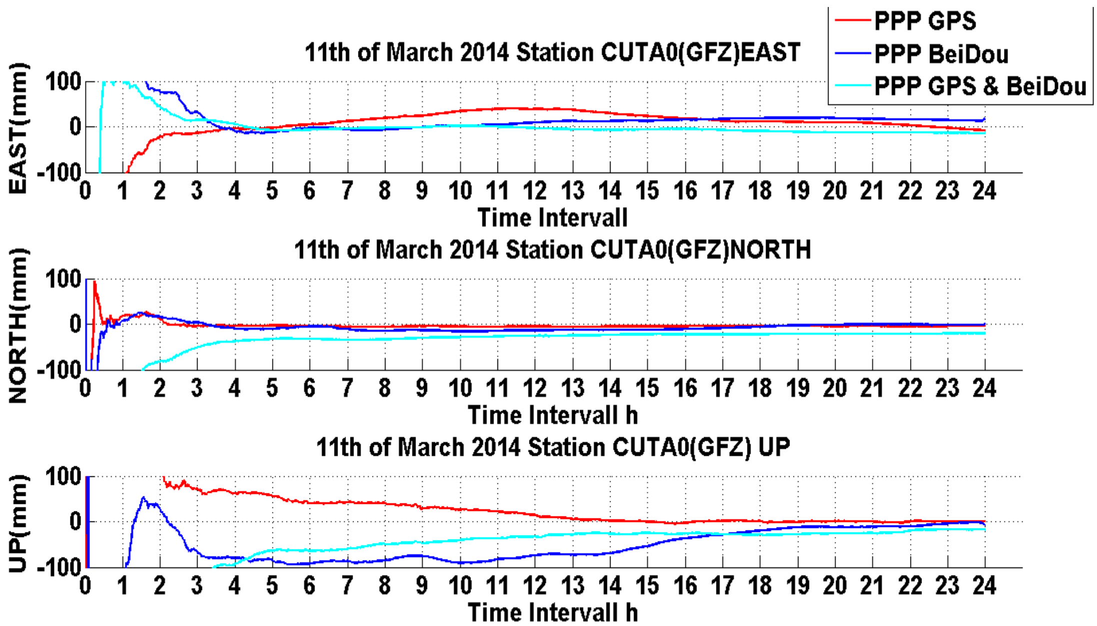


Figure 12: PPP positioning coordinate time series with the GFZ correction at station CUTA0 on 11 March 2014.

Fig.12 shows the results of PPP processing with the orbit and clock corrections produced by GFZ. Apparently, combined GPS & BeiDou data provides more unstable results than the GPS-only and BeiDou-only cases within the first hours. The cyan line approaches to zero after 3 hours. In the first 3 hours the combined GPS & BeiDou solution shows jumps in all components. In the East and in the North components the positioning accuracy for GPS-only and BeiDou-only processing is at a quite similar level and provides more stable results. The BeiDou-only and the combined GPS & BeiDou processings show worse and unstable results in the Up component.

Table 7: The Bias, STD and RMS of positioning using the GFZ corrections at CUTA0

		GPS-only [mm]	BeiDou-only [mm]	GPS & BeiDou [mm]
MEAN	East	5	19	1
	North	3	7	-37
	Up	34	54	80
STD	East	45	36	24
	North	6	9	40
	Up	62	46	235
RMS	East	45	40	24
	North	6	11	54
	Up	71	71	157
3D Accuracy		49	67	91
3D RMS		85	82	168

The formal errors for the PPP GPS-only solution are at the 45mm level with a bias of 5mm in the East component, at the 6mm level with a bias of 3mm in the North component and at the 62mm level with a bias of 34mm in the Up component. In contrast, the combined GPS & BeiDou PPP solutions are at the 24mm level with a bias of 1mm in the East component, at the 40mm level with a bias of -37mm in the North component and at the 235mm level with bias of up to 80mm in the Up component. The formal errors of the BeiDou-only processing are at the 36mm level with a bias of 19mm in the East component, at the 9mm level with a bias of 7mm in the North component and at the 46mm level with bias of up to 54mm in the Up component. The GPS & BeiDou processing provides a large3D RMS of 168mm, whereas the GPS-only solution provides a 3D RMS of 85mm. BeiDou-only delivers a 3D RMS of 82mm. Adding BeiDou observations to the processing with GPS does not improve the accuracy.

In general, the GFZ orbit and clock products for BeiDou seem to perform worse in the investigated period. Furthermore it shall be noted that the PPP standard deviations are of course much larger than STD obtained for the baseline approach though effects like atmosphere delay are not eliminated by differencing and ambiguities cannot be fixed to integer numbers.

5.2.1.1 Coordinate Convergence Analysis

Let's have a closer look at PPP convergence analysis. The PPP convergence period, the length of time required from a cold start to a decimeter level positional solution, is typically about 30 minutes under normal conditions and will be significantly longer before the position solution can converge to the few centimeter level (Bisnath and Gao, 2008). After a period of one hour the convergence behaviour in all investigated cases are at a quite similar level. The convergence time within the first four hours data sets is plotted and investigated. The first investigation bases on the orbit and clock corrections from ESA. Fig.13 shows the four-hours processing from GPS–only, BeiDou-only and GPS & BeiDou at station CUTA0. The convergence behavior of the PPP positioning solution is analyzed in order to see the impact of adding BeiDou observations to simultaneous PPP processing with GPS. As a result, the GPS & BeiDou processing improves the convergence time PPP static data processing for 50cm, 20cm, 10cm and 5cm in the horizontal and vertical components. Convergence times are provided in table 8.

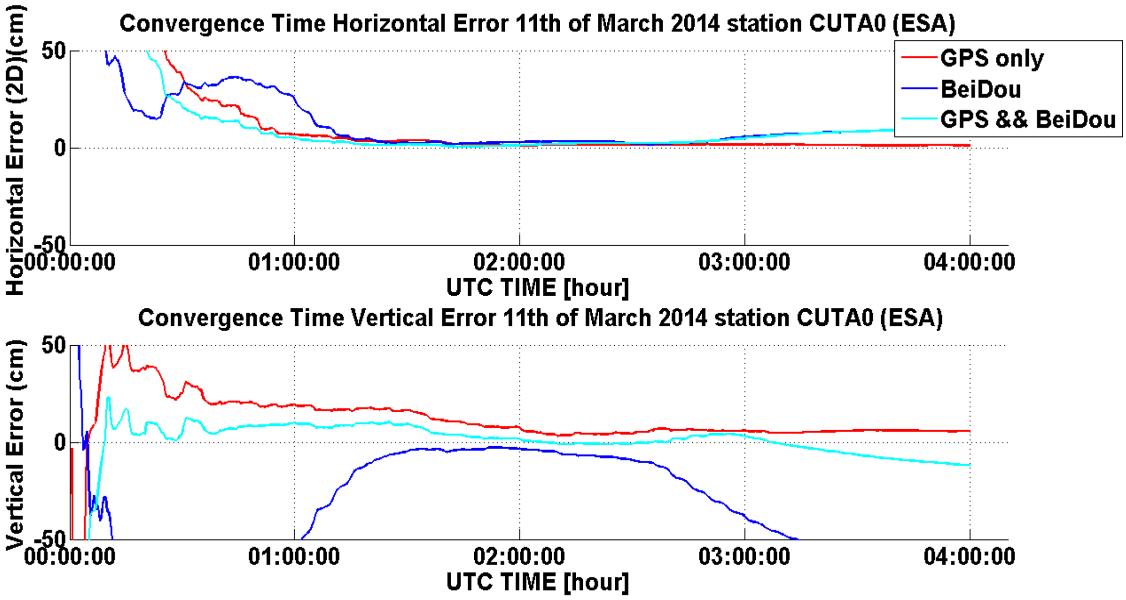


Figure 13: Convergence behavior for PPP by using the ESA corrections at station CUTA0

Table 8: The convergence time by using the ESA corrections for 5cm, 10cm, 20cm and 50cm at station CUTA0

	GPS-only [min]	BeiDou-only [min]	GPS & BeiDou [min]
Horizontal < 50cm	25.5	10.0	21.0
Horizontal < 20cm	45.5	17.0	30.5
Horizontal < 10cm	51.0	70.0	49.0
Horizontal < 5cm	72.0	75.0	60.0
Vertical < 50cm	4.5	61.5	5.5
Vertical < 20cm	49.0	74.5	11.0
Vertical < 10cm	105.5	81.0	21.5
Vertical < 5cm	124.5	90.0	24.5

The 2D GPS-only solution converges to 5cm, 10cm, 20cm and 50cm within 72, 51, 45.5 and 25.5 minutes. On the other hand, processing GPS & BeiDou data requires 60, 49, 30.5 and 21 minutes for the same quality, while BeiDou-only needs 75, 70, 17 and 10 minutes for these same accuracies. This is a slight improvement (about 15% less time) for 10cm and 5cm convergence in the case of GPS & BeiDou compared to GPS-only. However, other convergence criteria do not indicate any significant improvement. In the vertical component GPS-only solutions need 124.5, 105.5, 49 and 4.5 minutes to converge to 5cm, 10cm, 20cm and 50cm, whereas GPS & BeiDou solutions achieve the same quality after 24.5, 21.5, 11 and 5.5minutes. The BeiDou-only processing requires shows very irregular results and does not coverage at all. Obviously, the combined GPS & BeiDou processing has led to an improvement of about 80% in the case of 20, 10 and 5 cm convergence.

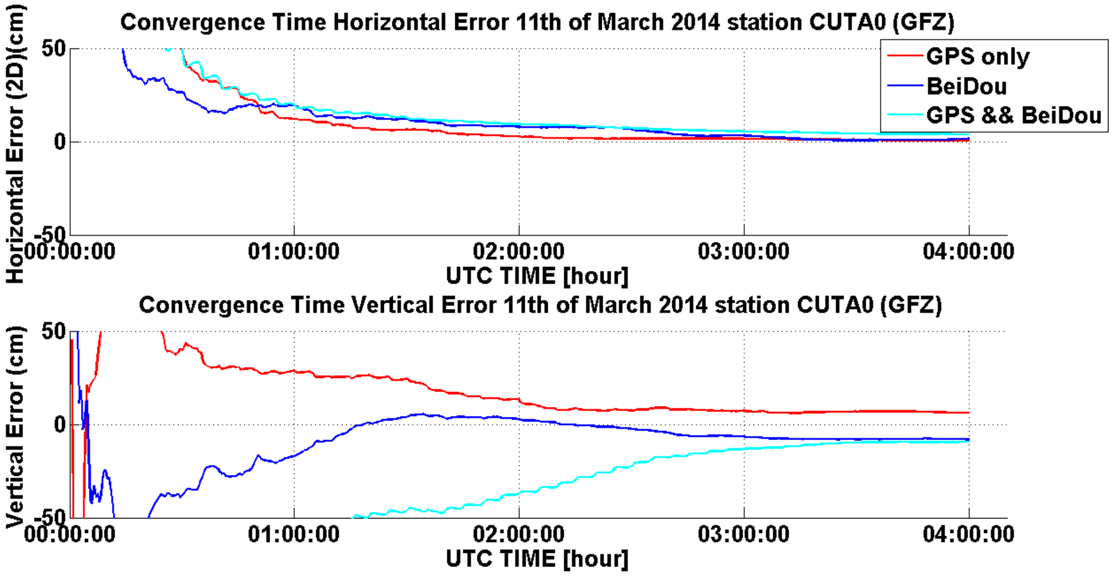


Figure 14 : Convergence behavior for PPP by using the GFZ corrections at station CUTA0

Fig.14 shows the convergence time investigation at the station CUTA0 based on the orbit and clock corrections from GFZ. The convergence behaviour differs considerably in the three processing scenarios. It can be observed that the BeiDou-only and GPS-only cases perform better for all convergence time categories. The convergence times are provided in table 9.

Table 9: The convergence time by using the GFZ corrections for 5cm, 10cm, 20cm and 50cm accuracy at station CUTA0

	GPS-only [min]	BeiDou-only [min]	GPS & BeiDou [min]
Horizontal <50cm	30.0	14.5	30.0
Horizontal <20cm	50.5	34.5	60.0
Horizontal <10cm	69.5	97.5	111.0
Horizontal <5cm	100.0	156.5	190.0
Vertical <50cm	24.5	21.5	79.5
Vertical <20cm	95.5	56.0	155.0
Vertical <10cm	125.0	65.5	206.0
Vertical <5cm		73.5	

BeiDou-only data converged to 50cm, 20cm accuracy after 14.5 and 34.5 minutes, GPS-only converged to 5cm, 10cm accuracy after 69.5 and 100 minutes, respectively, for the horizontal component. In the vertical component, BeiDou-only data converged to 50cm, 20cm, 10cm and 5cm accuracy after 21.5, 56, 65,5 and 73.5 minutes. GPS-only data required twice as much in time for that. It has been observed that combined GPS & BeiDou processing and GPS-only processing do not deliver coordinate deviations less than 5cm but BeiDou-only data converges after 73.4minutes. Again the BeiDou and GPS precise orbit and clock products seem to be inconsistent.

5.2.1.2 Number of visible satellites and PDOP

For the PPP processing with GPS-only, BeiDou-only and combined GPS & BeiDou data the elevation masks were set to 15 degrees. The PDOP value and the number of visible satellites were analyzed.

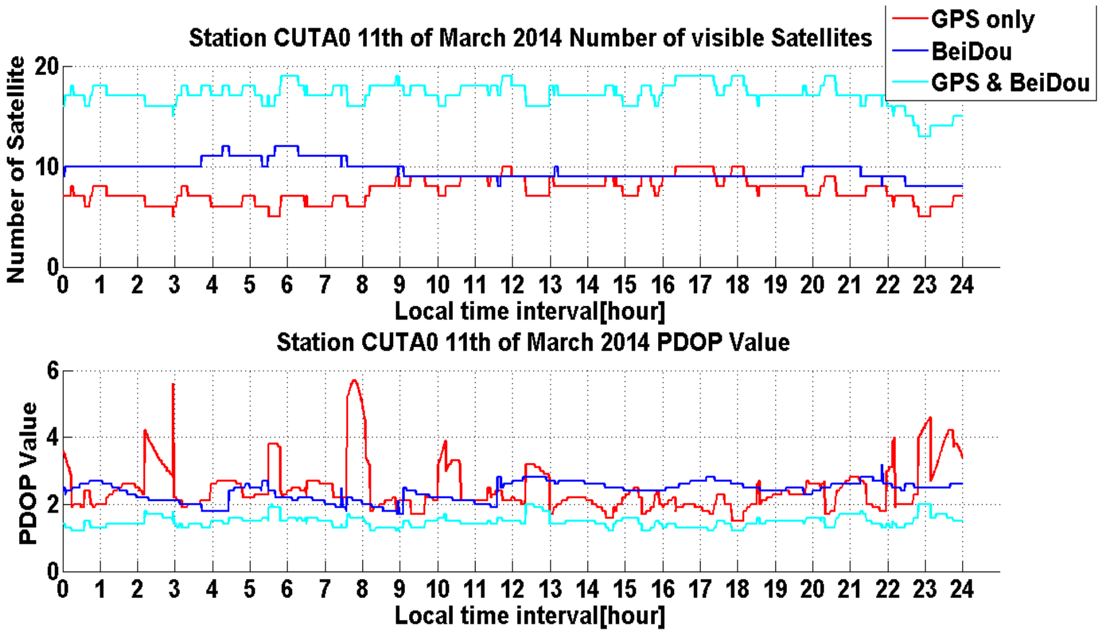


Figure 15: The number of visible satellites and PDOP values at station CUTA0 on 11 March 2014

During the 24 hours processing period the number of visible satellites has increased for the combined GPS & BeiDou constellation up to 20 satellites. The PDOP value improves significantly by adding BeiDou observations while GPS-only data experiences few periods with poor satellite geometry (PDOP>5).

5.2.2 March 19 2014 at station CUTA0

Secondly, data on 19th of March at station CUTA0 was chosen. The orbit and clock corrections are again obtained from ESA and GFZ. The aim of this second session is to confirm the results of the first PPP positioning. The positioning accuracy of GPS-only, BeiDou-only and GPS & BeiDou data computations is presented in Fig.16 and Fig.17.

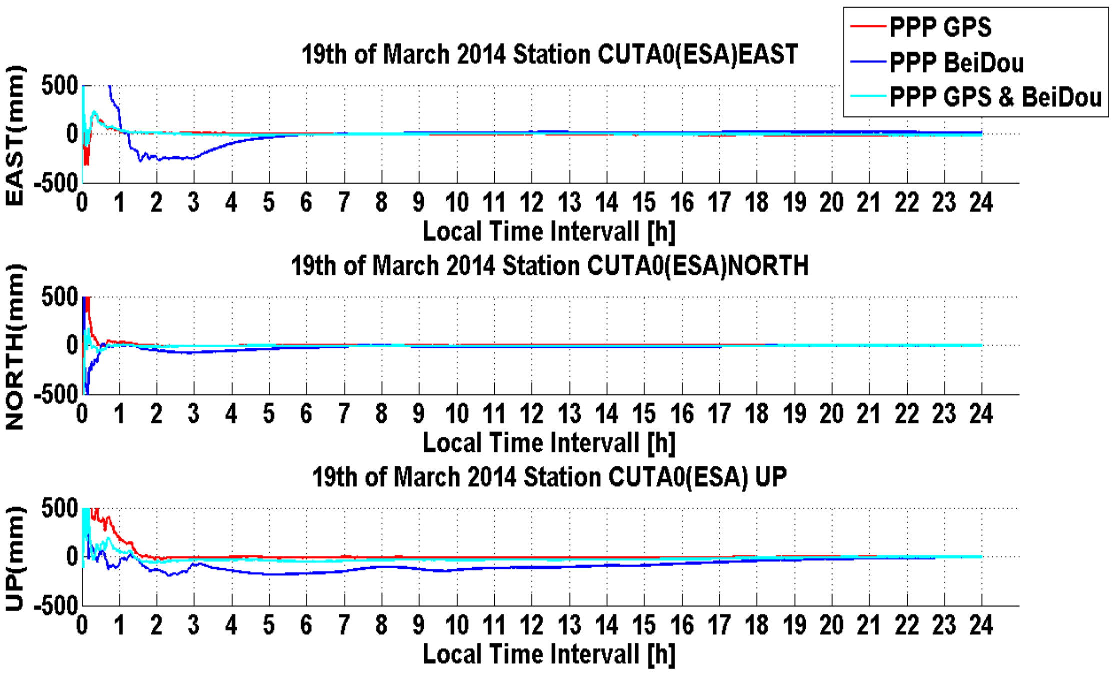


Figure 16: PPP positioning accuracy with ESA corrections at station CUTA0 on 19 March 2014. The red line shows the results of processing GPS observation, the blue line the results of processing BeiDou observations, and the cyan line shows the results of processing combined GPS & BeiDou observations.

Apparently, during the first two hours the combined GPS & BeiDou processing and GPS-only provide better and more stable results than BeiDou-only processing in all components. After two hours the deviation of the GPS-only and combined GPS & BeiDou solutions from ground truth are at a quite similar level. In general, the solutions from GPS-only and combined GPS & BeiDou data processing vary in a range of up to 10cm from the given true station coordinate. The BeiDou-only processing results are worse and more unstable than the other cases.

Table 10: The Bias, STD and RMS of positioning by using of ESA corrections

		GPS-only [mm]	BeiDou-only [mm]	GPS & BeiDou [mm]
MEAN	East	-5	-8	-2
	North	-2	-19	-7
	Up	2	-90	-23
STD	East	14	107	13
	North	7	20	4
	Up	51	55	27
RMS	East	14	106	13
	North	7	27	8
	Up	50	106	35
3D accuracy		22	119	32
3D RMS		53	152	38

When using the ESA orbit and clock corrections the formal errors for the PPP GPS-only solution are at the 14mm level with a bias -5mm in the East component, at the 7mm level with a bias of -2mm in the North component and at the 51mm level with bias of -2mm in the Up component. In contrast, the combined GPS & BeiDou PPP solution bias and standard deviation for the 24 hours data span is -2± 13mm, -7±4mm and -23±27mm for the East, North and Up components, respectively. The BeiDou-only processing solution accuracy is -8±107mm, -19±20mm and -90±55mm for East, North and Up components. The combined GPS & BeiDou coordinate solution provides a 3D accuracy of 32mm, whereas GPS-only solution provides a 3D accuracy of 22mm. The BeiDou-only solution delivers a 3D accuracy of 119mm. The combined GPS & BeiDou processing provides a 3D RMS of 38mm, whereas the GPS-only solution provides a 3D RMS of 53mm. BeiDou-only delivers a 3D large RMS of 152mm. The combined GPS & BeiDou processing helps to improve 3D RMS for this investigation. It can be observed that the accuracy for GPS-only and combined GPS & BeiDou processing outperformed the BeiDou-only processing. Adding BeiDou observations provides only a slight positive impact on the enhancement of positioning accuracy compared to GPS-only processing.

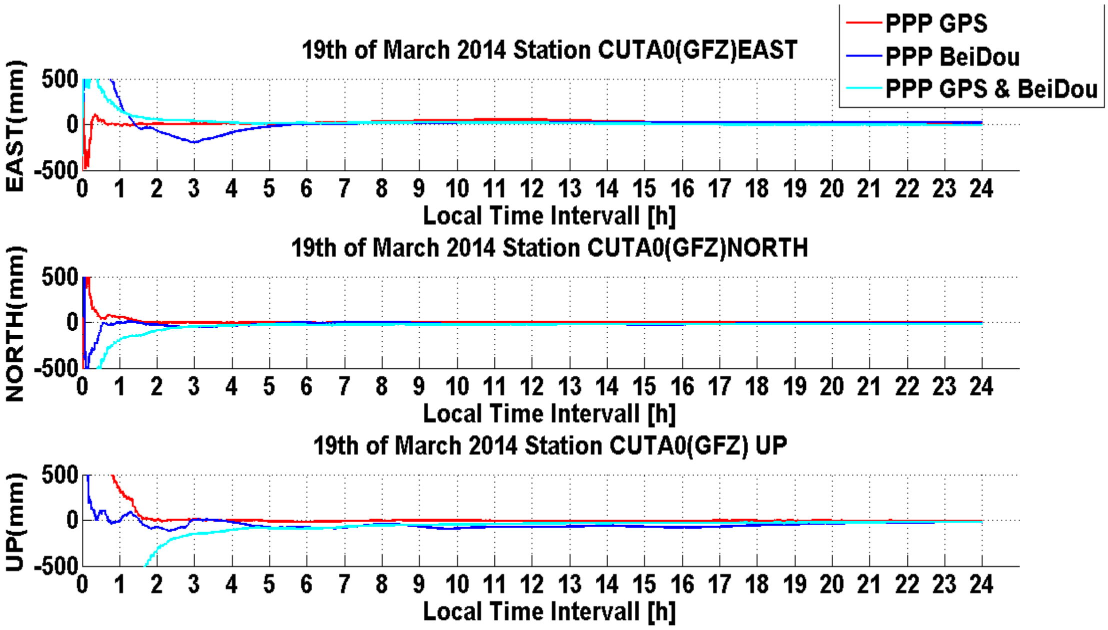


Figure 17: PPP positioning accuracy at station CUTA0 of the same session. The GFZ corrections were used

Fig.17 shows the coordinate time series of ground station CUTA0 obtained by PPP processing with orbit and clock corrections produced by GFZ. The processing performs for all three methods at a quite similar level in all components. It can be clearly observed that the cyan line overlaps the red and blue line except in the Up component. The BeiDou solution shows some jumps in the Up component. The GPS-only processing provides the most stable results over the processing period.

Table 11: The Bias, STD and RMS of positioning by using of the GFZ corrections at CUTA0 are shown

		GPS-only [mm]	BeiDou-only [mm]	GPS & BeiDou [mm]
MEAN	East	22	14	19
	North	-2	-16	-35
	Up	10	-54	-99
STD	East	16	93	41
	North	12	12	46
	Up	84	32	194
RMS	East	27	94	46
	North	12	20	58
	Up	84	63	219
3D accuracy		40	86	109
3D RMS		89	115	231

The formal errors for the PPP GPS-only solution are at the 16mm level with a bias 22mm in the East component, at the 12mm level with a bias of -2mm in the North component and at the 84mm level with a bias of 10mm in the Up component. On the other hand, the combined GPS & BeiDou PPP solutions bias and standard deviation for the 24 hours data span is 19± 41mm, -35± 46mm and -99±194mm for the East, North and Up components, respectively. The BeiDou-only processing solutions deviate by are 14±93mm, -16±12mm and -54±32mm for East, North and Up components. In case of using the corrections produced by GFZ the accuracy solutions of the combination of BeiDou and GPS processing does not show any improvement compared to the other two methods for station CUTA0.

The results of PPP processing by using the GFZ orbit and clock products for BeiDou look similar to the first investigation. Using the ESA corrections seems to provide better statistical values in the investigated period.

5.2.2.1 Convergence Analysis

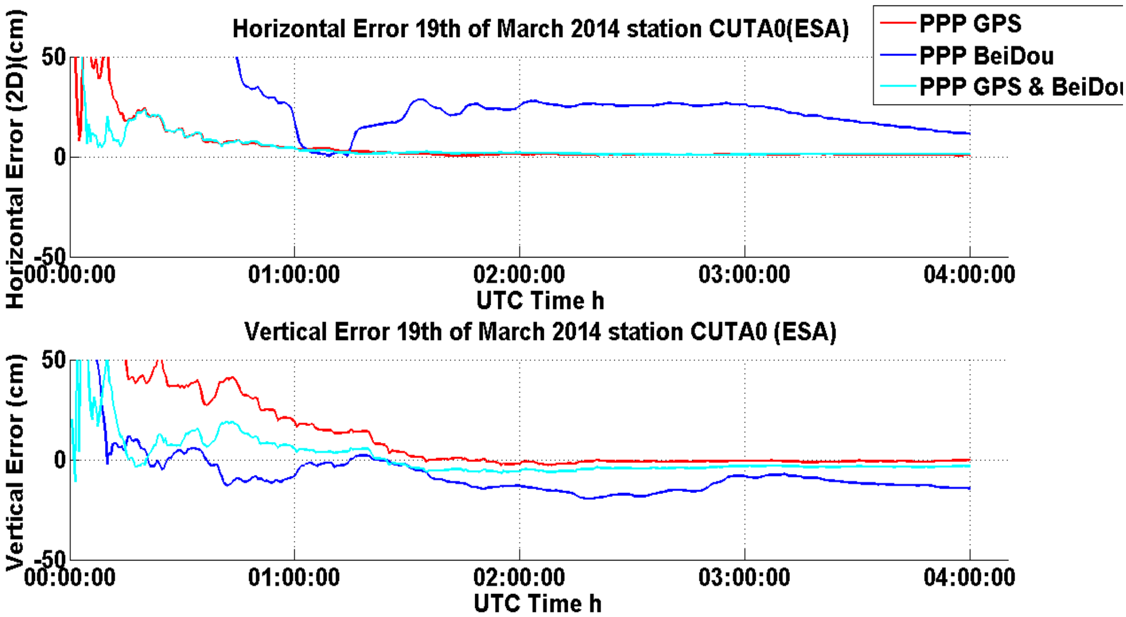


Figure 18: The convergence time for PPP in the case of using of the ESA corrections

Fig.18 and Fig.19 show the convergence behaviours within the first four hours of PPP processing. The convergence time for reaching 5cm, 10cm, 20cm and 50cm accuracy in the horizontal and vertical components are shown in table 12 and table 13.

Table 12: The convergence time for 5cm, 10cm, 20cm and 50cm accuracy at station CUTA0 in the case of using of the ESA corrections

	GPS-only [min]	BeiDou-only [min]	GPS & BeiDou [min]
Horizontal <50cm	10.5	44.5	3.5
Horizontal <20cm	24.0	60.0	4.5
Horizontal <10cm	35.5	61.0	35.5
Horizontal <5cm	55.5	62.5	55.0
Vertical <50cm	12.5	7.5	10.5
Vertical <20cm	59.5	9.5	12.5
Vertical <10cm	81.0	10.0	14.5
Vertical <5cm	85.0	20.0	15.0

In the horizontal component there is a major improvement (about 80% less time) for 20cm and 50cm convergence in the case of the GPS & BeiDou processing compared to GPS-only and 90% in the case of compared to BeiDou-only. However, only a slight improvement is shown for the other convergence limits. In the vertical component the convergence times for the BeiDou-only processing and the combined GPS & BeiDou processing are at a similar level. The combined data processing in the case of compared to the GPS-only processing has led to an improvement of about 80% for 10cm and 5cm convergence.

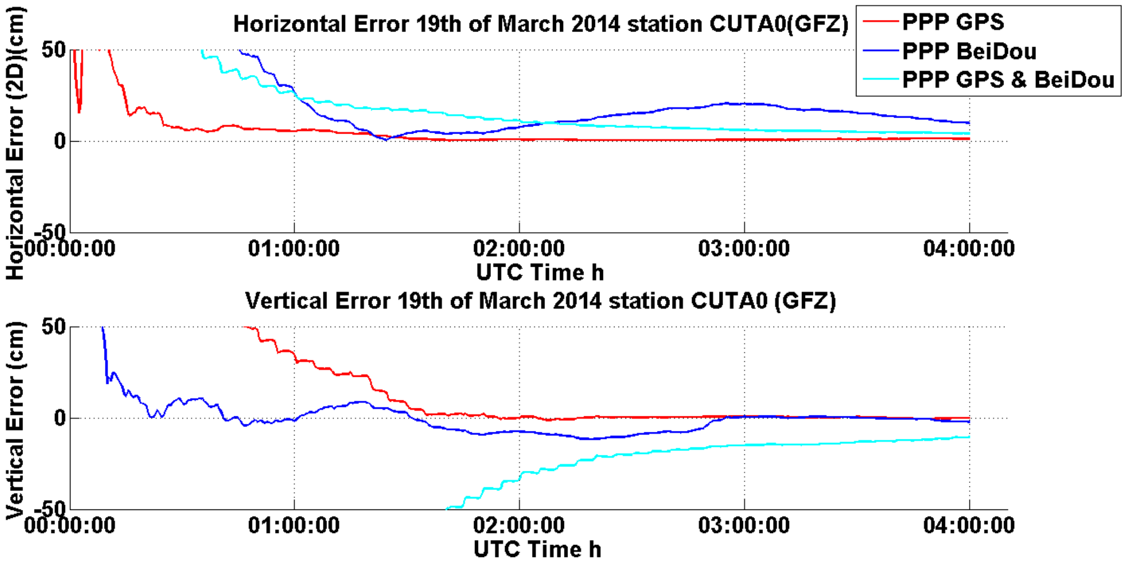


Figure 19: The convergence time for 5cm, 10cm, 20cm and 50cm accuracy at the same station. The GFZ corrections were used for processing

Table 13: The convergence time for 5cm, 10cm, 20cm and 50cm accuracy at station CUTA0 in the case of using the GFZ corrections

	GPS-only [min]	BeiDou-only [min]	GPS & BeiDou [min]
Horizontal <50cm	10.5	45.5	35.5
Horizontal <20cm	15.5	63.5	70.5
Horizontal <10cm	25.0	75.0	125.5
Horizontal <5cm	70.5	80.0	206.0
Vertical <50cm	26.0	9.0	101.0
Vertical <20cm	80.5	13.5	150.5
Vertical <10cm	85.5	19.0	/
Vertical <5cm	91.0	40.0	/

In case of using the GFZ corrections there are major deteriorations (about 50% more time) for 10cm and 5cm convergence in the case of the combined GPS & BeiDou processing compared to the GPS-only computations and 60% compared to BeiDou-only in the horizontal component. A slight deterioration is shown for the other convergence criteria in the case of the combined GPS & BeiDou processing compared to GPS-only processing. In the vertical component BeiDou-only and GPS-only perform better for all convergence time categories. In case of the GPS & BeiDou processing compared to GPS-only, the former provides a major deterioration of up to 85% in the case of 50 cm and 20cm convergence. It can be shown that the processing of GPS & BeiDou data does not deliver coordinate deviations less than 10cm. No improvement is found for combined GPS & BeiDou processing in the horizontal and vertical components.

5.2.2.2 Number of visible satellites and PDOP

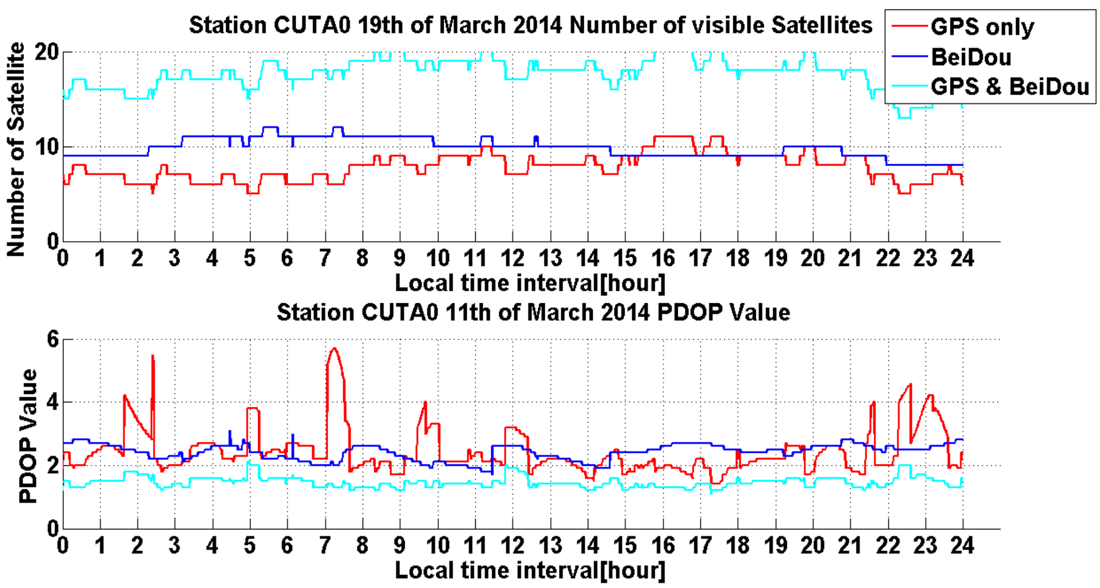


Figure 20: the number of visible satellites and PDOP values at station JFNG on 11 March 2014

The PDOP value and the number of visible satellites were analyzed. During the 24 hours processing, the visible satellites have increased for the combined GPS & BeiDou case to up to 20. The PDOP value improves significantly by adding BeiDou observations. A clear improvement of the satellite geometry is visible.

5.2.3 March 11 at station JFNG (China)

For another PPP investigation 24 hours of observations of GPS and BeiDou data acquired at the station JFNG were chosen. The orbit and clock corrections from ESA and GFZ on 11th March and on 19th March are used again. The aim of using another Mgex station is to confirm the quality of results of the previous PPP investigations. The calculated time series of the GPS-only, BeiDou -only and combined GPS & BeiDou processing steps are presented in Fig.21 and Fig.22. Furthermore, the convergence time, the number of visible satellites and the PDOP values of all three methods are determined.

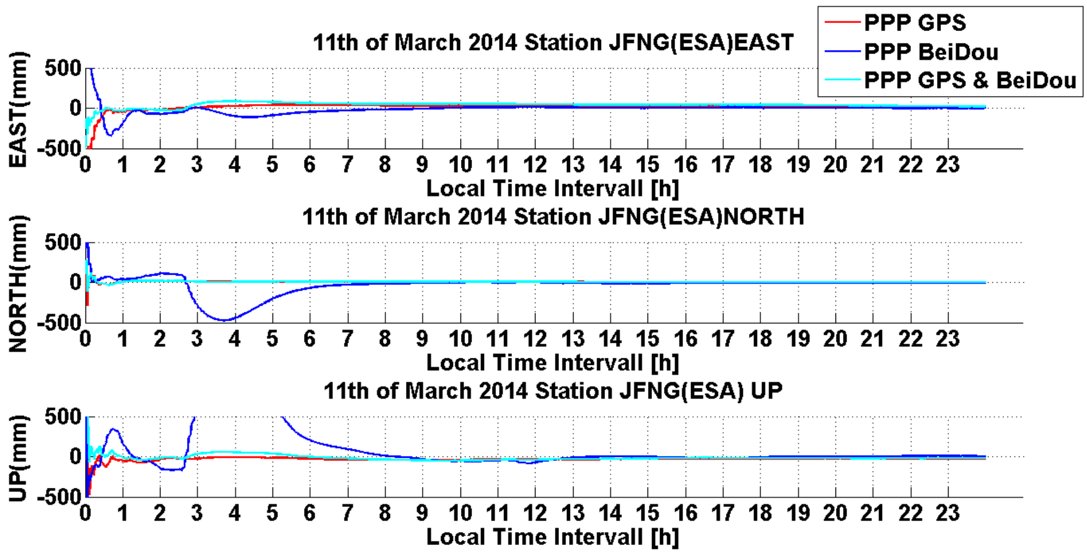


Figure 21: PPP station positioning coordinate time series at station JNFG (China) on 11 March 2014. The ESA orbit and clock correction was used.

Fig.21 shows that the combined GPS & BeiDou processing and GPS-only processing provide better and more stable results than the BeiDou-only processing. It can be shown that the coordinate time series for the GPS-only and the combined GPS & BeiDou data computation is at a similar level in all components. Most of the processing period the cyan lines overlap the red lines. Both lines are close to the reference. The BeiDou-only processing shows worse results and some jumps.

Table 14: The bias, STD and RMS of positioning at JNFG on 11 March 2014 are shown. The ESA corrections were used for the processing

		GPS-only [mm]	BeiDou-only [mm]	GPS & BeiDou [mm]
MEAN	East	14	-21	41
	North	14	-41	7
	Up	-17	108	-18
STD	East	17	50	25
	North	50	115	6
	Up	15	312	26
RMS	East	25	55	47
	North	9	122	9
	Up	34	330	31
3D accuracy		41	161	54
3D RMS		43	356	57

Table 14 shows the bias values and STD of the converged positioning. In case of using the ESA orbit and clock corrections the combined GPS & BeiDou results are capable of providing position solutions at an accuracy of several cm for a PPP scenario. The formal errors for the PPP GPS-only solution are at the 17mm and 50mm level with biases of 14mm in plane and at the 15 mm level with a bias of -17mm in the Up component. On the other hand, the combined GPS & BeiDou PPP solutions are at the 25mm level with a bias of 41mm in the East component, at the 6mm level with a bias of 7mm in the North component and at the 26mm level with bias of -18mm in the Up component. The addition of the BeiDou observations provide only a slight or no impact on the enhancement of the positioning accuracy compared to GPS-only processing. The formal errors of the BeiDou-only positioning are at the 50mm level with a bias of -21mm, at the 115mm level with a bias of -41mm in the North component and at the 312mm level with a bias of 108mm. Therefore the GPS-only and combined GPS & BeiDou processing examples outperformed clearly the BeiDou-only processing result.

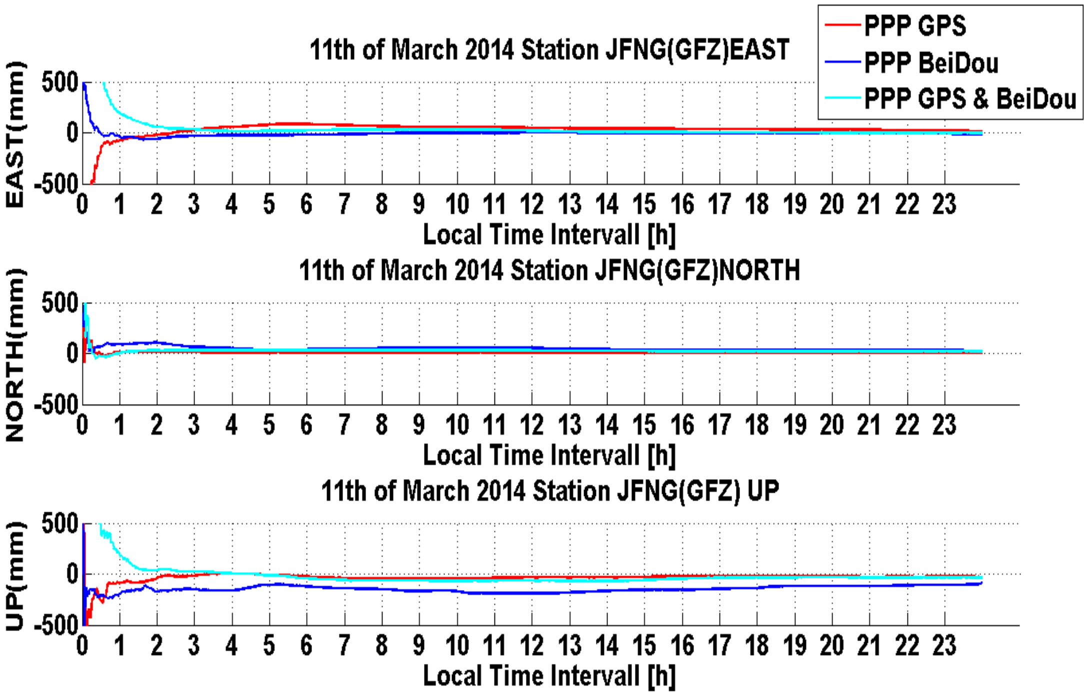


Figure 22: PPP station positioning coordinate time series at station JNFG (China) on 11 March 2014. The GFZ orbit and clock correction was used.

Fig.22 shows the coordinate time series for station JNFG obtained by PPP processing with GFZ corrections. The time series of the GPS-only processing look similar like the results of the BeiDou-only and the combined GPS & BeiDou processing in the East and North components. All cases show almost no bias and the curves overlap completely. A closer look at the calculated time series reveals that the positioning accuracy of the GPS-only and the combined GPS & BeiDou outperformed the BeiDou-only processing in the Up component. The GPS and the GPS & BeiDou time series show no bias.

Table 15: The bias, STD and RMS of positioning at JNFG on 11 March 2014 are shown. The GFZ correction file were used for the processing

		GPS-only [mm]	BeiDou-only [mm]	GPS & BeiDou [mm]
MEAN	East	37	-13	25
	North	7	46	25
	Up	-33	-148	27
STD	East	33	14	54
	North	5	18	8
	Up	24	29	65
RMS	East	50	19	60
	North	9	49	26
	Up	41	151	70
3D accuracy		59	157	70
3D RMS		65	160	96

In case of using the GFZ corrections the formal error of BeiDou-only processing is at the 29mm level with a bias of -148 in the Up component. It delivers the worst bias value compared to other cases in the Up component. In the other components the differences between all methods are small. Across table 15 the values of the GPS-only solution are close to the solution of the combined GPS & BeiDou processing in all components.

The ESA corrections for all processing methods seem to perform similar compared to the results by using the GFZ corrections in the investigated period. All cases show almost no bias and the curves overlap except for the BeiDou-only processing in the case of using the ESA corrections. The BeiDou-only processings show more unstable results and some jumps.

5.2.3.1 Convergence Analysis

Let's have a closer look at PPP convergence analysis. Fig.23 and Fig.24 show the convergence behaviour of the first four hours of PPP when introducing either the ESA or GFZ corrections. The convergence time for reaching 5cm, 10cm, 20cm and 50cm accuracy in horizontal and vertical components are shown in table 16 and table 17.

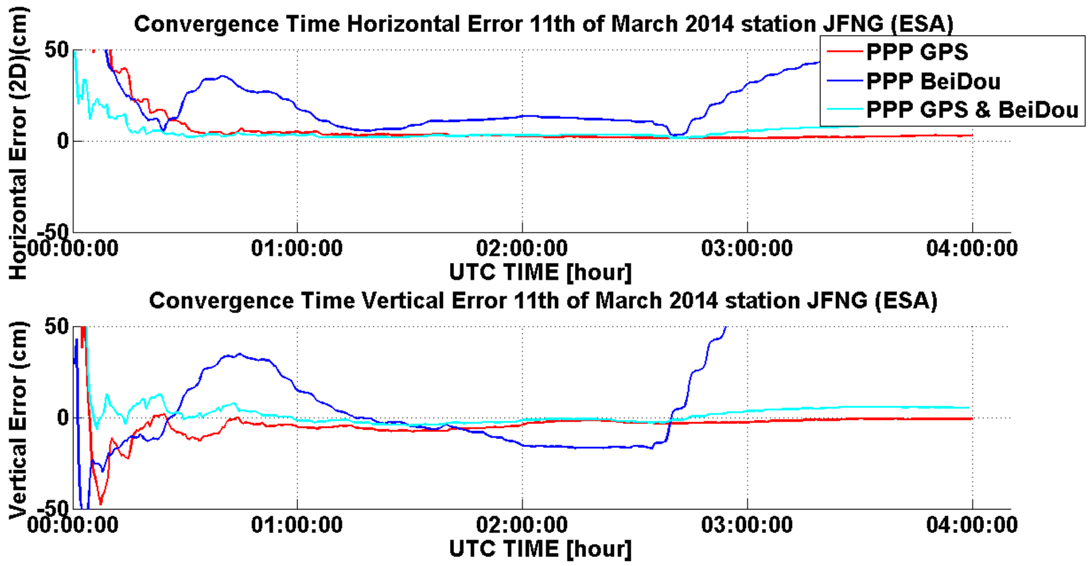


Figure 23: The convergence time for PPP at station JNFG when using the ESA corrections

Table 16: The convergence time for 5cm, 10cm, 20cm and 50cm accuracy at station JNFG

	GPS-only [min]	BeiDou-only [min]	GPS & BeiDou [min]
Horizontal <50cm	10.5	10.0	1.5
Horizontal <20cm	20.5	18.5	8.0
Horizontal <10cm	29.0	69.5	15.5
Horizontal <5cm	32.5	159.5	25.0
Vertical <50cm	3.5	5.5	5.0
Vertical <20cm	15.5	11.5	5.5
Vertical <10cm	16.5	25.0	10.5
Vertical<5cm	41.0	/	26.0

In the horizontal component there is a major improvement (about 80% less time) for 50 cm, 20cm and a slight improvement for 10cm and 5cm convergence in the case of GPS & BeiDou compared to GPS-only in the case of using the ESA corrections. A major improvement (80%) is also visible when of combined GPS & BeiDou compared to BeiDou-only for 10cm and 5cm. In the vertical component the combined GPS & BeiDou processing has led to an improvement of up to about 30% in the case of 10cm and 5 cm convergence. In general, a significant convergence improvement for the combined GPS & BeiDou processing is found both in the horizontal and the vertical component.

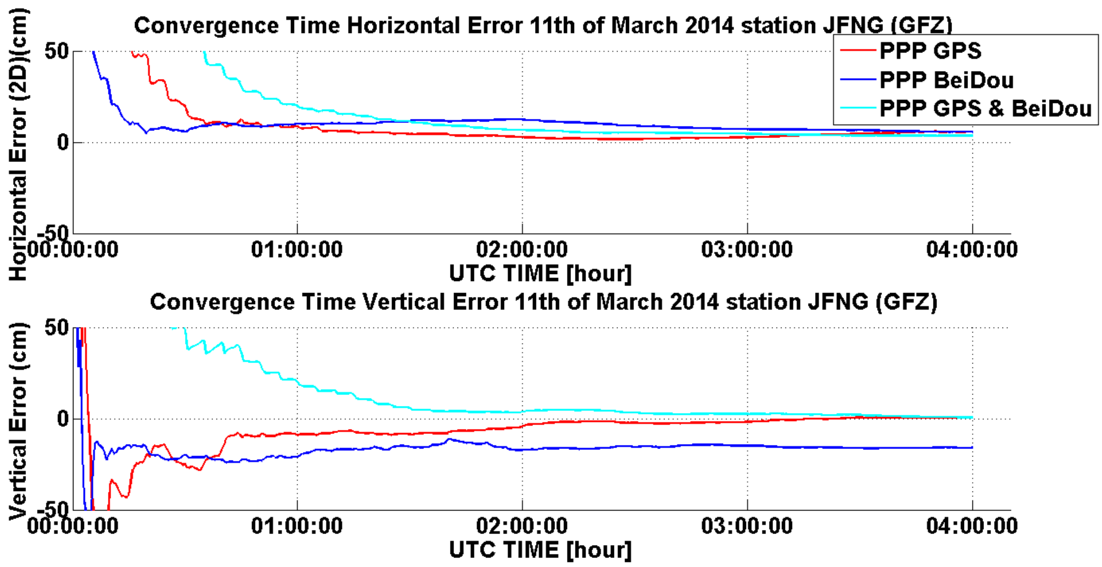


Figure 24: The convergence time for PPP at station JNFG on 11 March 2014 in the case of using of GFZ corrections

Table 17: The convergence time for 5cm, 10cm, 20cm and 50cm accuracy at station

	GPS-only [min]	BeiDou-only [min]	GPS & BeiDou [min]
Horizontal <50cm	16.0	5.5	35.5
Horizontal <20cm	30.0	11.5	60.0
Horizontal <10cm	50.0	16.5	95.5
Horizontal <5cm	85.0	24.5	160.5
Vertical <50cm	10.0	5.5	30.0
Vertical <20cm	39.5	10.0	60.0
Vertical <10cm	49.0	/	80.0
Vertical<5cm	118.5	/	90.5

By means of the GFZ corrections the horizontal component shows a major deterioration (about 50% more time) for 50cm, 20cm, 10cm and 5cm convergence in the case of the GPS & BeiDou processing compared to the GPS-only processing. A major deterioration (80%) is also visible in the case of GPS & BeiDou data compared to BeiDou-only. In the vertical component there is a major deterioration of about 60% for 50cm convergence and about 40% in 20cm, 10cm and 5 cm convergence in the case of the combined GPS & BeiDou processing compared to the GPS-only processing. It is also visible that processing of the BeiDou-only observation does not deliver coordinate deviations less than 20cm. However, the BeiDou-only solution converges to 50cm and 20cm within 5.5 and 10 minutes. The combined GPS & BeiDou data required six times longer for that. In the case of using the GFZ corrections it can be observed that no convergence improvement is found for the combined GPS & BeiDou processing.

5.2.3.2 Number of visible satellites and PDOP

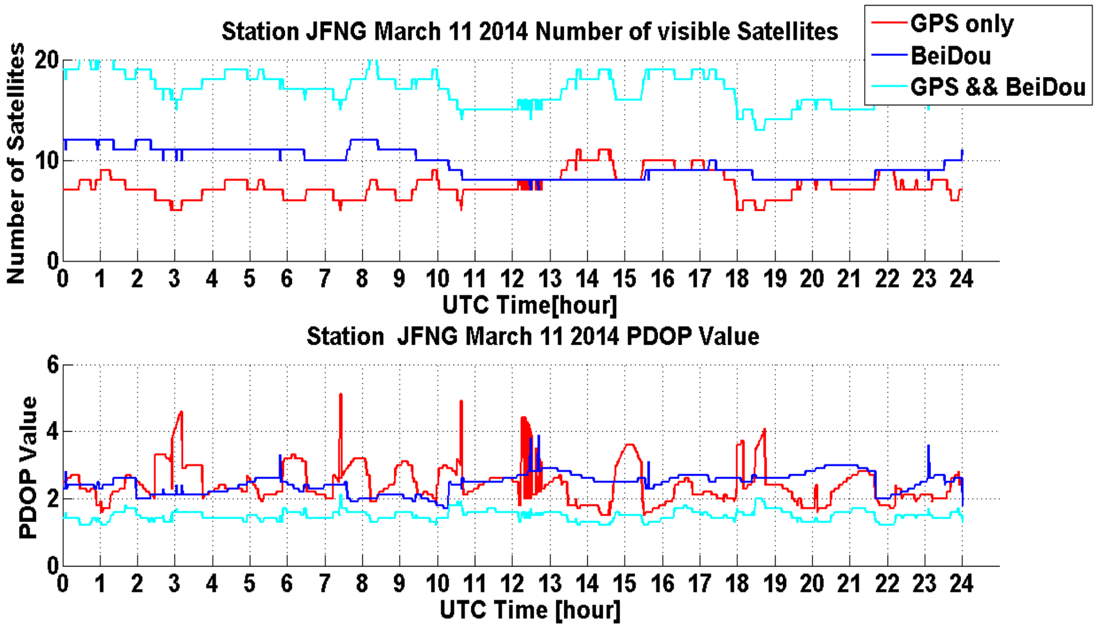


Figure 25: the number of visible satellites and PDOP values at station JFNG on 11 March 2014

During the 24 hours processing the number of tracked satellites for the GPS-only and the BeiDou-only observations are up to 10 and 12. The visible satellites have increased for the combined GPS & BeiDou data set and the satellites number varies between 15 and 20. The PDOP values of the GPS-only and the BeiDou-only observations vary between 2 and 3. On the other hand, the PDOP values of the combined GPS & BeiDou data sets vary between 1.7 and 2. Adding the BeiDou data to processing delivers a significant improvement of the PDOP value.

5.2.4 March 19 2014 at station JFNG

Secondly, observation data on 19th of March at station JFNG (China) was chosen, the ESA and GFZ corrections are again used for analysis. Across Fig.26 the GPS-only and the combined GPS & BeiDou processings provide PPP positioning solution with partial outliers. It can be shown that outliers appear in the GPS-only solutions from 4:30 to 12:00. In the combined GPS & BeiDou solutions outliers had arisen from 7:00 to 8:00. A low number of tracked satellites and poor satellite geometry (defined by a high DOP value) of the daily observations might be the reason for outliers. The outliers cause a deterioration of the bias values and standard deviation of the positioning solution. In RTKLIB "quality flag" Q provides different colors and numbers to define the quality of positioning solution. The red color denotes an unreliable accuracy of processing (outlier). A blue color denotes a reliable PPP solution. We used this graphics to detect the outliers in both processed solutions and to remove these outliers. Therefore, only 2677 epochs with 30 seconds interval from GPS-only data and 2754 epochs from combined GPS & BeiDou data are appropriate for this PPP investigation. In addition, 2820 epochs from the BeiDou-only data were used to calculate statistics.

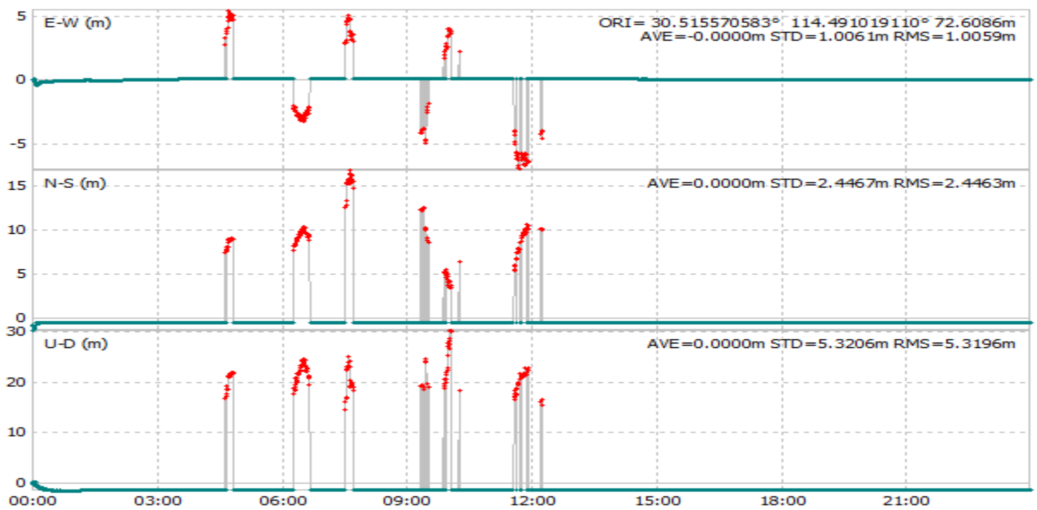


Figure 26: Outlier appear in GPS-only and in Combined GPS & BeiDou processing in RTKLIB

Fig.27 shows the time series of GPS-only, BeiDou-only and combined GPS & BeiDou data sets after removal of the outliers in the East, North and Up components. The ESA orbit and clock corrections are applied. Apparently, in all components the coordinate time series for the GPS-only and combined GPS & BeiDou processing are at a quite similar level. The red curve is completely overlapped by the cyan curve. The BeiDou-only processing shows worst and more unstable results compared to the other methods in the Up component.

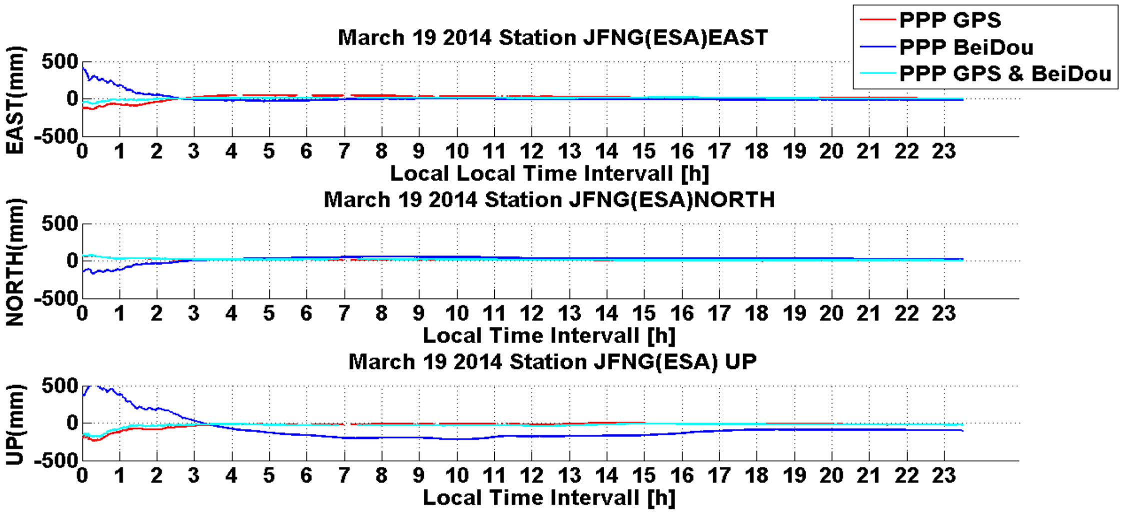


Figure 27: PPP station positioning coordinate time series with ESA corrections at station JNFG (China) on 19 March 2014.

Table 18: The bias, STD and RMS of positioning at JNFG on 19 March 2014 are shown. The ESA corrections were used for the processing

		GPS-only [mm]	BeiDou-only [mm]	GPS & BeiDou [mm]
MEAN	East	10	6	7
	North	13	22	16
	Up	-28	-87	-29
STD	East	36	60	12
	North	12	41	12
	Up	40	155	27
RMS	East	38	60	49
	North	17	47	18
	Up	48	20	40
3D accuracy		44	166	36
3D RMS		64	193	46

Table 18 shows the bias values and standard deviation (sigma values) of the converged positions. The formal errors for the PPP GPS-only solution are at the 36mm level with a bias of 10mm in the East component, at the 12mm level with a bias of 13mm in the North component and at the 40mm level with a bias of -28mm in the Up component. On the other hand, the combined GPS & BeiDou PPP solution are at the 12mm level with a bias of 7mm in the East component, at the 12mm level with a bias of 16mm in the North component and at the 27mm level with bias of up to -29mm in the Up component. Adding the BeiDou observation provides a slight enhancement of the positioning accuracy compared to the GPS-only processing. The formal errors of the BeiDou-only processing are quite large at the 60mm level in the East component with a bias of 6mm, at the 41mm level with a bias of 22mm in the North component and at the 155mm level with a bias of -87mm in the vertical component. The GPS & BeiDou processing provides a 3D RMS of 46mm, whereas the GPS-only solution provides a 3D RMS of 64mm. The BeiDou-only processing delivers a 3D RMS of 193mm. The GPS & BeiDou processing provides a 3D accuracy of 36mm, whereas the GPS-only solution provides a 3D accuracy of 44mm. The BeiDou-only processing delivers a large3D accuracy of 166mm. Adding BeiDou observations improves the 3D accuracy. The positioning accuracy achieved by the combined GPS & BeiDou processing and the GPS-only processing outperformed the BeiDou-only methods in all components.

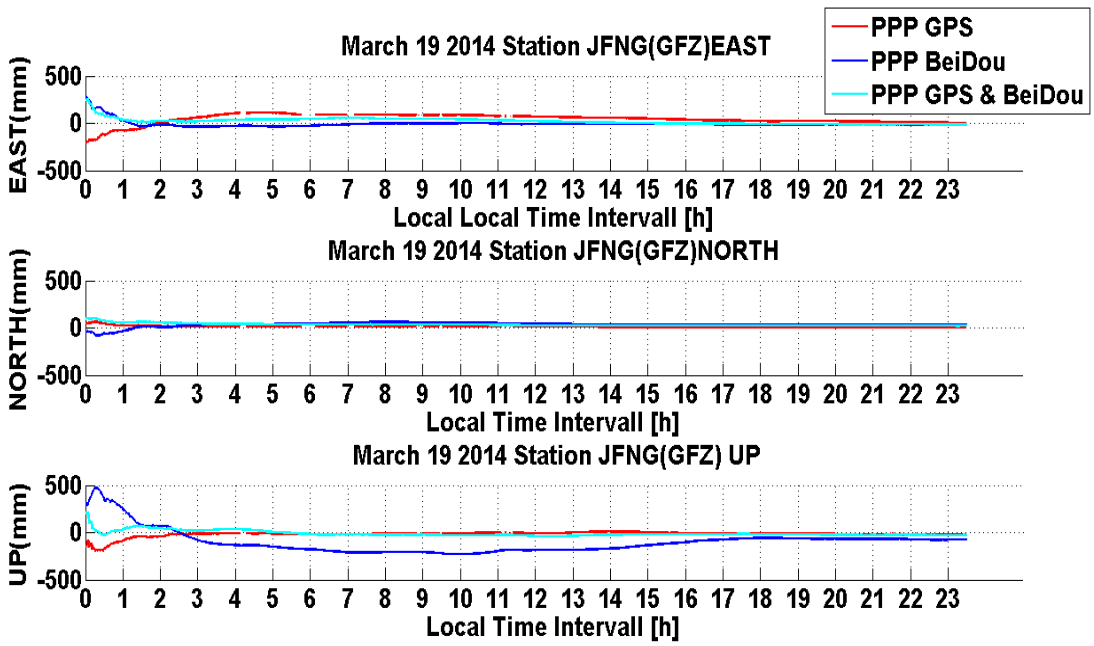


Figure 28: PPP station positioning coordinate time series at station JNFG (China) in the case of using the GFZ orbit and clock corrections.

Fig.28 shows the results from PPP processings with GFZ corrections. The time series of the GPS-only computations look similar like the results of the BeiDou-only and the combined GPS & BeiDou processing in the East and North components. It can be clearly observed that all data sets deliver unbiased plane coordinate. In the Up component the coordinate time series of the GPS-only and the combined GPS & BeiDou solution outperformed the BeiDou-only processing. Over most of the processing period the cyan curves and red curves overlap closely and experience no bias. The BeiDou solution shows some jumps in the Up component.

Table 19: The bias, STD and RMS of positioning by using GFZ corrections at JNFG are shown.

		GPS-only [mm]	BeiDou-only [mm]	GPS & BeiDou [mm]
MEAN	East	42	-8	21
	North	13	35	-34
	Up	-19	34	-12
STD	East	54	34	32
	North	9	24	14
	Up	31	127	30
RMS	East	68	35	38
	North	16	42	36
	Up	36	16	31
3D accuracy		66	151	53
3D RMS		79	170	60

When introducing GFZ products the GPS-only PPP solution bias and standard deviation for 24 hours data span is 42± 54mm, 13± 9mm and -19±31mm for the East, North and Up components, respectively. In contrast, the combined GPS & BeiDou PPP positioning solution accuracy is 21±32mm, -34±14mm and -12±30mm for East, North and Up components. Adding BeiDou observations provides a slight impact for the enhancement of positioning accuracy compared to GPS-only processing in the East and Up components. It is also visible that the BeiDou-only processing shows worse results in all components.

In summary the PPP solutions delivers stable coordinates for the station JNFG in the investigated period when ESA and GFZ corrections are used expect for the BeiDou only solution in the Up component. All cases show almost no bias. The BeiDou-only data processing shows more unstable results and some jumps in both cases.

5.2.4.1 Convergence Analysis

Fig.29 and Fig.30 present the convergence behaviour of the first four hours of PPP processing by using correction from ESA and GFZ. In both cases, the convergence time for reaching 5cm, 10cm, 20cm and 50cm accuracy in the horizontal and vertical components are shown in table 20 and table 21.

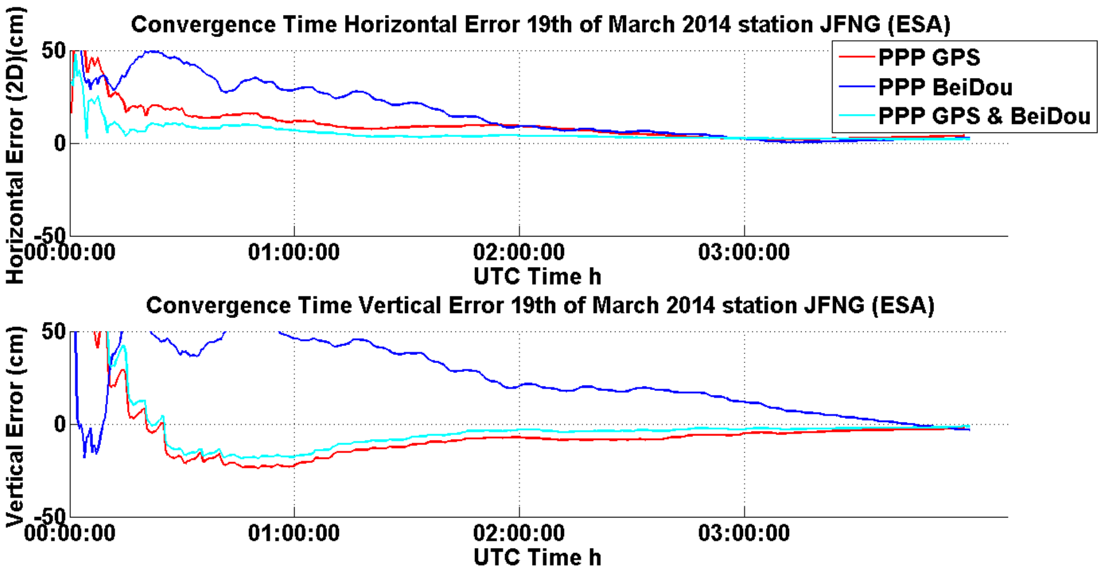


Figure 29: The convergence time for 5cm, 10cm, 20cm and 50cm accuracy at the station JFNG in the case of using the ESA corrections

Table 20: convergence time by using ESA corrections for 5cm, 10cm, 20cm and 50cm accuracy at station JFNG

	GPS-only	BeiDou-only	GPS & BeiDou
Horizontal <50cm	4.5	3.5	0.5
Horizontal <20cm	23.5	95.0	8.5
Horizontal <10cm	68.0	114.5	13.0
Horizontal <5cm	151.0	160.5	71.5
Vertical <50cm	10.0	2.0	10.5
Vertical <20cm	15.5	2.0	15.5
Vertical <10cm	15.5	185.0	20.0
Vertical <5cm	180.5	201.0	105.0

In the horizontal component there is a major improvement (about 80%) for 50, cm, 20cm and 10cm convergence in the case of the combined GPS & BeiDou processing compared to GPS-only and a major improvement (90%) in the case of the combined GPS & BeiDou processing compared to BeiDou-only for 20cm and 10cm. The convergence in the combined processing appears smoother. In the vertical component, the convergence times for BeiDou-only and combined GPS & BeiDou processing are at a similar level for 50cm, 20cm and 10cm. When looking at 5cm converage all solutions require up to 100 mnutes. Obviously the BeiDou-only solution performs worst. As a result, a significant convergence improvement is found in the horizontal component when adding BeiDou data to GPS while in the vertical component only a slight convergence improvement cannot be noted.

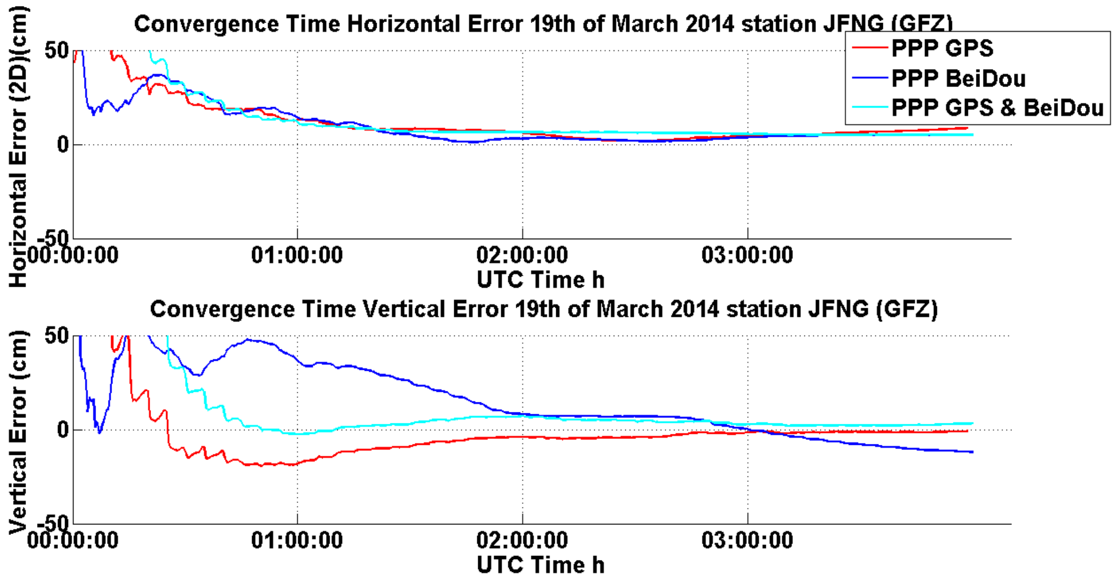


Figure 30: The convergence time for 5cm, 10cm, 20cm and 50cm accuracy at the station JFNG when using the GFZ orbit and clock corrections.

Table 21: The convergence time by using of GFZ corrections for 5cm, 10cm, 20cm and 50cm accuracy at station JFNG

	GPS-only	BeiDou-only	GPS & BeiDou
Horizontal <50cm	10.5	3.0	20.5
Horizontal <20cm	35.0	40.0	40.5
Horizontal <10cm	70.0	77.0	65.5
Horizontal <5cm	126.0	90.5	215.0
Vertical <50cm	15.0	2.0	25.5
Vertical <20cm	20.5	4.0	35.0
Vertical <10cm	85.0	114.5	40.0
Vertical<5cm	106.0	167.5	44.5

In the horizontal component there is a major deterioration (about 50% more time) to obtain 50cm convergence in the case of the GPS & BeiDou data processing compared to the GPS-only processing. This statement is also valid when comparing GPS & BeiDou data processing with BeiDou-only. In the vertical component there is a major improvement of about 50% for all convergence classes in the case of the combined GPS & BeiDou processing compared to the GPS-only processing. A major improvement (60% and 70%) for 10cm and 5cm convergence is also shown in the case of the GPS & BeiDou processing compared to the BeiDou-only processing.

In general in the horizontal component no convergence improvement is found. In the vertical component a major convergence improvement can be noted.

5.2.4.2 Number of visible satellites and PDOP

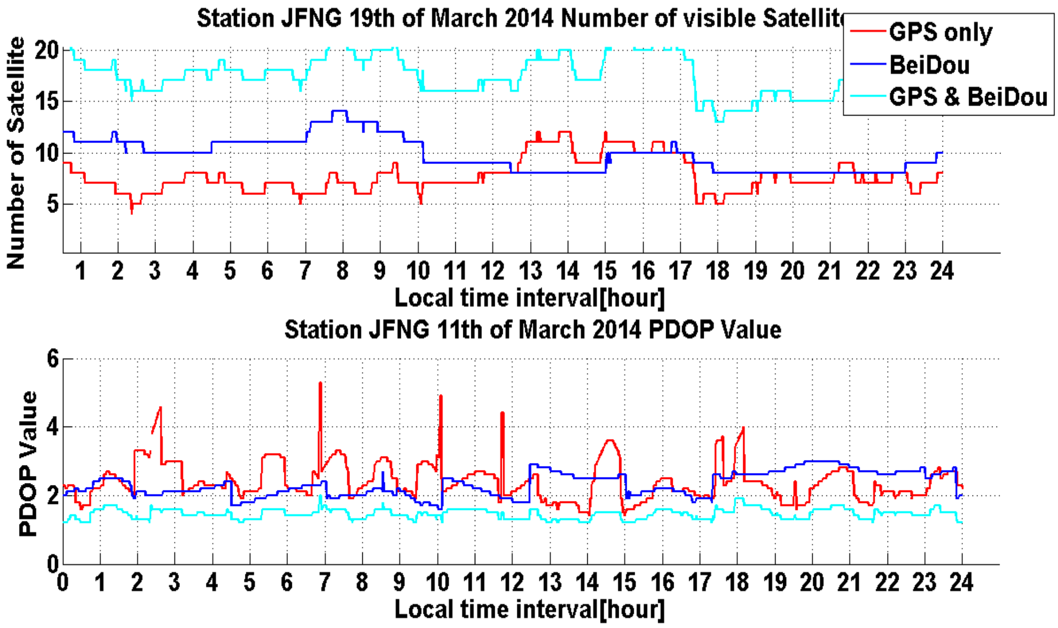


Figure 31: the number of visible satellites and PDOP values at station JFNG on 19 March 2014

During the 24 hours processing period the number of tracked satellites for the GPS-only and the BeiDou-only data sets are up to 10 and 12. The number of visible satellites increased up to 22 for the combined GPS & BeiDou observations. The PDOP values of the GPS-only and the BeiDou-only observations vary between 2 and 3. On the other hand, the PDOP values of the combined GPS & BeiDou observations vary between 1.7 and 2. Adding the BeiDou data obviously delivers a significant improvement of the PDOP value.

Chapter 6

6 Conclusions

In this thesis GNSS positioning techniques based on GPS and BeiDou observations have been investigated. This study focused on the potential improvement in positioning accuracy when utilizing both the L1 and L2 signals of GPS and the B1 and B2 signals of BeiDou. Although BeiDou is a new GNSS system, the IGS-MGEX project offers already precise Beidou orbit and clock correction information and therefore enables to combine observations of both systems for site data processing. The positioning accuracy obtained in three scenarios (GPS-only, Beidou-only, GPS&Beidou) has been investigated by means of a baseline and a PPP approach. In case of Double Difference (baseline) processing, the performance of the GPS-only and the combined GPS&BeiDou approach was found to be superior to that of BeiDou-only solutions.

In order to assess the positioning accuracy and convergence time in PPP, the 24-hour observation data sets and the orbit and clock corrections produced by ESA and GFZ were used. As expected the addition of BeiDou constellation data improved the satellite availability and the PDOP values. Based on the results the ESA Beidou and GPS orbit and clock correction data seems to be more consistent than the GFZ correction data within the investigated periods. On the other hand, the Beidou-only positioning improved in quality when preferring the GFZ corrections compared to the ESA corrections. While the position accuracy does not improve largely when using combined GPS&Beidou observation data compared to GPS-only, the convergence times of the vertical coordinate could be significantly reduced. Although the BeiDou constellation is not fully operational yet, the main advantage of processing combined observations was the tremendous increase in service availability especially for users at locations in the Asia-Pacific area.

In future the number of processed site data as well observation periods have to be increased to draw statistically founded conclusions. Further investigations have also to be conducted to assess the combined GPS& BeiDou PPP processing in a kinematic mode.

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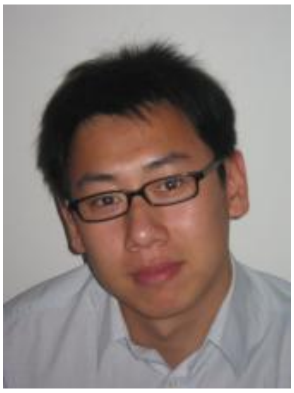
Figure list

Table list

Acronym list

AC………………………..	Analytical Center
APREF…………………..	Asia-Pacific Reference Frame
AUSPO…………………..	AUSLIG's Online GPS Processing Service
BDS………………………	BeiDou
BKG ……………………..	Bundesamt für Kartographie und Geodäsie
CGCS2000…………….	China Geodetic Coordinate System 2000
CNES …………………. .	France's Centre National d'Etudes Spatiales
DD………………………..	Double Difference
ESA………………………	European Space Agency
ESOC …………………….	European Space Operations Centre
FOC……………………….	Full Operational Capability
GDA………………………	Geocentric Datum of Australia
GEO………………………	Geosynchronous Earth orbit
GPS………………… …..	Global Positioning System
CDDIS…………………..	Crustal Dynamics Data Information System
GFZ ……………………..	GeoForschungsZentrum
GNSS……………….. ….	Global Navigation Satellite System
IAG……………………..	International Association of Geodesy
IGN……………………..	Institut Geographique National
IGS……………………...	International GNSS Service
IGSO …………………	Inclined Geosynchronous Orbit
ITRF…………………	International Terrestrial Reference Rrame

Mgex…………………	Multi–GNSS Experiment
MEO……………..….	Medium Earth orbit
NAVSTAR ………...	Navigation by Satellite Ranging and Timing
PPP…………………..	Precise Point Positioning
PPS…………………...	Precise Positioning Service
PVT……………………	Position, Velocity and Precise time
QPSK…………………..	Quadrature Phase Shift Keying
RMS…………………...	Root Mean Square
SPS …………………...	Standard Positioning Service
TAI ……………………	International Atomic Time
UTC …………………...	Coordinated Universal Time
WGS84………………..	World Geodetic System 1984



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