Evaluation of GNSS post processing Online Service

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الإهداء

إلى الرحمة المهداة في زمن الظلم والظلمات ... رسول الله صلى الله عليه وسلم

إلى ورثة الأنبياء بعلمهم ...علماؤنا الأجلاء

إلى من عبدت لي بحبها طريق الجنان ... نبع الحنان أمي الحبيبة

إلى الذي تناثرت قطرات العرق على جبينه كقطر الندى مجتهدا ليوفر لي الحياة الكريمة ...والدي الحبيب

إلى الذين كانوا لي أنسا في معمعان الحياة ... إخواني وأخواتي

إلى الذين رفعوا لواء العشق الأبدي عبورا نحو جنان الرحمن شهداؤنا الأماجد

إلى البيارق الخفاقة في سماء العزة والإباء ... أسيراتنا وأسرانا البواسل

إلى أقصانا ومسرانا مَهْوَ القلوب وإلى كل ذرة من أرض الرباط فلسطين بأهلها وطهرها وقفارها..

إلى مسيرات العودة في شتى ربوع الوطن شمالها وجنوبها ...

إلى كل الإخوة والأخوات الذين ساهموا وعملوا في هذا المشروع، بتشجيعهم ودعائهم المتواصل، والذين كان لهم صدق مؤازرتنا في تنفيذه.

" وقل اعملوا فسيرى الله عملكم ورسوله والمؤمنون، وستردون إلى عالم الغيب والشهادة فينبئكم بما كنتم تعملون"

إليكم جميعا نهدي هذا العمل

ABSTRACT

Evaluation of GNSS post processing Online Service

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Supervisor

Dr. Ghadi Zakarneh.

The aim of project is to evaluate the use and limitation of global navigation satellite system (GNSS) freely available online services according to accuracy and usability.

To make evaluation static observation is be done for group of points. In the observation different parameters will be changed, these parameters are times, file types, Rinex version and the change in observation rates. Positions will be calculated with different parameters and conditions to make the proper evaluation. The requirements and methodologies of data processing will be documented.

As find results were prepared, an overview of the methods to use these service with clear conditions and target is done. To avoid the use commercial software for static precise point positioning (PPP). One of the remarkable results was the ability to solve position in difficult situation using services that can deal with Rinex 3.02.

الملخص

Evaluation of GNSS post processing Online Service

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الهدف من المشروع هو تقييم استخدام وتقييد خدمات النظام العالمي للملاحة باستخدام السواتل (GNSS) المتاحة مجاناً على الإنترنت وفقاً للدقة وسهولة الاستخدام.

لعمل التقييم وايجاد النتائج وتم إجراء رصد ثابت (static) لمجموعة من النقاط، حيث تم تغيير بعض المتغيرات والمعايير، واهم هذه المتغيرات هو الوقت، وأنواع الملفات، وإصدار Rinex والتغير في معدل القراءات وتم حساب موقع هذه النقاط وفق شروط ومعايير مختلفة لإجراء التقييم المناسب، وتم توثيق متطلبات ومنهجيات معالجة البيانات التي تم استخراجها.

كما وتم اعداد نتائج البحث التي تم التوصل اليها، وهناك نظرة عامة على طرق استخدام هذه الخدمة مع ظروف واضحة وقد تم إنجاز الهدف. لتجنب استخدام البرامج التجارية لتحديد المواقع الثابتة بدقة نقطة (PPP) ، وكانت احدى النتائج الرائعة القدرة على تحديد الموقع في ظروف صعبة وذلك باستخدام واحد من الخوادم الالكترونية التي تتوافق مع Rinex 3.02.

Acknowledge

Table Of Content

List of Figures

List of Table

Chapter one

INTRODUCTION

1.1 Background.

1.2 problem statement .

1.3 Objective.

1.4 Literature Review .

1.5 Methodology.

1.6 Project Scope.

1.1 Background

The Global Navigation Satellite Systems (GNSS) are systems of satellites that continuously provide positioning possibilities with global coverage. They allow small electronic receivers to determine their location (longitude, latitude, and altitude) to a high precision (within a few meters to sub centimeter) using time radio signals transmitted along a line of sight by satellites. The signals also allow the electronic receivers to calculate the current local time to high precision. [1]

The global geocentric reference frame and coordinates system known as the World Geodetic System 1984 (WGS84) has been developed continuously since its creation in the mid-1980s. The WGS84 continues to provide a single, common, accessible 3-dimensional coordinate system for globally data collected from different sources. Some of this geospatial data requires a high degree of accuracy and requires a global reference frame which is free of any significant distortions or biases. For this reason, a series of improvements to WGS84 were developed in the past years, which served to refine the original version. The data collected by the GNSS according to the WGS84 reference system can easily be transformed to any local coordinates system. [1]

Real Time Kinematic (RTK) is one of the most common poisoning methods in GNSS. It is a Kinematic method of GNSS survey carried out in real time. The Reference Station has a radio (link / internet connection) attached and rebroadcasts the data and correction it receives from the satellites to rover station. The virtual reference station (VRS) concept of RTK can help to satisfy this requirement using a network of reference stations, to cover a wide area and high positioning accuracy using continuously operation network of reference stations and internet connections to the users. [1]

Static surveying is a relative positioning technique which employs two (or more) stationary receivers simultaneously tracking the same satellites. One receiver, the base receiver, is set up over a point with precisely known coordinates such as a survey monument. The other receiver, the remote receiver, is set up over a point whose coordinates are unknown. This method of surveying is based on collecting simultaneous measurements at both the base and remote receivers for a certain period of time, which, after processing, yield the coordinates of the unknown point. This type of survey is primarily used to create control where no control exists to very high accuracies. [1]

There are two methods of GNSS (The Global Navigation Satellite Systems) data processing. These are Post Processing and Real Time Processing. The Post Processing method of involves downloading of complete survey data and processing in office.

These are some of the online services for data processing: [2]

The 1st online service is AUSPOS is a free online GPS data processing service provided by Geoscience Australia.

The 2nd online service is TRIMBLE CENTREPOINT RTX POST PROCESSING: Trimble RTX™ is a global GNSS technology providing centimeter-level positioning accuracy, worldwide, at any time.

THE 3rd online service is CSRS – PRECISE POINT POSITIONING: Canadian Spatial Reference System – Precise Point Positioning (CSRS-PPP) is an online application for GNSS data post-processing that allows users to submit observation data over the Internet and recover, using precise GNSS Orbit and Clock information, enhanced positioning precisions in the Canadian Spatial Reference System (CSRS) and the International Terrestrial Reference Frame (ITRF). [2]

The 4th online service is SCRIPPS ORBIT AND PERMANENT ARRAY CENTER (SOPAC) SCRIPPS COORDINATE UPDATE TOOL (SCOUT): The Scripps Coordinate Update Tool (SCOUT) can be used to compute mean coordinates of a specific site, by submitting a RINEX file of a particular day.

The 5th online service is The AUTOMATIC PRECISE POSITIONING SERVICE (APPS) – JET PROPULSION LABORATORY APPS accepts GPS measurement files, and applies the most advanced GPS positioning technology from NASA's Jet Propulsion Laboratory to estimate the position of your GPS receivers, whether they are static, in motion, on the ground, or in the air.

The 6th online service is (OPUS): This Online Positioning User Service provides simple access to high-accuracy National Spatial Reference System (NSRS) coordinates. Upload a data file collected with a survey-grade GPS receiver and obtain an NSRS position via email.

The 7th online service GPS ANALYSIS AND POSITIONING SOFTWARE (GAPS): Precise point positioning (PPP) is one of the existing techniques for determining point coordinates using a GPS receiver. In this technique, observations produced by a single receiver are used to determine the receiver's location as well as other parameters such as receiver clock and total neutral atmosphere delay. [2]

The GPS Analysis and Positioning Software (GAPS) was initially developed at the University of New Brunswick by Rodrigo Leandro. Additions to the source code of the online version have been made by Landon Urquhart and Carlos Alex Garcia. [2]

The 8th online service is MAGICGNSS/PPP:The email version of magic GNSS/PPP (Precise Point Positioning), allows processing static and kinematic GPS and GLONASS real-time data in RINEX format. Only dual-frequency PPP is supported at the moment. [2]

1.2 problem statement:

This project is evaluating of (GNSS) post processing will be applied on a group of points that's finding its position using static survey, and then we used the online services to get the reports about these point and then we compare between these online services according to accuracy and usability.

1.3 Objective:

- To know the limitation of GNSS (The Global Navigation Satellite Systems) freely available online services.
- To know the best online service that provide us the best accuracy and usability.
- To know the change in the different parameters like time, file types, Rinex version and the changes in the observation rates.

1.4 Literature Review:

A similar previous study was caries out Palestine polytechnic university ,The first team worked to defined the relation between the Palestinian system and the GNSS coordinates. The second team aimed to verify the Palestinian geodetic network by measuring trigs using static method and calculating the difference between the original coordinates and the measured ones.

1.5 Methodology

The Methodology of work in this project will be achieved by observing several points using the static GNSS (The Global Navigation Satellite Systems) surveying in different period of time , Then processing the data by the online services .

1.6 Project Scope

This project consists of sex chapters as follows:

- Chapter One: A simple explanation about the project and an introduction to what will be done in the project.
- Chapter Two: gives an introduction about GNSS systems and satellite positioning me .
- Chapter Three: GNSS precise point positioning.
- Chapter Four: GNSS precise point positioning (PPP) online services.
- Chapter Five: Results and Analysis.
- Chapter Sex: conclusion and recommendation.

Chapter Two

GNSS Principles

2.1 Introduction.

2.2 Basics of GNSS.

2.3 GNSS System.

2.4 GNSS Segment.

2.5 Space Segment.

2.6 Control Segment.

2.7 User Segment.

2.8 GNSS Signals.

2.9 Current satellite constellation .

2.1　Introduction

A GNSS involves a set of satellites orbiting the Earth, continuously transmitting signals that enable users to determine their three dimensional (3D) position with global coverage.

The positioning principle uses at least four GNSS satellites with known coordinates to solve the elemental geometric problem involving the distances (ranges) of a user from these satellites. These ranges and satellite coordinates are determined by the user's receiver using signals and navigation data transmitted by the satellites; the resulting user coordinates can be computed to an accuracy of several meters. However, centimeter-level positioning can be achieved using more advanced techniques. [3]

2.2　Basics of GNSS

Navigation satellites work on the principle of trilateration. Position of an object is determined by its latitude, longitude on the spheroid and height above Mean Sea Level. If at the time of measurement, the instantaneous position of three satellites are known and the distance of the point of measurement from each of these three satellites is known, then the latitude, longitude and height of the point can be determined using simple distance formula. In practice, a fourth satellite is needed to adjust for timing biases. [4]

It does so by comparing a code generated by a satellite with the same code generated internally in the receiver. The time difference between the two codes multiplied by the speed of light gives the distance. That requires a very stable signal source on the satellites which is provided by the Rubidium clock which is used to generate the code and the carrier signal for the code. Each satellite has a unique code hence the receiver can identify each satellite in its view. The carrier also contains the precise orbital parameters of the satellite which is updated regularly. The orbital parameters are updated using Integrity and Range Monitoring Stations. A central control station uploads the orbital parameters and synchronizes the Rubidium clocks regularly on each GNSS satellite. [4]

Signals from the GNSS satellites are transmitted in the L-band in five designated frequencies named L1 to L5. Of these L1 and L2 are used by all GNSS satellites, L3 is set apart for transmission from satellites to ground stations to detect nuclear explosions. L4 is to be used for ionospheric corrections and L5 will eventually support safety-of-life applications for aviation and provide improved availability and accuracy. [4]

2.3   GNSS System

Global Positioning System, GPS – US

This is the oldest system which began operations in 1978 and grew to 32 planned satellites in Medium Earth Orbit, MEO of 20180 km. The orbits are so selected that at any given time at least six satellites are in view an observer anywhere on earth. Initially exclusive for military use, it was opened to the public in the mid 80s with a selective availability that restricted the positional accuracy to 100m. The military continues to enjoy 5m or better accuracy. SA was discontinued from 2000 during which time the military also developed technologies to deny GPS service on regional basis to potential adversaries. It is widely believed that this was used during the Kargil War. [4]

GLONASS – Russia

Starting with a decision in 1978 GLONASS became operational by 1993 over Russia with 12 satellites in 2 orbits at 19,130 km. Its full capacity and global coverage was achieved by 2015 with 23 of 27 satellites operational. The accuracies are comparable to but a little lower than GPS. However, the accuracies are better than GPS in the higher latitudes. The frequencies are the same L1 and L2 but originally adopted a different access mode, FDMA before shifting to CDMA. GLONASS also works on a different spheroid model but its difference from the WGS84 is less than 40cm. Using both GLONASS and GPS together, GNSS receivers have access to 50 satellites and therefore can provide better position location faster, particularly in urban canyons and rugged mountainous areas. [4]

Galileo – European Union

This project is being established by ESA under the leadership of Germany, France and Italy. Other European countries who have joined the project are Norway and Switzerland. Israel, Morocco and Ukraine have also joined the program. China was to have joined but later withdrew as it decided to proceed with its own Beidou program. The program seeks to develop independent capability in the civilian space as opposed to GPS, Beidou and GLONASS which are under military control. Galileo will have accuracy higher than GPS and GLONASS at one meter for public use and one centimeter for paid users. There is a provision for exclusive military use in case of extreme situations like war. The program was beset by funding problems as well as friction with US on security issues. However, these have been overcome and 12 of the planned 30 satellites are in orbit. Full operational status is expected by 2020. [4]

Galileo is unique as it is designed to provide a new global search and rescue (SAR) function as part of the MEOSAR system. Apart from relaying the distress signals from emergency beacons to the rescue coordination center, it will also provide a return link to the beacon to confirm receipt of the distress signal and launch of rescue efforts. This does not exist in the current Cospas Sarsat system. [4]

BeiDou-2 / COMPASS – China

The Chinese system began as a regional system, BeiDou-1 with three geostationary satellites serving China and its neighborhood. The signals were in the S-band and offered an accuracy of 20m. BeiDou-1 was decommissioned by end of 2012. [4]

BeiDou-2 is a completely new system consisting of 35 satellites of which five are planned to be in geostationary orbit to provide BeiDou-1 compatibility to existing ground systems, 25 are planned in MEO and 5 are planned in inclined geosynchronous orbits. From records of launches there are 6 in geostationary orbit, 8 in inclined geosynchronous orbit and 5 in MEO. The extra satellites in GEO and IGSO are possibly in orbit spares. The BeiDou-2 frequencies overlap the Galileo frequencies, thus providing interoperability between the two systems. As of now, the system is referred as the Beidou Navigation System, BDS, and currently serves China and its neighborhood. Beidou is expected to become operational globally by 2020 providing 10m accuracy for public and higher for military use. [4]

2.4 GNSS Segments

Global Navigation Satellite System (GNSS) is a generic term denoting a satellite navigation system (e.g. GPS, Glonass, Galileo and Beidou) (see fig 2.1)that provides continuous positioning over the globe. [3]
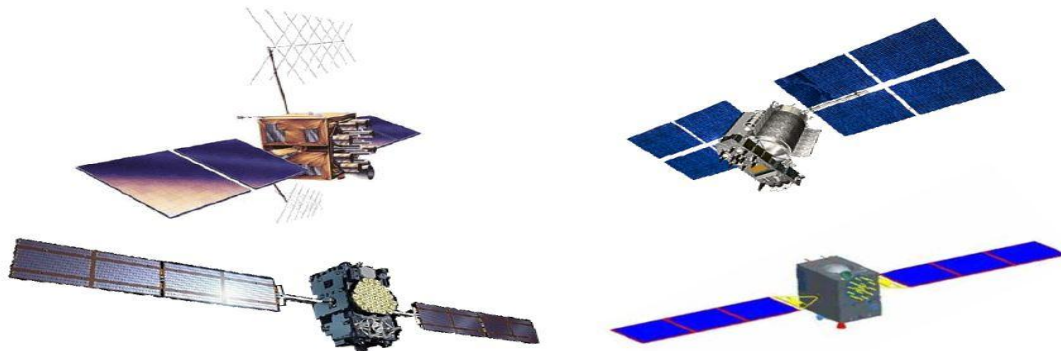
Figure 2.1: GNSS satellites GPS IIR-M (top left), Glonass-M(top right), Galileo IOV (bottom left) and Beidou-M (bottom right).

A GNSS basically consists of three main segments: the space segment, which comprises the satellites; the control segment (also referred to as the ground segment)(see fig 2.1), which is responsible for the proper operation of the system; and the user segment, which includes the GNSS receivers providing positioning, velocity and precise timing to users. [3]
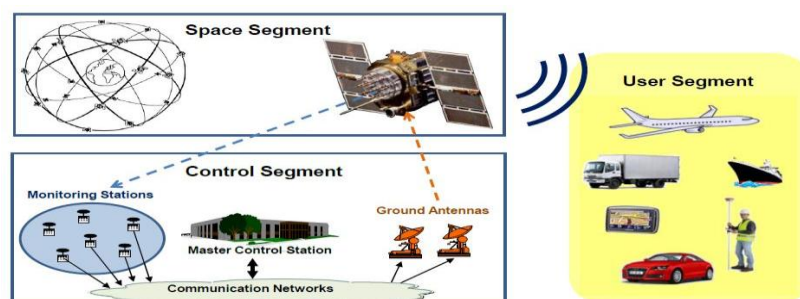
Figure 2.2: GNSS architecture.

2.5   Space Segment

The main functions of the space segment are to generate and transmit code and carrier phase signals, and to store and broadcast the navigation message uploaded by the control segment. These transmissions are controlled by highly stable atomic clocks onboard the satellites. The GNSS space segments are formed by satellite constellations with enough satellites to ensure that users will have at least four satellites in view simultaneously from any point on Earth's surface at any time. [3]

2.5.1 Satellite constellation

The GPS satellites are arranged in six equally spaced orbital planes surrounding Earth, each with four `slots' occupied by baseline satellites. This 24-slot arrangement ensures there are at least four satellites in view from virtually any point on the planet. The satellites are placed in a Medium Earth Orbit (MEO) orbit, at an altitude of 20200 km and an inclination of 55_ relative to the equator. Orbits are nearly circular, with an eccentricity of less than 0:02, a semi-major axis of 26 560km and a nominal period of 11 hours, 58 minutes and 2 seconds (12 sidereal hours), repeating the geometry each sidereal day. [3]

The nominal Glonass constellation consists of 24 MEO satellites deployed in three orbital planes with eight satellites equally spaced in each plane. The orbits are roughly circular, with an inclination of about 64:8°, and at an altitude of 19 100km with a nominal period of 11 hours, 15 minutes and 44 seconds, repeating the geometry every eight sidereal days. [3]

Due to funding problems, the number of satellites decreased from the 24 available in 1996 to only 6 in 2001. In August 2001, the Russian government committed to recover the constellation and to modernize the system, approving new funding. A total of 24 operational satellites plus 2 in maintenance were again available in December 2011, restoring the full constellation. [3]

The planned Galileo constellation in Full Operational Capability (FOC) phase consists of 27 operational and 3 spare MEO satellites at an altitude of 23 222 km and with an orbit eccentricity of 0:002. Ten satellites will occupy each of three orbital planes inclined at an angle of 56_ with respect to the equator. The satellites will be spread around each plane and will take about 14 hours, 4 minutes and 45 seconds to orbit Earth, repeating the geometry each 17 revolutions, which involves 10 sidereal days.

This constellation guarantees, under nominal operation, a minimum of six satellites in view from any point on Earth's surface at any time, with an elevation above the horizon of more than 10º. [3]

The Beidou (Compass) constellation (Phase III) will consist of 35 satellites, including 5 Geostationary Orbit (GEO) satellites and 30 non-GEO satellites in a nearly circular orbit. The non-GEO satellites include 3 Inclined Geosynchronous Satellite Orbit (IGSO) ones, with an inclination of about 55º, and 27 MEO satellites orbiting at an altitude of 21 528km in three orbital planes with an inclination of about 55º and with an orbital period of about 12 hours and 53 minutes, repeating the ground track every seven sidereal days. The GEO satellites, orbiting at an altitude of about 35 786 km, are positioned at 58.75ºE, 80ºE, 110.5ºE, 140ºE and 160ºE, respectively, and are expected to provide global navigation service by 2020. [3]

The previous Phase II involves a reduced constellation of four MEO, five GEO and five IGSO satellites to provide regional coverage of China and surrounding areas. The initial Phase II operating service with 10 satellites started on 27 December 2011. [3]

2.6 Control Segment

The control segment (also referred to as the ground segment) is responsible for the proper operation of the GNSS. Its basic functions are:

- to control and maintain the status and conjuration of the satellite constellation;
- to predict ephemeris and satellite clock evolution;
- to keep the corresponding GNSS time scale (through atomic clocks);
- and to update the navigation messages for all the satellites.

2.6.1 GPS Control Segment

The GPS control segment is composed of a network of Monitoring Stations (MS), a Master Control Station (MCS) and the Ground Antennas (GA) [ICD-GPS-200]. (See the layout in Fig. 2.3).

The Master Control Station is responsible for operating the system and providing command, control and maintenance services to the space segment. A new, fully functional backup station, known as the Alternate Master Control Station (AMCS), was set up as part of a modernization Plan. [3]

The Monitoring Stations are distributed around the world, They are equipped with atomic clock standards and GPS receivers to collect GPS data continuously for all the satellites in view from their locations.The collected data are sent to the Master Control Station where they are processed to estimate satellite orbits (ephemerides) and clock errors, among other parameters, and to generate the navigation message. [3]

The Ground Antennas uplink data to the satellites via S-band radio signals. These data include ephemerides and clock correction information transmitted within the navigation message, as well as command telemetry from the MCS. Every satellite can be uploaded three times per day, that is every eight hours; nevertheless, it is usually updated just once a day. [3]
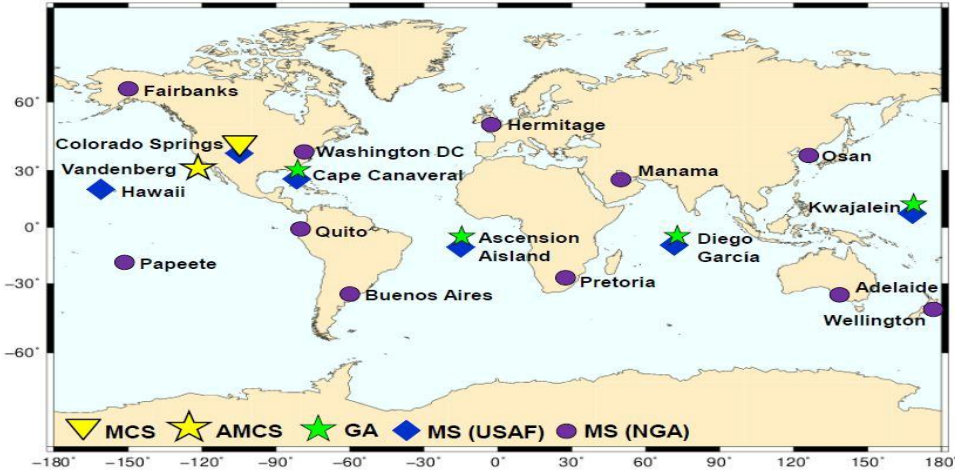
Figure 2.3: GPS ground infrastructure.

2.6.2 Glonass Control Segment

As in GPS, the Glonass control segment (or Ground-based Control Facilities) monitors the status of satellites, determines the ephemerides and satellite clock offsets with respect to Glonass time and Coordinated Universal Time (UTC), and, twice a day, uploads the navigation data to the satellites. [3]

The Glonass control segment comprises the System Control Centre (SCC), the Network of Command and Tracking Stations, entirely located within former Soviet Union territory, and the Central Synchronizer (CC-M) (the system clock) in Moscow.The SCC coordinates all functions and operations at the system level. It processes information from the command and tracking stations to determine the satellite clock and orbit states, and it updates the navigation message for each satellite. The command and tracking stations comprise a main network of five Telemetry, Tracking and Control (TT&C) stations distributed throughout the Russian territory, some of them equipped with laser ranging (Laser Station (LS)) and other monitoring facilities (MS), This network is complemented in the modernization plan by additional MS in the former Soviet Union territory See the layout in(Fig. 2.4) [3].

The Central Synchronizer is responsible for the Glonass time scale. It is connected with the phase control system' that monitors satellite clock time and phase signals.
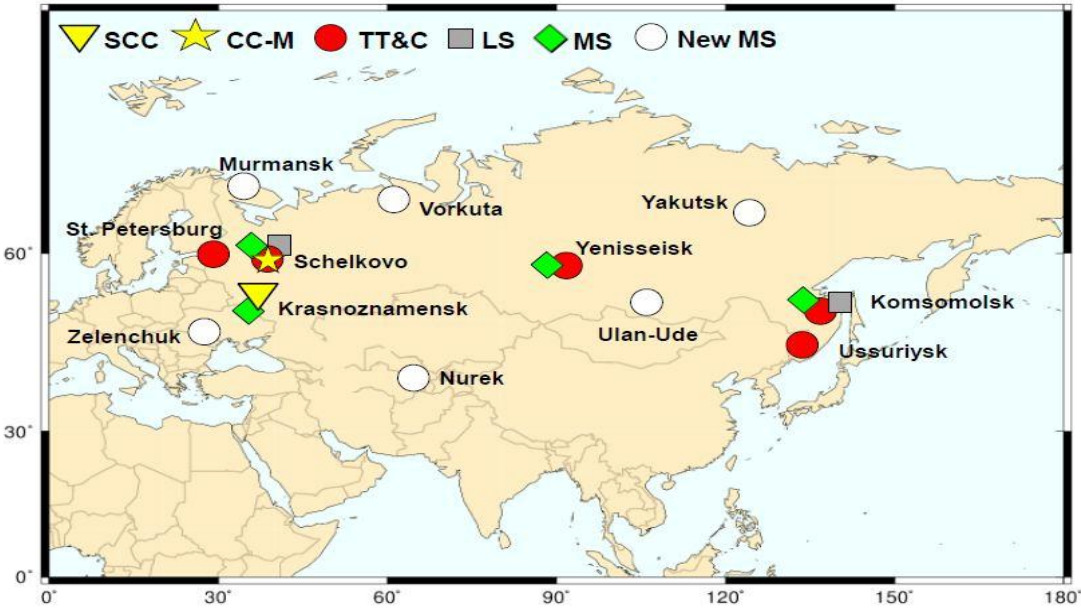
Figure 2.4: Glonass ground infrastructure.

2.6.3 Galileo Ground Segment

The Galileo ground segment controls the entire satellite constellation, the navigation system facilities and the dissemination services. The FOC involves two Ground Control Centre (GCC), five Telemetry, Tracking and Control (TT&C) stations, nine Mission Uplink Stations (ULS) and a worldwide network of Galileo Sensor Stations (GSS) ,(See the layout in Fig. 2.4) [3].

The Ground Control Segment (GCS) is responsible for the constellation control and management of Galileo satellites. It provides the TT&C function for the whole satellite constellation.

Its functional elements are deployed within the GCCs and the globally distributed TT&C stations. The TT&C stations use S-band frequency antennas 13m in diameter to provide a secure exchange of data between the control centers and satellites [3].

The Ground Mission Segment (GMS) is responsible for the determination and uplink of the navigation and integrity data messages needed to provide the navigation and UTC time transfer service. The GMS includes a worldwide network of GSS, continuously collecting data to be processed by GCC for determining Galileo navigation and integrity data messages. Each of the GSS is equipped with three parallel reception channels: one channel for the determination of orbit data and clock synchronization, a second channel for integrity determination, and a third redundant channel [3].

The global geographical distribution of such stations has been selected to ensure permanent access to any satellite of the constellation at any time. Navigation and integrity data are uplinked from the GCC to the satellites by nine ULS. These stations are equipped with C-band parabolic antennas about 3m in diameter [3].
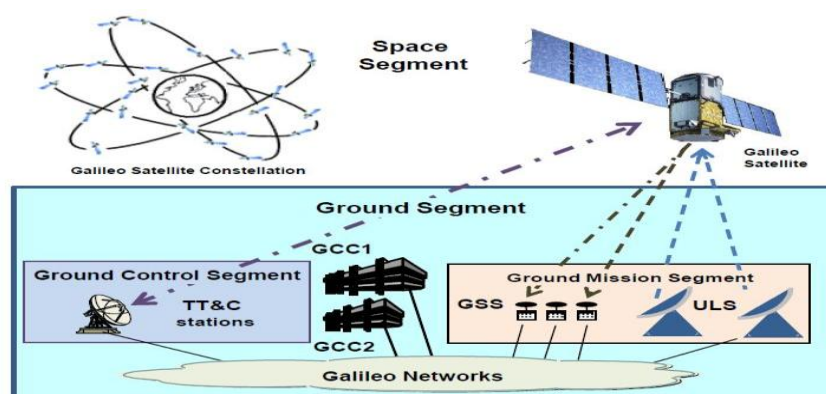
Figure 2.5: Galileo ground segment layout.

The uplinks are designed to ensure the provision of navigation and integrity information worldwide for all users, even in the case of a potential failure due to the loss of a single antenna.

A hybrid communication network interconnects the remote stations (ULS, GSS and TT&C stations) with the GCC by different means of standard and special radio, wired data and voice communication links, ensuring communication between all the sites [3].

The two GCC constitute the core of the ground segment. There are two redundant elements. Some of their main functions are:

- orbit determination and synchronization;
- control of all Galileo satellites and uploading navigation data messages;
- monitoring and control, performance monitoring, performance prediction and maintenance management functions of the ground segment elements;
- monitoring and control of all ground segment elements in real time;
- generation of navigation messages; and
- computation of Galileo System Time (GST) and provision of a reliable and stable coordinated time reference for the Galileo system.

2.6.4 Beidou Control Segment

- a Master Control Station: responsible for satellite constellation control and processing the measurements received by the Monitor Stations to generate the navigation message.
- Upload Stations: responsible for uploading the orbital corrections and the navigation message to BeiDou satellites.
- Monitor Stations, which collect BeiDou data for all the satellites in view from their locations.
- Currently, the Ground Segment includes one Master Control Station, two Upload Stations and 30 Monitor Stations.
- In addition, the system supports a short message communication service that can be exchanged between the station and the users.

2.7 User Segment

The user segment is composed of GNSS receivers. Their main function is to receive GNSS signals, determine pseudo ranges (and other observables) and solve the navigation equations in order to obtain the coordinates and provide a very accurate time.

The basic elements of a generic GNSS receiver are: an antenna with preamplification, a radio frequency section, a microprocessor, an intermediate-precision oscillator, a feeding source, some memory for data storage and an interface with the user. The calculated position is referred to the antenna phase center [3].

2.8 GNSS Signals

GNSS satellites continuously transmit navigation signals at two or more frequencies in band. These signals contain ranging codes and navigation data to allow users to compute both the travel time from the satellite to the receiver and the satellite coordinates at any epoch. [3]

The main signal components are described as follows:

Carrier*:* Radio frequency sinusoidal signal at a given frequency.

Ranging code*:* Sequences of zeros and ones which allow the receiver to determine the travel time of the radio signal from the satellite to the receiver. They are called PRN sequences or PRN codes.

Navigation data*:* A binary-coded message providing information on the satellite ephemeris (pseudo-Keplerian elements or satellite position and velocity), clock bias parameters, almanac (with a reduced-accuracy ephemeris data set), satellite health status and other complementary information.

2.8.1 GPS Signals

Legacy GPS signals are transmitted on two radio frequencies in the L band, referred to as Link 1 (L1) and Link 2 (L2), or L1 and L2 bands, (see table 2.1). They are right-hand circularly polarized and their frequencies are derived from a fundamental frequency f0 = 10:23 MHz, generated by onboard atomic clocks [3].

$$L1 = 154 \times 10:23 MHz = 1575.420 MHz$$
$$L2 = 120 \times 10:23 MHz = 1227.60 MHz$$

Two services are available in the current GPS system:

SPS: The Standard Positioning Service is an open service, free of charge for worldwide users. It is a single-frequency service in the frequency band L1.

PPS: The Precise Positioning Service is restricted by cryptographic techniques to military and authorized users. Two navigation signals are provided in two different frequency21 bands, L1 and L2. The GPS uses the CDMA technique to send different signals on the same radio frequency, and the modulation method used is Binary Phase Shift Keying (BPSK) .

Table 2.1: Legacy GPS signal structure.

Atomic clock frequency	f0 = 10:23 MHz
Frequency L1	154 _ f0
	1575.420 MHz
Wavelength L1	19.03 cm
Frequency L2	120 _ f0
	1227.600 MHz
Wavelength L2	24.42 cm
P code frequency (chipping rate)	f0 = 10:23 MHz (Mbps)
P code wavelength	29.31m
P code period	266 days, 7 days/satellite
C/A code frequency (chipping rate)	f0=10 = 1:023 MHz
C/A code wavelength	293.1m
C/A code period	1 ms
Navigation message frequency	50 bps
Frame length	30 s
Total message length	12.5 min

Table 2.2 contains a summary of the current and future GPS signals, frequencies and applied modulations. The ranging code rate and data rate are also given in the table.

Table 2.2: Current and new GPS navigation signals. All civil signals are provided free of charge to all users worldwide (Open Services).

Link	Carrier frequency (MHz)	PRN code	Modulation Type	Code rate (Mcps)	Data rate (bps)	Service
L1	1 575.420	C/A	BPSK(1)	1.023	50	Civil
		P	BPSK(10)	10.23	50	Military
		M	BOCsin(10,5)	5.115	N/A	Military
		L1C-I data	MBOC(6,1,1/11)	1.023	50	Civil
		L1C-I data			-	
L2	1 227.600	P	BPSK(10)	10.23	50	Military
		L2C M L	BPSK(1)	1.023	25	Civil
					-	
		M	BOCsin(10,5)		N/A	Military
L5	1 176.450	L5-I data	BPSK(10)	10.23	50	Civil
		L5-Q pilot			-	

The following types of PRN codes and messages are modulated over the two carriers. [3]

- Coarse/Acquisition (C/A) code, also known as civilian code C(t): This sequence contains 1023 bits and is repeated every millisecond (i.e. a chipping rate of 1:023 Mbps). Then, the duration of each C/A code chip is 1 µs, which means a chip width or wavelength of 293.1 m. This code is modulated only on L1. The C/A code defines the SPS.

- Precision code, P(t): This is reserved for military use and authorized civilian users. The sequence is repeated every 266 days (38 weeks) and a weekly portion of this code is assigned to every satellite, called the PRN sequence. Its chipping rate is 10 Mbps, which leads to a wavelength of 29.31 m. It is modulated over both carriers L1 and L2. This code defines the PPS.

- Navigation message, D(t): This is modulated over both carriers at 50 bps, reporting on ephemeris and satellite clock drifts, ionospheric model coefficients and constellation status, among other information.

$$S_{L1}(t) = a_p P_i(t) D_i(t) \sin(w_1 t + \emptyset_{L1}) + a_c C_i(t) D_i(t) \cos(w_1 t + \emptyset_{L1}).$$

$$S_{L2}(t) = b_p P_i(t) D_i(t) \sin(w_2 t + \emptyset_{L2}).$$

The index i stands for the i-the satellite. In order to restrict access of civilian users to full system accuracy, the following protection was introduced:

- S/A or Selective Availability: This covers intentional satellite clock degradation (process δ) and ephemeris manipulation (process δ). The effect on horizontal positioning ranges from about 10 m (S/A off) to 100 m (S/A on) (2σ error). The process δ acts directly on the satellite clock fundamental frequency, which has a direct impact on pseudo ranges to be calculated by users' receivers. The process δ consists of truncating information related to orbits. US President Bill Clinton ordered the cessation of GPS S/A on 2 May 2000. It was permanently removed in 2008, and not included in the next generations of GPS satellites. [3]

• A/S or Anti-Spoofing: This consists of P code encryption by combining it with a secret W code, resulting in the Y code, which is modulated over the two carriers L1 and L2. The purpose is to protect military receivers against an adversary transmitting a faulty copy of the GPS signal to mislead the receiver, and to deny access of nonauthorised users to the precise ranging code P at L1 and L2 frequencies (as the only C/A code available on L1). [3]

GPS Navigation Message

Every satellite receives from the ground antennas the navigation data, which are sent back to users through the navigation message. The navigation message contains all the necessary information to allow users to perform the positioning service. This includes the ephemeris parameters, needed to compute the satellite coordinates with sufficient accuracy, the time parameters and clock corrections, needed to compute satellite clock offsets and time conversions, the service parameters with satellite health information, the ionospheric parameters model, needed for single-frequency receivers, and the almanacs, allowing computation of the position of 'all satellites in the constellation', with a reduced accuracy (1{ 2 km of 1σ error), which is needed for acquisition of the signal by the receiver. The ephemeris and clock parameters are usually updated every two hours, while the almanac is updated at least every six days. [3]

2.8.2 Glonass Signals

Legacy Glonass signals are right-hand circularly polarized and centered on two radio frequencies in the L band, referred to here as the G1 and G2 bands, (see table 2.3&2.4) [3].

Two services are currently available from Glonass:
SPS: The Standard Positioning Service (or Standard Accuracy Signal Service) is an open service, free of charge to worldwide users. The navigation signal was initially provided only in the frequency band G1, but since 2004 the new Glonass-M satellites also transmits a second civil signal in G2. [3]
PPS: The Precise Positioning Service (or High-Accuracy Signal Service) is restricted to military and authorized users. Two navigation signals are provided in the two frequency bands G1 and G2.

Table 2.3: Legacy Glonass signal structure.

Atomic clock frequency	f0 = 10:23 MHz
Frequency L1	154 _ f0
	1575.420 MHz
Wavelength L1	19.03 cm
Frequency L2	120 _ f0
	1227.600 MHz
Wavelength L2	24.42 cm
P code frequency (chipping rate)	f0 = 10:23 MHz (Mbps)
P code wavelength	29.31m
P code period	266 days, 7 days/satellite
C/A code frequency (chipping rate)	f0=10 = 1:023 MHz
C/A code wavelength	293.1m
C/A code period	1 ms
Navigation message frequency	50 bps
Frame length	30 s
Total message length	12.5 min

Table 2.4: Legacy Glonass navigation Signals. All civil signals free of charge to all users . The military codes are for authorized users only.

Band	Carrier freq (MHz)	PRN code	Modulation type	Code rate (Mcps)	Data rate (bps)	Service
G1	1602.0000+ +0.5625k	C/A	BPSK(0.511Mcps)	0.511	50	Civil
		P	BPSK(5.11 Mcps)	5.11	50	Military
G2	1246.0000+ +0.4375k	C/A	BPSK(0.511 Mcps)	0.511	50	Civil
		P	BPSK(5.11 Mcps)	5.11	50	Military

Note: k = 1,…..,24 for satellites launched before 2005; subsequently k = -7,…..,6.

Glonass Navigation Message

Glonass satellites modulate two navigation messages at 50 bps onto the standard (C/A) and high-accuracy (P) signals , each message giving users the necessary information for positioning (i.e. parameters to compute the coordinates of the Glonass satellites, their clock offsets and various other system parameters). [3]

The navigation message of the standard accuracy signal (C/A) is broadcast as continuously repeating super frames with a duration of 2:5 min. Each superframe consists of five frames of 30 s, and each frame consists of 15 strings of 2 s duration (100 bits long).

The message content divides the data into immediate data of the transmitting satellite and non-immediate data for the other satellites. The immediate data are repeated in the first four strings of every frame and comprise the ephemeris parameters, satellite clock offsets, satellite healthy flag and the relative difference between the carrier frequency of the satellite and its nominal value. The non-immediate data are broadcast in strings 5 to 15 of each frame (almanac for 24 satellites). Frames I to IV contain the almanac for 20 satellites (5 per frame), and the fifth frame almanac for 4 satellites.The last two strings of frame are reserved bits (the almanac of each satellite uses two strings). [3]

2.8.3 Galileo Signals

In FOC phase, each Galileo satellite will transmit 10 navigation signals in the frequency bands E1, E6, E5a and E5b, each right-hand circularly polarized, (see table2.5). These signals are designed to support the different services that will be offered by Galileo and EGNOS, based on various user needs as follows: [3]

OS: The Open Service (OS) is free of charge to users worldwide. Up to three separate signal frequencies are offered within it. Singlefrequency receivers will provide performances similar to GPS C/A.

In general, OS applications will use a combination of Galileo and GPS signals, which will improve performance in severe environments such as urban areas.

PRS: The Public Regulated Service (PRS) is intended for the security authorities (police, military, etc.) who require a high continuity of service with controlled access. It is under governmental control. Enhanced signal modulation/encryption is introduced to provide robustness against jamming and spoofing. Two PRS navigation signals with encrypted ranging codes and data will be available.

CS: The Commercial Service (CS) provides access to two additional signals protected by commercial encryption (ranging data and messages).Higher data rates (up to 500 bps) for broadcasting data messages are introduced.

SAR: This service contributes to the international Cospas-Sarsat system for Search and Rescue (SAR). A distress signal will be relayed to the Rescue Coordination Centre and Galileo will inform users that their situation has been detected.

SoL: The Safety-of-Life (SoL) Service is already available for aviation to International Civil Aviation Organization (ICAO) standards thanks to EGNOS; Galileo will further improve the service performance. [3]

Table 2.5: Galileo navigation signals. The two signals located in the E5a and E5b bands respectively are modulated onto a single E5 carrier frequency of 1191.795 MHz using the AltBOC technique: AltBOC(15,10).

Band	Carrier freq. (MHz)	Channel or sig. comp.	Modulation type	Code rate (Mcps)	Data rate (bps)	Services
E1	1575.420	E1-A data	BOCcos(15,2.5)	2.5575	N/A	PRS
		E1-B data	MBOC(6,1,1/11)	1.023	125	OS, CS, SoL
		E1-C pilot			-	
E6	1278.750	E6-A data	BOCcos(10,5)	5.115	N/A	PRS
		E6-B data	BPSK(5)		500	CS
		E6-C pilot			-	
E5a	1176.450	E5a-I data	BPSK(10	10.23	25	OS
		E5a-Q pilot			-	
E5b	1207.140	E5b-I data	BPSK(10	10.23	125	OS, CS, SoL
		E5b-Q pilot			-	

Galileo Navigation Message

The Galileo satellites will broadcast five types of data in four navigation messages: the Freely accessible Navigation Message (F/NAV) and Integrity Navigation Message (I/NAV),the Commercial Navigation Message (C/NAV) and the Governmental Navigation Message (G/NAV).Table2.6 summarizes the contents of the Galileo messages, with an indication of the associated channels and services. [3]

Table 2.6: Contents of the Galileo message types.

Message-type	F/NAV	I/NAV		C/NAV	G/NAV
Galileo Services	OS	OS/CS/SoL		CS	PRS
Channels	E5a-I	E1B	E5b-I	E6B	E1A E6A
Navigation/Positioning	×	×	×		×
Integrity		×	×		×
Supplementary				×	
Public Regulated					×
Search and Rescue		×			

2.8.4 Beidou Signals

Beidou Phase II/III satellites will transmit right-hand circularly polarized signals centered on three radio frequencies in the L band, referred to here astheB1,B2 and B3 bands. Two services are foreseen for the Beidou system (in Phase II as a regional service and Phase III as a global service)(see table 2.7&2.8) [3].

Open Service: The SPS (or Standard Accuracy Signal Service) is an open service, free of charge to all users.

Authorized Service: This service will ensure very reliable use, providing safer positioning, velocity and timing services, as well as system information, for authorized users.

Table 2.7: Beidou Phase II navigation signals .Quadrature Phase Shifted Keying (QPSK) and BPSK modulation squemes are applied.

Band	Carrier freq. (MHz)	PRN code	Modulation type	Code rate (Mcps)	Services
B1	1561.098	B1-I	QPSK(2)	2.046	Open
		B1-Q			Authorized
B2	1207.14	B2-I	BPSK(2)	2.046	Open
		B2-Q	BPSK(10)	10.23	Authorised
B3	1268.52	B3	QPSK(10)	10.23	Authorised

Table 2.8: Beidou Phase III navigation signals.

Band	Carrier freq. (MHz)	PRN code	Modulation type	Code rate (Mcps)	Data rate (bps)	Services
B1	1575.42	B1-C_D	MBOC(6,1,1/11)	1.023	50	Open
		B1-C_D			-	
		B1	BOC(14,2)	2.046	50	Authorised
B2	1191.795	B2-a_D	AltBOC(15,10)	10.23	25	Open
		B2-a_P			-	
		B2-b_D			50	
		B2-b_P			-	
B3	1268.52	B3	QPSK(10)	10.23	500	Authorised
		B3-A_D	BOC(15,2.5)	2.5575	50	
		B3-A_P			-	

2.9 Current satellite constellation

2.9.1 GPS constellation Status [5]

GPS CONSTELLATION STATUS, 06.04.18

Total satellites in constellation	32 SC
Operational	31 SC
In commissioning phase	-
In maintenance	1 SC
In decommissioning phase	-

GPS CONSTELLATION STATUS FOR 06.04.18 UNDER THE ANALYSIS OF THE ALMANAC ACCEPTED IN IAC

Plane	Slot	PRN	NORAD	Type SC	Launch date	Input date	Outage date	Life-time (months)	Notes
A	1	24	38833	II-F	04.10.12	14.11.12		64.7	
	2	31	29486	IIR-M	25.09.06	13.10.06		137.9	
	3	30	39533	II-F	21.02.14	30.05.14		46.3	
	4	7	32711	IIR-M	15.03.08	24.03.08		120.5	
B	1	16	27663	II-R	29.01.03	18.02.03		181.7	
	2	25	36585	II-F	28.05.10	27.08.10		91.4	
	3	28	26407	II-R	16.07.00	17.08.00		211.8	
	4	12	29601	IIR-M	17.11.06	13.12.06		135.8	
	5	26	40534	II-F	25.03.15	20.04.15		35.6	
	6		34661	IIR-M	24.03.09				
C	1	29	32384	IIR-M	20.12.07	02.01.08		123.2	
	2	27	39166	II-F	15.05.13	21.06.13		57.5	
	3	8	40730	II-F	15.07.15	12.08.15		31.8	
	4	17	28874	IIR-M	26.09.05	13.11.05		148.8	
	5	19	28190	II-R	20.03.04	05.04.04		168.1	
D	1	2	28474	II-R	06.11.04	22.11.04		160.5	
	2	1	37753	II-F	16.07.11	14.10.11		77.8	
	3	21	27704	II-R	31.03.03	12.04.03		179.9	
	4	6	39741	II-F	17.05.14	10.06.14		45.9	
	5	11	25933	II-R	07.10.99	03.01.00		219.2	
	6	18	22877	II-A	26.10.93	22.11.93		292.6	
E	1	3	40294	II-F	29.10.14	12.12.14		39.8	
	2	10	41019	II-F	30.10.15	09.12.15		27.9	
	3	5	35752	IIR-M	17.08.09	27.08.09		103.4	
	4	20	26360	II-R	11.05.00	01.06.00		214.3	
	6	22	28129	II-R	21.12.03	12.01.04		170.9	
F	1	32	41328	II-F	05.02.16	09.03.16		24.9	
	2	15	32260	IIR-M	17.10.07	31.10.07		125.3	
	3	9	40105	II-F	02.08.14	17.09.14		42.6	
	4	23	28361	II-R	23.06.04	09.07.04		165.0	
	5	14	26605	II-R	10.11.00	10.12.00		208.0	
	6	13	24876	II-R	23.07.97	31.01.98		242.3	

2.9.2 GLONASS constellation Status [6]

GLONASS CONSTELLATION STATUS, 06.04.2018

Total satellites in constellation		25 SC
Operational		24 SC
	In commissioning phase	-
	In maintenance	-
	Under check by the Satellite Prime Contractor	-
	Spares	-
	In flight tests phase	1 SC

GLONASS CONSTELLATION STATUS AT 06.04.2018 BASED ON BOTH THE ALMANAC ANALYSIS AND NAVIGATION MESSAGES RECEIVED AT 12:00 06.04.18 (UTC) IN IAC PNT TSNIIMASH

Orb. slot	Orb. pl.	RF chnl	# GC	Launched	Operation begins	Operation ends	Life-time (months)	Satellite health status		Comments
								In almanac	In ephemeris (UTC)	
1	1	01	730	14.12.09	30.01.10		99.8	+	+ 12:06 06.04.18	In operation
2	1	-4	747	26.04.13	04.07.13		59.4	+	+ 12:06 06.04.18	In operation
3	1	05	744	04.11.11	08.12.11		77.1	+	+ 12:06 06.04.18	In operation
4	1	06	742	02.10.11	25.10.11		78.2	+	+ 12:06 06.04.18	In operation
5	1	01	734	14.12.09	10.01.10		99.8	+	+ 12:06 06.04.18	In operation
6	1	-4	733	14.12.09	24.01.10		99.8	+	+ 12:06 06.04.18	In operation
7	1	05	745	04.11.11	18.12.11		77.1	+	+ 12:06 06.04.18	In operation
8	1	06	743	04.11.11	20.09.12		77.1	+	+ 12:06 06.04.18	In operation
9	2	-2	702	01.12.14	15.02.16		40.2	+	+ 12:06 06.04.18	In operation
10	2	-7	717	25.12.06	03.04.07		135.5	+	+ 12:06 06.04.18	In operation
11	2	00	753	29.05.16	27.06.16		22.3	+	+ 12:06 06.04.18	In operation
12	2	-1	723	25.12.07	22.01.08		123.5	+	+ 12:06 06.04.18	In operation
13	2	-2	721	25.12.07	08.02.08		123.5	+	+ 12:06 06.04.18	In operation
14	2	-7	752	22.09.17	16.10.17		6.4	+	+ 12:06 06.04.18	In operation
15	2	00	716	25.12.06	12.10.07		135.5	+	+ 12:06 06.04.18	In operation
16	2	-1	736	02.09.10	04.10.10		91.2	+	+ 12:06 06.04.18	In operation
17	3	04	751	07.02.16	28.02.16		25.9	+	+ 12:06 06.04.18	In operation
18	3	-3	754	24.03.14	14.04.14		48.5	+	+ 12:06 06.04.18	In operation
19	3	03	720	26.10.07	25.11.07		125.4	+	+ 12:06 06.04.18	In operation
20	3	02	719	26.10.07	27.11.07		125.4	+	+ 12:06 06.04.18	In operation
21	3	04	755	14.06.14	03.08.14		45.8	+	+ 12:06 06.04.18	In operation
22	3	-3	731	02.03.10	28.03.10		97.2	+	+ 12:06 06.04.18	In operation
23	3	03	732	02.03.10	28.03.10		97.2	+	+ 12:06 06.04.18	In operation
24	3	02	735	02.03.10	28.03.10		97.2	+	+ 12:06 06.04.18	In operation
20	3	-5	701	26.02.11			85.3			Flight Tests

2.9.3 BEIDOU constellation Status [7]

BEIDOU CONSTELLATION STATUS 06.04.18

Total satellites in constellation	31
SV is included in operational orbital constellation	15
SV is not included in operational orbital constellation	16

BEIDOU CONSTELLATION STATUS 06.04.18

Satellite Number	No.	NORAD	Satellite Name	Type of sistem	Launch date	Outage date	Life-time (days)	Notes
---	002	34779	BDS-G2	Beidou-2	15.04.2009		---	Not in operational orbital constellation
C01	003	36287	BDS-G1	Beidou-2	16.01.2010		2999	In operation
C02	016	38953	BDS-G6	Beidou-2	25.10.2012		1989	In operation
C03	004	36590	BDS-G3	Beidou-2	02.06.2010		2865	In operation
C04	006	37210	BDS-G4	Beidou-2	31.10.2010		2713	In operation
C05	011	38091	BDS-G5	Beidou-2	24.02.2012		2232	In operation
C06	005	36828	BDS-IGSO1	Beidou-2	31.07.2010		2805	In operation
C07	007	37256	BDS-IGSO2	Beidou-2	17.12.2010		2666	In operation
C08	008	37384	BDS-IGSO3	Beidou-2	09.04.2011		2553	In operation
C09	009	37763	BDS-IGSO4	Beidou-2	26.07.2011		2445	In operation
C10	010	37948	BDS-IGSO5	Beidou-2	01.12.2011		2317	In operation
C11	012	38250	BDS-M3	Beidou-2	29.04.2012		2167	In operation
C12	013	38251	BDS-M4	Beidou-2	29.04.2012		2167	In operation
C13	014	38774	BDS-M5	Beidou-2	18.09.2012	21.10.2014	---	Not in operational orbital constellation
C13	017	41434	BDS-IGSO6	Beidou-2	29.03.2016		737	In operation
C14	015	38775	BDS-M6	Beidou-2	18.09.2012		2025	In operation
C17	018	41586	BDS-G7	Beidou-2	12.06.2016		663	In operation
C19	201	43001	BDS-3-M1	Beidou-3	05.11.2017		---	Not in operational orbital constellation
C20	202	43002	BDS-3-M2	Beidou-3	05.11.2017		---	Not in operational orbital constellation
C21	205	43207	BDS-3-M3	Beidou-3	12.02.2018		---	Not in operational orbital constellation
C22	206	43208	BDS-3-M4	Beidou-3	12.02.2018		---	Not in operational orbital constellation
C27	203	43107	BDS-3-M7	Beidou-3	11.01.2018		---	Not in operational orbital constellation
C28	204	43108	BDS-3-M8	Beidou-3	11.01.2018		---	Not in operational orbital constellation
C29		43245	BDS-3-M9	Beidou-3	30.03.2018		---	Not in operational orbital constellation
C30	001	31115	BDS-M1	Beidou-2	13.04.2007		---	Not in operational orbital constellation
C30		43246	BDS-3-M10	Beidou-3	30.03.2018		---	Not in operational orbital constellation
C31	101	40549	BDS-I1-S	Beidou-3	30.03.2015		---	Not in operational orbital constellation
C32	104	40938	BDS-I2-S	Beidou-3	29.09.2015		---	Not in operational orbital constellation
C33	102	40748	BDS-M1-S	Beidou-3	25.07.2015		---	Not in operational orbital constellation
C34	103	40749	BDS-M2-S	Beidou-3	25.07.2015		---	Not in operational orbital constellation
C35	105	41315	BDS-M3-S	Beidou-3	01.02.2016		---	Not in operational orbital constellation

Chapter Three

GNSS Time Reference, Coordinate Frames and Orbits

3.1 Introduction

Accurate and well-defined time references and coordinate frames are essential in GNSSs, where positions are computed from signal travel time measurements and provided as a set of coordinates. [3]

3.2 Time

Everyday life follows the alternation of day and night, and the seasons of the year, so the initial conception of time was based on the motion of the Sun. However, as science and technology evolved, more precise, uniform and well-defined time scales were needed .Several time references are currently in operation, based on different periodic processes associated with Earth's rotation, celestial mechanics or transitions between the energy levels in atomic oscillators. (Table 3.1) summarizes the different time systems and their associated periodic process. [3]

Table 3.1: Different time systems.

Periodic process	Time
Earth's rotation	Universal Time (UT0, UT1, UT2) Greenwich Sidereal Time (Θ)
Earth revolution	Terrestrial Dynamic Time (TDT) Bar centric Dynamic Time (TDB)
Atomic oscillators	International Atomic Time (TAI) Coordinated Universal Time (UTC) GNSS Reference Time

Universal and sidereal times are associated with the daily rotation of the Earth. Universal Time (solar time) uses the Sun as a reference. Sidereal time uses the vernal equinox (the Aries point).1 This leads to the fact that, in a year, both times differ by 24 h (one lap) and, hence, the sidereal day is shorter than the solar day by 3m 56s ·4. That is, 1 mean sidereal day = 1 mean solar day - 3m 56s ·4 UT (UT0, UT1, UT2) is not completely uniform,2 so atomic time TAI was introduced to achieve a more uniform time scale. TAI and UT accumulate drift over time and, consequently, UTC was defined, which is an atomic time that remains within 0:9 s of UT1. This is maintained by the systematic introduction of a certain number of seconds called leap seconds.3 Over time, the difference between UTC and TAI varies in integer leaps of 1s. [3]

UTC is generated by the Bureau International des Poids et Measures, located in Paris. Leap seconds are determined by the International Earth Rotation and Reference Systems Service (IERS). UTC is obtained from about 250 cesium clocks and hydrogen masers located in about 65 different laboratories, distributed around the world, and applying a set of algorithms to ensure a uniform time. It is not determined in real time, but generated with a delay of about half a month. Realtime estimates of UTC are computed and provided by different centers, such as UTC(USNO), from the United States Naval Observatory (USNO); UTC(NIST), from the National Institute of Standards and Technology (NIST); and UTC(SU) from Russia. In general, UTC(k) is a realization of UTC by a given laboratory k, The following relations are met;

$$TAI=UTC+1s\times n \qquad\qquad TAI=TDT-32s\cdot184$$

$$UTC=UT1+dUT1 \qquad\qquad jdUT1j < 0s \cdot 9$$

where n is the number of leap seconds introduced for a given epoch (e.g.1 Jan 1999   n = 32, 1 Jan 2006 n = 33, 1 Jan 2009 n = 34, 1 Jul 2012n = 35); see Fig. 3.1. GPS Time (GPST) is a continuous time scale (no leap seconds) defined by the GPS control segment on the basis of a set of atomic clocks at the MCS and onboard the satellites. It starts at 0h UTC (midnight) of 5{6 January 1980 (6d · 0). At that epoch, the difference TAI-UTC was 19 s, hence GPS-UTC = n - 19s. GPST is synchronized with UTC(USNO) at the 1 m_s level (modulo 1 s), but actually kept within 25ns. [3]
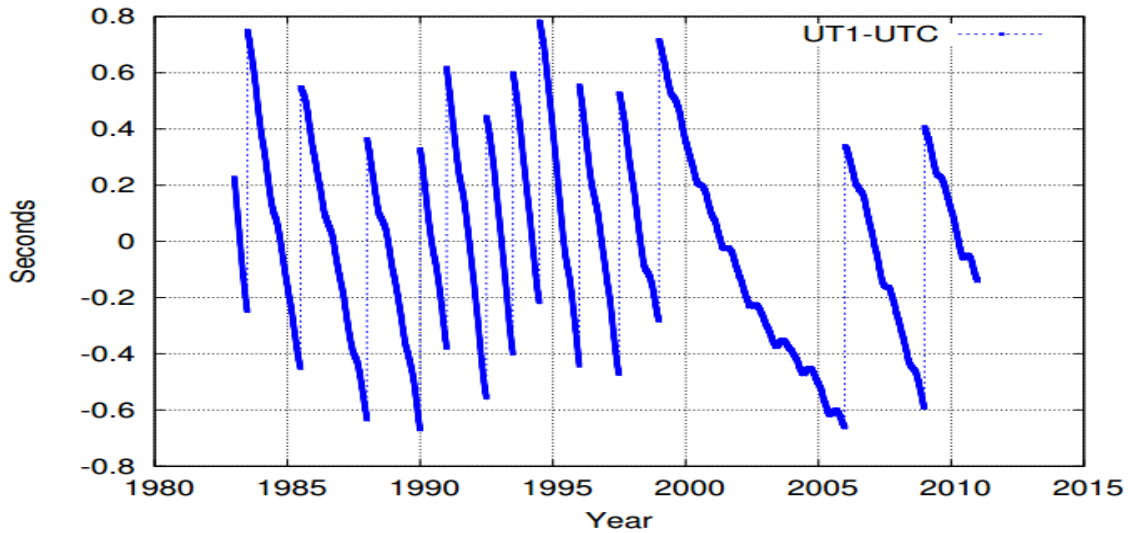
Figure 3.1: UT1-UTC and the leap second adjustments (data from USNO).

Glonass Time (GLNT) is generated by the Glonass Central Synchronizer. The difference between UTC(SU) and GLNT should not exceed 1 ms plus 3 h (i.e., tGlonass = UTC(SU) + 3h - τ, where jτj < 1 ms), but τ is typically better than 1 μs. Note that, unlike GPS, Galileo or Beidou, the Glonass time scale implements leap seconds, like UTC. [3]

Galileo System Time (GST) is a continuous time scale maintained by the Galileo central segment and synchronized to TAI with a nominal offset below 50 ns. The GST start epoch is 0h UTC on Sunday, 22 August 1999. [3]

BeiDou Time (BDT) is a continuous time scale starting at 0h UTC on 1 January 2006, and is synchronized to UTC within 100 ns (modulo 1 s). In order to facilitate calculations for long time intervals, the Julian date is used (after Julio Scalier). It has as reference epoch the 1st of January of 4713 BC and, starting from there, days are counted in a correlative way. The Julian Day (JD) starts at 12h of the corresponding civil day (e.g. 6d · 0 January 1980 = JD 2 444 244:5). The current reference standard epoch for the scientific community is

$$J2000.0 = 1d:5 \text{ January } 2000 = JD \ 2 \ 451 \ 545:0$$

The Modified Julian Day (MJD) is also used, and is obtained by subtracting 2400 000:5 days from the JD. [3]

The following expression gives the JD for a civil date (YYMMDDUT)

> JD = int[365:25 × y] + int[30:6001 × (m + 1)] + DD + UT(h)=24 + 1 720 981:5
>
> where: y=Y-1,m=MM+12,   MM≤2
>
>   y = YY, m = MM,   MM >2

From the JD, and taking into account that GPS reference date (6 January 1980) corresponds to JD 2 444 244.5, one can immediately obtain the GPST. Then, using modulo 7, the GPS week can be found. [3]

As another example, the 00:00 hours (Moscow time) on 1 January 1975 (21:00 hours GMT on 31 December 1974) used by Glonass as a reference time in some computations corresponds to JD 2 442 413:375 (GMT).Greenwich Mean Sidereal Time (GMST) (θG) and UT are related by the following expression. [3]

> θ_G = r.UT1 + $6^h41^m50^s$. 5481+8 640 184^s.812 866 T_u +0.^{s}093 104 T_u^2- 6.^{s} 2.10^{-6} T_u^2
>
> where: r = 1.0027379093 and Tu = (JD[UT1 date] − 2451545.0)/36525.0

3.3 Reference Systems and Frames

Satellite coordinates and users' receivers must be expressed in a well-defined reference system. Therefore an accurate definition and determination of such systems is essential to ensure precise positioning in GNSS. Two of the main reference systems used in satellite navigation (see Fig. 3.2) are introduced below: the Conventional Celestial Reference System (also called the Conventional Inertial System, CIS) and the Conventional Terrestrial Reference System (also called the Coordinated Terrestrial System, CTS). [3]

• Conventional Celestial Reference System (CRS): This is a quasi-inertial reference system. It has its origin at the Earth's center of mass, or geocentre. The X-axis points in the direction of the mean vernal equinox at the J2000.0 epoch, the Z-axis is orthogonal to the plane defined by the mean equator at the J2000.0 epoch (fundamental plane) and the Y-axis is orthogonal to the former axes, so the system is directly (right-handed) oriented. [3]

The practical implementation is called the (conventional) Celestial Reference Frame (CRF) and it is determined from a set of precise coordinates of extragalactic radio sources (i.e. it is fixed with respect to distant objects of the Universe). The mean equator and equinox J2000.0 were defined by International Astronomical Union (IAU) agreements. which are valid analytic expressions for long time intervals . [3]

• Conventional Terrestrial Reference System (TRS): This is a reference system co-rotating with the Earth in its diurnal rotation, and is also called the Earth-Centered, Earth-Fixed (ECEF) system. Its definition involves a mathematical model of the physical Earth in which point positions are expressed and have small temporal variations due to geophysical effects (plate motion, tides, etc.). [3]

The TRS has its origin in Earth's center of mass. The Z-axis is identical to the direction of Earth's axis of rotation as defined by the Conventional Terrestrial Pole (CTP), the X-axis is defined as the intersection of the equatorial plane (orthogonal to the Z-axis) with the mean Greenwich meridian, and the Y-axis is orthogonal to both of them, directly orienting the system. The realization of this system is called the (conventional) Terrestrial Reference Frame (TRF) and it is determined through the coordinates of a set of points on Earth serving as reference points.10 An example of the TRF is the International Terrestrial Reference Frame (ITRF), introduced by the International Earth Rotation and Reference Systems Service (IERS) and updated every year (ITRF98, ITRF99, etc.). Other terrestrial reference frames are the World Geodetic System 84 (WGS-84), which is applied for GPS, the Parameter Zemli 1990 (Parameters of the Earth 1990) (PZ-90) for Glonass, the Galileo Terrestrial Reference Frame (GTRF) for Galileo, or the China Geodetic Coordinate System 2000 (CGCS2000) for Beidou. [3]
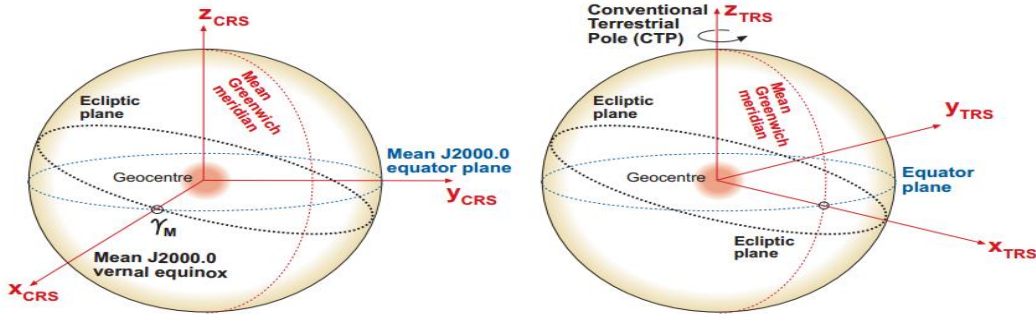
Figure 3.2: Reference systems :CRS (*left*) and TRS (*right*).

3.3.1 Transformation between Celestial and Terrestrial Frames

Coordinate transformations between CRF and TRF frames are performed by mean of rotations corresponding to precession, nutation and pole movement, described briefly as follows.

• Precession and nutation (forced rotation): Earth's axis of rotation (and its equatorial plane) is not kept fixed in space (i.e. in relation to so-called 'fixed stars'), but rotates about the pole of the ecliptic, (as shown in Fig. 3.3). This movement is due to the effect of the gravitational attraction of the Moon and the Sun and major planets over the terrestrial ellipsoid. The total movement can be split into a secular component (precession, with a period of 26 000 years) and a periodic component (nutation, with a period of 18:6 years).

• Pole movement (free rotation): Due to the structure of Earth's distribution of mass and its variation, Earth's axis of rotation is not fixed in relation to Earth's crust. It moves about on the surface of Earth within a square of about 20 m side in relation to a point with fixed coordinates on Earth. This movement has a period of about 430 sidereal days (the Chandler period). On the other hand, Earth's velocity of rotation is not constant but changes in time (although in very small quantities), as mentioned in the previous section. The following equations briefly summarize such a transformation. [3]

For a given epoch t, the coordinate transformation can be decomposed into a rotation matrix (i.e. orthogonal matrix) product as

$$[TRF] = R_M(t)R_s(t)N(t)P(t)[CRF] \tag{3.1}$$

And the inverse transformation

$$[CRF] = P^T(t) \, N^T(t) \, R_S^T(t) R_M^T(t)[\text{TRF}] \tag{3.2}$$

P is the transformation matrix associated with the precession between the reference epoch and the epoch t,

N is the transformation matrix associated with the nutation at epoch t,

RS is the transformation matrix associated with Earth's rotation around the Celestial Ephemeris Pole (CEP) axis,

RM is the transformation matrix associated with the polar motion. [3]

The matrices P and N are associated with the rotations needed to transform the coordinates from the [CRF] to the [CEP]. They are provided by analytical expressions and do not require external parameters. [3]

The matrices RS and RM are associated with the rotations needed to transform the coordinates from the [CEP] to the [TRF]. Their computation requires the Earth Rotation Parameters (ERP) and Earth Orientation Parameters (EOP) files that are compiled periodically; [3]

$$R_M(t) = R_2(-x_p)R_1(-y_p) \tag{3.3}$$

Where

x_p and y_p are the coordinates of the CEP in the TRF, and R_1 and R_2 are the rotation matrices defined by equation (3.6) below,

The transformation matrix associated with Earth's rotation around the CEP-axis is given by

$$R_s(t) = R_3(\theta_G) \tag{3.4}$$

Where

θ_G is the Greenwich true sidereal time at epoch t and R_3 is from equation (3.6) below.

Figure 3.3 outlines the transformation between the celestial and terrestrial frames. Through precession and nutation corrections, the mean equator and mean equinox J2000.0 (γ_M) are transformed to the true equator and true equinox (γ_T) at the epoch of observation. They define a reference system with the Z-axis in the direction of the instantaneous axis of rotation of Earth (CEP), and with the X-axis pointing to the true Aries point. Finally, using ERP and EOP files, the CEP system is transformed to the TRF. [3]
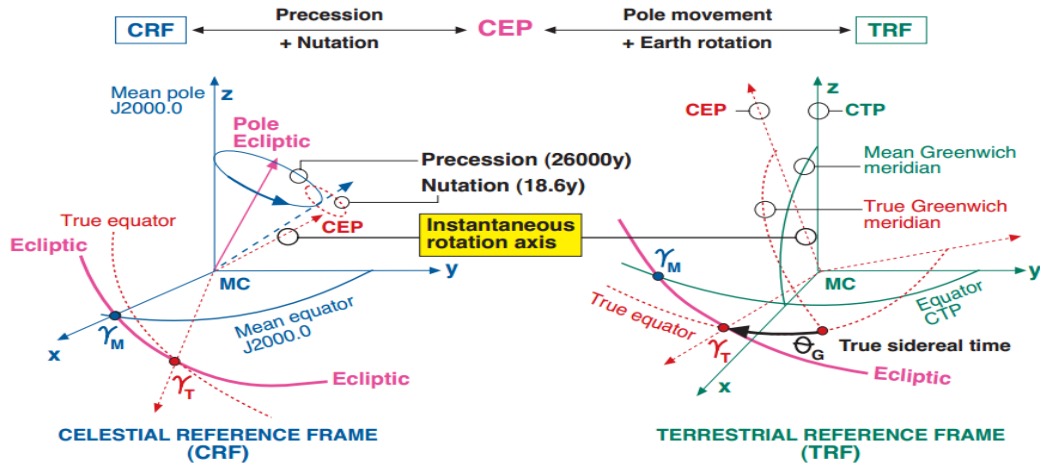
Figure 3.3: Transformations between the CRF and TRF.

3.3.2 Transformation between Terrestrial Frames

From elemental linear algebra, all transformations between two Cartesian coordinate systems can be decomposed into a shift vector ($\Delta X = [\Delta x; \Delta y; \Delta z]$), three consecutive rotations around the coordinate axes (θ_1, θ_2, θ_3), and a scale factor (α). That is, they can be described by the following equation, which involves seven parameters: [3]

$$X_{TRE2} = \Delta X + \alpha R_1[\theta_1]R_2[\theta_2]R_3[\theta_3]X_{TRE1} \tag{3.5}$$

Where:

$$R_1[\theta] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix}, \qquad R_2[\theta] = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}$$

$$R_1[\theta] = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.6}$$

By adopting the convention used by IERS, equation (3.5) can be written as:

$$
\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{TRF2} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{TRF1} + \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} + \begin{bmatrix} D & -R_3 & R_2 \\ R_3 & D & -R_1 \\ -R_2 & R_1 & D \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{TRF1} \tag{3.7}
$$

Where T_1, T_2, T_3 are three translation parameters, D is a scale factor and R_1, R_2 and R_3 are three rotation angles.

3.4 GNSS Reference Frames

Brief descriptions of the GPS WGS-84, Glonass PZ-90, Galileo GTRF and Beidou CGCS2000 reference frames are given below.

3.4.1 GPS Reference Frame WGS-84

From 1987, GPS has used the World Geodetic System WGS-84, developed by the US DoD, which is a unified terrestrial reference system for position and vector referencing. Indeed, the GPS broadcast ephemerides are linked to the position of the satellite antenna phase center in the WGS-84 reference frame. Thus, the user's receiver coordinates will be expressed in the same ECEF frame. [3]

The initial implementation of WGS-84 was realized from a set of more than a thousand terrestrial sites, whose coordinates were derived from transit observations. Successive refinements (which also led to some adjustments of the fundamental constants), using more accurate coordinates of the MS, approximate some ITRS realizations. For instance, realizations WGS-84(G730) and WGS-84(G873) correspond to ITRF92 and ITRF94, respectively. The refined frame WGS-84(G1150) was introduced in 2002, and agrees with ITRF2000 at the centimeter level. The parameters of the WGS-84 ellipsoid are given in Table 3.2. [3]

Table 3.2: Ellipsoidal parameters of WGS-84.

Ellipsoid		
Semi-major axis of the ellipse	a	6 378137.0m
Flattening factor	f	1/298.257223563
Earth's angular velocity	ω_E	$7292115.0 * 10^{-11}$ rad/s
Gravitational constant	μ	$3986004.418 * 10^8$ m^3/s^2
Speed of light in vacuum	c	$2.99792458 * 10^8$ m/s

3.4.2 Glonass Reference Frame PZ-90

The Glonass broadcast ephemerides are given in the PZ-90 reference frame. As with WGS-84, this is an ECEF frame with a set of associated fundamental parameters (see table 3.3 from [GLONASS ICD, 2008]). [3]

The determination of a set of parameters to transform the PZ-90 coordinates to ITRF97 was the target of the International Glonass Experiment (IGEX-98). [Boucher and Altamimi, 2001] present a review of the IGEX- 98 experiment and, as a conclusion, they suggest the following transformation from (x, y, z) in PZ-90 to (ẋ, ẏ, ż,) in WGS-84, to meter-level accuracy:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} -3ppb & -353\,mas & -4\,mas \\ 353\,mas & -3\,ppb & 19\,mas \\ 4\,mas & -19\,mas & -3\,ppb \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} 0.07\,m \\ -0.0\,m \\ -0.77m \end{bmatrix} \quad (3.8)$$

Following the notation of equation (3.7), the previous transformation is defined by the following table of parameters:

T1	T2	T3	D	R1	R2	R3
	(cm)		(ppb)		(mas)	
7	0	- 77	-3	-19	-4	353

According to the Glonass modernization plan, the ephemeris information implementing the PZ-90.02 reference system was updated on all operational Glonass satellites from 12:00 to 17:00 UTC, 20 September 2007.From this time on, the satellites have been broadcasting in PZ-90.02. This ECEF reference frame is an updated version of PZ-90,the closest one to ITRF2000. [3]

The transformation from PZ-90.02 to ITRF2000 contains only an origin shift vector, but no rotations or scale factor, as shown in the following equation

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{ITRF2000} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{PZ-90.02} + \begin{bmatrix} -0.36m \\ 0.08\ m \\ 0.18\ m \end{bmatrix} \tag{3.9}$$

Table 3.3:The parameters associated with PZ-90 and PZ-90.02

Ellipsoid		
Semi-major axis of the ellipse	a	6 378137.0m
Flattening factor	f	1/298.257223563
Earth's angular velocity	ω_E	$7292115.0 * 10^{-11}$ rad/s
Gravitational constant	μ	$3986004.4 * 10^8$ m^3/s^2
Speed of light in vacuum	c	$2.99792458 * 10^8$ m/s
Second zonal harmonic coefficient	J_2^0	$1082625.75 * 10^{-9}$

3.4.3 Galileo Reference Frame (GTRF)

A consortium called the Galileo Geodetic Service Provider (GGSP) consisting of seven institutions under the leadership of Geo For schungsZentrum Potsdam, was in charge of building a prototype for the development of the GTRF and the establishment of a service with products and information for potential users. [3]

The initial coordinates for the reference stations were provided using GPS observations, because the GTRF was already required by the time when the first Galileo signals were emitted during the In-Orbit Validation (IOV) phase. Subsequent GTRF versions will use both GPS and Galileo observations. Weekly solutions will be performed for the long-term maintenance of the GTRF. [3]

The GTRF must be compatible with the latest ITRF to within a precision level of 3 cm (2σ), since its maintenance is one of the main functions of the GGSP. [3]

Connection to the ITRF is realized and validated by International GNSS Service (IGS) stations,18 which are part of the ITRF, and especially by local ties to other geodetic techniques like satellite laser ranging and Very Long Baseline Interferometry (VLBI). [3]

As is the case for GPS and Glonass, the Galileo satellites broadcast their orbits in Galileo's own GTRF system. [3]

3.4.4 Beidou Reference Frame (CGCS2000)

The Beidou system adopts CGCS2000, which is a geocentric coordinate system associated with Earth's ellipsoid given in (Table 3.4). CGCS2000 is referred to ITRF97 at the epoch of 2000.0. The reference frame of CGCS2000 currently consists of the national GPS control network 2000 and the national astro-geodetic network after combined adjustment with the GPS network. The GNSS Continuously Operating Reference Stations (CORS) network will be the main part of China's geodetic infrastructure and a key technique for maintaining CGCS2000. [3]

Ellipsoid		
Semi-major axis of the ellipse	a	6 378137.0m
Flattening factor	f	1/298.257222101
Earth's angular velocity	ω_E	$7292115.0 * 10^{-11}$ rad/s
Gravitational constant	μ	$3986004.418 * 10^8$ m^3/s^2
Speed of light in vacuum	c	$2.99792458 * 10^8$ m/s

3.5 Cartésien and Ellipsoidal Coordinats

The (x, y, z) ECEF Cartesian coordinates of the above-mentioned terrestrial frames can be expressed in the associated ellipsoid as (φ, λ, h) ellipsoidal coordinates , where φ and λ are respectively the ellipsoidal latitude and longitude and h the height above the ellipsoid. Figure 3.4 illustrates the relation between Cartesian and ellipsoidal coordinates. [3]
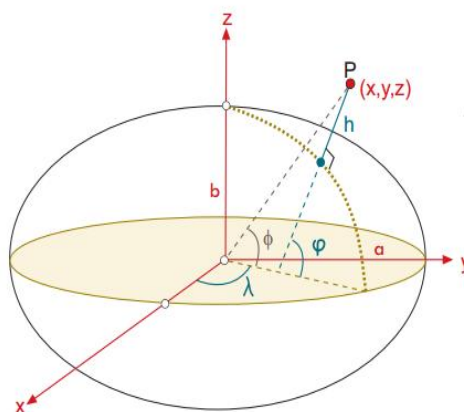
Figure 3.4: Cartesian (x; y; z) and ellipsoidal (φ, λ, h) coordinates. Geocentric latitude is denoted as φ.

3.6 Regional Datums and Map Projections

A datum consists of an ellipsoid relative to which the latitude and longitude of points are defined, and a geoid defining the surface at zero height. Different organizations, countries or groups of countries have developed their own datum's for civil and military applications. [3]

These ellipsoids are conventionally defined as fitting the geoid in the region of interest, without being necessarily geocentric or having their axes constrained to a given orientation. A valuable contribution of GPS was to provide a Global Reference Frame, simplifying the mapping of Earth and unifying the diverse datum's . (Figure 3.5) illustrates the concept of local and global datum's, and their relation to the geoid. [3]

The ellipsoidal coordinates of the datum must then be mapped to plane coordinates using a proper projection to build a map. Different projections have been defined (preserving areas, angles, distances, etc.), but all of them introduce distortions due to the mapping of a curved surface to a plane. [3]

The local maps edited by the official organizations are referenced to a given datum. The coordinates expressed in one datum can be transformed into another with a seven-parameter transformation (i.e. a transformation in the space between two coordinate frames). In this way, most of the commercial receivers incorporate the parameters for several official datum's to map the WGS-84 coordinates. [3]

The Geoid
(mean sea level)

Local Datum
(best fits a local area)

Global Datum (e.g., WGS84)
(best fit globally)
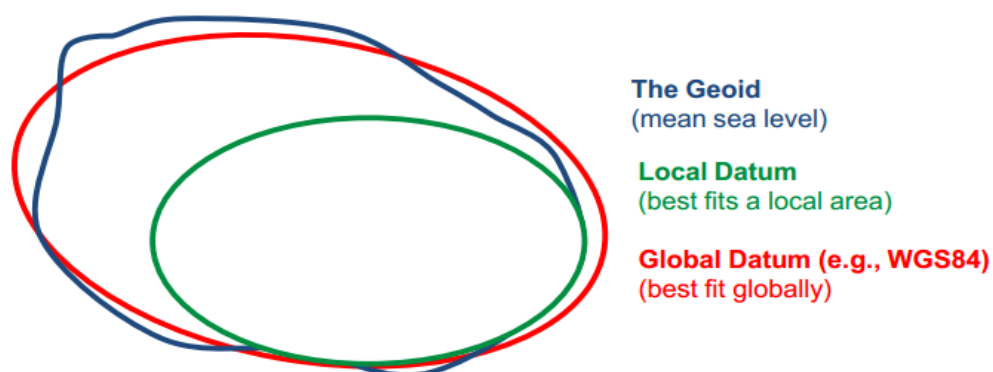
Figure 3.5: Global and local geodetic datums and the geoid

3.7 Palestine Datums and Map Projections

Map Projection (Grid Coordinates System)

The basic idea at map projection is to convert from geographic ($\emptyset$, λ) to local (E, N) Grid system and in the opposite direction, map projections are attempts to portray the surface of the earth or a portion of the earth on a flat surface, see (Figure 3.6). Some distortions of conformity, distance, direction, scale and area always result from this process. Some projections minimize distortions in some of these properties at the expense of maximizing errors in others. Some projections are attempts to only moderately distort all of these properties, the properties are: [3]

1. Conformity: when the scale of a map at any point on the map is the same in any direction, the projection is conformal. Meridians (Lines of longitude) and parallels (lines of latitude) intersect at right angles. Shape is preserved locally on conformal maps.
2. Distance: A map is equidistant when it portrays distances from the center of the projection to any other place on the map.
3. Direction: A map preserves direction when azimuths (angles from a point on a line to another point) are portrayed correctly in all directions.
4. Scale: is the relationship between a distance portrayed on a map and the same distance on the earth.
5. Area: When a map portrays areas over the entire map so that all mapped areas have the same proportional relationship to the areas on the earth that they represent, the map is an equal-area map.
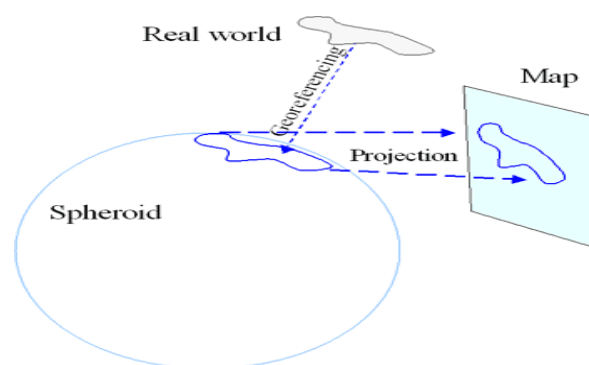
Figure 3.6: Map projection (from 3D to grid system).

Cassini Soldner Projection

The name Cassini-Soldner refers to the more accurate ellipsoidal version, developed in the 19th century. This transverse cylindrical projection maintains scale along the central meridian and all lines parallel to it and is neither equal area nor conformal. It is most suited for large scale mapping of areas predominantly north-south in extent. [3]

- The British Mandate using this system in Palestine, because it was used in the British and thus calculation for this system was ready and do not have to make new calculation, in addition the shape of Palestine was most accurate in Cassini Soldner.

To define a coordinate system using Cassini projection the following parameters are to be considered reference ellipsoid: [3]

- False Easting
- False Northing
- Central Meridian
- Scale Factor = 1
- Latitude of Origin

The Palestinian grid named Palestine_1923_Grid is built using Cassini projection, which normally used in land surveying and engineering projects with the following parameters: [3]

- False Easting   170251.555000
- False Northing   126867.909000
- Central Meridian   35.212081
- Scale Factor   1.000000
- Latitude of Origin   31.734.097
- Spheroid   Clarke_1880_Benoit
- Semi major axis   6378300.790000000
- Semi minor axis   6356566.430000036
- Inverse flattening   293.46623457099997

Datum and Ellipsoids

The shape of the earth is ellipsoid because the distance from the center of the earth to the equator is larger than the distance from the center to the poles by about 23km.

To make an ellipsoid model of the earth, rotate the ellipse about the shorter polar axis (semi-minor axis b) to form a solid surface, (see figure 3.7) a datum is defined by choosing an ellipsoid and then a primary reference point. [3]
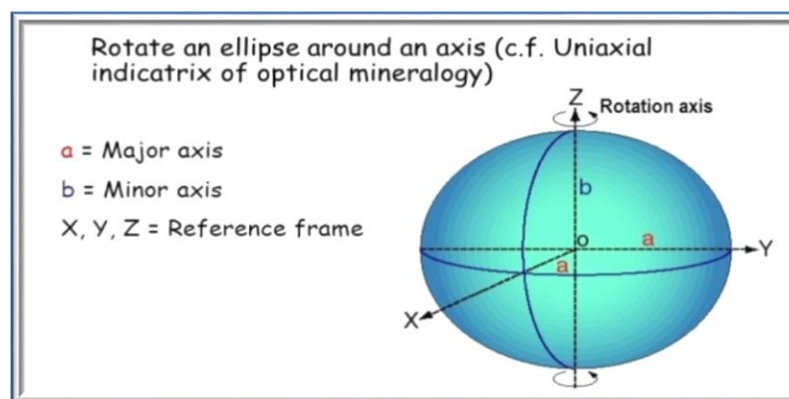
Figure 3.7: Ellipse Rotation.

The reference ellipsoid of the Palestine_1923_Grid is the Clarke_1880_Benoit.

3.8 Computation of GNSS Satellite Coordinates

The algorithms for computing the satellite coordinates from the broadcast navigation messages of GPS, Glonass, Galileo and Beidou are provided as follows. [3]

3.8.1 Computation of GPS, Galileo and Beidou Coordinats

Table 3.5 lists the GPS, Galileo or Beidou broadcast ephemeris parameters for computing the satellite coordinates at any observational epoch. These parameters are renewed periodically (typically every two hours for GPS) and must not be used after the prescribed time (about four hours), because the extrapolation error grows exponentially beyond this validity period. The Galileo and Beidou satellites follow the same scheme. [3]

Table 3.5: GPS/Galileo/Beidou broadcast ephemeris and clock message parameters.

Parameter	Explanation
t_{oe}	Ephemerides reference epoch in seconds within the week
$\sqrt{a}$	Square root of semi-major axis
e	Eccentricity
M_o	Mean anomaly at reference epoch
ω	Argument of perigee
i_o	Inclination at reference epoch
Ω_0	Longitude of ascending node at the beginning of the week
Δn	Mean motion difference
$\dot{i}$	Rate of inclination angle
$\dot{\Omega}$	Rate of node's right ascension
c_{uc} ; c_{us}	Latitude argument correction
c_{rc} ; c_{rs}	Orbital radius correction
c_{ic} ; c_{is}	Inclination correction
a_0	Satellite clock offset
a_1	Satellite clock drift
a_2	Satellite clock drift rate

- Compute the time t_k from the ephemerides reference epoch toe (t and toe are expressed in seconds in the GPS week): [3]

$$t_k = t - t_{eo} \qquad (3.10)$$

If $t_k > 302\ 400$ s, subtract $604\ 800$ s from t_k. If $t_k < -302\ 400$ s, add $604\ 800$ s.

- Compute the mean anomaly for t_k:

$$M_k = M_o + \left(\frac{\sqrt{\eta}}{\sqrt{a^3}} + \Delta n\right) t_k \qquad (3.11)$$

- Solve (iteratively) the Kepler equation for the eccentric anomaly E_k:

$$M_k = E_k - e \sin E_k \qquad (3.12)$$

- Compute the true anomaly v_k:

$$v_k = \arctan\left(\frac{\sqrt{1-e^2}}{\cos E_k - e} \sin E_k\right) \qquad (3.13)$$

- Compute the argument of latitude $\boldsymbol{u_k}$ from the argument of perigee ω, true anomaly v_k and corrections c_{uc} and c_{us}:

$$\boldsymbol{u_k} = \omega + v_k + c_{uc} \cos 2(\omega + v_k) + c_{us} \sin 2(\omega + v_k) \qquad (3.14)$$

- Compute the radial distance r_k, considering corrections c_{rc} and c_{rs}:

$$r_k = a\,(1 - e \cos E_k) + c_{rc} \cos 2(\omega + v_k) + c_{rs} \sin 2(\omega + v_k) \qquad (3.15)$$

- Compute the inclination $\boldsymbol{i_k}$ of the orbital plane from the inclination $\boldsymbol{i_o}$ at reference time toe, and corrections c_{ic} and c_{is}:

$$i_k = i_o + i\dot{}\, t_k + c_{ic} \cos 2(\omega + v_k) + c_{is} \sin 2(\omega + v_k) \qquad (3.16)$$

- Compute the longitude of the ascending node λ_k (with respect to Greenwich). This calculation uses the right ascension at the beginning of the current week (Ω_o), the correction from the apparent sidereal time variation in Greenwich between the beginning of the week and reference time $t_k = t - t_{eo}$. and the change in longitude of the ascending node from the reference time t_{eo}: [3]

$$\lambda_k = \Omega_o + (\Omega^\cdot - \omega_E)\, t_k - \omega_E\, t_{eo} \tag{3.17}$$

- Compute the coordinates in the TRS frame, applying three rotations (around u_k, i_k and λ_k):

$$\begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix} = R_3\,(-\lambda_k) R_1\,(-i_k) R_3\,(-u_k) \begin{bmatrix} r_k \\ 0 \\ 0 \end{bmatrix} \tag{3.18}$$

Where R_1 and R_3 are the rotation matrices defined in equation (3.6).

3.8.2 Computation of Glonass Satellite Coordinats

The Glonass satellite coordinates are computed according to the specifications in the Glonass-ICD document. An accuracy level of about 3 m can be achieved using the algorithm provided by this ICD. [3]

Table 3.9 lists the broadcast ephemeris parameters which are used to compute the Glonass satellite coordinates. Essentially, the ephemerides contain the initial conditions of position and velocity to perform numerical integration of the Glonass orbit within the interval of measurement $\lvert$t-te$\rvert$ < 15 min. The accelerations due to solar and lunar gravitational perturbations are also given. [3]

Table 3.6: Glonass broadcast ephemeris and clock message parameters.

Parameter	Explanation
t_e	Ephemerides reference epoch
$X(t_e)$	Coordinate at t_e in PZ-90
$y(t_e)$	Coordinate at t_e in PZ-90
$z(t_e)$	Coordinate at t_e in PZ-90
$v_x(t_e)$	Velocity component at t_e in PZ-90
$v_y(t_e)$	Velocity component at t_e in PZ-90
$v_z(t_e)$	Velocity component at t_e in PZ-90
$X''(t_e)$	Moon and Sun acceleration at t_e
$Y''(t_e)$	Moon and Sun acceleration at t_e
$Z''(t_e)$	Moon and Sun acceleration at t_e
$\tau_n(t_e)$	Satellite clock offset
$\gamma_n(t_e)$	Satellite relative frequency offset

3.9 Satellite Orbits

Knowledge of the orbits and clocks of the satellites is fundamental for the right positioning. Any error in the GNSS satellite coordinates or satellite clock will affect the positioning accuracy. Information on orbital parameters and clocks is transmitted in the navigation message. Precise ephemerides and clocks are also provided by some organizations such as IGS [3].

3.9.1 Keplerian Elements (Two-Body Problem)

According to Newtonian mechanics, the equation of motion of a mass m2 relative to another mass m1, considering only the central attractive force between them, is defined by the second-order homogeneous differential equation. [3]

$$r^{..} + \frac{\mu}{r^3} r = 0 \tag{3.19}$$

Where r is their relative position vector, $\mu = G(m_1 + m_2)$, and G is the universal gravitational constant. In the case of motion of an artificial Earth satellite, its mass can be neglected with respect to the mass of Earth (i.e. $\mu \cong GM_E$). Integration of this equation leads to the Keplerian orbit of the satellite [3]

$$r(t) = r(t.a.e.i.\Omega.\omega.\tau) \tag{3.19}$$

defined by the following six orbital parameters22 (see Fig 3.8):

• Ω, the right ascension of ascending node, is the geocentric angle between the ascending node direction and the Aries point directions. Note that the intersection of the equatorial plane and orbital plane is called the nodal line. Its intersection with the unit sphere defines two points: the ascending node, through which the satellite crosses to the region of the positive Z-axis; and the descending node. Right ascension (Ω) is measured in a counterclockwise sense when viewed from the positive Z-axis. [3]

• i, the inclination of the orbital plane, is the angle between the orbital plane and the equator.

• ω, the argument of perigee, is the angle between the ascending node and perigee directions, measured along the orbital plane. Perigee is the point of closest approach of the satellite to Earth's center of mass. The most distant position is apogee. Both are in the direction of the orbital ellipse semi-major axis.

• a, the semi-major axis of the orbital ellipse, is the semi-major axis of the ellipse defining the orbit.

• e, the numerical eccentricity of the orbit, is the eccentricity of the orbital ellipse.

• T_0, the perigee passing time, is the time of satellite passage through the closest approach to Earth (perigee). The satellite's orbital position can be obtained at a given moment to using any one of the following 'anomalies', see Fig. 3.8:

$-V(t)$. the true anomaly, is the geocentric angle between the perigee direction and the satellite direction. The sum of the true anomaly and the argument of perigee defines the argument of latitude. Note that for a circular orbit (e = 0) the argument of perigee and the true anomaly are undefined. The satellite's position, however, can be specified by the argument of latitude. [3]

$-E(t)$. the eccentric anomaly. A line that is normal to the major axis and passes through the satellite, it defines a point when it intersect a circle of radius a. Thus, the eccentric anomaly is the angle (measured from the center of the orbit) between the perigee and such a point.

$-M(t)$. the mean anomaly, is a mathematical abstraction relating to mean angular motion.

The three anomalies are related by the formulae (see Fig. 3.8)

$$M(t) = n(t - T_0)E \tag{3.20}$$

$$(t) = M(t) + e \sin E(t) V \tag{3.21}$$

$$(t) = 2 \arctan[\sqrt{\frac{1+e}{1-e}} \tan \frac{E(t)}{2i}] \tag{3.22}$$

$$n = 2\pi/P = \sqrt{\frac{\mu}{a^3}} \tag{3.23}$$

where n denotes the mean angular velocity of the satellite, or mean motion, with period of revolution P. Substituting the values for the semi-major axis

$a = 26560\ km$ and gravitational constant $\mu = 3\ 986004.418*10^8\ m^3/s^2$

(see Table 3.5) into the last of the above equations (3.12), an orbital period of 12 sidereal hours . [3]
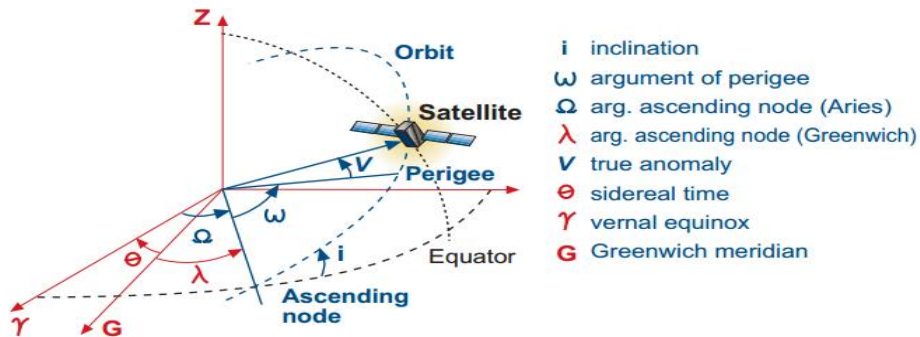
Figure 3.8: GNSS satellite orbital elements.
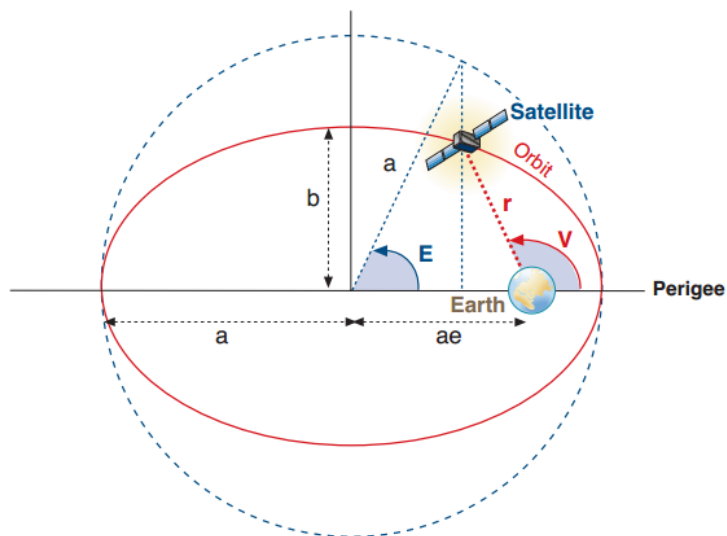
Figure 3.9: Elliptic orbit representation.

3.9.2 Precise orbits (IGS)

The International GNSS Service (IGS) has ensured open access, high-quality GNSS data products since 1994. These products enable access to the definitive global reference frame for scientific, educational, and commercial applications – a tremendous benefit to the public, and key support element for scientific advancements. [8]

The IGS at a Glance

- A voluntary federation of over 200 self-funding agencies, universities, and research institutions in more than 100 countries; working together to provide the highest precision GPS satellite orbits in the world.

- Providing free and open access to the highest precision products available for scientific advancement and public benefit. These products support a wide variety of applications that touch millions of users in virtually all segments of the global economy.

- Producing products that support realization of the International Terrestrial Reference Frame while providing access to tracking data from over 400 worldwide reference stations.

- Working for the continuous development of new applications and products through Working Groups and Pilot Projects.

- Supporting geodetic research and scholarly publications.

- Functioning as a component of the Global Geodetic Observing System (GGOS) and member of the World Data System (WDS). [8]

Mission

The International GNSS Service provides, on an openly available basis, the highest quality GNSS data, products and services in support of the terrestrial reference frame, Earth observation and research; positioning, navigation and timing; and other applications that benefit science and society. [8]

Products

The IGS, as a component of the Global Geodetic Observing System, operates a global network of GNSS ground stations, data centers, and data analysis centers to provide data and derived data products that are essential for Earth science research; multi-disciplinary positioning, navigation, and timing (PNT) applications; and education. The IGS Reference Frame Coordinator determines tracking site coordinates and velocities in the International Terrestrial Reference Frame (ITRF), and organizes the IGS contribution to ITRF. [8]

IGS products include:

- GNSS satellite ephemerides
- Earth rotation parameters
- Global tracking station coordinates and velocities
- Satellite and tracking station clock information
- Zenith tropospheric path delay estimates
- Global ionosphere maps

These products support Earth science analyses and other efforts, such as

- Improving and extending the International Terrestrial Reference Frame (ITRF) maintained by the International Earth Rotation and Reference Systems Service (IERS),
- Monitoring deformation of the Earth,
- Monitoring Earth rotation,
- Monitoring the troposphere and ionosphere,
- Determining orbits of scientific satellites, and other diverse applications.

Table 3.7: GPS Satellite Ephemerides / Satellite & Station Clocks.

Type	Accuracy		Latency	Updates	Sample Interval
Broadcast	orbits	~100 cm	real time	--	daily
	Sat. clocks	~5 ns RMS ~2.5 ns SDev			
Ultra-Rapid (predicted half)	orbits	~5 cm	real time	at 03, 09, 15, 21 UTC	15 min
	Sat. clocks	~3 ns RMS ~1.5 ns SDev			
Ultra-Rapid (observed half)	orbits	~3 cm	3 - 9 hours	at 03, 09, 15, 21 UTC	15 min
	Sat. clocks	~150 ps RMS ~50 ps SDev			
Rapid	orbits	~2.5 cm	17-41 hours	at 17 UTC daily	15 min
	Sat. & Stn. clocks	~75 ps RMS ~25 ps SDev			5 min
Final	orbits	~2.5 cm	12 - 18 days	every Thursday	15 min
	Sat. & Stn. clocks	~75 ps RMS ~20 ps SDev			Sat.:30s Stn.: 5 min

Table 3.8: GLONASS Satellite Ephemerides.

Type	Accuracy	Latency	Updates	Sample Interval
Final	~3 cm	12 - 18 days	every Thursday	15 min

Table 3.9: Geocentric Coordinates of IGS Tracking Stations.

Type	Accuracy		Latency	Updates	Sample Interval
Final positions	horizontal	3 mm	11 - 17 days	every Wednesday	weekly
	vertical	6 mm			
Final velocities	horizontal	2 mm/yr	11 - 17 days	every Wednesday	weekly
	vertical	3 mm/yr			

Table 3.10: Earth Rotation(Polar Motion (PM) Polar Motion Rates (PM rate) Length-of-day (LOD)).

Type	Accuracy		Latency	Updates	Sample Interval
Ultra-Rapid (predicted half)	PM	~200 µas	real time	at 03, 09, 15, 21 UTC	daily integrations at 00, 06 12, 18 UTC
	PM rate	~300 µas/day			
	LOD	~50 µs			
Ultra-Rapid (observed half)	PM	~50 µas	3 - 9 hours	at 03, 09, 15, 21 UTC	daily integrations at 00, 06, 12, 18 UTC
	PM rate	~250 µas/day			
	LOD	~10 µs			
Rapid	PM	~40 µas	17 - 41 hours	at 17 UTC daily	daily integrations at 12 UTC
	PM rate	~200 µas/day			
	LOD	~10 µs			
Final	PM	~30 µas	11 - 17 days	every Wednesday	daily integrations at 12 UTC
	PM rate	~150 µas/day			
	LOD	~10 µs			

Note 1: 100 µas = 3.1 mm of equatorial rotation; 10 µs = 4.6 mm of equatorial rotation.

Note 2: The IGS uses VLBI results from IERS Bulletin A to partially calibrate for LOD biases over 21-day sliding window, but residual time-correlated LOD errors remain. [8]

Table 3.11: Atmospheric parameters

Type	Accuracy	Latency	Updates	Sample Interval
Final tropospheric zenith path delay with N, E gradients	4 mm (ZPD)	< 4 weeks	daily	5 minutes
Final ionospheric TEC grid	2-8 TECU	~11 days	weekly	2hours; 5 deg(lon) x 2.5 deg (lat)
Rapid ionospheric TEC grid	2-9 TECU	<24 hours	daily	2hours; 5 deg(lon) x 2.5 deg (lat)

The IGS contributes to, extends, and densities the International Terrestrial Reference Frame (ITRF). The ITRF provides an accurate and consistent frame, or datum, for referencing positions at different times and in different locations around the world. The IGS realization of ITRF, which extends the number of stations significantly, makes the reference frame easily accessible.

In particular, the accuracies of IGS products are sufficient for the improvement and extension of the International Terrestrial Reference Frame (ITRF), the monitoring of solid Earth deformations, the monitoring of Earth rotation and variations in the liquid Earth (sea level, ice-sheets, etc.), for scientific satellite orbit determinations, ionosphere monitoring, and recovery of perceptible water vapor measurements. [8]

Chapter four

GNSS Positioning

4.1 Point positioning

4.2 Differential positioning

4.3 Relative positioning

4.1 Point positioning

4.1.1 Point positioning with code ranges

Code range model

The code pseudo range at an epoch t can be modeled, by

$$R_r^s(t) = \rho_r^s(t) + c\,\Delta\delta_r^s(t) \tag{4.1}$$

Here, $R_r^s(t)$ is the measured code pseudo range between the observing receiver site r and the satellite s, the term $\rho_r^s(t)$ is the geometric distance between the observing point and the satellite, and c is the speed of light. The last item to be explained is $\delta_r^s(t)$. This clock bias represents the combined clock offsets of the receiver and the satellite clock with respect to system time. [1]

Examining Eq. (4.1), the desired coordinates of the receiver site to be deter- mined are implicit in the distance $\rho_r^s(t)$. which can explicitly be written as

$$\rho_r^s(t) = \sqrt{(Xs(t) - Xr)^2 + (Ys(t) - Yr)^2 + (Zs(t) - Zr)^2} \ . \tag{4.2}$$

Where $Xs(t), Ys(t), Zs(t)$ are the components of the geocentric position vector of the satellite at epoch t, and Xr , Yr , Zr are the three ECEF coordinates of the (stationary) observing receiver site. Now, the clock bias $\Delta\,\delta^s(t)$ must be investigated in more detail. For the moment consider a single epoch; a single position r is automatically implied. Each satellite contributes one unknown clock bias which can be recognized from the superscript s at the clock term. Neglecting, for the present, the site r clock bias, the pseudo range equation for the first satellite would have four unknowns. These are the three site coordinates and one clock bias of this satellite. Each additional satellite adds one equation with the same site coordinates but with a new satellite clock bias. Thus, there would always be more unknowns than measurements. Even when an additional epoch is considered, new satellite clock biases must be modeled due to clock drift. Fortunately, the satellite clock information is known with sufficient accuracy and transmitted via the broadcast navigation message, e.g., in the form of three polynomial coefficients $a0$, $a1$, $a2$ with a reference time t_c. [1]

Therefore, the equation

$$\delta^s(t) = a_0 + a_1(t - t_c) + a_2(t - t_c)^2 \tag{4.3}$$

Enables the calculation of the satellite clock bias at epoch t. It should be noted that the polynomial (4.3) removes a great deal of the satellite clock uncertainty, but a small amount of (random) error remains. It should also be noted that the relative effects are not included in the polynomial. Therefore, for a more complete user algorithm for satellite clock correction, the term δ^{rel} must also be taken into account by [1]

$$\delta^s(t) = a_0 + a_1(t - t_c) + a_2(t - t_c)^2 + \delta^{rel}, \tag{4.4}$$

The combined bias term $\Delta\delta^s(t)$ is split into two parts by

$$\Delta\delta^s(t) = \delta_r(t) - \delta^s(t), \tag{4.5}$$

Where the satellite-related part $\delta s(t)$ is known and the receiver-related term $\delta_r(t)$ remains unknown. Substituting (4.5) into (4.1) and shifting the satellite clock bias to the left side of the equation yields [1]

$$R_r^s(t) + c\,\delta^s(t) = \rho_r^s(t) + c\,\delta_r(t) \tag{4.6}$$

Note that the left side of the equation contains observed or known quantities, while the terms on the right side are unknown. [1]

Basic configurations

Basic configurations are defined by the condition that the number of observations must be equal to or greater than the number of unknowns. This condition is sufficient but does not necessarily give a solution. The reason for this is that inherent rank deficiencies may prevent a numerical solution because of a singularity. More explanations are given later when the rank deficiency becomes an issue. [1]

The number of observations is ns n_t , where ns denotes the number of satellites and n_t the number of epochs.

For static point positioning, the three coordinates of the observing site and the receiver clock bias for each observation epoch are unknown. Thus, the number of unknowns is $3 + n_t$. The basic configuration is defined by

$$n_s \, n_t \geq 3 + n_t \, , \tag{4.7}$$

which yields the explicit relation

$$n_t \geq \frac{3}{n_s - 1} \tag{4.8}$$

The minimum number of satellites to get a solution is $n_s = 2$, leading to $n_t \geq 3$ observation epochs. For $n_s = 4$, the solution $n_t \geq 1$ is obtained. [1]

This solute reflects the instantaneous positioning capability of GNSS, where the four unknowns at any epoch are solved if at least four satellites are tracked.

For kinematic point positioning, the basic configuration can be directly derived from the following consideration. Due to the motion of the receiver, the number of the unknown station coordinates is $3 \, n_t$. Adding the n_t unknown receiver clock biases, the total number of unknowns is 4 nt. Hence, the basic configuration is defined by Eq. (4.7), [1]

$$n_s \, n_t \geq 4 n_t \tag{4.9}$$

yielding $n_S \geq 4$. In other words, the position (and system time) of a moving receiver can be determined at any instant as long as at least four satellites are tracked. Geometrically, the solution is represented by the intersection of four pseudoranges. [1]

The basic configurations must be considered from a theoretical point of view. The solution $n_S = 2$, $n_t \geq 3$ for static point positioning, for example, means that simultaneous observations of two satellites over three epochs would theoretically suffice. In practice, however, this situation would yield unacceptable results or the computation would fail because of an ill-conditioned system of observation equations unless the epochs were widely spaced (e.g., hours). A solution is also possible if observations of three epochs for two satellites are made, followed by three additional epochs (e.g., seconds apart) for two other satellites. Such an application will be rare but is imaginable under special circumstances (e.g., in urban areas). [1]

4.1.2 Point positioning with carrier phases

Phase range model

Pseudo ranges can also be obtained from carrier phase measurements. The mathematical model for these measurements is given by

$$\varphi_r^s(t) = \frac{1}{\Lambda^s}\rho_r^s(t) + N_r + \frac{c}{\Lambda^s}\Delta\delta_r^s(t) \tag{4.10}$$

Where $\varphi_r^s(t)$ is the measured carrier phase expressed in cycles, Λ^s is the wavelength, and $\rho_r^s(t)$ is the same as for the code range model. The time-independent phase ambiguity N_r is an integer number and, therefore, often called integer ambiguity or integer unknown or simply ambiguity. The term c denotes the speed of light and is the combined receiver and satellite clock bias. [1]

Inserting Eq. (4.5) into Eq. (4.10) and shifting the (known) satellite clock bias to the left side of the equation yields

$$\varphi_r^s(t) + f^s\delta^s(t) = \frac{1}{\Lambda^s}\rho_r^s(t) + N_r + f^s\delta_r(t) , \tag{4.11}$$

Where the frequency of the satellite carrier $f^s = c/\Lambda^s$ has been substitute

Basic configurations

Using the same notations as before, the number of observations is again n_s n_t .The number of unknowns, however, is increased by the number ns because of the ambiguities. [1]

For static point positioning, the number of unknowns is composed of 3 coordinates of the observing station, ns unknown ambiguities, and n_t unknown receiver clock biases. Referring to (4.11), the problem of rank deficiency is encountered. Mathematically less interested readers may skip the next paragraph. [1]

A few basics on rank and rank deficiency are given here. Deeper insight may be obtained from Koch (1987: Sects. 132, 333). Assume a large number of equations of type (4.11) being prepared to be solved for the unknowns. This implies a matrix- vector representation where the right side is composed of a product of a design matrix A and a vector comprising the unknowns in linear form. The rank of the de- sign matrix is equal to the order of the largest nonsingular matrix that can be formed inside A. Formulated differently: the maximum number of the linearly independent rows of matrix A is called the rank of the matrix and is denoted by rank A. Linear dependence of two rows means that their linear combination yields zero. The word "rows" in this definition may also be replaced by the word "columns". For a simpler discussion, assume a quadratic matrix with m × m rows and columns. Thus, if the largest nonsingular matrix is the matrix A itself, the rank equals rank A = m and the matrix is regular, i.e., it may be inverted without troubles. On the other hand, if the largest nonsingular matrix inside A is a matrix with, e.g., (m − 2) × (m − 2) rows and columns, the rank would be m − 2 and implies a rank deficiency of m − rank A which turns out to be m − (m − 2) which amounts to 2. As a consequence, the singular sys- tem becomes regularly solvable if two unknowns (also denoted as parameters) are arbitrarily chosen. This equals the "fixing" of two parameters. Figuratively speaking, two of the parameters may be transferred to the left side of the matrix-vector system comprising the measurements. This transfer reduces on the other hand the columns of the matrix on the right side by the amount of the rank deficiency, i.e., by two in the example discussed. This concludes the short discussion on rank and rank deficiency. [1]

The model in the form (4.11) comprises a rank deficiency of 1, this means that one of the unknown parameters may (and must) be arbitrarily chosen. Suppose that a receiver clock bias at one epoch is chosen, then, instead of n_S unknown receiver clock biases, only $n_t - 1$ clock biases remain. Therefore, the basic configuration for static point positioning without rank deficiency is defined by the relation [1]

$$n_S \, n_t \geq 3 + n_S + (n_t - 1),\tag{4.12}$$

which yields explicitly the required number of epochs as

$$n_t \geq \frac{n_S + 2}{n_S - 1}\tag{4.13}$$

The minimum number of satellites to get a solution is $n_S = 2$ leading to $n_t \geq 4$ observation epochs. Another integer solution pair is ns = 4, $n_t \geq 2$.

For kinematic point positioning with phases, 3 n_t unknown station coordinates must be considered because of the roving receiver compared to the 3 unknowns in (6.12). The other considerations including the discussion on the rank deficiency remain unchanged. Therefore, the basic configuration is defined by

$$n_S \, n_t \geq 3n_t + n_S + (n_t - 1)\tag{4.14}$$

yielding the explicit relation

$$n_t \geq \frac{n_S + 2}{n_S - 1}\tag{4.15}$$

The minimum number of satellites to get a solution is $n_S = 5$ which have to be tracked for $n_t \geq 4$ epochs. Another integer solution pair is $n_S = 7$, $n_t \geq 2$.

Note that solutions for a single epoch (i.e., $n_t = 1$) do not exist for point positioning with carrier phases. As a consequence, kinematic point positioning with phases is only possible if the ns phase ambiguities are known from some initialization. In this case, the phase range model converts to the code range model. [1]

4.1.3 Precise point positioning

Basic model

Considering the methods of point positioning described in the previous sections, the main limiting factors with respect to the achievable accuracy are the orbit errors, the clock errors, and the atmospheric influences (ionospheric and tropospheric refraction). Therefore, precise point positioning (PPP) uses accurate orbital data and accurate satellite clock data (as provided, e.g., by the IGS), and dual frequency code pseudo ranges and/or carrier phase observations by definition. The preferred model is based on an ionosphere-free combination of code pseudo ranges and carrier phases as well. [1]

The respective equation for the code pseudo ranges is

$$\left[R_1 \frac{f_2^2}{f_1} R_2\right] \frac{f_1^2}{f_1^2 - f_2^2} = \rho + c\Delta\delta + \Delta^{Trop} \tag{4.16}$$

Where a term to model the tropospheric delay has been added.

The ionosphere-free carrier phase relation reads

$$\left[\varphi_1 - \frac{f_2}{f_1}\varphi_2\right] \frac{f_1^2}{f_1^2 - f_2^2} = \frac{f_1}{c}\rho + f_1\Delta\delta + \left[N_1 - \frac{f_2}{f_1}N_2\right] \frac{f_1^2}{f_1^2 - f_2^2} \tag{4.17}$$

This equation is now multiplied by the factor c/ f1 yield in

$$\left[\varphi_1 - \frac{f_2}{f_1}\varphi_2\right] \frac{f_1^2}{f_1^2 - f_2^2} = \rho + c\Delta\delta + \left[N_1 - \frac{f_2}{f_1}N_2\right] \frac{f_1^2}{f_1^2 - f_2^2} \tag{4.18}$$

or, by substituting c = λ1 f1 and adding the tropospheric delay,

$$\left[\varphi_1 - \frac{f_2}{f_1}\varphi_2\right] \frac{\lambda_1 f_1^2}{f_1^2 - f_2^2} = \rho + c\Delta\delta + \Delta^{Trop} + \left[N_1 - \frac{f_2}{f_1}N_2\right] \frac{f_1^2}{f_1^2 - f_2^2} \tag{4.19}$$

is obtained. This formula yields after a slight rearrangement and by using c = λ2 f2

$$\frac{\lambda_1 \varphi_1 f_1^2}{f_1^2 - f_2^2} - \frac{\lambda_2 \varphi_2 f_2^2}{f_1^2 - f_2^2} = \rho + c\Delta\delta + \Delta^{Trop} + \frac{\lambda_1 N_1 f_1^2}{f_1^2 - f_2^2} - \frac{\lambda_2 N_2 f_2^2}{f_1^2 - f_2^2} \tag{4.20}$$

In summary, (4.20) and (4.24) are the desired ionosphere-free combinations of code pseudorange and carrier phases for PPP:

$$\frac{R_1 f_1^2}{f_1^2 - f_2^2} - \frac{R_2 f_2^2}{f_1^2 - f_2^2} = \rho + c\Delta\delta + \Delta^{Trop} \tag{4.21}$$

$$\frac{\Lambda_1 \varphi_1 f_1^2}{f_1^2 - f_2^2} - \frac{\Lambda_2 \varphi_2 f_2^2}{f_1^2 - f_2^2} = \rho + c\Delta\delta + \Delta^{Trop} + \frac{\Lambda_1 N_1 f_1^2}{f_1^2 - f_2^2} - \frac{\Lambda_2 N_2 f_2^2}{f_1^2 - f_2^2} \tag{4.22}$$

Where (4.16) has been slightly rearranged. The unknown parameters to be deter- mined are the point position contained in , the receiver clock error contained in $\Delta\delta$, the tropospheric delay Δ^{Trop}, and the ambiguities. Based on this model, PPP may be applied either in static or in kinematic mode. [1]

4.2 Differential positioning

4.2.1 Basic concept

Differential positioning with GNSS, abbreviated by DGNSS, is a real-time positioning technique where two or more receivers are used. One receiver, usually at rest, is located at the reference or base station with (assumed) known coordinates and the remote receivers are fixed or roving and their coordinates are to be deter- mined (Fig. 4.1). The reference station commonly calculates pseudo range corrections (PRC) and range rate corrections (RRC) which are transmitted to the remote receiver in real time. The remote receiver applies the corrections to the measured pseudo ranges and performs point positioning with the corrected pseudo ranges. The use of the corrected pseudo ranges improves the position accuracy with respect to the base station. [1]
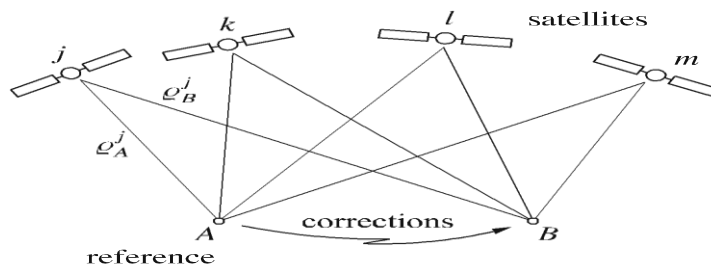
Figure 4.1. Basic concept of differential positioning.

4.2.2 DGNSS with code ranges

Generalizing (4.6) and following Lichtenberger (1998), the code range at base station A to satellite s measured at epoch t0 may be modeled by

$$R_A^S(t_0) = \rho_A^s(t_0) + \Delta\rho_A^s(t_0) + \Delta\rho^s(t_0) + \Delta\rho_A(t_0) \tag{4.23}$$

where $\boldsymbol{\rho_A^s(t_0)}$ is the geometric range, the term $\Delta\boldsymbol{\rho_A^s(t_0)}$ denotes range biases depending on the terrestrial base position and satellite position as well (e.g., radial orbital error , refraction effects), the range bias $\Delta\boldsymbol{\rho^s(t_0)}$ is purely satellite-dependent (e.g., effect of satellite clock error) , and the rangebias $\Delta\boldsymbol{\rho_A(t_0)}$ is purely receiver dependent (e.g., effect of receiver clock error, multipath). Note that noise has been neglected in (4.23). [1]

The pseudo range correction for satellite s at reference epoch t_0 is defined by the relation

$$PRC^S(t_0) = \rho_A^s(t_0) - R_A^s(t_0) \quad = - \Delta\rho_A^s(t_0) - \Delta\rho^s(t_0) - \Delta\rho_A(t_0) \tag{4.24}$$

And can be calculated since the geometric range $\rho_A^s(t_0)$ is obtained from the known position of the reference station and the broadcast ephemerides and $R_A^s(t_0)$ is the measured quantity. In addition to the pseudo range correction $PRC^S(t_0)$, the time derivative or range rate correction RRCs(t_0) is determined at the base station. [1]

Range and range rate corrections referring to the reference epoch t_0 are transmitted t_0 the rover site B in real time. At B the pseudorange corrections are predicted for the observation epoch t using the relation

$$\mathrm{PRC}^s(t) = \mathrm{PRC}^s(t_0) + \mathrm{RRC}^s(t_0)\,(t - t_0)\,, \tag{4.25}$$

Where $t - t_0$ is defined as latency. The achievable accuracy increases for smaller variations of the pseudorange corrections and for smaller latencies Adapting (4.23) to the rover site B and epoch t, the code pseudorange measured at the rover can be modeled by

$$R_B^S(t_0) = \rho_B^s(t) + \Delta\rho_B^s(t) + \Delta\rho^s(t) + \Delta\rho_B(t) \tag{4.26}$$

Applying the predicted pseudorange correction $RRC^s(t)$, cf. Eq. (4.25), to the measured pseudorange Rs (t) yields

$$R_A^s(t)_{corr} = R_B^s(t) + PRC^s(t) \tag{4.27}$$

or, after substitution of (4.26) and the pseudorange correction according to

 (4.24) and (4.25), respectively,

$$R_B^S(t)_{corr} = \rho_B^s(t) + [\Delta\rho_B^s(t) - \Delta\rho_A^s(t)] + [\Delta\rho_B(t) - +\Delta\rho_A(t)] \tag{4.28}$$

Where the satellite-dependent bias has canceled out. For moderate distances between the base and the rover site, the satellite–receiver-specific biases are highly correlated. Therefore, the influence of radial orbital errors and of refraction is significantly reduced. Neglecting these biases, Eq. (6.31) simplifies to

$$R_B^S(t)_{corr} = \rho_B^s(t) + \Delta\rho_{AB}(t) \,, \tag{4.29}$$

Where $\Delta\rho_{AB}(t) = \Delta\rho_B(t) - \Delta\rho_A(t)$. If multipath is neglected, this term converts to the combined receiver clock bias scaled to range, i.e., $\Delta\rho_{AB}(t) = c\delta_{AB}(t) = c\delta_B(t) - c\delta_A(t)$. If no latency exists, the equation is identical with the between- receiver single difference of code ranges measured at A and B, and differential positioning converts to relative positioning. [1]

Positioning at the rover site B is performed with the corrected code pseudo- ranges $R_B^S(t)_{corr}$ leading to improved position accuracies. The basic configuration for DGNSS with code ranges is identical with that for kinematic point positioning with code ranges, cf. Eq. (4.9). [1]

4.2.3 DGNSS with phase ranges

Generalizing (4.10) and following Lichtenberger (1998), the phase pseudorange measured at the base station A at epoch t0 can be modeled by

$$\Lambda^s \varphi^s(t_0) = \rho_A^s(t_0) + \Delta\rho_A^s(t_0) + \Delta\rho^s(t_0) + \Delta\rho_A(t_0) + \Lambda^s N_A^s \tag{4.30}$$

Where , in analogy to the code range model, $\rho_A^s(t_0)$ is the geometric range, $\Delta\rho_A^s(t_0)$ is the satellite – receiver dependent bias , $\Delta\rho^s(t_0)$ is purely Satellite dependent, $\Delta\rho_A(t_0)$ is purely receiver - dependent. [1]

Finally, N_A^s is the phase ambiguity. Consequently, the phase range correction at reference epoch t_0 is given by

$$PRC^S(t_0) = \rho_A^s(t_0) - \Lambda^s \varphi_A^s(t_0) = -\Delta\rho_A^s(t_0) - \Delta\rho^s(t_0) - \Delta\rho_A(t_0) - \Lambda^s N_A^s \tag{4.31}$$

The formulation of range rate corrections at the base station A as well as the application of predicted range corrections to the observed phase ranges at the rover site B is carried out in full analogy to the previously described code range procedure. Therefore,

$$\Lambda^s \varphi_B^S(t)_{corr} = \rho_B^s(t) + \Delta\rho_{AB}(t) + \Lambda^s N_{AB}^S \tag{4.32}$$

Results for the corrected phase ranges, where $\Delta\rho_{AB}(t) = \Delta\rho_B(t) - \Delta\rho_A(t)$. And $N_{AB}^s = N_B^s - N_A^s$ is the (single-) difference of the phase ambiguities. As in the code range model, if multipath is neglected, the term $\Delta e_{AB}(t)$ converts to the combined receiver clock bias scaled to range, i.e.,

$$\Delta\rho_{AB}(t) = c\,\delta_{AB}(t) = c\,\delta_B(t) - c\,\delta_A(t).$$

Point positioning at the rover site B is performed with the corrected phase pseudo ranges $\lambda^s \Phi^s (t)_{corr}$. The basic configuration for DGNSS with phase ranges is identical with that for kinematic point positioning with phase ranges, cf. Eq. (6.15). [1]

DGNSS with phase ranges, sometimes denoted as carrier phase differential technique, is used for most precise kinematic applications. For this mode of operation, on the fly (OTF) techniques are required to resolve the ambiguities. [1]

Note that DGNSS with phases converts to relative positioning with phases if the latency becomes zero. This method is usually denoted real-time kinematic (RTK) technique. [1]

4.2.4 Local-area DGNSS

An extension of DGNSS is the local-area DGNSS (LADGNSS) which uses a net- work of GNSS reference stations. As the name implies, LADGNSS covers a larger territory than can be reasonably accommodated by a single reference station. One of the main advantages of LADGNSS is that a more consistent accuracy can be achieved throughout the region supported by the network. In the case of DGNSS with a single reference station, the accuracy decreases as a function of distance from the reference station at a rate of approximately 1 cm per 1 km. Other advantages of LADGNSS are that inaccessible regions can be covered, e.g., large bodies of water, and that in case of a failure in one of the reference stations, the network will still maintain a relatively high level of integrity and reliability compared to a collection of individual DGNSS reference stations. [1]

Apart from the monitor stations, the LADGNSS network includes (at least) one master station. This station collects the range corrections from the monitor stations, processes these data to form LADGNSS corrections which are transmitted to the user community as well as to the monitor stations (Mueller 1994). The networks may cause slight additional delay beyond regular DGNSS due to the additional communication required between the monitor stations and the master station. [1]

Since the reference stations of the LADGNSS network may be very distant from the user location, the virtual reference station (VRS) concept has been developed (Wanninger 1999). Here, the user gets range corrections or even the observables of a nonexistent (i.e., virtual) reference station at a user-specified position. This concept is a prerequisite mainly for RTK applications which require short distances to reference stations to facilitate ambiguity resolution. [1]

4.3 Relative positioning

4.3.1 Basic concept

The objective of relative positioning is to determine the coordinates of an unknown point with respect to a known point which, for most applications, is stationary. In other words, relative positioning aims at the determination of the vector between the two points, which is often called the baseline vector or simply baseline (Fig. 4.2). Let A denote the (known) reference point, B the unknown point, and b_{AB} the base- line vector. Introducing the corresponding position vectors XA, XB, the relation [1]

$$X_B = X_A + b_{AB} \tag{4.33}$$

May be formulated, and the components of the baseline vector b_{AB} are

$$b_{AB} = \begin{bmatrix} X_B - X_A \\ Y_B - Y_A \\ Z_B - Z_A \end{bmatrix} = \begin{bmatrix} \Delta X_{AB} \\ \Delta Y_{AB} \\ \Delta Z_{AB} \end{bmatrix} \tag{4.34}$$

The coordinates of the reference point must be given and can be approximated by a code range solution. More often the coordinates are precisely known based upon GNSS or other methods. [1]
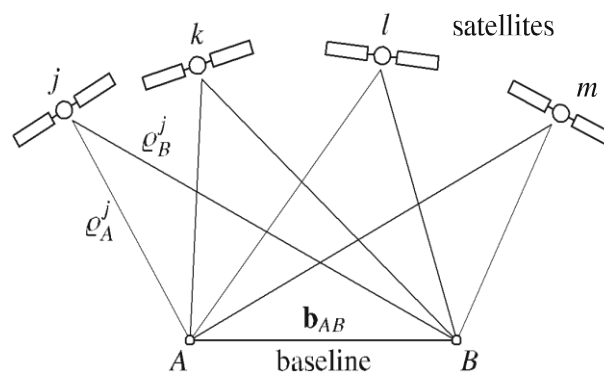
Figure 4.2. Basic concept of relative positioning.

Relative positioning can be performed with code ranges, cf. Eq. (4.6), or with phase ranges, cf. Eq. (4.11). Subsequently, only phase ranges are explicitly considered because solutions based on phase ranges are far more accurate. Relative positioning requires simultaneous observations at both the reference and the unknown point. This means that the observation time tags for the two points must be the same. Assuming such simultaneous observations at the two points A and B to satellites j and k, linear combinations can be formed leading to single- differences, double- differences, and triple-differences. Differencing can basically be accomplished in three different ways: across receivers, across satellites, across time. Instead of "across" frequently "between" is used. In order to avoid overburdened expressions, shorthand notations will be used throughout the textbook with the following meanings: single difference corresponds to across receiver difference (or between-receiver difference), double difference corresponds to across receiver and across-satellite difference, and triple difference corresponds to across receiver and across-satellite and across-time difference. [1]

4.3.2 Phase differences

Single- different

Two receivers and one satellite are involved. Denoting the receiver sites by A and B and the satellite by j and using Eq. (4.11), the phase equations for the two points are

$$\varphi_A^j(t) + f^j \delta^j(t) = \tfrac{1}{\lambda^j} \rho_A^j(t) + N_A^j + f^j \delta_A(t)$$

(4.35)

$$\varphi_B^j(t) + f^j \delta^j(t) = \tfrac{1}{\lambda^j} \rho_B^j(t) + N_B^j + f^j \delta_B(t)$$

And the difference of the two equations is

$$\varphi_B^j(t) - \varphi_A^j(t) = \tfrac{1}{\lambda^j} \left[\rho_B^j(t) - \rho_A^j(t) \right] + N_B^j - N_A^j + f^j [\delta_B(t) - \delta_A(t)] \qquad (4.36)$$

Equation (4.36) is referred to as single-difference equation. This equation stresses one aspect of the solution for the unknowns on the right side. A system of such equations would lead to a rank deficiency even in the case of an arbitrarily large redundancy. [1]

This means that the design matrix of the adjustment has linearly dependent columns and a rank deficiency exists. Therefore, the relative quantities

$$N_{AB}^j = N_B^j - N_A^j \,,$$

(4.37)

$$\delta_{AB}(t) = \delta_B(t) - \delta_A(t),$$

are introduced. Using additionally the shorthand notations

$$\varphi_{AB}^j(t) = \varphi_B^j(t) - \varphi_A^j(t) \,,$$

(4.38)

$$\rho_{AB}^j(t) = \rho_B^j(t) - \rho_A^j(t)$$

and substituting (4.37) and (4.38) into (4.36) gives

$$\varphi_{AB}^j(t) = \frac{1}{\lambda^j} \rho_{AB}^j(t) + N_{AB}^j - f^j \,\delta_{AB}(t) \,,$$
(4.39)

Which is the final form of the single-difference equation. Note that the satellite clock bias has canceled, compared to the phase equation (4.11). [1]

Double-differences

Assuming the two points A, B, and the two satellites j, k, two single-differences according to Eq. (6.42) may be formed:

$$\varphi_{AB}^j(t) = \frac{1}{\lambda^j} \rho_{AB}^j(t) + N_{AB}^j - f^j \,\delta_{AB}(t) \,,$$

(4.40)

$$\varphi_{AB}^k(t) = \frac{1}{\lambda^k} \rho_{AB}^k(t) + N_{AB}^k - f^k \,\delta_{AB}(t) \,,$$

To obtain a double-difference, these single-differences are subtracted. Two cases must be considered. [1]

Case 1

Assuming equal frequencies f = f j = f k for the satellite signals, the result is

$$\varphi_{AB}^k(t) - \varphi_{AB}^j(t) = \frac{1}{\lambda}\left[\rho_{AB}^k(t) - \rho_{AB}^j(t)\right] + N_{AB}^k - N_{AB}^j \ ,$$ (4.41)

Using shorthand notations for the satellites j and k analogously to (4.38),

the final form of the double-difference equation is

$$\varphi_{AB}^{jk}(t) = \frac{1}{\lambda}\rho_{AB}^{jk}(t) + N_{AB}^{jk} \quad ,$$ (4.42)

where λ = λ j = λk . The elimination of the receiver clock biases is the main reason why double-differences are preferably used. This cancellation resulted from the assumptions of simultaneous observations and equal frequencies of the satellite signals. [1]

Symbolically, the convention

$$*_{AB}^{jk} = *_{AB}^k + *_{AB}^j$$ (4.43)

has been introduced, where the asterisk may be replaced by Φ, e , or N. Note that these terms comprising two subscripts and two superscripts are actually composed of four terms. The symbolic notation

$$*_{AB}^{jk} = *_{B}^k - *_{B}^j - *_{A}^k + *_{A}^j$$ (4.44)

Characterizes, in detail, the terms in the double-difference equation:

$$\varphi_{AB}^{jk}(t) = \varphi_B^k(t) - \varphi_B^j(t) - \varphi_A^k(t) + \varphi_A^j(t$$

$$\rho_{AB}^{jk}(t) = \rho_B^k(t) - \rho_B^j(t) - \rho_A^k(t) + \rho_A^j(t)$$ (4.45)

$$N_{AB}^{jk}(t) = N_B^k(t) - N_B^j(t) - N_A^k(t) + N_A^j(t)$$

Case 2

Now different frequencies f j $\neq$ f k are considered. Referring to Eq. (4.35), the model equations for carrier phases measured at the two sites A and B to the satellite j are now given by

$$\varphi_A^j(t) + f^j \delta^j(t) = \frac{1}{\Lambda^j}\rho_A^j(t) + N_A^j - f^j \,\delta_A(t)\,,$$

(4.46)

$$\varphi_B^j(t) + f^j \delta^j(t) = \frac{1}{\Lambda^j}\rho_B^j(t) + N_B^j - f^j \,\delta_B(t),$$

The measured phases are scaled to ranges by

$$\tilde{\Phi}^{\,j}(t) = \lambda^j \,\Phi^j(t)\,,$$

(4.47)

where $\tilde{\Phi}$ j(t) is output by the receiver. The single-difference of the two

equations (4.46) leads to

$$\varphi_B^j(t) - \varphi_A^j(t) = \rho_B^j(t) - \rho_A^j(t) + \Lambda^j\left[N_B^j - N_A^j\right] + c\,[\delta_B(t) - \delta_A(t)$$

(4.48)

With $c = \Lambda^j f^j$ being the speed of light. Introducing the shorthand notations of (6.40) and (6.41), i.e., symbolically $*_{AB}^{jk} = *_B^k - *_B^j$ a more compact form is achieved By

$$\varphi_{AB}^j(t) = \rho_{AB}^j(t) + \Lambda^j N_{AB}^j + c\,\delta_{AB}(t)\,.$$

(4.49)

Assuming two satellites j, k gives rise to two single-differences (4.49). From these the double-difference

$$\varphi_{AB}^k(t) - \varphi_{AB}^j(t) = \rho_{AB}^k(t) - \rho_{AB}^j(t) + \Lambda^k N_{AB}^k - \Lambda^j N_{AB}^j$$

(4.50)

is obtained. Introducing again shorthand notations, symbolically $*_{AB}^{jk} = *_{AB}^k + *_{AB}^j$ there results

$$\varphi_{AB}^{jk}(t) = \rho_{AB}^{jk}(t) + \Lambda^k N_{AB}^k - \Lambda^j N_{AB}^j\,,$$

(4.51)

Which may be rearranged by "adding zero" in the form of $-\lambda^k N_{AB}^j + \lambda^k N_{AB}^j$ so that

$$\varphi_{AB}^{jk}(t) = \rho_{AB}^{jk}(t) + \lambda^k N_{AB}^{jk} + N_{AB}^j(\lambda^k - \lambda^j) \tag{4.52}$$

Is finally obtained. This equation differs from the double-difference equation (4.42) by the "single-difference bias" $b_{SD} = N^j(\lambda^k - \lambda^j)$. The unknown single-difference can be estimated from single-point positioning with an accuracy of about 10 m corresponding to 50 cycles (for a typical wavelength of some 20 cm). If the wave- length difference for two carriers corresponds to 0.000 351 cycles (which is typical for GLONASS carriers being separated by one carrier number, then the result $b_{SD} = 0.02$ cycles is obtained. This shows that for small frequency differences b_{SD} acts as a nuisance parameter. For larger differences, iterative processing has been proposed. In the first step, only satellites with small wavelength differences are considered. Hence, the double differenced ambiguities of these satellites can be resolved and an improved position is obtained leading to a more accurate estimation for N^j. [1]

The procedure is then continued and stepwise extended to all satellites until all ambiguities have been resolved.

Triple-differences

So far only one epoch t has been considered. To eliminate the time-independent ambiguities, Remondi (1984) has suggested differencing double-differences between two epochs. Subsequently, only the case $f^j = f^k$ is considered explicitly. Denoting the two epochs in (6.43) by t_1 and t_2, then

$$\varphi_{AB}^{jk}(t_1) = \frac{1}{\lambda} \rho_{AB}^{jk}(t_1) + N_{AB}^{jk} \quad,$$

$$\tag{4.53}$$

$$\varphi_{AB}^{jk}(t_2) = \frac{1}{\lambda} \rho_{AB}^{jk}(t_2) + N_{AB}^{jk} \quad,$$

are the two double-differences, and

$$\varphi_{AB}^{jk}(t_2) - \varphi_{AB}^{jk}(t_1) = \frac{1}{\lambda}[\rho_{AB}^{jk}(t_2) - \rho_{AB}^{jk}(t_1)] \tag{4.54}$$

Is the triple-difference, which may be written in the simplified form

$$\varphi_{AB}^{jk}(t_{12}) = \frac{1}{\lambda}\rho_{AB}^{jk}(t_{12}) \qquad (4.55)$$

if the symbolic formula

$$*(t_{12}) = *(t_2) - *(t_1) \qquad (4.56)$$

is applied to the terms Φ and e. It should be noted that both $\varphi_{AB}^{jk}(t_{12})$ and $e_{AB}^{jk}(t_{12})$ are actually composed of eight terms each. Re substituting (4.54) and either (4.44) or (4.45) yields

$$\varphi_{AB}^{jk}(t_{12}) = \varphi_B^k(t_2) - \varphi_B^j(t_2) - \varphi_A^k(t_2) - \varphi_A^j(t_2) - \varphi_B^k(t_1) - \varphi_B^j(t_1) - \varphi_A^k(t_1) - \varphi_A^j(t_1) \qquad (4.57)$$

And

$$\rho_{AB}^{jk}(t_{12}) = \rho_B^k(t_2) - \rho_B^j(t_2) - \rho_A^k(t_2) - \rho_A^j(t_2) - \rho_B^k(t_1) - \rho_B^j(t_1) - \rho_A^k(t_1) - \rho_A^j(t_1) \qquad (4.58)$$

It may be proved by the reader that for the case $f^j \neq f^k$ the equation

$$\varphi_{AB}^{jk}(t_{12}) = \rho_{AB}^{jk}(t_{12}) \qquad (4.59)$$

is obtained instead of (4.55).

The advantage of triple-differences is the canceling effect for the ambiguities, which eliminates the need to determine them. [1]

GPS satellite a
epoch t₁

GPS satellite b
epoch t₁

$p_q^a(t_1)$

$p_q^b(t_1)$

GPS receiver q

Carrier beat phase ranges

Single difference
(between satellites)

$p_q^a(t_1)$
$p_q^b(t_1)$
receiver clock Error cancels → $p_q(t_1)$

GPS satellite a
epoch t₁

$p_q^a(t_1)$

$p_r^a(t_1)$

GPS receiver q

GPS receiver r

Carrier beat phase ranges

Single difference
(between receivers)

$p_q^a(t_1)$
$p_r^a(t_1)$
Satellite clock Error cancels → $p^a(t_1)$

GPS satellite a
epoch t_1

GPS satellite b
epoch t_1

$p_q^a(t_1)$ $p_q^b(t_1)$ $p_r^a(t_1)$ $p_r^b(t_1)$

GPS
receiver q

GPS
receiver r

Carrier beat phase banges

Single differences
(between receivers)

Double differences
(between receivers and between satellites)

$p_q^a(t_1)$ Satellite clock
$p_r^a(t_1)$ Error cancels $\rightarrow$ $p^a(t_1)$

Satellite and receiver clock Errors cancel $\rightarrow$ $p(t_1)$

$p_q^b(t_1)$ Satellite clock
$p_r^b(t_1)$ Error cancels $\rightarrow$ $p^b(t_1)$

4.3.3 Static relative positioning

In a static survey of a single baseline vector between points A and B, the two receivers must stay stationary during the entire observation session. In the following, the single-, double-, and triple-differencing are investigated with respect to the number of observation equations and unknowns. It is assumed that the two sites A and B are able to observe the same satellites at the same epochs. The practical problem of satellite blockage is not considered here. The number of epochs is again denoted by n_t , and ns denotes the number of satellites. [1]

The un differenced phase as shown in Eq. (4.11) (where the satellite clock is assumed to be known) is not included here, because there would be no connection (no common unknown) between point A and point B. The two data sets could be solved separately, which would be equivalent to point positioning. [1]

A single-difference may be expressed for each satellite and for each epoch. The number of measurements is, therefore, $n_s\ n_t$. The number of unknowns is written. [1]

below the corresponding terms of the single-difference equation, cf. Eq. (4.39):

$$\varphi_{AB}^{j}(t) = \tfrac{1}{\lambda^j}\rho_{AB}^{j}(t) - N_{AB}^{j} - f^{j}\,\delta_{AB}(t)\,,$$

(4.60)

$$n_s\,n_t \geq 3 +\ n_s + (\,n_t - 1\,)\ .$$

The $n_t - 1$ unknown clock biases indicate a rank deficiency of 1. The explanation is the same as for static point positioning, cf. Eq. (4.12). From above, the relation

$$n_t \geq \frac{n_s+2}{n_s-1}$$

(4.61)

May be derived. Although this equation is equivalent to Eq. (4.13), it is useful to repeat the (theoretically) minimum requirements for a solution. A single satellite does not provide a solution because the denominator of (4.61) becomes zero. With two satellites, there results $n_t \geq 4$, and for the normal case of four satellites, $n_t \geq 2$ is obtained. [1]

For double-differences, the relationship of measurements and unknowns is obtained using the same logic. Note that for one double-difference two satellites are necessary. For ns satellites, therefore, $n_s - 1$ double-differences are obtained at each epoch so that the total number of double-differences is $(n_s - 1) \, n_t$. The number of unknowns is written below the corresponding terms of the double-difference equation, cf. Eq. (4.42): [1]

$$\varphi_{AB}^{jk}(t) = \frac{1}{\lambda}\rho_{AB}^{jk}(t) - N_{AB}^{jk} \ ,$$

(4.62)

$$(n_t - 1)\, n_t \geq 3 + n_s + (n_s - 1)$$

From above, the relation

$$n_t \geq \frac{n_s + 2}{n_s - 1}$$

(4.63)

Is obtained, which is identical with Eq. (4.61) and, therefore, the basic configurations are again given by the pairs $n_s = 2$, $n_t \geq 4$ and $n_s = 4$, $n_t \geq 2$. To avoid linearly dependent equations when forming double-differences, a reference satellite is used, against which the measurements of the other satellites are differenced. For example, take the case where measurements are made to the satellites 6, 9, 11, and 12 and 6 is used as reference satellite. Then, at each epoch the following double-differences can be formed: (9-6), (11-6), and (12-6). Other double-differences are linear combinations and, thus, linearly dependent. [1]

For instance, the double-difference (11-9) can be formed by subtracting (11-6) and (9-6).

Note that relation (4.63) also applies if the frequencies of the satellite signals are not equal. Referring to (4.51), the number of single-difference ambiguities corresponds to that of (4.50) and amounts to n_s, which may be combined to $n_s - 1$ Double-difference ambiguities if the single-difference ambiguities of one satellite are taken as reference. [1]

The triple-difference model includes only the three unknown point coordinates. For a single triple-difference, two epochs are necessary. Consequently, in the case of n_t epochs, $n_t - 1$ linearly independent epoch combinations are possible. Thus, [1]

$$\varphi_{AB}^{jk}(t_{12}) = \frac{1}{\Lambda} \rho_{AB}^{jk}(t_{12})$$

(4.64)

$$(n_t - 1)(n_s - 1) \geq 3$$

are the resulting equations. From above, the relation

$$n_t \geq \frac{n_s + 2}{n_s - 1}$$

(4.65)

Is obtained. This equation is identical with Eq. (4.61) and, hence, the basic configurations are again given by the pairs $n_s = 2$, $n_t \geq 4$ and $n_s = 4$, $n_t \geq 2$.

This completes the discussion on static relative positioning. As shown, each of the mathematical models – single-difference, double-difference, triple-difference may be used. The relationships between the number of observation equations and the number of unknowns will be referred to again in the discussion of the kinematic case. [1]

4.3.4 Kinematic relative positioning

In kinematic relative positioning, the receiver on the known point A of the baseline vector remains fixed. The second receiver moves, and its position is to be deter- mined for arbitrary epochs. The models for single-, double-, and triple-difference implicitly contain the motion in the geometric distance. Considering point B and satellite j, the geometric distance in the static case is given by, cf. Eq. (4.2), [1]

$$\rho_B^j(t) = \sqrt{(X^j(t) - X_B)^2 + (Y^j(t) - Y_B)^2 + (Z^j(t) - Z_B)^2} \ ,$$

(4.66)

And in the kinematic case by

$$\rho_B^j(t) = \sqrt{(X^j(t) - X_B(t))^2 + (Y^j(t) - Y_B(t))^2 + (Z^j(t) - Z_B(t))^2} \qquad (4.67)$$

Where the time dependence for point B appears. In this mathematical model, three coordinates are unknown at each epoch. Thus, the total number of unknown site coordinates is $3\ n_t$ for n_t epochs. The relations between the number of observations and the number of unknowns for the kinematic case follow from the static single- and double-difference models, cf. Eqs. (4.60), (4.62):

single-difference: $n_s n_t \geq 3 n_t + n_s + (n_t - 1)$,

double-difference: $(n_s - 1) n_t \geq 3 n_t + (n_s - 1)$,

For example, the relation

$$n_t \geq \frac{n_s - 1}{n_s - 4} \qquad (4.68)$$

The continuous motion of the roving receiver restricts the available data for the determination of its position to one epoch. But none of the above two models pro- vides a useful solution for $n_t = 1$. Thus, these models are modified: the number of unknowns is reduced by omitting the ambiguity unknowns, i.e., the ambiguities are assumed to be known. For the single-difference case, this has a twofold effect: first, the ns ambiguities may be omitted and, second, the rank deficiency vanishes because of the known ambiguities so that n_t unknown clock biases have to be deter- mined. The modified observation requirement for the single-difference is therefore ns $n_t \geq 4\ n_t$ and reduces to $n_S \geq 4$ for a single epoch. Similarly, for the double-difference ns $- 1$ ambiguities are omitted in (4.68) so that $(n_S - 1)\ n_t \geq 3\ n_t$ results, which reduces to $n_S \geq 4$ for a single epoch. Hence, the single-difference and the double-difference models end up again with the fundamental requirement of four simultaneously observable satellites. [1]

The use of triple-differences for kinematic cases is strongly restricted. In principle, the definition of triple-differences with two satellites at two epochs and two stations at – with respect to the two epochs – fixed positions exclude any application since the rover position changes epoch by epoch. However, triple-differences could be used if, e.g., the coordinates of the roving receiver were known at the reference epoch. In this case, adapting (4.64) to the kinematic case with 3 n_t unknowns and reducing the number of unknown rover positions by 3 because of the known rover position at the reference epoch, the relationship obtained would be $(n_S - 1)(n_t - 1) \geq 3(n_t - 1)$. This leads to $n_S \geq 4$, which is the same requirement as for the ambiguity-reduced single- and double-differences. [1]

Omitting the ambiguities for single- and double-difference means that they must be known. The corresponding equations are simply obtained by rewriting (4.60) and (4.62) with the ambiguities shifted to the left side of the equations. The single-differences become

$$\varphi_{AB}^{j}(t) - N_{AB}^{j} = \frac{1}{\lambda^{j}}\rho_{AB}^{j}(t) - f^{j}\,\delta_{AB}(t)\,, \tag{4.70}$$

and the double-differences

$$\varphi_{AB}^{jk}(t) - N_{AB}^{jk} = \frac{1}{\lambda}\rho_{AB}^{jk}(t) \tag{4.71}$$

where the unknowns now appear only on the right sides.

If the frequencies of the satellite signals are not equal, an analogous relation for the double-difference is obtained. Referring to (4.52), the two terms containing. [1]
Ambiguities may be shifted to the left side to indicate that they are known. Then the only remaining term on the right side is $\rho_{AB}^{jk}(t)$

Thus, all of the equations can be solved if one position of the moving receiver is known. Preferably (but not necessarily), this will be the starting point of the moving receiver. The baseline related to this starting point is denoted as the starting vector. With a known starting vector, the ambiguities are determined and are known for all subsequent positions of the roving receiver as long as no loss of signal lock occurs and a minimum of four satellites is in view. [1]

Static initialization

Three methods are available for the static determination of the starting vector. In the first method, the moving receiver is initially placed at a known point, creating a known starting vector. The ambiguities can then be calculated from the double- difference model (6.91) as real values and are then fixed to integers. A second method is to perform a static determination of the starting vector. The third initialization technique is the antenna swap method according to B.W. Remondi. The antenna swap is performed as follows: denoting the reference mark as A and the starting position of the moving receiver as B, a few measurements are taken in this configuration, and with continuous tracking, the receiver at A is moved to B, while the receiver at B is moved to A, where again a few measurements are taken. [1]

This is sufficient to precisely determine the starting vector in a very short time (e.g., 30 seconds). Often, a second antenna swap is performed by moving the receivers to their starting positions. [1]

Kinematic initialization

Special applications require kinematic GNSS without static initialization since the moving object whose position is to be calculated is in a permanent motion (e.g., a buoy or an airplane while flying). Translated to model equations, this means that the most challenging case is the determination of the ambiguities on-the-fly (OTF). The solution requires an instantaneous ambiguity resolution or an instantaneous positioning (i.e. , for a single epoch) . This strategy sounds very simple but it can require advanced methods . A vast literature has been written on this important topic. The main problem is to find the position as fast and as accurately as possible. This is achieved by starting with approximations for the position and improving them by least - squares adjustments or search techniques. [1]

4.3.5   Pseudo kinematic relative positioning

The pseudo kinematic method can be identified as static surveying with large data gaps , The mathematical model, e.g., for double-differences, corresponds to Eq. (4.62) where generally two sets of phase ambiguities must be resolved since the point is occupied at different times. B.W. Remondi also has applied the triple-difference method followed by the ambiguity function method to avoid ambiguities altogether. Processing of the data could start with a triple-difference solution for the few minutes of data collected during the two occupations of a site. Based on this solution, the connection between the two ambiguity sets is computed . After the successful ambiguity connection, the normal double-difference solutions are performed. [1]

The time span between the two occupations is an important factor affecting accuracy. investigate the accuracy improvements by an increasing time span between the two occupations. As a rule of thumb, the minmum time span should be one hour.Note that the pseudo kinematic relative positioning method is rarely used today. [1]

4.3.6   Virtual reference stations

When processing a baseline, the effects of orbit errors, ionospheric and tropospheric refraction are reduced by forming differences of the observables, e.g., double- differences. These effects grow with increasing baseline length. Therefore, it is good practice to use short baselines requiring a reference station close to the rover. These basic considerations have led to reference station networks like the Austrian positioning service (APOS), the German satellite positioning service (SAPOS), and several others. After the establishment of such networks, some new ideas have evolved to exploit the available data accordingly. Among many others, real-time differential error modeling in reference station networks, multi- base real-time kinematic (RTK) positioning using virtual reference stations, and network-based techniques for RTK applications are respective examples. [1]

Even in case of an existing reference station network it is desirable to further reduce the baseline length. The idea is to generate "observation data" for a non-existing station, i.e., a virtual station, from real observations of a multiple reference station network and to transmit these data to the rover station. This is the basic principle of the virtual reference station (VRS) concept. Usually, the data of three or more reference stations surrounding the VRS are taken to calculate the observation data for the VRS. The result of this concept yields a horizontal accuracy at the level of 5 cm for baselines up to 35 km .Understanding the VRS principle by an elementary approach. [1]

The objective is to transform measurements made at real reference stations to the location of the VRS, i.e., to a different location. This implies that all terms of the observation equation model depending on the reference receiver location have to be corrected to account for the new location. To keep it as simple as possible, the phase pseudo range. [1]

$$\varphi_r^s(t) = \frac{1}{\lambda^s}\rho_r^s(t) - N_r^s \, \Delta\delta_r^s(t) \, , \tag{4.72}$$

as given in (4.10) after substitution of $f^s = c/\lambda^s$, is. On the left side, $\varphi_r^s(t)$ is the measured carrier phase which is modeled by $\rho_r^s(t)$, the geometric distance between receiver and satellite, the time-independent integer ambiguity N_r^s, and $\Delta\delta_r^s(t)$, the combined receiver and satellite clock bias. Now the key question is which of the terms is location-dependent? In other words, which of the terms changes if the same receiver is assumed at another location but considered at the same epoch t? The answer is $\varphi_r^s(t)$ and $\rho_r^s(t)$, because the other two terms do not change with varying location.

Now it is assumed that receiver r is once located at the real reference station A represented by the coordinate vector XA and once at the virtual reference station (VRS) represented by X_V. Then there result from these two locations from (4.72) the two equations

$$\varphi_r^s(X_A.t) = \frac{1}{\lambda^s}\rho_r^s(X_A.t) - N_r^s \, \Delta\delta_r^s(t) \, . \tag{4.73}$$

$$\varphi_r^s(X_V.t) = \frac{1}{\lambda^s}\rho_r^s(X_V.t) - N_r^s \, \Delta\delta_r^s(t) \, , \tag{4.74}$$

Where the location dependence is indicated accordingly. Forming the difference of the two equations yields

$$\varphi_r^s(X_V.t) - \varphi_r^s(X_A.t) = \frac{1}{\Lambda^s}\rho_r^s(X_V.t) - \frac{1}{\Lambda^s}\rho_r^s(X_A.t) \; , \tag{4.75}$$

Where the ambiguity and the clock error have vanished. After a slight rearrangement,

$$\varphi_r^s(X_V.t) = \varphi_r^s(X_A.t) + \frac{1}{\Lambda^s}[\rho_r^s(X_V.t) - \rho_r^s(X_A.t)] \; , \tag{4.76}$$

Results. The left-hand side is the desired "measurement quantity" at the virtual reference station. Therefore, if all terms on the right-hand side may be obtained, then there is no need to actually measure it. The term $\Phi^s(X_A, t)$ refers to the real reference station A and is measured. Accordingly, s(XA, t) is known since the station coordinates of A and the satellite coordinates of s are known and calculable, respectively. The only remaining term to be discussed is s(XV , t), which comprises the coordinates of the virtual reference station. Figure 4.3 shows the network of reference stations A, B, C,.. the virtual reference station, and the user receiver position indicated by r. In principle, the location of the virtual reference station is arbitrary. [1]
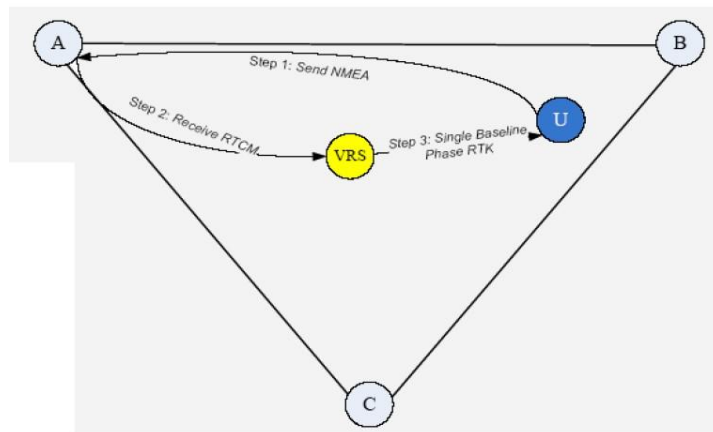
Figure 4.3. Network of reference stations with the VRS denoted as V and the roving user receiver indicated by r.

However , the baseline between the receiver r and the virtual reference station V should be smaller than the baselines between r and any other of the real reference stations. A very useful and convenient location is therefore an approximate position of the user receiver which may readily be obtained by point positioning with code measurements, yielding XV , the coordinates of the VRS. Once the coordinates of the virtual station are known, they may remain fixed for the subsequent epochs (unless the roving user receiver moves too far from the VRS). [1]

In summary, the right-hand side of (4.76) is now fully determined. Thus, the observable $\varphi_r^s(X_V.t)$ of the VRS may be obtained without actually measuring it. Since XA and XV are known as well, the computation of $\rho_r^s(X_A.t)$ and $\rho_r^s(X_V.t)$ is straight forward for the subsequent epochs; and $\varphi_r^s(X_A.t)$ is measured at the real reference station A. [1]

Area Correction Parameter (ACP) and Flaechen Korrektur - Parameter (FKP)

- Each reference base covers a part of the region.
- A single (closest) base transfers the correction to the rover.
- The baselines are less than 30km Special case FKP-method (Flaechen-Korrektur-Parameter): corrections are interpolated from the surrounding base

stations,(see Figure 4.4).
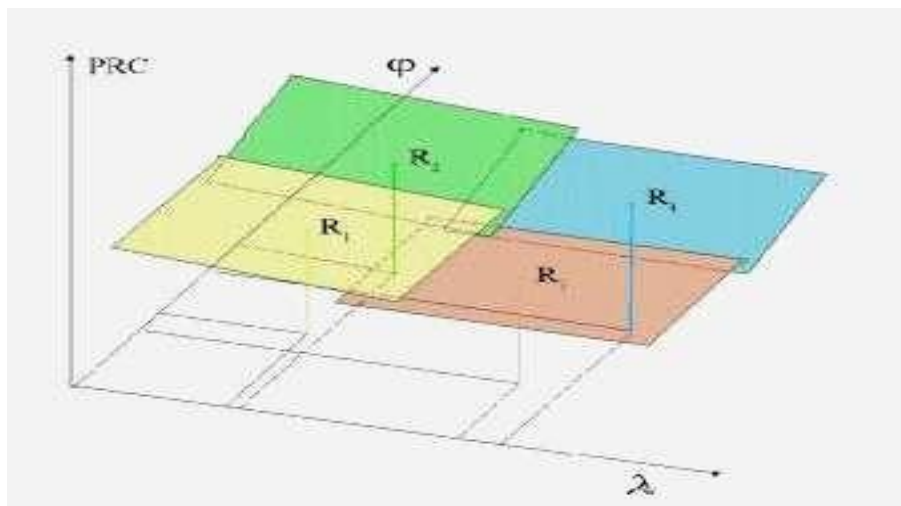
Figure 4.4. Area Correction Parameter (ACP) Structure.

Master Auxiliary Concept (MAC)

The Master Auxiliary Concept (MAC) is different than the VRS and ACP, since it just broadcasts all the information and error models for each reference station in simplex mode. The burden of modeling the GNSS-Positioning error is totally on the rover side to calculate it and then uses it to compute its corrected observations. Mainly, the transmitted data includes the data of the master reference station, and the data of other auxiliary reference stations are transmitted as offset from master reference station to compact the size of the message,(see Figure 4.4) [1].
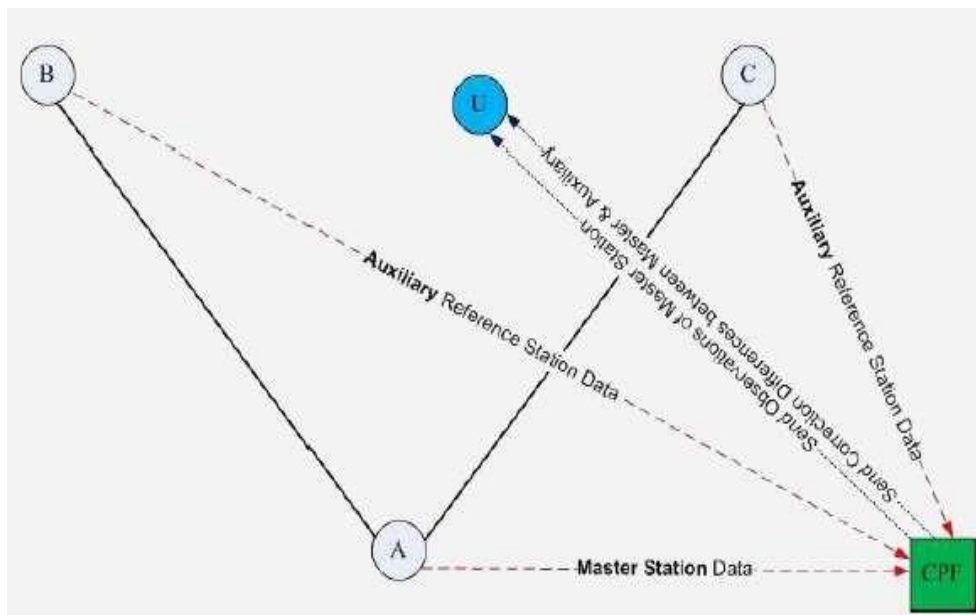
Figure 4.5. The Master Auxiliary Concept (MAC) Structure.

Chapter five

Online precise point positioning

5.1 Introduction

5.2 Benefits and Prospects

5.3 Online precise point positioning services

5.1 Introduction

Precise Point Positioning (PPP) for global precise positioning is provided by many online service, since it requires the availability of precise reference satellite orbit and clock products in real-time using a network of GNSS reference stations distributed worldwide. [4]

Combining the precise satellite positions and clocks with a dual-frequency GNSS receiver (to remove the first order effect of the ionosphere), PPP is able to provide position solutions at centimeter to decimeter level, even less than 1 cm-level positioning in static mode. PPP differs from double-difference Real Time Kinematics (RTK) positioning in the sense that it does not require access to observations from one or more close reference stations accurately-surveyed and that PPP provides an absolute positioning instead of the location relative to the reference station as RTK does. PPP just requires precise orbit and clock data, computed by a processing center with measurements from reference stations from a relatively sparse station network (thousands of km apart would suffice). This makes PPP a very attractive alternative to RTK for those areas where RTK coverage is not available. On the contrary, the PPP technique is still not so much consolidated as RTK and requires a longer convergence time to achieve maximum performances (in the order of tens of minutes). Currently, there exist several consolidated post-processing PPP services. On the contrary, real-time PPP systems are in an incipient development phase. [4]

The PPP algorithm uses as input raw code and phase observations from at least dual-frequency GPS/GNSS receiver, and precise satellite orbits and clocks from IGS services alternative, in order to calculate precise receiver coordinates and clock. The observations coming from all the satellites are processed together in a filter that solves for the different unknowns, namely the receiver coordinates, the receiver clock, the zenith tropospheric delay and the phase ambiguities. [4]

The accuracy of the satellite clocks and orbits is one of the most important factors affecting the quality of the PPP. Another relevant factor that affects the PPP performances is the amount and quality of the observations. Like any GNSS technique, PPP is affected by satellite line-of-sight obstructions. Even the most precise orbit and clock data is useless if the user cannot track particular satellites. When satellite visibility is partially obstructed, a best possible service can be ensured by using the full range of satellites from both the GPS , GLONASS, Galileo and Beidou. [4]

5.2 Benefits and Prospects

As it has been mentioned before, PPP technique offers significant benefits compared to differential precise positioning techniques:

- PPP involves only a single GPS receiver and, therefore, no reference stations are needed to occupied by the user.

- PPP can be regarded as a global position approach because its position solutions referred to a global reference frame. As a result, PPP provides much greater positioning consistency than the differential approach in which position solutions are relative to the local base station or stations.

- PPP reduces software and equipment cost and simplifies operational costs to field work since it eliminates the dependency on base station(s).

- PPP can support other applications beyond positioning. For example, as PPP technique estimates receiver clock and tropospheric effect parameters in addition to position coordinate parameter, it provides another way for precise time transfer and troposphere estimation using a single GPS receiver.

With respect to challenges, PPP faces several in order to achieve its full potential to applications. Between these challenges:

- A long initialization time, this is a drawback for real-time applications.

- Integer ambiguity resolution, to have a more precise solution.

5.3 Online precise point positioning services

5.3.1 AUSPOS - Online GPS Processing Service

AUSPOS is a free online GPS data processing facility provided by Geoscience Australia. It takes advantage of both the IGS Stations Network and the IGS product range. AUSPOS works with data collected anywhere on Earth. submitting dual-frequency geodetic quality GPS RINEX data observed in a 'static' mode to the GPS data processing system. An AUSPOS report will be emailed to who use it with the Geocentric Datum of Australia 2020 (GDA2020), Geocentric Datum of Australia 1994 (GDA94) and International Terrestrial Reference Frame (ITRF) coordinates. [9]

The service aims to support a variety of users from the private and public sector who require GDA94 and ITRF coordinates. This includes people undertaking surveys such as:

- DGPS reference station positioning
- Remote GPS station positioning
- Ultra-long GPS baseline positioning
- GPS connections to IGS and ARGN stations
- High accuracy vertical GPS positioning
- GPS network quality control

The requirement for use it and submit the data and receive the report is:
- Geodetic quality dual frequency GPS receiver data in RINEX format
- Access to a web browser with an Internet connection
- An email account.

All the GPS data processing occurs in the AUSPOS GPS data processing server, so the type and capability of the computer is NOT important.

For submitting the GPS RINEX file/s, you should ensure that:

1. The GPS RINEX file/s contain more than one hour (preferably two) of GPS data.

2. The GPS RINEX file/s do not contain any data from the current UT day.

3. The GPS RINEX file/s do not contain more than seven days of data.

4. The GPS RINEX file/s names do not contain spaces.

5. When submitting multiple files, ensure the first four characters / numbers of the file names are not the same.

6. You have used the IGS naming convention for the antenna type.

7. The antenna height provided is the vertical distance from the ground mark to the Antenna Reference Point (ARP).

All computations are undertaken using the Bernese Software System (Bernese is a high precision orbit and geodetic parameter determination software system).The International GPS Service (IGS) product range is used in the computation process(Precise orbit parameters, Earth orientation parameters and coordinate solution IGS products are used). [9]

Once a user has submitted a RINEX file, the nearest 15 IGS and APREF stations are used as the reference stations for the processing. That data is retrieved from Geoscience Australia's GNSS Data Archive, (see fig 5.1). A precise solution using a 'double difference' technique is then computed using these stations. The coordinates of the IGS stations are constrained with uncertainties of 1mm for horizontal and 2mm for the vertical. [9]
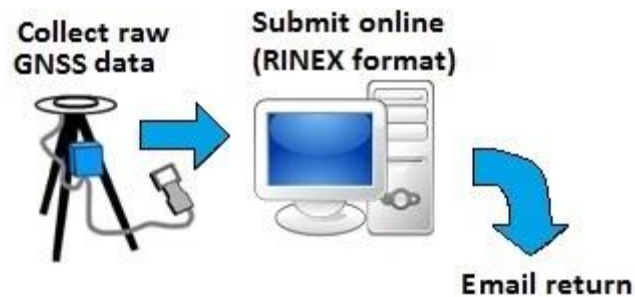
Figure 5.1: the functionality and components of System.

5.3.2 Online Positioning User Service (OPUS)

This Online Positioning User Service (OPUS) provides simplified access to high-accuracy National Spatial Reference System (NSRS) coordinates. Upload a GPS data file collected with a survey-grade GPS receiver and obtain an NSRS position via email.

OPUS requires minimal user input and uses software which computes coordinates for NGS' Continuously Operating Reference Station (CORS) network. The resulting positions are accurate and consistent with other National Spatial Reference System users.

Uploading

Using OPUS requires just five simple steps:
Data File of dual-frequency GPS (L1/L2) full-wavelength carrier observables:

- Static data only; the antenna must remain unmoved throughout the observing session.
- 15-minutes of data or more, up to 48-hours, but not crossing UTC midnight more than once.
- Files under 2 hours, processed as rapid-static, must include the P2 and either P1 or C1 observables.
- GLONASS or Galileo observables may be included; though only the GPS are used.
- Any elevation cut-off or mask angle; though only satellites more than 10° above the horizon are used.
- Recording (epoch) rates of 1, 2, 3, 5, 10, 15, or 30 seconds; though all are decimated to 30 seconds.
- RINEX 2.x data format, or many raw data formats
- Compressed UNIX, gzip, pkzip, or Hatanaka formats are allowed, including multiple file archives (all must share the same antenna type & height).

Processing

OPUS will use either a static or rapid-static process, depending on the duration of your data file.

Static: Files are processed using PAGES static software. Your coordinates are averaged from three independent, single-baseline solutions, each computed by double-differenced, carrier-phase measurements from one of three nearby CORS.

Rapid-static: Files are processed using RSGPS rapid-static software. Rapid-static processing employs more aggressive algorithms to resolve carrier phase ambiguities, but has more stringent data continuity and geometry requirements; therefore there are some remote areas of the country in which it will not work.

Accuracy

Under normal conditions, most positions can be resolved to within a few centimeters. Estimating the accuracy for a specific solution is difficult, however, as formal error propagation is notoriously optimistic for GPS reductions. Systematic errors, such as misidentification of antenna or height, are not detected. Local multipath or adverse atmospheric conditions may also negatively impact your solution.

Static: Static processing provides peak-to-peak errors for each coordinate (X, Y, Z, Φ, λ, h, and H). These describe the error range, the disagreement between the 3 baseline solutions, as shown above.

One advantage of peak-to-peak errors is that they include any error from the CORS reference coordinates.

Rapid static: Absent any warning messages, the best estimates of coordinate accuracy are the standard deviations reported by single baseline analysis. Our experiments indicate that the actual error is less than these estimated accuracies more than 95 percent of the time.

5.3.3 CSRS-PPP Online

CSRS-PPP is an online application for GNSS data post-processing allowing users to compute higher accuracy positions from their raw observation data. uses the precise GNSS satellite orbit ephemerides to produce corrected coordinates of a fixed accuracy no matter where you are on the globe, regardless of proximity to known base stations. [10]

Users can submit RINEX observation data from single or dual-frequency receivers operating in static or kinematic mode over the Internet and recover enhanced positioning precisions in the Canadian Spatial Reference System (CSRS) and International Terrestrial Reference Frame (ITRF). [10]

CSRS-PPP Online Computation:

1. Enter email address to which the processing results will be sent
2. Select the processing mode: static or kinematic
3. Select the reference frame of the output coordinates: NAD83 (North American Datum of 1983) or ITRF.
4. Import the RINEX observation file by clicking on "Choose file"
5. Click "Submit to PPP"

Precise GNSS orbit ephemerides

CSRS-PPP online post-processing tool will use the best available ephemerides (FINAL, RAPID or ULTRA-RAPID).

- FINAL (+/- 2 cm): combined weekly and available 13 -15 days after the end of the week.
- RAPID (+/- 5 cm): available the next day.
- ULTRA RAPID (+/- 15 cm): available every 90 minutes (not available to download).

International Terrestrial Reference Frame (ITRF)

The specific ITRF used by CSRS-PPP is the one realized by the International GNSS Service (IGS) at the time for which the precise GNSS orbit ephemerides were computed. With the production of orbit estimates on a daily basis, the ITRF realization time will always be within a day of the submitted GNSS data. [10]

Methodologies of using CSRS-PPP

Suggested methodologies

1) It is better to compute the base station's coordinates before starting the Real Time Kinematic (RTK) work. The user could setup the base station ahead of time and collect raw GNSS data (anywhere from 2hrs to 24 hrs. depending on the accuracy required). Leave the base station in place. Transform the raw data to RINEX and submit it for Static CSRS-PPP processing. CSRS-PPP can process the data approximately 90 minutes after data collection. When the user achieve accurate coordinates from CSRS-PPP, he can begin the RTK work.

2) If it is not possible to collect raw data and run CSRS-PPP ahead of time, the RTK survey can still be performed entering the Base Station's approximate coordinates.by Ensure that base station raw data is recorded for as long as possible. Run Static CSRS-PPP after the RTK survey then compute the difference (between approximate and PPP coordinates) and apply a 3D shift to the entire survey. A minor drawback here is that for each ten meters of error in the Base Station position an additional 1ppm (1mm per kilometer) error is introduced in the baseline computation.

3) A popular methodology is to establish accurate coordinates for 2 points within the survey area (a fair distance apart and inter-visible). Collect raw GNSS data at the same time at both points and post-process both using StaticNAD83 (CSRS). Also process both files as a baseline (distance, azimuth) using your phase differential post-processing software. From the CSRS-PPP output coordinates, you can compute the distance and azimuth between points as well (program INDIR, inverse solution). Comparing these results can serve as quality control plus you now have 2 geodetic control points to choose from. Make one of them the main Base Station location; the survey will be anchored to this point. The other point can be tied with the Rover during the RTK survey (as an additional check) and used as a back sight for traditional surveying.

5.3.4 Scripps Orbit And Permanent Array Center (Sopac) Scripps Coordinate Update Tool (SCOUT)

The Scripps Orbit and Permanent Array Center (SOPAC) is located in California. SOPAC's primary role is to research and support high precision geodetic and geophysical measurements using Global Navigation Satellite Systems (GNNS), such as GPS, particularly for the study of earthquake hazards, tectonic plate motion, plate boundary deformation and, meteorology. [11]

SOPAC serves as a Global Data Center and a Global Analysis Center for the International GNSS Service (IGS), since its inception. SOPAC maintains a data archive of thousands of GNSS regional and global GNSS stations, and data products. SOPAC is the operations center for the California Spatial Reference Center (CSRC), which provides California's geodetic framework for scientific, surveying, engineering, and geographical information systems. They operate the California Real Time Network (CRTN) for the CSRC, serving GNSS data streams in real time to more than 800 users. SOPAC also maintains a clearinghouse of real-time high-rate GNSS data from more than 600 stations in the western U.S. The Real-time Earthquake Analysis for Disaster Mitigation Network (READI) project, includes real-time data from servers at UNAVCO/PBO, UC Berkeley (BARD), Central Washington Univ. (PANGA), and the U.S. Geological Survey. They are responsible for 22 real-time GNSS stations in southern California. [11]

Scripps Coordinate Update Tool (SCOUT)

The Scripps Coordinate Update Tool (SCOUT) is One of the application of SOPAC it can be used to compute mean coordinates of a specific site, by submitting a RINEX file of a particular day, it is uses ultra-rapid orbits to allow near-real-time data processing, and these GPS models are supported Receivers and Antennas. [11]

Users are limited to 10 uncompleted (queued) jobs at a time. Average run time is 30 minutes. SCOUT now launches jobs to multiple servers (when available) to reduce wait times.

To use this online service the user should ensure that:

1. Files may be in obs (o) or hatanaka (d) format, and may be compressed (.Z, .gz, .bz,.bz2). zip files are not supported. limit file upload size to 10 MB.

2. File names submitted must be in the standard form: SITEDDDF.YYT plus an optional compression suffix. Where SITE is a 4-character site code, DDD is day of year, Y is last two digits of year, T is type d or o, F is sequence code (0 for daily or a-x for hourly) File names may be upper or lower case, but must use UTF-8 characters.

3. Minimum recommended file time span: 1 hour.

5.3.5 The Automatic Precise Positioning Service of the Global Differential GPS (GDGPS) System

The Global Differential GPS (GDGPS) System is a complete, highly accurate, and extremely robust real-time GNSS monitoring and augmentation system. Employing a large ground network of real-time reference receivers, innovative network architecture, and award-winning real-time data processing software, the GDGPS System provides sub-decimeter (<10 cm) positioning accuracy and sub-nanosecond time transfer accuracy anywhere in the world, on the ground, in the air, and in space, independent of local infrastructure. [12]

A complete array of real-time GNSS state information, environmental data, and ancillary products are available in support of the most demanding GNSS Augmentation operations, Assisted GNSS (A-GNSS) services, situational assessment, and environmental monitoring - globally, uniformly, accurately, and reliably. [12]

Full product line services are available for GPS, GLONASS, BeiDou and Galileo.

Automatic Precise Positioning Service (APPS)

APPS accepts GPS measurement files, and applies the most advanced GPS positioning technology from NASA's Jet Propulsion Laboratory to estimate the position of the GPS receivers, whether they are static, in motion, on the ground, or in the air. APPS employs: [12]

- Real-time GPS orbit and clock products from JPL's GDGPS System.
- JPL's daily and weekly precise GPS orbit and clock products.

- JPL's GIPSY-OASIS software for processing the GPS measurements.
- APPS continues to provide JPL's venerable AutoGIPSY (AG) service - for free, for static post-processing (e.g. measurement latency of a week or more), but also offers new and unique services:
- APPS will generate a time series of positions if your receiver was in motion.
- APPS has access to real-time GPS orbit and clock products so you never have to wait.
- APPS is fast. Positioning is available in seconds.

APPS supports the following measurement file types:

- Formats: RINEX 2, RINEX 2.11 .
- Filename: arbitrary.
- Measurement rate: up to 1 second.
- Pressure measurements may be optionally uploaded, from which hydrostatic zenith delay will be derived.

APPS supports a variety of useful processing modes

- **Static.**
- **Kinematic.**

- **Near Real Time (NRT).**
- **Most Accurate.**

APPS will produce the following output:
- All coordinates are in ITRF2008.
- Summary file: Run status (success/error), key output values, list of output.
- XYZ file: Time, X, Y, Z coordinates, together with their formal errors.
- LLH file: Time, Lat, Lon, Height coordinates, together with their formal errors.
- GIPSY STACOV file: X, Y, Z coordinates with full covariance (for static only)
- GIPSY TDP file: Time, X, Y, Z coordinates in GIPSY's TDP format.
- Log file: GIPSY run time messages and statistics.

- Google Earth URL: with the plotted trajectory/site.
- Instant positioning for web users, where you will see the X, Y, Z coordinates and the Lat, Lon, Height on this web site.
- Access information: URL of output files and password.

The table 5.1 below summarizes the expected positioning accuracy of this service (cm, 3D RMS) for a data files spanning 24 hours with at 1 Hz.

Table 5.1: the expected positioning accuracy of APPS.

User type	Latency	
	Near Real Time (1 minute - 24 hours)	> 1 day
Stationary (dual frequency)	< 5 cm	~1 cm
Mobile (dual frequency)	< 15 cm	< 5 cm
Airborne (dual frequency)	< 20 cm	< 10 cm
Stationary (single frequency*)	~20 cm	~10 cm
Mobile (single frequency*)	~50 cm	~25 cm
Airborne (single frequency*)	~50 cm	~25 cm

5.3.6 GPS ANALYSIS AND POSITIONING SOFTWARE (GAPS)

The GNSS Analysis and Positioning Software (GAPS) was initially developed in 2007 at the University of New Brunswick in order to provide users with a free online PPP tool capable of estimating positions and other parameters of interest. Although mainly used for positioning, GAPS was designed and built as a veritable "Swiss Army Knife" for GNSS data processing, allowing the user to estimate ionospheric and neutral atmospheric delays, receiver clock and inter-system biases, and code multipath. [13]

GAPS provides users with accurate satellite positioning using a single GNSS receiver both in static and kinematic mode. Through the use of precise orbit and clock products provided by sources such as the International GNSS Service (IGS) and Natural Resources Canada (NRCan), it is possible to achieve centimeter-level positioning in static mode and decimeter-level positioning in kinematic mode given a sufficient convergence period. [13]

For PPP, there is one general rule of thumb: the longer the observation period, the more precise the processing results will be. When considering the typical convergence periods for the PPP technique, observation periods of at least 2-3 hours in order to achieve centimeter-level positional solutions in static mode. [13]

Another consideration in file submission to GAPS is product latency. If centimeter-level positional solutions are desired, it is highly recommend that you wait for the availability of the IGS Rapid orbit and clock solutions at a minimum. These products are typically available within 17-41 hours of the observation date. While we do provide solutions using the IGS Ultra-rapid product, users should certainly expect a degradation in the positional solution. Another concern in product selection should be the observation period, (see table5.2&5.3). As the Ultra-rapid product provides satellite clock corrections at a rate of just 15 minutes, a 1-hour long observation file will only process 4 periods of observations. [13]

The convergence period of the GAPS' PPP algorithm should be a factor when considering the minimal observation period. In most cases, GAPS requires a minimum of 2-3 hours of observations in order to converge to the centimeter level of a positional solution. Other considerations for the convergence period include the observation and/or processing rate. If the IGS 30-second product is utilized and the user-submitted RINEX file was logged at a 30-second rate, convergence time will be minimized. On the other hand, if the Ultra-rapid product is utilized (15-minute satellite clock corrections) and a user-submitted RINEX file was logged at a 5-minute rate, the user should expect a fairly large degradation in the final solution. [13]

Table 5.2: GAPS processing strategy [13]

Software Version	GAPS v6.0.0 r587
GNSS System(s)	GPS, Galileo [1], BeiDou
File Type	RINEX 2.xx, 3.xx, receiver raw data, and compressed packages. Raw files accepted: Trimble DAT and RT17. Compressed packages accepted: 7z, BZIP2, GZIP, TAR,ZIP, CAB, ISO, MSI, RAR, and Z.
Downloaded Products	GPS:IGS or NRCan Final and Rapid orbit and clock files as well as IGS Ultra-Rapid files Galileo/BeiDou:IGS MGEX Final orbit and clock files from the following contributors: CODE - Center for Orbit Determination in Europe . CNES - Centre National d'Etudes Spatial . GFZ - German Research Centre for Geosciences WUH - Wuhan University . TUM - Technische Universitat Munchen . IGS weekly ANTEX files (igsyy_wwww.atx) P1C1yymm.DCB, P2C2yymm.DCB, and P1P2yymm.DCB monthly differential code bias files from CODE

Table 5.3: Measurement models of gaps [13]

basic Observables	GPS:L1 and L2 undifferenced carrier-phase & pseudorange Galileo:E1 and E5a undifferenced carrier-phase & pseudorange BeiDou: B1 and B2 undifferenced carrier-phase & pseudorange if both P1 and C1 are reported, priority will be given to P1
Observable Strategy for RINEX 3.xx file processing **For GPS L2C** **For GPS L5** **For Galileo E5b** **For Galileo E5**	GPS: P1: C1W (if reported) C1: C1C (if reported) C2: C2W as default, otherwise C2P L1: L1W as default, then L1X followed by L1C L2: L2W as default, then L2P P2: C2C and C2C/C2W L2: L5X and C5X/L2W Galileo: C1: C1X as default, otherwise C1C E1: L1X as default, otherwise L1C C5: C5X as default, otherwise C5Q E5: L5X as default, otherwise L5Q C5: C7X as default, otherwise C7Q E5: L7X as default, otherwise L7Q C5: C8X as default, otherwise C8Q E5: L8X as default, otherwise L8Q BeiDou: C1: C1I as default, otherwise C1Q B1: L1I as default, otherwise L1Q C2: C7I as default, otherwise C7Q B2: L7I as default, otherwise L7Q If multiple observable types reported on same frequency, user selected or default observable is given priority.
Modelled Observables	Undifferenced, ionosphere-free linear combination .
Processing Modes	Static or Kinematic.
Ionosphere	1st order effect: eliminated by dual-frequency observations in linear combination. 2nd order effect: no corrections applied. Other effects: no corrections applied.

5.3.7 MAGICGNSS/PPP

Magic GNSS suite comprises a set of GNSS tools and services which have been developed and tailored by GMV throughout the years to cope with the needs of the wide variety of GNSS users, providing added-value services. Including multi-GNSS Precise Orbit and Clock Determination, Precise Point Positioning, GNSS Long-Term Ephemeris Predictions and Station Monitoring among others. Magic GNSS suite implements state-of-the-art GNSS algorithms developed by GMV as a result of 25 years' experience in the field. [14]

PRECISE POINT POSITIONING Multi-constellation single and double frequency precise point positioning service which uses measurements from a single multi-frequency GNSS receiver, together with detailed physical models and corrections, and precise GNSS orbit and clock products calculated beforehand. Four different services are provided: Post-processing service: Users can upload, store and manage RINEX files in the magic GNSS cloud system workspace, and compute the receiver's position. [14]

E-mail service: Users can access this free service via e-mail by sending their raw RINEX data files to magicppp@gmv.com, receiving a response email with the precise coordinates.

Real-time service: Real-Time PPP service which uses RTCM ephemeris corrections which are received through the Internet.

Rapid PPP convergence service: multi-GNSS real time regional corrections provision service for faster PPP convergence.

Instructions of sending email [14]

- Send an email to magicppp@gmv.com with the Subject Static or Kinematic and one RINEX observation file attached (or a maximum of two files for static PPP).
- The attached files must be in standard or Hatanaka RINEX 2.00, 2.10, 2.11, 3.00, 3.01 or 3.02 format, compressed or not.
- The filenames must follow the RINEX filename convention: daily, hourly, high-rate; if your file is compressed, you must keep the RINEX filename extension and the compression extension (for example gap10750.14o.gz)
- The file attached can be an unique compressed file containing more than one RINEX.

- The files can be compressed in the following formats: .Z, .gz and .zip.
- The RINEX data rate must be one of the following, in seconds: 1, 2, 5, 10, 15, 30, 60 and 300.
- The RINEX file must contain all of the following observables: P1 (or C1), P2, L1, L2.
- GPS data earlier than 2009/01/01 and GLONASS/GALILEO data earlier than 2014/01/01 cannot be processed.
- Real-time GPS, GLONASS and GALILEO orbits and clocks needed by PPP are generated internally. It is possible to force the use of IGS products writing in the email body: Products: IGS
- In addition, if the products themselves are not available, the IGS products will be used automatically.
- In static PPP, if the user attach two RINEX files and they belong to the same station, he will also get the comparison of the two PPP results (difference of coordinates).
- Kinematic PPP can be used in two modes: Terrestrial (default) and Aeronautical. This is configured within the email body, for example:

To: magicppp@gmv.com

Subject: Kinematic

Aeronautical

- It is possible to process GPS-only and GPS+GLONASS in PPP. This is configured according to the email Subject:

Static/Kinematic = GPS+GLONASS.

Static/Kinematic GR = GPS+GLONASS .

Static/Kinematic G = GPS-only.

Chapter Six

Results and Analysis

6.1 Introduction

6.2 Open Area Results

6.3 Near Building Results

6.4 Under Tree Results

6.1 Introduction

In this chapter we will present the results and analyze them, these result from point in different places .open area, near building and under trees.

Points are placed in different places, the first point in an open area where there is no effect of buildings, trees or electric waves and it is the recommended point (see figure 6.1), the second point was near the buildings to measure the impact of building on the accuracy of monitoring (see figure 6.2), and the third point was placed under the trees where it was completely blocked by trees(see figure 6.3).

Points were monitored at a rate of one to four hours and these point were processed on three online services (Opus, Ausops, CSRS).
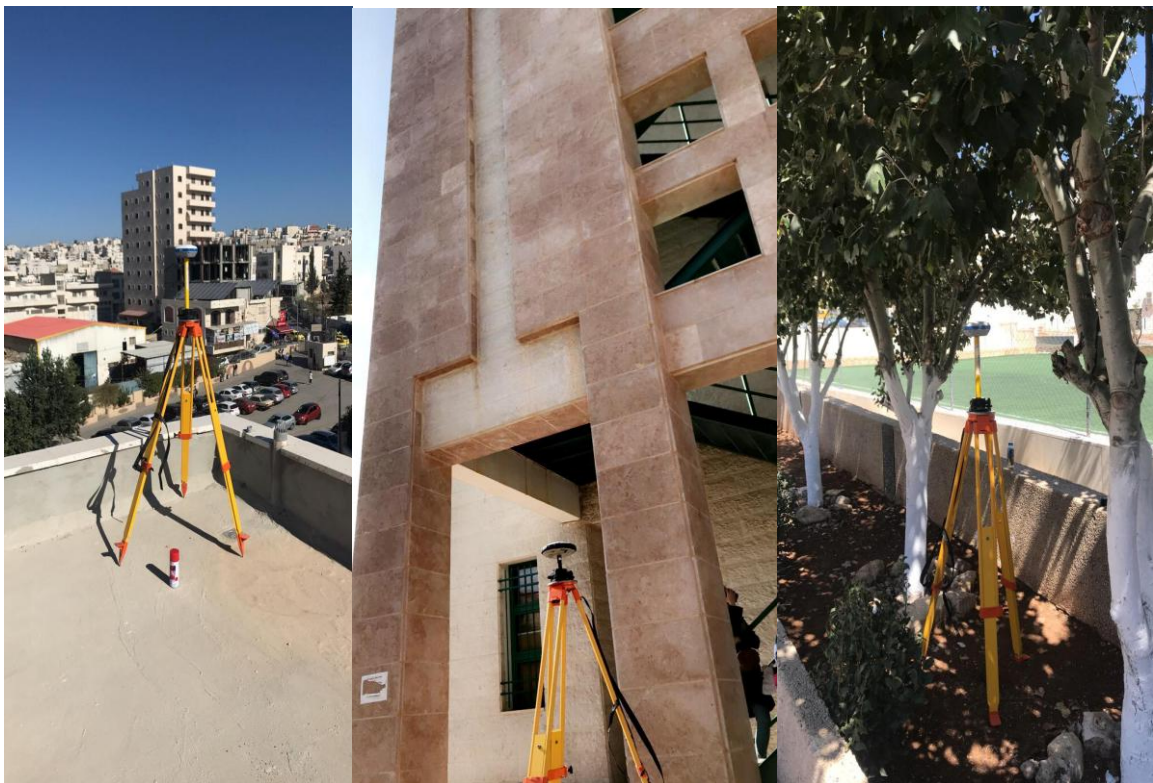
Figure (6.1): open area point.   Figure (6.2): near building point.   Figure (6.3): under trees point.

6.2 Open Area Results

The raw observation in the open area were used to calculate the position and its accuracy using Rinex format 2.1 & 3.02 . The ovservation were measured in multiple time periode (1hour to 4 hour).

6.2.1 OPUS results

Using opus for the position calculation at diffenent time intervals and file formats were tested .Table 6.1&6.2 shows the results that were achieved from OPUS (online positioning user service) online service .

Table 6.1:opus results in (x,y,z).

		Rinex 2.1				Rinex 3.02		
1 hour	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_z:	------ ------ ------	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_z:	------ ------ ------
2 hour	X: Y: Z:	4454130.418 3129395.688 3314513.704	σ_x: σ_y: σ_z:	0.045 0.037 0.025	X: Y: Z:	4454130.418 3129395.688 3314513.704	σ_x: σ_y: σ_z:	0.045 0.037 0.025
3 hour	X: Y: Z:	4454130.417 3129395.690 3314513.701	σ_x: σ_y: σ_z:	0.019 0.013 0.024	X: Y: Z:	4454130.417 3129395.690 3314513.701	σ_x: σ_y: σ_z:	0.018 0.013 0.024
4 hour	X: Y: Z:	4454130.430 3129395.706 3314513.712	σ_x: σ_y: σ_z:	0.033 0.049 0.019	X: Y: Z:	4454130.430 3129395.706 3314513.712	σ_x: σ_y: σ_z:	0.033 0.049 0.019

Table 6.2:opus results in(λ,ϕ,h).

		Rinex 2.1				Rinex 3.02		
1 hour	λ: ϕ: h:	------ ------ ------	EΔ nΔ hΔ	------ ------ ------	λ: ϕ: h:	------ ------ ------	EΔ NΔ hΔ	------ ------ ------
2 hour	λ: ϕ: h:	31 30 28.31443 35 5 28.39146 924.496(m)	EΔ NΔ hΔ	0.029 0.013 0.056	λ: ϕ: h:	31 30 28.31443 35 5 28.39146 924.496(m)	EΔ NΔ hΔ	0.029 0.013 0.056
3 hour	λ: ϕ: h:	31 30 28.31432 35 5 28.39153 924.495(m)	EΔ NΔ hΔ	0.017 0.014 0.024	λ: ϕ: h:	31 30 28.31432 35 5 28.39153 924.495 (m)	EΔ NΔ hΔ	0.018 0.014 0.023
4 hour	λ: ϕ: h:	31 30 28.31432 35 5 28.39175 924.517(m)	EΔ NΔ hΔ	0.028 0.023 0.051	λ: ϕ: h:	31 30 28.31432 35 5 28.39175 924.517(m)	EΔ NΔ hΔ	0.028 0.023 0.051

OPUS could not process data at one hour , increasing time could enhance the accuracy but in four hour shown worse accuracy due to worse satellite distribution.

6.2.2 AUSPOS results

Using Auspos for the position calculation at diffenent time intervals and file formats were tested .Table 6.3&6.4 shows the results that were achieved from AUSPOS online service .

Table 6.3:AUSPOS results in (x,y,z).

		Rinex 2.1			Rinex 3.02			
1 hour	X: Y: Z:	4454130.452 3129395.721 3314513.720	σ_x: σ_y: σ_z:		X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_z:	------ ------ ------
2 hour	X: Y: Z:	4454130.420 3129395.692 3314513.698	σ_x: σ_y: σ_z:		X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_z:	------ ------ ------
3 hour	X: Y: Z:	4454130.417 3129395.690 3314513.692	σ_x: σ_y: σ_z:		X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_z:	------ ------ ------
4 hour	X: Y: Z:	4454130.440 3129395.712 3314513.710	σ_x: σ_y: σ_z:		X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_z:	------ ------ ------

Table 6.4:AUSPOS results in(λ,ϕ,h).

		Rinex 2.1			Rinex 3.02		
1 hour	λ: ϕ: h:	31 30 28.31407 35 05 28.39173 924.544	EΔ NΔ hΔ	0.013 0.020 0.098	λ: ϕ: h:	------ ------ ------	EΔ ------ NΔ ------ hΔ ------
2 hour	λ: ϕ: h:	31 30 28.31419 35 05 28.39153 924.496	EΔ NΔ hΔ	0.009 0.013 0.030	λ: ϕ: h:	------ ------ ------	EΔ ------ NΔ ------ hΔ ------
3 hour	λ: ϕ: h:	31 30 28.31408 35 05 28.39153 924.490	EΔ NΔ hΔ	0.007 0.010 0.026	λ: ϕ: h:	------ ------ ------	EΔ ------ NΔ ------ hΔ ------
4 hour	λ: ϕ: h:	31 30 28.31405 35 05 28.39173 924.526	EΔ NΔ hΔ	0.006 0.008 0.022	λ: ϕ: h:	------ ------ ------	EΔ ------ NΔ ------ hΔ ------

Auspos could not process data in rinex format 3.02 , the report dose not contain the accuracy of (x,y,z). increasing the time enhance the accuracy as shown in the table.

6.2.3 CSRS results

Using CSRS for the position calculation at diffenent time intervals and file formats were tested .Table 6.5&6.6 shows the results that we have achieved from CSRS (Canadian spatial referance system) online service .

Table 6.5:CSRS results in (x,y,z).

		Rinex 2.1				Rinex 3.02		
1 hour	X: Y: Z:	4454130.5011241 3129395.7331054 3314513.7462097	σ_x: σ_y: σ_z:	--- --- ---	X: Y: Z:	4454130.50112418 3129395.73310548 3314513.74620979	σ_x: σ_y: σ_z:	------ ------ ------
2 hour	X: Y: Z:	4454130.47973647 3129395.74130146 3314513.73837056	σ_x: σ_y: σ_z:		X: Y: Z:	4454130.47973647 3129395.74130146 3314513.73837056	σ_x: σ_y: σ_z:	
3 hour	X: Y: Z:	4454130.46997002 3129395.73443972 3314513.73105394	σ_x: σ_y: σ_z:		X: Y: Z:	4454130.46997002 3129395.73443972 3314513.73105394	σ_x: σ_y: σ_z:	
4 hour	X: Y: Z:	4454130.47846027 3129395.75201613 3314513.74150625	σ_x: σ_y: σ_z:		X: Y: Z:	4454130.47846027 3129395.75201613 3314513.74150625	σ_x: σ_y: σ_z:	

Table 6.6: CSRS results in(λ,ϕ,h)

		Rinex 2.1				Rinex 3.02		
1 hour	λ: ϕ: h:	31° 30' 28.31402 35° 5' 28.39108" 924.598 m	EΔ NΔ hΔ	0.033 0.047 0.084	λ: ϕ: h:	31° 30' 28.31402" 35° 5' 28.39108" 924.598 m	EΔ NΔ hΔ	0.033 0.047 0.084
2 hour	λ: ϕ: h:	31°30'28.31402" 35° 5' 28.39181" 924.583 m	EΔ NΔ hΔ	0.012 0.041 0.037	λ: ϕ: h:	31° 30' 28.31402" 35° 5' 28.39181" 924.583 m	EΔ NΔ hΔ	0.012 0.041 0.037
3 hour	λ: ϕ: h:	31°30'28.31410" 35° 5' 28.39175" 924.569 m	EΔ NΔ hΔ	0.006 0.020 0.025	λ: ϕ: h:	31° 30' 28.31410" 35° 5' 28.39175" 924.569 m	EΔ NΔ hΔ	0.006 0.020 0.025
4 hour	λ: ϕ: h:	31°30'28.31413" 35°5'28.39228" 924.589 m	EΔ NΔ hΔ	0.004 0.016 0.017	λ: ϕ: h:	31° 30' 28.31413" 35° 5' 28.39228" 924.589 m	EΔ NΔ hΔ	0.004 0.016 0.017

As shown in the table when the time increased the accuracy increased. the report of CSRS dose not contain the accuracy of (x,y,z).

6.3 Near Building Results

The raw observation in the near building point were used to calculate the position , its accuracy and how the accuracy affected by the blocking from the building using Rinex format 2.1 & 3.02 . The observation were measured in multiple time periode (1hour to 4 hour).

6.3.1 OPUS results

Using opus for the position calculation at diffenent time intervals and file formats were tested Table 6.7&6.8 shows the results that we have achieved from opus (online positioning user service) online service .

Table 6.7:opus results in(x,y,z)

		Rinex 2.1				Rinex 3.02		
1 hour	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_z:	------ ------ ------	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_z:	------ ------ ------
2 hour	X: Y: Z:	4454124.907 3129382.633 3314503.472	σ_x: σ_y: σ_z:	0.117 0.161 0.048	X: Y: Z:	4454124.907 3129382.633 3314503.472	σ_x: σ_y: σ_z:	0.117 0.161 0.048
3 hour	X: Y: Z:	4454124.814 3129382.269 3314503.469	σ_x: σ_y: σ_z:	0.125 0.182 0.10	X: Y: Z:	4454124.796 3129382.434 3314503.464	σ_x: σ_y: σ_z:	0.113 0.077 0.094
4 hour	X: Y: Z:	4454126.034 3129384.116 3314505.448	σ_x: σ_y: σ_z:	3.481 5.180 5.724	X: Y: Z:	4454124.867 3129382.364 3314503.524	σ_x: σ_y: σ_z:	0.10 0.088 0.103

Table 6.8:opus results in(λ,ϕ,h)

		Rinex 2.1				Rinex 3.02		
1 hour	λ: ϕ: h:	------ ------ ------	EΔ NΔ hΔ	------ ------ ------	λ: ϕ: h:	------ ------ ------	EΔ NΔ hΔ	------ ------ ------
2 hour	λ: ϕ: h:	31 30 28.23505 35 5 28.10674 908.905(m)	EΔ NΔ hΔ	0.048 0.171 0.102	λ: ϕ: h:	31 30 28.23509 35 5 28.10677 908.905(m)	EΔ NΔ hΔ	0.049 0.171 0.103
3 hour	λ: ϕ: h:	31 30 28.23984 35 5 28.09748 908.661(m)	EΔ NΔ hΔ	0.149 0.164 0.12	λ: ϕ: h:	31 30 28.23833 35 5 28.10299 908.726(m)	EΔ NΔ hΔ	0.010 0.024 0.166
4 hour	λ: ϕ: h:	31 30 28.25964 35 5 28.12816 911.451(m)	EΔ NΔ hΔ	1.845 2.269 7.959	λ: ϕ: h:	31 30 28.23970 35 5 28.09928 908.773(m)	EΔ NΔ hΔ	0.021 0.048 0.164

OPUS could not process data at one hour , the accuracy from rinex 3.02 better than from 2.1 ,increasing time could enhance the accuracy but in four hour shown worse accuracy due to worse satellite distribution.

6.3.2 AUSPOS results

Using auspos for the position calculation at diffenent time intervals and file formats were tested .Table 6.9&6.10 shows the results that we have achieved from auspos online service .

Table 6.9:AUSPOS results in (x,y,z).

		Rinex 2.1			Rinex 3.02		
1 hour	X: Y: Z:	4454124.952 3129382.357 3314503.265	σ_x: σ_y: σ_Z:	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_Z:	------ ------ ------
2 hour	X: Y: Z:	4454124.964 3129382.706 3314503.522	σ_x: σ_y: σ_Z:	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_Z:	------ ------ ------
3 hour	X: Y: Z:	4454124.721 3129382.459 3314503.393	σ_x: σ_y: σ_Z:	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_Z:	------ ------ ------
4 hour	X: Y: Z:	4454124.761 3129382.418 3314503.471	σ_x: σ_y: σ_Z:	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_Z:	------ ------ ------

Table 6.10:AUSPOS results in(λ,ϕ,h).

		Rinex 2.1				Rinex 3.02		
1 hour	λ: ϕ: h:	31 30 28.23141 35 05 28.09719 908.693	EΔ NΔ hΔ	0.155 0.638 0.682	λ: ϕ: h:	------ ------ ------	EΔ NΔ hΔ	------ ------ ------
2 hour	λ: ϕ: h:	31 30 28.23495 35 05 28.10776 909.008	EΔ NΔ hΔ	0.067 0.417 0.383	λ: ϕ: h:	------ ------ ------	EΔ NΔ hΔ	------ ------ ------
3 hour	λ: ϕ: h:	31 30 28.23717 35 05 28.10538 908.649	EΔ NΔ hΔ	0.013 0.029 0.083	λ: ϕ: h:	------ ------ ------	EΔ NΔ hΔ	------ ------ ------
4 hour	λ: ϕ: h:	31 30 28.23916 35 05 28.10324 908.698	EΔ NΔ hΔ	0.012 0.022 0.067	λ: ϕ: h:	------ ------ ------	EΔ NΔ hΔ	------ ------ ------

Auspos could not process data in rinex format 3.02 , the report dose not contain the accuracy of (x,y,z). increasing the time enhance the accuracy as shown in the table.

6.3.3 CSRS results

Using CSRS for the position calculation at different time intervals and file formats were tested .Table 6.11&6.12 shows the results that we have achieved from CSRS (Canadian spatial referance system) online service .

Table 6.11:CSRS results in (x,y,z).

		Rinex 2.1				Rinex 3.02		
1 hour	X: Y: Z:	4454124.92459591 3129382.38677019 3314503.46248853	σ_x: σ_y: σ_Z:		X: Y: Z:	4454124.92459591 3129382.38677019 3314503.46248853	σ_x: σ_y: σ_Z:	------ ------ ------
2 hour	X: Y: Z:	4454124.85398021 3129382.58099367 3314503.44348475	σ_x: σ_y: σ_Z:		X: Y: Z:	4454124.85398021 3129382.58099367 3314503.44348475	σ_x: σ_y: σ_Z:	
3 hour	X: Y: Z:	4454124.85492945 3129382.52360422 3314503.50177949	σ_x: σ_y: σ_Z:		X: Y: Z:	4454124.85492945 3129382.52360422 3314503.50177949	σ_x: σ_y: σ_Z:	
4 hour	X: Y: Z:	4454124.88865804 3129382.48924492 3314503.51959582	σ_x: σ_y: σ_Z:		X: Y: Z:	4454124.88935565 3129382.48973505 3314503.52011843	σ_x: σ_y: σ_Z:	

Table 6.12: CSRS results in(λ,ϕ,h).

		Rinex 2.1				Rinex 3.02		
1 hour	λ: ϕ: h:	31° 30' 28.23682" 35° 5' 28.09879" 908.792 m	EΔ NΔ hΔ	0.029 0.095 0.110	λ: ϕ: h:	31° 30' 28.23682" 35° 5' 28.09881" 908.792 m	EΔ NΔ hΔ	0.029 0.095 0.110
2 hour	λ: ϕ: h:	31° 30' 28.23556" 35° 5' 28.10629" 908.828 m	EΔ NΔ hΔ	0.018 0.040 0.073	λ: ϕ: h:	31° 30' 28.23556" 35° 5' 28.10629" 908.828 m	EΔ NΔ hΔ	0.018 0.040 0.073
3 hour	λ: ϕ: h:	31° 30' 28.23756" 35° 5' 28.10454" 908.831 m	EΔ NΔ hΔ	0.010 0.026 0.048	λ: ϕ: h:	31° 30' 28.23756" 35° 5' 28.10454" 908.831 m	EΔ NΔ hΔ	0.010 0.026 0.048
4 hour	λ: ϕ: h:	31° 30' 28.23802" 35° 5' 28.10270" 908.847 m	EΔ NΔ hΔ	0.014 0.030 0.043	λ: ϕ: h:	31° 30' 28.23803" 35° 5' 28.10270" 908.848 m	EΔ NΔ hΔ	0.014 0.030 0.043

As shown in the table when the time increased the accuracy increased. the report of CSRS dose not contain the accuracy of (x,y,z).

6.4 Under Trees Results

The raw observation under trees were used to calculate the position , its accuracy and how the accuracy affected by the blocking from the trees using Rinex format 2.1 & 3.02 . The ovservation were measured in multiple time periode (1hour to 4 hour).

6.3.1 OPUS results

Using opus for the position calculation at diffenent time intervals and file formats were tested .Table 6.13&6.14 shows the results that we have achieved from opus (online positioning user service) online service .

Table 6.13:opus results in(x,y,z).

		Rinex 2.1				Rinex 3.02		
1 hour	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_Z:	------ ------ ------	X: Y: Z:	------ ------ ------	σ_x: σ_y: σ_Z:	------ ------ ------
2 hour	X: Y: Z:	4454148.005 3129350.115 3314502.303	σ_x: σ_y: σ_Z:	0.929 1.471 0.745	X: Y: Z:	4454148.326 3129350.250 3314502.555	σ_x: σ_y: σ_Z:	0.317 0.584 0.120
3 hour	X: Y: Z:	4454148.350 3129351.534 3314502.882	σ_x: σ_y: σ_Z:	0.420 1.083 0.189	X: Y: Z:	4454148.771 3129351.063 3314503.025	σ_x: σ_y: σ_Z:	0.452 0.736 0.453
4 hour	X: Y: Z:	4454148.607 3129350.681 3314502.797	σ_x: σ_y: σ_Z:	0.231 0.216 0.119	X: Y: Z:	4454148.535 3129350.746 3314502.919	σ_x: σ_y: σ_Z:	0.206 0.255 0.175

Table 6.14:opus results in(λ,ϕ,h).

		Rinex 2.1				Rinex 3.02		
1 hour	λ: ϕ: h:	------ ------ ------	EΔ NΔ hΔ	------ ------ ------	λ: ϕ: h:	------ ------ ------	EΔ NΔ hΔ	------ ------ ------
2 hour	λ: ϕ: h:	31 30 28.19884 35 5 26.59664 908.490(m)	EΔ NΔ hΔ	0.187 0.779 1.712	λ: ϕ: h:	31 30 28.20042 35 5 26.59258 908.892(m)	EΔ NΔ hΔ	0.141 0.659 0.161
3 hour	λ: ϕ: h:	31 30 28.19660 35 5 26.63189 909.709(m)	EΔ NΔ hΔ	0.025 1.113 0.353	λ: ϕ: h:	31 30 28.19934 35 5 26.60809 909.864(m)	EΔ NΔ hΔ	0.186 0.594 0.710
4 hour	λ: ϕ: h:	31 30 28.19902 35 5 26.59981 909.426(m)	EΔ NΔ hΔ	0.128 0.230 0.21	λ: ϕ: h:	31 30 28.20276 35 5 26.60341 909.471(m)	EΔ NΔ hΔ	0.152 0.173 0.298

OPUS could not process data at one hour , the accuracy from rinex 3.02 better than from 2.1 ,increasing time could enhance the accuracy but in four hour shown worse accuracy due to worse satellite distribution.

6.4.2 AUSPOS results

Using auspos for the position calculation at diffenent time intervals and file formats were tested .Table 6.15&6.16 shows the results that we have achieved from auspos online service .

Table 6.15:AUSPOS results in (x,y,z) .

		Rinex 2.1				Rinex 3.02		
1 hour	X:	4454148.058	σ_x:	------	X:	------	σ_x:	------
	Y:	3129348.213	σ_y:	------	Y:	------	σ_y:	------
	Z:	3314502.316	σ_z:	------	Z:	------	σ_h:	------
2 hour	X:	4454148.645	σ_x:		X:	------	σ_x:	------
	Y:	3129351.323	σ_y:		Y:	------	σ_y:	------
	Z:	3314502.820	σ_z:		Z:	------	σ_h:	------
3 hour	X:	4454148.854	σ_x:		X:	------	σ_x:	------
	Y:	3129351.196	σ_y:		Y:	------	σ_y:	------
	Z:	3314503.091	σ_z:		Z:	------	σ_h:	------
4 hour	X:	4454148.476	σ_x:		X:	------	σ_x:	------
	Y:	3129350.860	σ_y:		Y:	------	σ_y:	------
	Z:	3314502.810	σ_z:		Z:	------	σ_h:	------

Table 6.16:AUSPOS results in(λ,ϕ,h).

		Rinex 2.1				Rinex 3.02		
1 hour	λ:	31 30 28.21739	EΔ	1.013	λ:	------	EΔ	------
	ϕ:	35 05 26.53527	NΔ	8.514	ϕ:	------	NΔ	------
	h:	907.582	hΔ	8.866	h:	------	hΔ	------
2 hour	λ:	31 30 28.19285	EΔ	0.118	λ:	------	EΔ	------
	ϕ:	35 05 26.61892	NΔ	0.234	ϕ:	------	NΔ	------
	h:	909.779	hΔ	0.390	h:	------	hΔ	------
3 hour	λ:	31 30 28.19870	EΔ	0.050	λ:	------	EΔ	------
	ϕ:	35 05 26.61041	NΔ	0.199	ϕ:	------	NΔ	------
	h:	910.004	hΔ	0.212	h:	------	hΔ	------
4 hour	λ:	31 30 28.19945	EΔ	0.114	λ:	------	EΔ	------
	ϕ:	35 05 26.60823	NΔ	0.495	ϕ:	------	NΔ	------
	h:	909.428	hΔ	0.214	h:	------	hΔ	------

Auspos could not process data in rinex format 3.02 , the report dose not contain the accuracy of (x,y,z). increasing the time enhance the accuracy as shown in the table.

6.4.3 CSRS results

Using CSRS for the position calculation at diffenent time intervals and file formats were tested .Table 6.17&6.18 shows the results that we have achieved from CSRS (Canadian spatial referance system) online service .

Table 6.17:CSRS results in (x,y,z).

		Rinex 2.1				Rinex 3.02		
1 hour	X: Y: Z:	4454148.62913925 3129350.51761114 3314502.71682251	σ_x: σ_y: σ_z:	------ ------ ------	X: Y: Z:	4454148.61869715 3129350.49866362 3314502.71791516	σ_x: σ_y: σ_z:	------ ------ ------
2 hour	X: Y: Z:	4454148.5466711 3129351.09828834 3314502.84106267	σ_x: σ_y: σ_z:		X: Y: Z:	4454148.54736871 3129351.09877846 3314502.84158529	σ_x: σ_y: σ_z:	
3 hour	X: Y: Z:	4454148.62112098 3129351.10414973 3314502.90648439	σ_x: σ_y: σ_z:		X: Y: Z:	4454148.62797795 3129351.09735601 3314502.90752962	σ_x: σ_y: σ_z:	
4 hour	X: Y: Z:	4454148.66330379 3129351.11056367 3314502.98193062	σ_x: σ_y: σ_z:		X: Y: Z:	4454148.66202769 3129351.12127834 3314502.98506631	σ_x: σ_y: σ_z:	

Table 6.18: CSRS results in(λ,ϕ,h)

		Rinex 2.1				Rinex 3.02		
1 hour	λ: ϕ: h:	31° 30' 28.19823" 35° 5' 26.59418" 909.319 m	EΔ NΔ hΔ	0.054 0.277 0.270	λ: ϕ: h:	31° 30' 28.19834" 35° 5' 26.59382" 909.303 m	EΔ NΔ hΔ	0.053 0.277 0.271
2 hour	λ: ϕ: h:	31° 30' 28.19684" 35° 5' 26.61418" 909.611 m	EΔ NΔ hΔ	0.025 0.047 0.120	λ: ϕ: h:	31° 30' 28.19684" 35° 5' 26.61419" 909.612 m	EΔ NΔ hΔ	0.025 0.047 0.120
3 hour	λ: ϕ: h:	31° 30' 28.19758" 35° 5' 26.61251" 909.700 m	EΔ NΔ hΔ	0.016 0.050 0.056	λ: ϕ: h:	31° 30' 28.19758" 35° 5' 26.61245" 909.702 m	EΔ NΔ hΔ	0.016 0.050 0.056
4 hour	λ: ϕ: h:	31° 30' 28.19916" 35° 5' 26.61189" 909.772 m	EΔ NΔ hΔ	0.012 0.027 0.049	λ: ϕ: h:	31° 30' 28.19915" 35° 5' 26.61222" 909.778 m	EΔ NΔ hΔ	0.012 0.027 0.049

As shown in the table when the time increased the accuracy increased. the report of CSRS dose not contain the accuracy of (x,y,z).

Chapter Seven

Conclusion and Recommendation

7.1 Conclusion.

7.2 Recommendation.

7.1 Conclusion

At the end of this project was conclude the following:-

1) Free online calculation services could be used easily to calculate precise point positioning using static observation without the need of good knowledge of GNSS processing algorithms and calculation procedure .

2) The precise point positioning (PPP) could be achieved without the need of high cost commercial software that could cost from 1000s to 10000s of dollars (e.g. Trimble business center , Leica geo office , Bernese software …..etc.).

3) generally ; the accuracy of positioning could be achieved in centimeters level in all software with ideal positions(no obstacles) without the need to care about types of observations. The only effecting factor was the time of observation see sec.(6.2).

4) Having obstacles like trees and building very close to calculated position could highly affect the accuracy negatively as explained by results in section (6.3&6.4). at this point the differences and limitation of the used service appeared frankly.

5) To solve the problem of obstacles two possibilities are used , first possibility increasing the observation time, this could solve the problem in some cases. But some services like (opus) could not solve. the second possibility is to increase the number of observations , this means the use of higher raw data file format (Rinex 3.02) that uses all GNSS signals (GPS: L1,L2,L5 ; Glonass:G1,G2 ; Galileo:E1,E6,E5a,E5b ; Beidou:B1,B2,B3) as shown in results of section (6.2.1, 6.2.3 , 6.3.1, 6.3.3 , 6.4.1 , 6.4.3).

6) one difficult thing to use online services is that the user has no control about coordinate system of the calculated position this means the user has to search for a transformation method.For example: OPUS uses IGS08 (EPOCH:2018.7683), where AUSPOS uses ITRF14 and CSRS uses ITRF14(18).

7.2 Recommendation.

At the end of this project the following is Recommendation:

1. It is highly recommended to use the free online services for GNEE precis point positioning for the calculation of static observation due to low cost (free charge), and the high complicated and accurate algorithms in easy method of practice (upload data-download results in short time).

2. It is recommended to use the methods carefully with knowledge about the advantages and limitation of each service.

3. It is required to have the dynamic earth model for the areas of calculations to enable the transformations between different coordinate systems and the local coordinate systems.

4. It is recommended to have a coordinate system locally that is defined on the basis of ITRF systems, So that the GNSS, IGS and ITRF definitions are combatable with both GNSS measurements and the local coordinate systems.

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List of acronym:

GNSS	The Global Navigation Satellite Systems.
WGS	The World Geodetic System.
RTK	Real Time Kinematic.
VRS	The virtual reference station.
PPP	Precise point positioning.
MEO	Medium Earth Orbit.
GPS	Global Positioning System.
ESA	The European Space Agency.
FDMA	Frequency division multiple access.
CDMA	Code-division multiple access.
GEO	Geosynchronous equatorial orbit.
IGS	International GNSS Service.
BDS	The Beidou Navigation System.
FOC	Full Operational Capability.
IGSO	Inclined Geosynchronous Satellite Orbit.
MCS	Master Control Station.
MS	Monitoring Stations.
GA	The Ground Antennas.
AMCS	The Alternate Master Control Station.
UTC	Coordinated Universal Time.
SCC	System Control Centre.
TT&C	Telemetry, Tracking and Control.
LS	Laser Station.
GCC	Ground Control Centre.
IERS	International Earth Rotation and Reference Systems Service
USNO	The United States Naval Observatory.
NIST	The National Institute of Standards and Technology.
MJD	The Modified Julian Day.
GMST	Greenwich Mean Sidereal Time.
CIS	Conventional Inertial System.
CTS	Coordinated Terrestrial System.
CRS	Conventional Celestial Reference System.
CRF	Celestial Reference Frame.
TRS	Conventional Terrestrial Reference System.
ECEF	The Earth-Centered, Earth-Fixed.
CTP	The Conventional Terrestrial Pole.
TRF	Terrestrial Reference Frame.
ITRF	International Terrestrial Reference Frame.
IERS	International Earth Rotation and Reference Systems Service
GTRF	Galileo Terrestrial Reference Frame.
CORS	Continuously Operating Reference Stations.
SDev	The standard deviation.
PRC	Pseudo range corrections.
RRC	Range rate corrections.
ACP	Area Correction Parameter.
FKP	Flaechen Korrektur – Parameter.
MAC	The Master Auxiliary Concept.
GDA2020	The Geocentric Datum of Australia 2020.
Rinex	The Receiver Independent Exchange Format

| RINEX v. 2.10 | GPS and GLONASS observations, meteorological data, and navigation file |
| RINEX v. 3.02 | a new header message to specify the GLONASS code-phase bias; the existing GLONASS frequency to slot header message has been specified as mandatory and a new RINEX file naming convention |