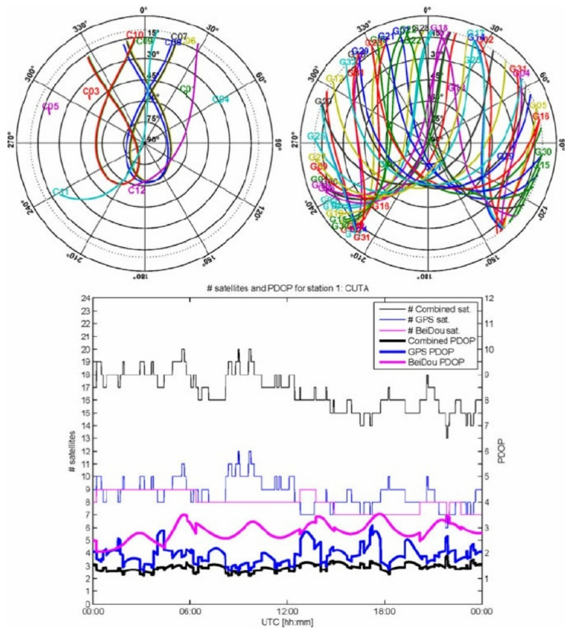
MSc Surveying Sciences
Year II Semester I
Faculty of Geomatics
Sabaragamuwa University of Sri Lanka 70140 Belihuloya

COURSE MATERIAL :

GNSS FOR SURVEYORS



Curricula Enrichment delivered through the Application of Location-based Services to Intelligent Transport Systems (LBS2ITS)

Erasmus+

Co-funded by the Erasmus+ Programme of the European Union

MS214 –GNSS for Surveyors

Teaching Guide

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Module Overview

1.0 GNSS Basics
- 1.1 Introduction and present GNSS's
- 1.2 Satellites, orbits and data messages
- 1.3 GNSS reference systems and time
- 1.4 How GNSS Works
- 1.5 Global and Local Augmentation Systems

2.0 GNSS signals and Receivers
- 2.1 Codes and Modulation
- 2.2 Signal-to-Noise Ratio and Ranging Precision
- 2.3 Receiver technologies and functions

3.0 Position Solutions
- 3.1 Absolute and Relative positioning
- 3.2 Differential correction and various relative positioning techniques
- 3.3 Precise Positioning with Carrier Phase
- 3.4 Geo-location techniques and indoor positioning techniques

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- 4.1 Application of GPS/GNSS for land surveying
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- 4.4 Creating maps with GNSS data

5.0 GNSS Modernization and Future
- 5.1 New signals and Their Benefits
- 5.2 Future Trends

Module Overview:

This course provides a conceptual overview and hands-on experience with Global Navigation Satellite System (GNSS) including GPS theory, techniques, and field data collection using various GPS technologies.

Learning Outcomes and Academic Skills

By the end of the course, students should be able to:

- Describe the principles of GNSS based positioning methods
- Describe the main components in a satellite navigation system and their functions
- Describe the satellites and signal structures used in the GNSS systems
- Explain the measurements, methods, related errors and mitigation approaches
- Explain and apply differential correction and precise positioning concepts
- Plan, perform and process GNSS measurements
- Use different GNSS positioning methods for surveying

Assessment

Assignments	40 %
Reports/Presentations	40 %
Final Exam	20 %

Teaching Organization

TEACHING ACTIVITY	*SEMESTER WORKLOAD (HOURS)*
lectures	30 hours
exercises / assignments	5 hours
final examination	1 hours
other (specify):	
Preparation - Student Centred Learning activities	25 hours
Field/Lab Practical activities	15 hours
Self-Learning (Library & Internet)	38 hours
Field reports and presentations	6 hours
total number of hours	150 hours

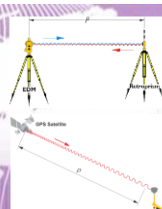
MS 214 – GNSS for Surveyors

Introduction & Overview

Course contents

- GNSS Introduction and Overview
- GNSS Signals and Data
- GNSS Measurements
- GNSS Positioning Techniques
- Data files and formats
- Hands-on experience on GNSS observation and data processing
- GNSS Error sources
- GNSS receivers
- Differencing and Ambiguity resolution
- GNSS modernization and future
- GNSS applications

Trilateration



- Both GNSS and Trilateration techniques rely on the measurement of distances to fix positions
  - Trilateration – P1, P2 and P3 are ground control points (3 knowns)
  - GNSS - P1, P2 and P3 are satellites (3?.....4 knowns)
  - Both use speed of electromagnetic waves (two-way/one-way)

What is Global Navigation Satellite Systems (GNSS) ?

- Global navigation satellite system (GNSS) is a general term describing any satellite constellation that provides positioning, navigation, and timing (PNT) services on a global or regional basis.
- GNSS provides global coverage. Examples of GNSS include Europe's Galileo, the USA's NAVSTAR Global Positioning System (GPS), Russia's Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and China's BeiDou Navigation Satellite System.
- GPS is the most prevalent GNSS

What is Global Navigation Satellite Systems (GNSS) ?

- Sometimes, GNSS can also refer to augmentation systems

GNSS => *GPS+GLONASS+GALILEO+BDS+QZSS+IRNSS + Augmentation systems*

Performance of GNSS

Four (04) criteria:

1. **Accuracy**: the difference between a receiver's measured and real position, speed or time;
2. **Integrity**: a system's capacity to provide a threshold of confidence and, in the event of an anomaly in the positioning data, an alarm;
3. **Continuity**: a system's ability to function without interruption;
4. **Availability**: the percentage of time a signal fulfils the above accuracy, integrity and continuity criteria.

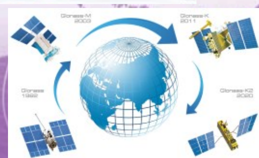
Other GNSS

- **GLONASS**

GLONASS (*Globalnaya Navigazionnaya Sputnikovaya Sistema*, or Global Navigation Satellite System) is a global GNSS owned and operated by the Russian Federation. The fully operational system consists of 24+ satellites.

GLONASS website (glonass-iac.ru)

https://glonass-iac.ru/en/about_glonass/



GLONASS Enhancements

The level of GLONASS capability enhancement :

- Development of the GLONASS orbital constellation structure
- new generation "GLONASS-K" with enhanced capabilities
- GLONASS ground control segment development including GLONASS orbit and clock segment enhancement
- Augmentations design and development:
  - The System of Differential Correction and Monitoring
  - Global system of high precision definition of navigation and orbit and clock information in real time for civil users

More information: https://glonass-iac.ru/en/about_glonass/

Capabilities	Glonass	Glonass-M	Glonass-K	Glonass-K2
Time of Deployment	1982-2005	2003-2016	2011-2018	2017+
Status	Decommissioned	In use	Design maturation based on in-orbit validation	In development
Nominal Orbit Parameters	Circular Altitude - 19,100 km Inclination - 64,8° Period - 11 h 15 min 44 sec			
Number of Satellites in the Constellation (Used for Navigation)	24			
Number of Orbital Planes	3			
Number of Satellites in a Plane	8			
Launchers		Soyuz-2.1b, Proton-M		
Design Lifetime, years	3.5	7	10	10
Open Access Signals (for FDMA Signals Center Frequency Values are Provided)	L1OF (1602 MHz)	L1OF (1602 MHz) L2OF (1246 MHz) L3OC (1202 MHz) for SVs 755+	L1OF (1602 MHz) L2OF (1246 MHz) L3OC (1202 MHz) L2OC (1248 MHz) for SVs 17L+	L1OF (1602 MHz) L2OF (1246 MHz) L1OC (1600 MHz) L2OC (1248 MHz) L3OC (1202

Other GNSS

- **Galileo**

Galileo is a global GNSS owned and operated by the European Union. The EU declared the start of Galileo Initial Services in 2016 and plans to complete the system of 24+ satellites by 2020 (currently 26 satellites).

Currently providing Initial Services
Galileo is interoperable with GPS and Glonass

GALILEO

European Commission's Galileo website (europa.eu)
European Space Agency's Galileo website (esa.int)

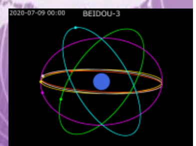
https://www.esa.int/Applications/Navigation/Galileo/Galileo_satellites

https://www.esa.int/Applications/Navigation/Galileo/Galileo_satellites#:~:text=The%20Galileo%20Space%20Segment%20will,signals%2C%20ephemeris%20and%20other%20data.

Other GNSS

- **BeiDou Navigation Satellite System (BDS)**

- BeiDou, or BDS, is now a global GNSS owned and operated by the People's Republic of China.
- BDS was previously called Compass.
- expanded the system to provide global coverage with 35 satellites by 2020. BDS-3 (BeiDou-3) was commissioned in August 2020. Currently 42 operational satellites.
- With BDS-3, full global coverage for PNT, offered an alternative to Russia's **GLONASS**, the European **Galileo**, and the US's **GPS**.



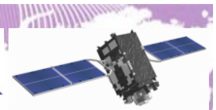
BDS website (beidou.gov.cn)

Other GNSS

- **BeiDou Navigation Satellite System (BDS)**

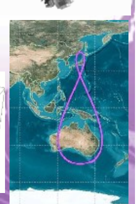
Summary of satellites, as of 23 June 2020					
Block	Launch period	Satellite launches			Currently in orbit and healthy
		Success	Failure	Planned	
1	2000–2006	4	0	0	0
2	2007–2019	20	0	0	12
3	2015–present	35	0	0	30
Total		59	0	0	42

Other GNSS



Quasi-Zenith Satellite System (QZSS)

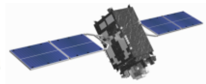
QZSS is a regional GNSS owned by the Government of Japan and operated by QZS System Service Inc. (QSS). QZSS complements GPS to improve coverage in East Asia and Oceania. Japan declared the official start of QZSS services in 2018 with 5 operational satellites, and plans to expand the constellation to 7 satellites by 2025 for autonomous capability (Still in process).



QZS satellite orbit

QZSS website (qzss.go.jp)

Other GNSS



Quasi-Zenith Satellite System (QZSS)

Current Constellation

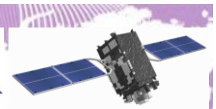
Name	Launch date	Status	Notes
QZS-1 (Michibiki-1)	11 September 2010	Replaced by QZS-1R	-
QZS-2 (Michibiki-2)	1 June 2017	Operational	Improved solar panels and increased fuel
QZS-3 (Michibiki-3)	19 August 2017	Operational	Heavier design with additional S-band antenna on geostationary orbit
QZS-4 (Michibiki-4)	10 October 2017	Operational	Improved solar panels and increased fuel
QZS-1R (Michibiki-1R)	26 October 2021	Operational	Replacement for QZS-1

QZS-1R launched on 26.10.2021

Future 7 satellite Constellation

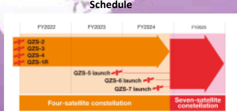
Name	Planned launch date	Status
QZS-5	2023	Future
QZS-6	2023	Future
QZS-7	2024	Future

Other GNSS

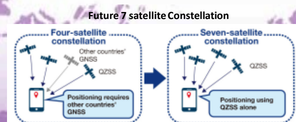


Quasi-Zenith Satellite System (QZSS)

Schedule

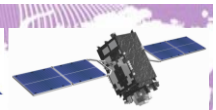


Future 7 satellite Constellation



- Satellite positioning requires four or more positioning satellites
- When QZSS becomes a seven-satellite constellation, at least four QZSS satellites will always be in the sky above Japan, making sustained positioning possible with QZSS alone

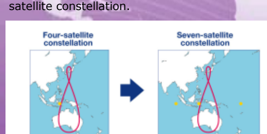
Other GNSS



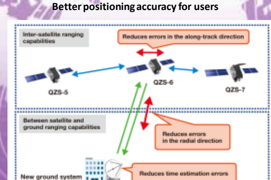
Quasi-Zenith Satellite System (QZSS)

Expanded service range

One quasi-zenith satellite, one geostationary satellite, and one quasi-geostationary satellite will be added to create the seven-satellite constellation.



Better positioning accuracy for users



Other GNSS

Indian Regional Navigation Satellite System (IRNSS) / Navigation Indian Constellation (NavIC)

IRNSS is a regional GNSS owned and operated by the Government of India. IRNSS is an autonomous system designed to cover the Indian region and 1500 km around the Indian mainland. The system consists of 8 satellites. In 2016, India renamed IRNSS as the Navigation Indian Constellation (NavIC, meaning "sailor" or "navigator").

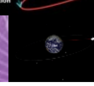
IRNSS provides Standard Positioning Service (SPS) which is provided to all the users and Restricted Service (RS), which is an encrypted service provided only to the authorised users.

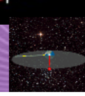
8 navigation satellites IRNSS-1A, 1B, 1C, 1D, 1E, 1F, 1G and IRNSS-1I launched 12.04.2018

IRNSS/NavIC website (isro.gov.in)

Other GNSS

Indian Regional Navigation Satellite System (IRNSS) / Navigation Indian Constellation (NavIC)





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IRNSS/NavIC website (isro.gov.in)

Other GNSS

Indian Regional Navigation Satellite System (IRNSS) / Navigation Indian Constellation (NavIC)

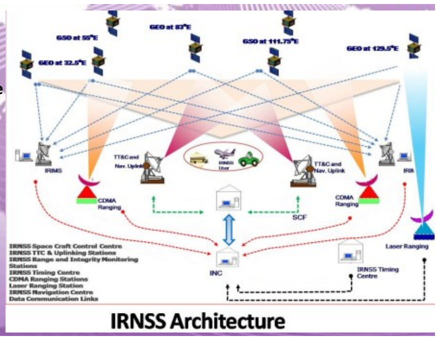
off Mass	1432 kg
Physical Dimensions	1.58 metre x 1.50 metre x 1.50 metre
Orbit	Geosynchronous, at 55 deg East longitude with 29 deg inclination
Power	Two solar panels generating 1660 W, one lithium-ion battery of 90 Ampere-Hour capacity
Propulsion	440 Newton Liquid Apogee Motor, twelve 22 Newton Thrusters
Control System	Zero momentum system, orientation input from Sun & star Sensors and Gyroscopes; Reaction Wheels, Magnetic Torquers and 22 Newton thrusters as actuators
Mission Life	10 years
Launch date	Apr 04, 2014
Launch site	SDSC SHAR Centre, Sriharikota, India
Launch vehicle	PSLV - C24

Lift-off Mass	1425.4 kg
Physical Dimensions	1.58 metre x 1.50 metre x 1.50 metre
Orbit	Geostationary, at 83 deg East longitude
Power	Two solar panels generating 1660 W, one lithium-ion battery of 90 Ampere-Hour capacity
Propulsion	440 Newton Liquid Apogee Motor, twelve 22 Newton Thrusters
Control System	Zero momentum system, orientation input from Sun & Star Sensors and Gyroscopes; Reaction Wheels, Magnetic Torquers and 22 Newton thrusters as actuators
Mission Life	10 years
Launch date	Oct 16, 2014
Launch site	SDSC SHAR Centre, Sriharikota, India
Launch vehicle	PSLV - C26

IRNSS/NavIC website (isro.gov.in)

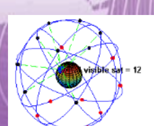
Other GNSS

IRNSS Architecture



Global Positioning System (GPS)

The Global Positioning System (GPS) is a U.S.-owned utility that provides users with positioning, navigation, and timing (PNT) services. This system consists of three segments: the space segment, the control segment, and the user segment. The U.S. Air Force develops, maintains, and operates the space and control segments.



Global Positioning System (GPS)

Space segment

- GPS satellites fly in medium Earth orbit (MEO) at altitude 20,200 km
- Six equally-spaced orbital planes
- 24 baseline satellites = 6 x 4 → can view 4 any location
- Extra satellites may increase GPS performance
- GPS constellation is a mix of old and new satellites
- Block IIA (2nd generation, "Advanced"), Block IIR ("Replenishment"), Block IIR-M ("Modernized"), Block IIF ("Follow-on"), GPS III, and GPS IIIF ("Follow-on")
- As of July 3, 2023, there were a total of **31 operational satellites** in the GPS constellation

Global Positioning System (GPS)

Space segment

Block II/IIA satellite (retired)

Block IIR

Block IIR-M

Block IIF

Block III

LEGACY SATELLITES		MODERNIZED SATELLITES		
BLOCK IIA	BLOCK IIR	BLOCK IIR-M	BLOCK IIF	GPS III/IIIF
0 operational	6 operational	7 operational	12 operational	6 operational
• Coarse Acquisition (C/A) code on L1 frequency for civil users • Precise P(Y) code on L1 & L2 frequencies for military users • 7.5-year design lifespan • Launched in 1990-1997 • Last one decommissioned in 2019	• C/A code on L1 • P(Y) code on L1 & L2 • On-board clock monitoring • 7.5-year design lifespan • Launched in 1997-2004	• All legacy signals • 2nd civil signal on L2 (L2C) LEARN MORE • New military M code signals for enhanced jam resistance • Flexible power levels for military signals • 7.5-year design lifespan • Launched in 2005-2009	• All Block IIR-M signals • 3rd civil signal on L5 frequency (L5) LEARN MORE • Advanced atomic clocks • Improved accuracy, signal strength, and quality • 12-year design lifespan • Launched in 2010-2016	• All Block IIF signals • 4th civil signal on L1 (L1C) LEARN MORE • Enhanced signal reliability, accuracy, and integrity • No Selective Availability LEARN MORE • 15-year design lifespan • IIIF: laser reflectors; search & rescue payload • First launch in 2018

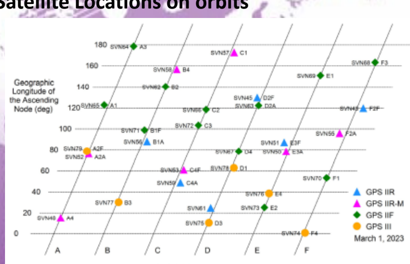
Block	Launch period	Satellite launches				Currently in orbit and healthy
		Success	Failure	In preparation	Planned	
I	1978–1985	10	1	0	0	0
II	1989–1990	9	0	0	0	0
IIA	1990–1997	19	0	0	0	0
IIR	1997–2004	12	1	0	0	7
IIR-M	2005–2009	8	0	0	0	7
IIF	2010–2016	12	0	0	0	12
IIIA	2018–	6	0	4	0	6
IIIF	—	0	0	0	22	0
Total		76	2	4	22	32

Block IIA (2nd generation, "Advanced"), Block IIR ("Replenishment"), Block IIR-M ("Modernized"), Block IIF ("Follow-on"), GPS III, and GPS IIIF ("Follow-on").

Jun 17, 2021 launched 5th GPSIII satellite. May 25, 2022: The Space Force set the fifth GPS III satellite to healthy (usable) status.

As of July 3, 2023, there were a total of **31 operational satellites** in the GPS constellation

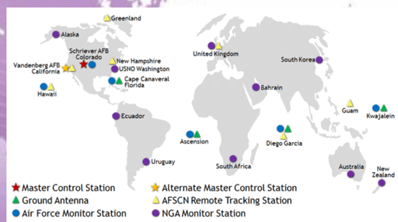
GPS Satellite Locations on orbits



Global Positioning System (GPS)

Control segment

The current Operational Control Segment (OCS) includes a master control station, an alternate master control station, 11 command and control antennas, and 16 monitoring sites



Global Positioning System (GPS)

Control segment elements – Monitor Stations

- Track GPS satellites as they pass overhead
- Collect navigation signals, range/carrier measurements, and atmospheric data
- Feed observations to the master control station
- Utilize sophisticated GPS receivers
- Provide global coverage via 16 sites: 6 from the Air Force + 10 from NGA

Global Positioning System (GPS)

Control segment elements – Master Control Station

- Provides command and control of the GPS constellation
- Uses global monitor station data to compute the precise locations of the satellites
- Generates navigation messages for upload to the satellites
- Monitors satellite broadcasts and system integrity to ensure constellation health and accuracy
- Performs satellite maintenance and anomaly resolution, including repositioning satellites to maintain optimal constellation
- Backed up by a fully operational alternate master control station

Global Positioning System (GPS)

Control segment elements – Ground Antennas

- Send commands, navigation data uploads, and processor program loads to the satellites
- Collect telemetry
- Communicate via S-band and perform S-band ranging to provide anomaly resolution and early orbit support
- Consist of 4 dedicated GPS ground antennas plus 7 Air Force Satellite Control Network (AFSCN) remote tracking stations

Global Positioning System (GPS)

User Segment

- Military and Civilians usage
- Receivers with geodetic accuracy
- Single frequency & Dual frequency
- New signals for users and improved navigation message
- Proper error modelling and improved algorithms

GPS Services

GPS satellites provide service to civilian and military users. The civilian service is freely available to all users on a continuous, worldwide basis. The military service is available to U.S. and allied armed forces as well as approved Government agencies.

Two services: Standard Positioning Service (SPS) and Precise Positioning Service (PPS)

GPS Services

Standard Positioning Service (SPS)

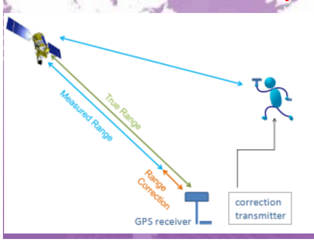
- Civil, commercial and scientific use
- C/A-code signal, the CM/CL-code signals, and the I5-code/Q5- code signals
- C/A codes modulated only on L1
- CM/CL-code signals are both modulated in L2
- In-phase (I5) and Quadraphase (Q5) signals are modulated in L5
- Models ionospheric errors

Precise Positioning Service (PPS)

- Authorized access
- signals broadcast at the GPS L1 and L2 frequencies
- Precision (P) code which is encrypted to become P(Y) code reserves for authorized use.
- Has encryption capability
- Calculates ionospheric errors

Satellite-based & Ground-based Augmentation Systems (SBAS & GBAS)

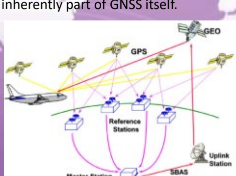
Why ?



- Receivers at fixed and known location can determine ranging error
- True range – measured range= range correction
- Correction can be sent to user near the fixed receiver
- User applies correction and gets better position accuracy
- But what about integrity, continuity, availabilty

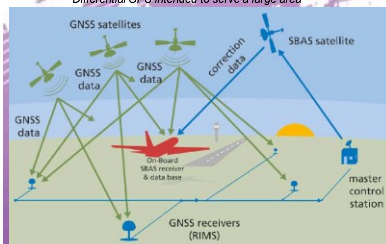
Satellite-based Augmentation Systems (SBAS)

A satellite-based augmentation system is any system that aids GNSS by providing accuracy, integrity, availability, or any other improvement to positioning, navigation, and timing that is not inherently part of GNSS itself.



Satellite-based Augmentation Systems (SBAS)

Differential GPS intended to serve a large area



- SBAS uses GNSS measurements taken by accurately located reference stations deployed across an entire continent.
- All measured GNSS errors are transferred to a central computing centre, where differential corrections and integrity messages are calculated.
- These calculations are then broadcast over the covered area using geostationary satellites that serve as an augmentation, or overlay, to the original GNSS message.

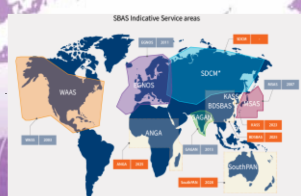
Satellite-based Augmentation Systems (SBAS)

Existing SBAS

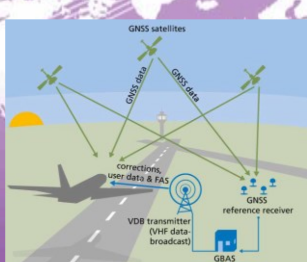
Several countries have implemented their own Satellite-based Augmentation System. For example, in Europe EGNOS covers the majority of the European Union (EU), along with some neighbouring countries and regions.

Other national SBASs include:

USA: Wide Area Augmentation System (WAAS)
Japan: Michibiki Satellite Augmentation System (MSAS)
India: GPS-aided GEO-Augmented Navigation (GAGAN)
China: BeiDou SBAS (BDSBAS) (in development)
South Korea: Korea Augmentation Satellite System (KASS) (in development)
Russia: System for Differential Corrections and Monitoring (SDCM) (in development)
ASECNA: Augmented NaviGation for Africa (ANGA) (in development)
Australia and New Zealand: Southern Positioning Augmentation Network (SouthPAN) (in development)

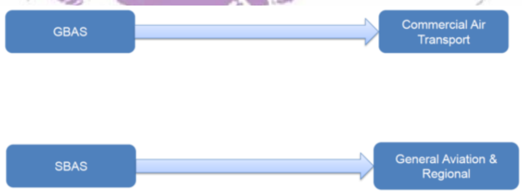


Ground-based Augmentation Systems (GBAS)



- Differential GPS for aviation with multiple antennas and receivers (three to four)
- Uses local augmentation system
- Integrity data provided to user locally using VHF link

Augmentation Systems and main Users



GPS augmentation systems

Nationwide Differential GPS System (NDGPS)

NDGPS is a ground-based augmentation system that provides increased accuracy and integrity of GPS information to users on U.S. waterways.

The system consists of the Maritime Differential GPS System

GPS augmentation systems

Wide Area Augmentation System (WAAS)

WAAS, a regional space-based augmentation system (SBAS) operated by the Federal Aviation Administration (FAA), supports aircraft navigation across North America.

Although designed primarily for aviation users, WAAS is widely available in receivers used by other positioning, navigation, and timing communities.

The WAAS service is interoperable with other regional SBAS services, including those operated by Japan (MSAS), Europe (EGNOS), and India (GAGAN).

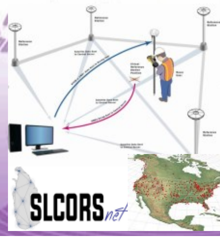
GPS augmentation systems

Continuously Operating Reference Stations (CORS)

To distribute GPS data for precise positioning tied to the National Spatial Reference System.

GNSS reference stations at remote designated locations that transmit the collected GNSS raw data to the Control Centre.

This raw data is processed and transmitted to the users in the field over the internet based on their geographic location in the form of RTCM corrections.



GPS augmentation systems

Global Differential GPS (GDGPS)

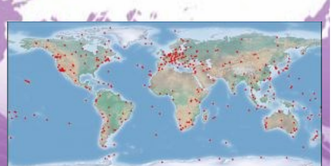
GDGPS is a high accuracy GPS augmentation system developed by the NASA Jet Propulsion Laboratory (JPL) to support the real-time positioning, timing, and determination requirements of NASA science missions.

GPS augmentation systems

International GNSS Service (IGS)

IGS is a network of over 350 GPS monitoring stations from 200 contributing organizations in 80 countries.

Its mission is to provide the highest quality data and products as the standard for global navigation satellite systems (GNSS) in support of Earth science research, multidisciplinary applications, and education, as well as to facilitate other applications benefiting society.



GPS Time

- UTC, or Coordinated Universal Time, is a global time standard that synchronizes clocks and timekeeping devices worldwide. It is based on the primary standard of time, the atomic clock, and is adjusted periodically to account for the Earth's irregular rotation (leap second).
- The atomic clocks on the satellites are set to **GPS time**
- GPS time is not corrected to match the rotation of the Earth (leap second)
- GPS time was set to match UTC in 1980, At the moment, the offset of UTC to GPS is +18sec.
- The GPS navigation message includes the difference between GPS time and UTC

GPS Week Number

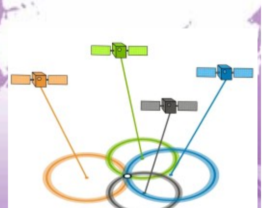
- The GPS date is expressed as a week number
- The week number is transmitted as a ten-bit (2^{10}) field in the navigation messages. it becomes zero again every 1,024 weeks (19.6 years), **GPS Week number rollover**
- GPS week zero started at 00:00:00 UTC (00:00:19 TAI) on January 6, 1980. First rollover: 23:59:47 UTC on August 21, 1999, Second rollover: 23:59:42 UTC on April 6, 2019…
- The modernized GPS civil navigation (CNAV) message will use a 13-bit field that only repeats every 8,192 weeks (157 years), thus lasting until 2137 (157 years after GPS week zero)
- **GPS Calendar:** https://geodesy.noaa.gov/CORS/resources/gpscals.shtml

GPS Accuracy

GPS satellites broadcast their signals in space with a certain accuracy, but what you receive depends on additional factors, including satellite geometry, signal blockage, atmospheric conditions, and receiver design features/quality.

For example, GPS-enabled smartphones are typically accurate to within a 4.9 m (16 ft.) radius under open sky. However, their accuracy worsens near buildings, bridges, and trees.

High-end users boost GPS accuracy with dual-frequency receivers and/or augmentation systems. These can enable real-time positioning within a few centimeters, and long-term measurements at the millimeter level.



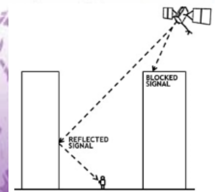
GPS Accuracy cont…

Many things can degrade GPS positioning accuracy. Common causes include:

- Satellite signal blockage due to buildings, bridges, trees, etc.
- Indoor or underground use
- Signals reflected off buildings or walls ("multipath")

Far less common causes may include:

- Radio interference or jamming
- Major solar storms
- Satellite maintenance creating temporary gaps in coverage
- Improperly designed devices that do not comply with GPS Interface Specifications



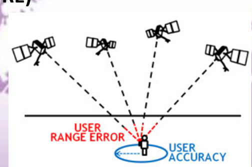
Accuracy and User Range Error (URE)

The accuracy commitments do not apply to GPS devices, but rather to the signals transmitted in space.

GPS time is theoretically accurate to about 14 nanoseconds, roughly 100 nanoseconds

Global average user range error (URE) of ≤0.715 m (2.3 ft.)with 95% probability.

≤ 9 m 95% Horizontal, global average
≤ 15 m 95% Vertical, global average
≤ 17 m 95% Horizontal, worst site
≤ 37 m 95% Vertical, worst site
≤ 40 nsec time transfer error 95% of the time



URE is not user accuracy. User accuracy depends on a combination of satellite geometry, URE, and local factors such as signal blockage, atmospheric conditions, and receiver design features/quality.

Military GPS Vs. Civilian GPS

The user range error (URE) of the GPS signals in space is actually the same for the civilian and military GPS services.

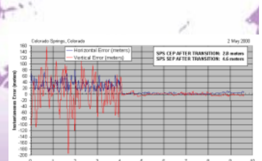
Mostly civilian - single frequency, Military - Dual-frequency

Dual-frequency is commercially available for civilian use, but its cost and size has limited it to professional applications.

Using two GPS frequencies improves accuracy by correcting signal distortions caused by Earth's atmosphere.

With augmentation systems, civilian users can actually receive better GPS accuracy than the military. Also GPS modernization introduces new signals for civilians

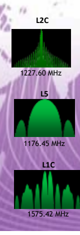
Selective Availability ended in May 2000.

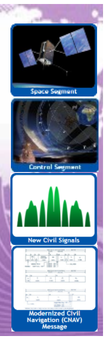


The Future of GPS

GPS Modernization

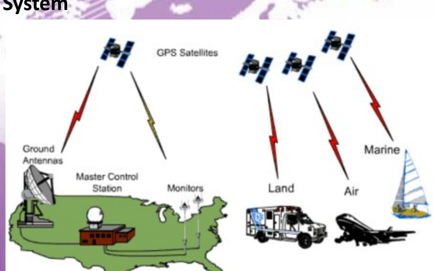
- The GPS modernization program is ongoing… to upgrade the features and overall performance of the GPS
- The upgraded features include new civilian and military GPS signals
- Implementation of second (L2C), third (L5)and forth (L1C) civil signals on GPS satellites
- Second civil signals improve the accuracy of civilian service and support safety-of-life applications, such as aviation
- Third and forth signals further enhance civilian capability and safety-of-life applications
- As of July, 2023, there were a total of 31 operational satellites in the GPS constellation





GPS Signal and Data

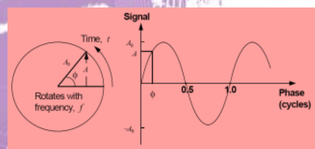
GPS System



Signal Basis

"Phase" and "Frequency"

"Phase" - "angle of rotation," units of "cycles"



Frequency - Cycles per second
Number of times the line completes a full 360º rotation in one second

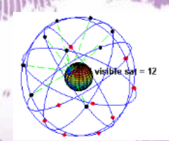
First derivative of phase with respect to time - Angular speed

$$f = \frac{d\varphi(t)}{dt}$$

Phase - fundamental quantity
Frequency - derived quantity

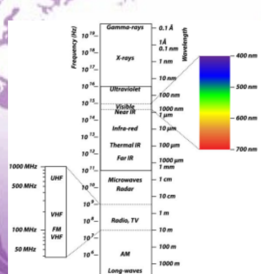
GPS Signals

- Broadcast by GPS satellites to enable satellite navigation.
- Satellite constellation is operated by US DOD
- GPS signals include ranging signals, used to measure the distance to the satellite, and navigation messages.
- The navigation messages include **Ephemeris** data, used to calculate the position of each satellite in orbit, and information about the time and status of the entire satellite constellation, called the **almanac**.



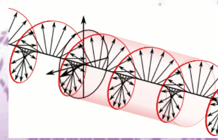
What signal does GPS use?

- GPS signal that is carried by radio waves in the microwave part of the electromagnetic spectrum
- Broadcasts a navigation message at 50 bits per second on the microwave carrier frequency of approx. 1600 MHz (L1-1575.42 MHz , L2-1227.6 MHz
- GPS week number and a health report for the satellite so that it can be discounted if faulty
- GPS signal is encoded with a high-rate pseudo-random (PRN) sequence that is different for each satellite



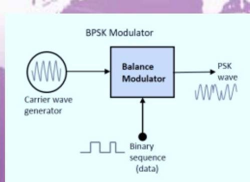
GPS signal structure

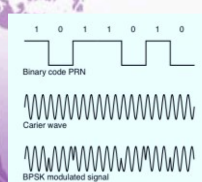
- GPS satellite transmits **right-hand circularly polarized signals** to the Earth at **L-band frequencies (1GHz-2GHz)**
- Why circularly polarized electromagnetic wave???
- Why L-band??? Two: L1 & L2 (three with L5) carrier frequencies
- Can be classified to **Legacy** and **Modernized** signals



Common characteristics of signals and space vehicles (SV)

- SVs transmit several ranging codes and navigation data simultaneously using binary phase-shift keying (BPSK) with limited frequencies.





Common characteristics of signals and space vehicles (SV)

- Satellites using the same frequency are distinguished by using different ranging codes, Pseudo Random Noise (PRN) Codes.
- Satellites are uniquely identified by a serial number called space vehicle number (SVN), space vehicle identifier (SV ID) and pseudorandom noise number (PRN number)
- PRN number which uniquely identifies the ranging codes that a satellite uses

Slot	Plane A	B	C	D	E	F
1	65	56	57	61	69	70
2	52	62	66	63	73	55
3	64		72	45	50	68
4	48	58	53	67	51	74
5		71	59	78	76	
6	79	77		75		43

PRN	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	–
IIR		O									S		O			O		S	O	O	O	R											
IIRM					O		O					O			O		O												O		O		S
IIF	O		O			O		O	O	O														O	O	O	O			O		O	
III				O							O			O				O					O					O					

- O – Operational
- T – Testing in preparation for operation
- S – On orbit Spare
- U – Unhealthy and unusable
- R – Retired

```
BLOCK IIR-M         G01                  G049      2009-014A TYPE / SERIAL NO
  2009     3    24     0     0    0.0000000                  VALID FROM
  2011     5     6    23    59   59.9999999                  VALID UNTIL
BLOCK IIR-M         G24                  G049      2009-014A TYPE / SERIAL NO
  2012     2     2     0     0    0.0000000                  VALID FROM
  2012     3    14    23    59   59.9999999                  VALID UNTIL
BLOCK IIR-M         G24                  G049      2009-014A TYPE / SERIAL NO
  2012     8     9     0     0    0.0000000                  VALID FROM
  2012     8    22    23    59   59.9999999                  VALID UNTIL
BLOCK IIR-M         G27                  G049      2009-014A TYPE / SERIAL NO
  2012    10    18     0     0    0.0000000                  VALID FROM
  2013     5     9    23    59   59.9999999                  VALID UNTIL
BLOCK IIR-M         G30                  G049      2009-014A TYPE / SERIAL NO
  2013     5    10     0     0    0.0000000                  VALID FROM
```

SVN 049 had been assigned PRNs 01, 24, 27, and 30 at different times of its lifespan

```
BLOCK IIA           G01                  G032      1992-079A TYPE / SERIAL NO
  1992    11    22     0     0    0.0000000                  VALID FROM
  2008    10    16    23    59   59.9999999                  VALID UNTIL
BLOCK IIA           G01                  G037      1993-032A TYPE / SERIAL NO
  2008    10    23     0     0    0.0000000                  VALID FROM
  2009     1     6    23    59   59.9999999                  VALID UNTIL
BLOCK IIR-M         G01                  G049      2009-014A TYPE / SERIAL NO
  2009     3    24     0     0    0.0000000                  VALID FROM
  2011     5     6    23    59   59.9999999                  VALID UNTIL
BLOCK IIA           G01                  G035      1993-054A TYPE / SERIAL NO
  2011     6     2     0     0    0.0000000                  VALID FROM
  2011     7    12    23    59   59.9999999                  VALID UNTIL
BLOCK IIF           G01                  G063      2011-036A TYPE / SERIAL NO
  2011     7    16     0     0    0.0000000                  VALID FROM
```

PRN 01 had been assigned to SVNs 032, 037, 049, 035, and 063 at different epochs

Pseudo-random noise codes

The Pseudo Random Code (PRC) is a fundamental part of GPS. Physically it's just a very complicated digital code, or in other words, a complicated sequence of "on" and "off" pulses

The signal is so complicated that it almost looks like random electrical noise. Hence the name "Pseudo-Random."

PRN code allows any receiver to identify exactly which satellite(s) it is receiving.

Pseudo-random noise codes

Standard Positioning Service (SPS) signals – L1 C/A, L1C, L2C, and L5 signals

L1 C/A, L1C, L2C, and L5 PRN code assignment

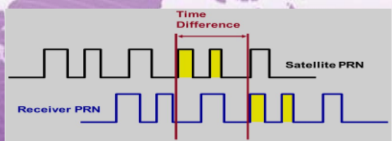
PRN Code	PRN Code Application
L1 C/A	
1 – 63	Reserved (GPS)
64 – 119	Other Augmentation Systems
120 – 158*	Satellite-Based Augmentation Systems (SBASs)
159 – 210	Other RNSS Elements & Applications
L1C	
1 – 63	Reserved (GPS)
64 – 119	Other Augmentation Systems
120 – 158*	Reserved (SBASs)
159 – 210	Other RNSS Elements & Applications
L2C	
1 – 63	Reserved (GPS)
64 – 119	Other Augmentation Systems
120 – 158*	Reserved (SBASs)
159 – 210	Other RNSS Elements & Applications
L5	
1 – 63	Reserved (GPS)
64 – 119	Other Augmentation Systems
120 – 158*	SBASs
159 – 210	Other RNSS Elements & Applications

* See Section 4.4.4 for SBAS-specific guidance

Pseudo-random noise codes

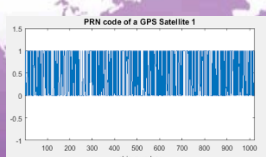
Main functions of these codes are:

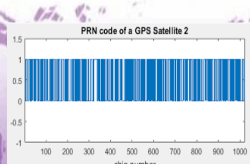
- To provide time delay measurements so the user can determine the distance from receiver's antenna to observed satellite (any code could be used, but the P(Y) code provides a more precise range estimate)



Pseudo-random noise codes

- To help the receiver in differentiating the incoming signals from different satellites





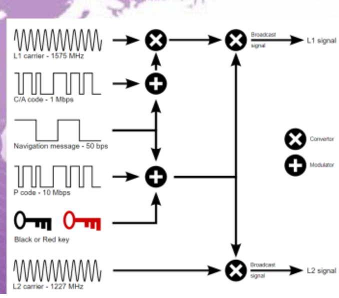
Modulated GPS Signal

The only frequency range suitable for transmission and reception purposes is 1-2 GHz

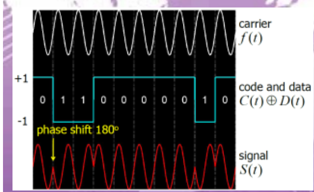
Signal is transmitted primarily by using phase modulation

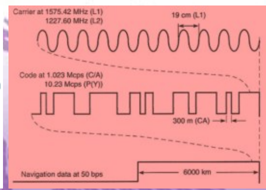
The L1 signal is modulated according to P-code (Precise Code) and C/A (Course Acquisition) code and navigation message.

The L2 signal with navigation message and the P-Code which encrypted to generate Y-code

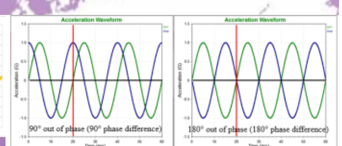


Modulated GPS Signal

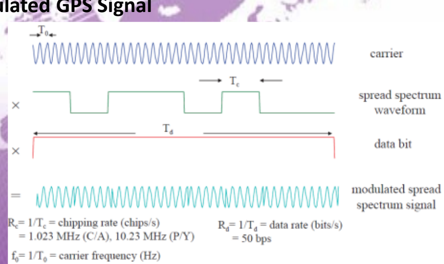




Phase offset (In-phase and Quadra-phase)

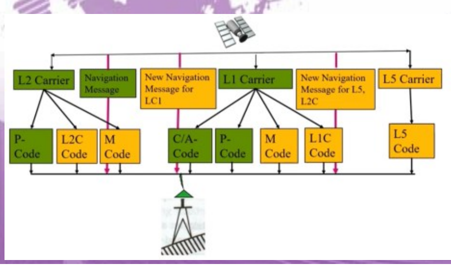


Modulated GPS Signal



Legacy and Modernized satellites

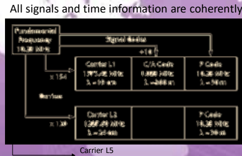
GPS signal structure of the modernized design



GPS Signal Characteristics

Signal components

All signals and time information are coherently derived from the basic frequency of f_0 **=10.23 MHz**



System	Signal	Freq. (MHz)	Wave-Length (m)	Chipping Rate (Mc/s)
GPS	L5	1176.45	0.254	10.23
	L2	1226.70	0.244	1.023
	L1	1575.42	0.190	1.023

	Signal	Modulation	Frequency (MHz)	Wavelength (m)	Chipping rage (Mc/s)
Modernized GPS	L1 C	BPSK	1575.42	0.190	1.023
	L2 C	BPSK	1227.60	0.244	1.023
	L5	BPSK	1176.45	0.254	10.23

GPS Signal Characteristics

L1 Band (1575.42 MHz = 10.23 MHz × 154)

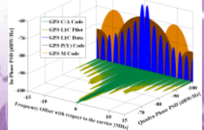
Four signals are transmitted at the moment by GPS in L1: C/A Code, P(Y) Code, M-Code and the new L1C signal

The Coarse/Acquisition (C/A) code signal was primarily thought for acquisition of the P (or Y) code. Chipping rate of 1.023 Mbps.

The P Code is the precision signal and is coded by the precision code. Y-Code is used in place of the P-code. 7 days long at a chipping rate of 10.23 Mbps

M-Code is designed exclusively for military use. M-Code provides better jamming resistance than the P(Y) signal

L1 Civil signal (L1C) designed for interoperability with other GNSS (Ex. Galileo/Glonass)

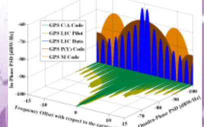


GPS Signal Characteristics

L1 Band (1575.42 MHz = 10.23 MHz × 154)

GPS L1 signal technical characteristics

GNSS System	GPS	GPS		GPS	GPS
Service Name	C/A	L1C		P(Y) Code	M-Code
Centre Frequency	1575.42 MHz	1575.42 MHz		1575.42 MHz	1575.42 MHz
Frequency Band	L1	L1		L1	L1
Access Technique	CDMA	CDMA		CDMA	CDMA
Signal Component	Data	Data	Pilot	Data	N.A.
Modulation	BPSK(1)	TMBOC(6,1,1/11)		BPSK(10)	$BOC_{sin}(10,5)$
Sub-carrier frequency [MHz]	-	1.023	1.023 & 6.138	-	10.23
Code frequency	1.023 MHz	1.023 MHz		10.23 MHz	5.115 MHz
Primary PRN Code length	1023	10230		$6.19 \cdot 10^{12}$	N.A.
Code Family	Gold Codes	Weil Codes		Combination and short-cycling of M-sequences	N.A.
Secondary PRN Code length	-	-	1800	-	N.A.
Data rate	50 bps / 50 sps	50 bps / 100 sps	-	50 bps / 50 sps	N.A.
Minimum Received Power [dBW]	-158.5	-157		-161.5	N.A.
Elevation	5°	5°		5°	5°

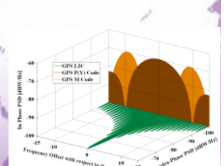


GPS Signal Characteristics

L2 Band (1227.60 MHz = 10.23 MHz × 120)

- Three signals are transmitted in L2: P(Y) Code, M-Code and the new L2C signal
- L2C transmits to meet commercial needs as it enables the development of dual-frequency solutions; together with the P(Y) Code and the M-Code
- L2C is transmitted by Block IIR-M and subsequent satellites (since April 2014).
- The current status of the L2C signal:

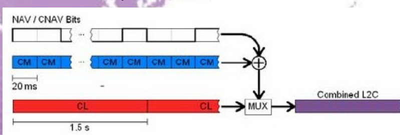
  Broadcasting from 23 GPS satellites (as of January 9, 2021)
  Began launching in 2005 with GPS Block IIR-M
  Available on 24 GPS satellites with ground segment control capability by 2023



GPS Signal Characteristics

L2 Band (1227.60 MHz = 10.23 MHz × 120)

CM and CL Codes



- Two additional PRN ranging codes are transmitted since Block IIR-M (IIR-M, IIF, III and subsequent blocks): L2 Civil Moderate (L2 CM) code and the L2 Civil Long (L2 CL) code.
- The CM code is 10,230 chips long, repeating every 20 ms
- The CL code is 767,250 chips long, repeating every 1,500 ms
- Each signal is transmitted at 511,500 chips per second (chips/s)
- Multiplex (Combined) together to form a 1,023,000-chip/s signal

GPS Signal Characteristics

L2 Band (1227.60 MHz = 10.23 MHz × 120)

GPS L2 signal technical characteristics

GNSS System	GPS	GPS	GPS	GPS
Service Name	L2 CM	L2 CL	P(Y) Code	M-Code
Centre Frequency	1227.60 MHz	1227.60 MHz	1227.60 MHz	1227.60 MHz
Frequency Band	L2	L2	L2	L2
Access Technique	CDMA	CDMA	CDMA	CDMA
Spreading modulation	BPSK(1) result of multiplexing 2 streams at 511.5 kHz		BPSK(10)	BOCsin(10,5)
Sub-carrier frequency	-	-	-	10.23 MHz
Code frequency	511.5 kHz	511.5 kHz	10.23 MHz	5.115 MHz
Signal Component	Data	Pilot	Data	N.A.
Primary PRN Code length	10,230 (20 ms)	767,250 (1.5 seconds)	6.19 x 1012	N.A.
Code Family	M-sequence from a maximal polynomial of degree 27		Combination and short-cycling of M-sequences	N.A.
Secondary PRN Code length	-	-	-	N.A.
Data rate	IIF 50 bps / 50 sps IIR-M Also 25 bps 50 sps with FEC	-	50 bps / 50 sps	N.A.
Minimum Received Power [dBW]	II/IIA/IIR -164.5 dBW IIR-M -161.5 dBW IIF -161.5 dBW		II/IIA/IIR -164.5 dBW IIR-M -161.4 dBW IIF -160.0 dBW	N.A.
Elevation	5°		5°	5°

GPS Signal Characteristics

L5 Band (1176.45 MHz = 10.23 MHz × 115)

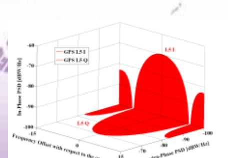
One of the new signals belonging to the GPS modernization plan. Available from Block IIF satellites.

Broadcast beginning in April 2014. currently 17 satellites, 24 in year 2027.

Reserved exclusively for aviation safety services

To be used in combination with L1 C/A to improve accuracy

The L5 signal consists of two carrier components: L5I & L5Q



GPS Signal Characteristics

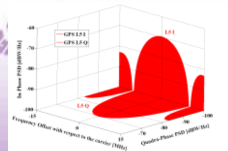
L5 Band (1176.45 MHz = 10.23 MHz × 115)

Two PRN ranging codes are transmitted on L5 in quadrature: the in-phase code (called *I5-code*) and the quadrature-phase code (called *Q5-code*).

Both codes are 10,230 chips long, transmitted at 10.23 Mchip/s

Compared to L1 C/A and L2:

- Higher transmitted power and wider bandwidth
- Improved signal structure for enhanced performanc

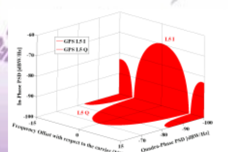


GPS Signal Characteristics

L5 Band (1176.45 MHz = 10.23 MHz × 115)

GPS L5 signal technical characteristic

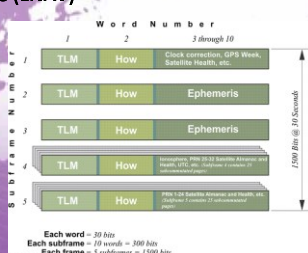
GNSS System	GPS	GPS
Service Name	L5 I	L5 Q
Centre Frequency	1176.45 MHz	1176.45 MHz
Frequency Band	L5	L5
Access Technique	CDMA	CDMA
Spreading modulation	BPSK(10)	BPSK(10)
Sub-carrier frequency	-	-
Code frequency	10.23 MHz	10.23 MHz
Signal Component	Data	Pilot
Primary PRN Code length	10230	10230
Code Family	Combination and short-cycling of M-sequences	
Secondary PRN Code length	10	20
Data rate	50 bps / 100 sps	-
Minimum Received Power [dBW]	-157.9 dBW	-157.9 dBW
Elevation	5°	5°



Legacy Navigation Message (LNAV)

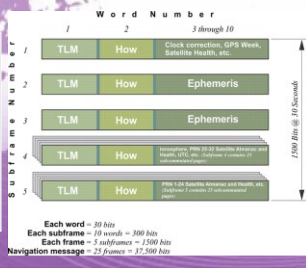
Low frequency signal added to L1 and L2 that gives information about the satellite's orbits, their clock corrections and other system status (Satellite Epimerits)

The entire Navigation message contains 37, 500 bits and at a rate of 50 bits-per-second takes 12½ minutes to broadcast and to receive



Legacy Navigation Message (LNAV)

Subframes	Description
1	Satellite clock, GPS time relationship
2–3	Ephemeris (precise satellite orbit)
4–5	Almanac component (satellite network synopsis, error correction)



Modernized Civil Navigation Message (CNAV)

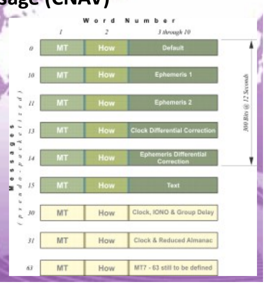
Upgraded version of the LNAV enabling the information of new signals.

Higher precision representation and more accurate data than the LNAV data

Time, status, ephemeris, and almanac) are transmitted using the new CNAV format

instead of frame/subframe, it uses a new pseudo-packetized format made of 12-second 300-bit *messages* analogous to LNAV frames.

The new format is designed to support 63 satellites, compared with 32 in the LNAV message



Modernized Civil Navigation Message (CNAV)

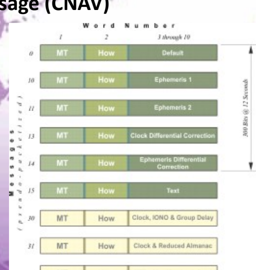
Important changes in the new CNAV message:

It uses forward error correction (FEC)

The GPS week number is now represented as 13 bits, or 8192 weeks, and only repeats every 157.0 years, meaning the next return to zero won't occur until the year 2137. This is longer compared to the L1 NAV message's use of a 10-bit week number, which returns to zero every 19.6 years.

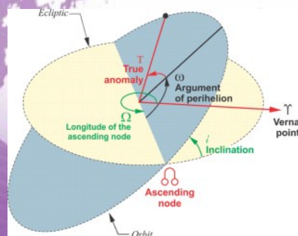
Better interoperability with other global systems (GPS-GLONASS offset is available)

Designed to support 63 satellites, compared with 32 in the legacy NAV message



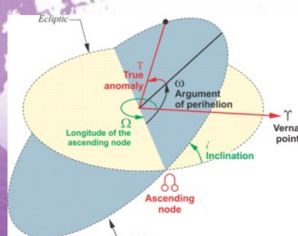
Ephemerides (Keplerian parameters)

- The satellite's ephemeris is the position of the satellite relative to the earth, with respect to time.
- The ephemeris is given in a right ascension (RA) system of coordinates
- Orbital elements (6):
  - Size of the orbit (a,e)
  - orientation of the orbital plane (Ω,i)
  - position of the satellite on the orbit (ω, T)
- To calculate earth-centered, earth-fixed, WGS84 Cartesian coordinates of the satellite (Ephemeris algorithms).



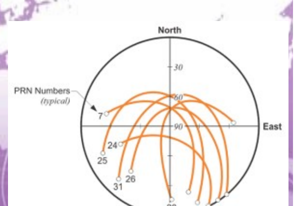
Ephemerides (Keplerian parameters)

- GPS satellites deviate from smooth elliptical paths because they are unavoidably perturbed by gravitational and other forces.
- The accuracies of both the broadcast clock correction and the broadcast ephemeris deteriorate with time
- Precise ephemerids are used for precise positioning



The Almanac

- Subframes 4 and 5 tells the receiver where to find all the GPS satellites
- The Control Segment generates and uploads a new almanac every day to each satellite
- Subframe 1 contains information about the health of the satellite the receiver is tracking
- Inform users of any satellite malfunctions, and whether the satellite are good and reliable



New GPS Civil Signals

- The legacy civil signal, called L1 C/A or C/A at L1, will continue broadcasting
- Three new signals designed for civilian use: L2C, L5, and L1C
- Users must upgrade their equipment to benefit from the new signals
- The new civil signals are transmitting with new GPS satellites to replace older ones (Modernized satellites, eg. GPSIII)

Second Civil Signal: L2C

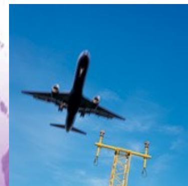
- L2C is the second civilian GPS signal, designed specifically to meet commercial needs. Transmitted by Block IIR-M and later design satellites
- Its name refers to the radio frequency used by the signal (1227 MHz, or L2) and the fact that it is for civilian use
- When combined with L1 C/A in a dual-frequency receiver, L2C enables ionospheric correction, a technique that boosts accuracy.
- L2C broadcasts at a higher effective power than the legacy L1 C/A signal, making it easier to receive under trees and even indoors
- The first GPS satellite featuring L2C launched in 2005. Every GPS satellite fielded since then has included an L2C transmitter

Second Civil Signal: L2C

- Contains two distinct PRN code sequences; the civil-moderate code (CM), and the civil-long length code (CL)
- CM - 10,230 bits CL - 767,250 bits long
- Chipping rate 511,500 bits per second
- current status of the L2C signal
    - Broadcasting from 23 GPS satellites (as of January 9, 2021)
    - Began launching in 2005 with GPS Block IIR-M
    - Available on 24 GPS by 2023

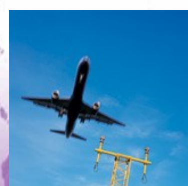
Third Civil Signal: L5

- L5 is the third civilian GPS signal, designed to meet demanding requirements for safety-of-life transportation and other high-performance applications
- Its name refers to the U.S. designation for the radio frequency used by the signal (1176 MHz)
- L5 is broadcast in a radio band reserved exclusively for aviation safety services
- Future aircraft will use L5 in combination with L1 C/A to improve accuracy (via ionospheric correction)
- The first GPS IIF satellite with a full L5 transmitter launched in May 2010



Third Civil Signal: L5

- Two PRN ranging codes: in-phase code (I5-code); quadrature phase code (Q5-code)
- Both codes are 10,230 bits long, transmitted at 10.23 MHz
- Changes in L5:
  - Higher transmitted power than L1/L2 signal
  - Wider bandwidth
- Current status:
  - Broadcasting from 17 GPS satellites
  - Available on 24 GPS satellites ~2027



Fourth Civil Signal: L1C

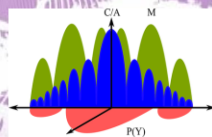
- L1C is the fourth civilian GPS signal, designed to enable interoperability between GPS and international satellite navigation systems
- Its name refers to the radio frequency used by the signal (1575 MHz, or L1) and the fact that it is for civilian use
- The United States and Europe originally developed L1C as a common civil signal for GPS and Galileo. Japan's Quasi-Zenith Satellite System (QZSS) and China's BeiDou system are also adopting L1C-like signals
- Broadcast from GPS III and later satellites. The first GPS satellite featuring L1C launched in December 2018
- Current status: Broadcasting from 5 GPS satellites

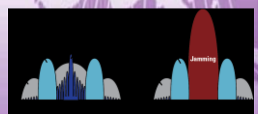
Military (M-code)

A major component of the modernization process is a new military signal. Called the Military code, or M-code

Improve the anti-jamming and secure access of the military GPS signals

The M-code is transmitted in the same L1 and L2 frequencies already in use by the previous military code, the P(Y)-code





GNSS Measurements

Basic Principles

GNSS Measurements
(Distance between receivers and satellites)

- **Code measurements**
- **Carrier phase measurements**

High-accuracy GNSS measurements

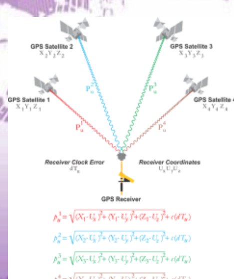
- Code measurement and carrier phase measurement are affected by different source of errors
- Impact of the sources of error can be reduced by measuring against many satellites, or by trying to estimate or model the sources of error
- Relative positioning
- Geodetic measurement with GNSS – relative carrier phase measurements

Code Measurements

Two Questions…

"How do we know the position of the satellites??"

"What are Pseudoranges ??"



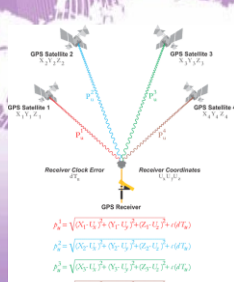
Code Measurements

Two Questions…

"Navigation Message,"

It includes orbit parameters (broadcast ephemeris) from which the receiver can compute satellite coordinates (X,Y,Z).

Algorithm which transforms the orbit parameters into WGS-84 satellite coordinates at any specified time is called the "Ephemeris Algorithm,"



Code Measurements

Two Questions…

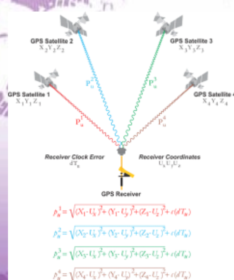
Transmitted time is encoded on the signal, using atomic clock on-board the satellite

Received time is recorded by receiver using a quartz crystal clocks

Receiver measures the time difference

Pseudorange = (time difference) X (speed of light)

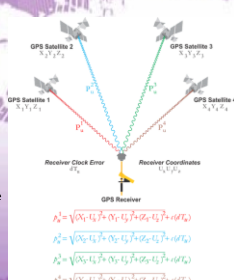
It includes clock errors because the receiver clocks are far from perfect



Code Measurements

How do we correct for clock errors?

- Satellite clock error is given in the Navigation Message
- In the form of a polynomial
- The unknown receiver clock error can be estimated by the user along with unknown station coordinates.
- There are 4 unknowns. Minimum of 4 pseudorange measurements

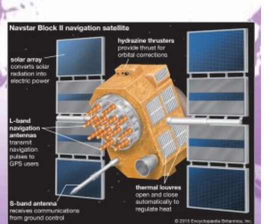


GPS signal transmission and reception

- GPS signals modulated into the carrier waves (L1, L2 and L5) are random binary codes (C/A, P, M, navigation message, etc.) called Pseudo Random Noise codes (PRN codes)
- The GPS signal starts in the satellite as a voltage which oscillates at the fundamental clock frequency of 10.23 MHz
- Separately multiplied in frequency by the integers 154, 120 and 115, to create the L1 , L2 and L5 carrier signals
- Multiplied by +1 and -1 according the code generation algorithms to generate the C/A code (on L1) and the P code (on both L1 and L2).
- Codes are unique to each satellite
- Navigation Message is encoded onto the signal

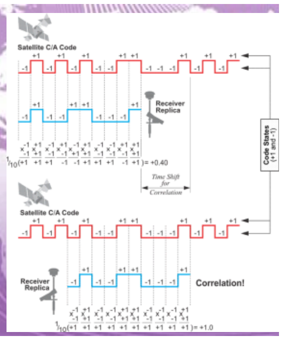
GPS signal transmission and reception

- Antenna of satellite radiate the signal into space in the form of electromagnetic waves
- Signal transmit at very close to the speed of light in a vacuum
- signal then enters the receiver and measures it using a process known as **"Autocorrelation."**

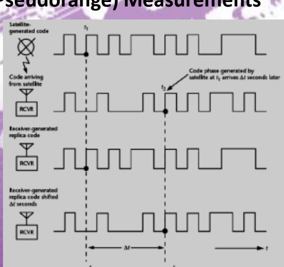


Autocorrelation

- Receiver generates GPS-like signals internally
- Receiver then compares the replica signal with the actual signal
- Receiver's replica signal must be delayed in to match up the incoming signal with the replica signal
- The time delay is measured by the receiver (it includes satellite and receiver clock errors)
- The time delay is computed by the receiver by matching signals using autocorrelation technique. In peak autocorrelation, the inferred time displacement between the two signals is multiplied by the speed of light, **Pseudorange**

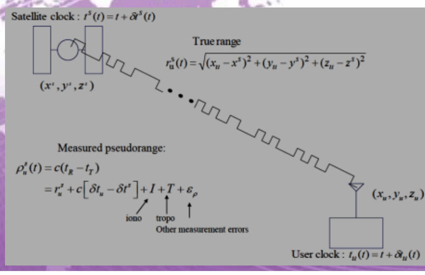


Code (Pseudorange) Measurements



- **With a perfect user clock, signal transit time can be multiplied by the speed of light to yield a range measurement**
- **With an imperfect user clock, measured transit time for each satellite's signals are biased by a common user clock error – measurements are referred to as *pseudorange.***

Code (Pseudorange) Measurements - Pseudorange Model



Code (Pseudorange) Measurements - Pseudorange Model

τ ?	transit time → 70 to 90 ms
t ?	**true** GPS time at which code is received
$t^s(t-\tau)$	emission time (imprinted on signal)
$t_u(t)$	measured arrival time (clock reading)
$\rho(t) = c\left[t_u(t) - t^s(t-\tau)\right]$	pseudorange

Code (Pseudorange) Measurements - Pseudorange Model

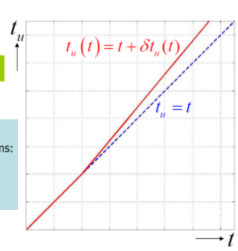
$$t_u(t) = t + \delta t_u(t)$$

receiver clock bias

Receiver clocks: drift!

Deviation from GPS time limited to ±1 ms:

- continuous clock steering
- reset (clock jump!) when certain threshold is reached



Code (Pseudorange) Measurements - Pseudorange Model

$$t_u(t) = t + \delta t_u(t)$$

receiver clock bias

$$t^s(t-\tau) = (t-\tau) + \delta t^s(t-\tau)$$

satellite clock bias

estimated by control segment

Code (Pseudorange) Measurements - Pseudorange Model

$$t_u(t) = t + \delta t_u(t)$$

$$t^s(t-\tau) = (t-\tau) + \delta t^s(t-\tau)$$

Unmodeled effects and errors

$$\begin{aligned}\rho(t) &= c\left[t_u(t) - t^s(t-\tau)\right] + \varepsilon_\rho(t)\\ &= c\left[t + \delta t_u(t) - (t-\tau) - \delta t^s(t-\tau)\right] + \varepsilon_\rho(t)\\ &= c\tau + c\left[\delta t_u(t) - \delta t^s(t-\tau)\right] + \varepsilon_\rho(t)\end{aligned}$$

Code (Pseudorange) Measurements - Pseudorange Model

$$\rho(t) = c\tau + c\left[\delta t_u(t) - \delta t^s(t-\tau)\right] + \varepsilon_\rho(t)$$

clock biases

noise + errors

distance traveled by signal

$$c\tau = r(t, t-\tau) + I_\rho(t) + T_\rho(t)$$

geometric range

ionosphere and troposphere delays

Code (Pseudorange) Measurements - Pseudorange Model

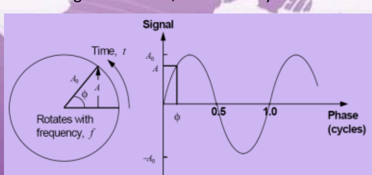
$$\rho = r + I_\rho + T_\rho + c\left[\delta t_u - \delta t^s\right] + \varepsilon_\rho$$

pseudorange measurement = biased and noisy measurement of the **geometric range *r***

Carrier Phase measurements

"Phase," "Frequency" and "Clock Time"

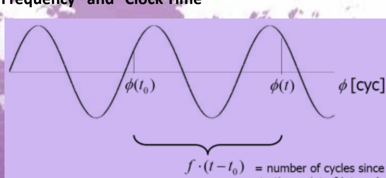
"Phase" - "angle of rotation," units of "cycles"



"phase" $\varphi(t)$ at any given time *t* can be defined as the angle through which this line has rotated

Carrier Phase measurements

"Phase," "Frequency" and "Clock Time"



Carrier phase $\phi(t) = \phi(t_0) + f \cdot (t - t_0)$

Carrier Phase measurements

"Phase," "Frequency" and "Clock Time"

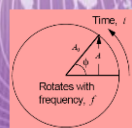
Time - based on some form of periodic motion

The rotation of the Earth, the orbit of the Earth around the Sun – **Dynamic time (Day/Year)**

The oscillation of a quartz crystal in a wristwatch - **Atomic time**

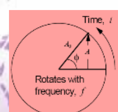
Angles of rotation (Phase) - measure of time

Clock time T(t) $T(t) = k(\varphi(t) - \varphi_0)$



Carrier Phase measurements

"Phase," "Frequency" and "Clock Time"

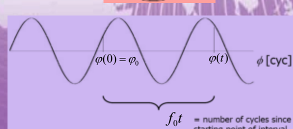


Frequency - Cycles per second
Number of times the line completes a full 360° rotation in one second

Constant frequency (f_0) - ideal clock

Phase of an ideal clock:

$$\varphi_{ideal} = \varphi(t) = f_0 t + \varphi_0$$



Carrier Phase measurements

"Phase," "Frequency" and "Clock Time"

Ideal clock time: $T(t) = kf_0 t$

Also, $T(t) = k(\varphi(t) - \varphi_0)$

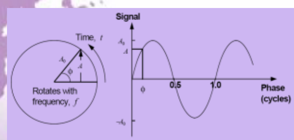
Clock second to be equal a conventional second $(T = t)$ $k = 1/f_0$

So, $T(t) = \dfrac{\varphi(t) - \varphi_0}{f_0}$

Carrier Phase measurements

At time *t*, the height of point *A*(*t*) above the centre of the circle,

$$A(t) = A_0 \sin[2\pi\varphi(t)]$$



$A(t)$ - Signal A_0 - Amplitude of the signal

Phase, $\varphi(t)$ and clock time – by inverting

Carrier Phase measurements - Carrier Beat Signal

$$R(t)\otimes G(t) = G_0 \sin 2\pi\varphi_G(t)\times R_0 \sin 2\pi\varphi_R(t)$$
$$= \frac{G_0 R_0}{2}\left[\cos 2\pi(\varphi_R(t)-\varphi_G(t)) - \cos 2\pi(\varphi_R(t)+\varphi_G(t))\right]$$

Low frequency High frequency

Carrier Phase measurements - Carrier Beat Signal

Filtering high frequency components, **carrier beat signal *B(t)***

$$B(t) = \text{Filter}\{R(t)\otimes G(t)\}$$
$$= \frac{G_0 R_0}{2}\cos 2\pi(\varphi_R(t)-\varphi_G(t))$$
$$\equiv B_0 \cos 2\pi(\varphi_B(t))$$

So, carrier beat phase $\varphi_B(t)$ - difference in phase between the replica signal and the GPS signal

$$\varphi_B(t) \equiv \varphi_R(t) - \varphi_G(t)$$

Beat frequency - difference in frequencies of the two input signals

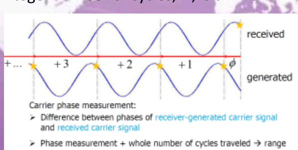
$$f_B \equiv \frac{d\varphi_B}{dt} = f_R - f_G$$

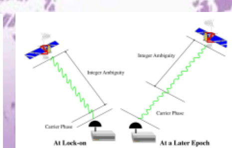
Carrier Phase measurements - Carrier Beat Signal

- Satellite carrier signal (from antenna) is mixed with reference signal generated by receiver’s clock
- The result, after high pass filtering, is a “beating” signal
- The phase of this beating signal equals the reference phase minus the incoming GPS carrier phase from a satellite
- It is ambiguous by an integer number of cycles

Carrier Phase measurements - Phase/Integer Ambiguity

- Only record the fractional phase of the first measurement
- Integer number of cycles, N, is unknown

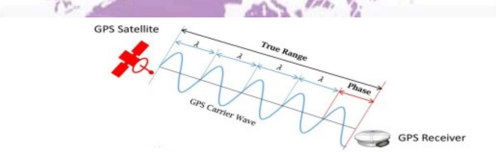




$$\Phi + N = \varphi_R - \varphi_G$$

Carrier Phase measurements - Observation model

How can phase be used to measure distance?



$$Phase(\phi) = TrueRange - \lambda N + Clk^{Tx} + Clk_{Rx} + Delay_{atm}$$

Carrier Phase measurements - Observation model

$$\Phi + N = \varphi_R - \varphi_G$$

$$\Phi^S(T) = \varphi(T) - \varphi^S(T) - N^S$$

φ replica phase generated by the receiver clock time T
φ^S incoming signal phase received from GPS satellite S

So, phase:

$$\varphi(T) = f_0 T + \varphi_0$$
$$\varphi^S_{\text{transmit}}(T^S) = f_0 T^S_{\text{transmit}} + \varphi^S_0$$

T^S - satellite clock time at the time of signal transmission

So, the carrier phase observable becomes:

$$\Phi^S(T) = f_0 T + \varphi_0 - f_0 T^S - \varphi^S_0 - N^S$$
$$= f_0\left(T - T^S\right) + \varphi_0 - \varphi^S_0 - N^S$$

carrier phase bias (constant)

Carrier Phase measurements - Observation model

For multi-receiver and multi-satellite analysis,

$$\Phi^j_A(T_A) = f_0\left(T_A - T^j\right) + \varphi_{0A} - \varphi_0{}^j - N^j_A$$

carrier phase observed by receiver *A* from satellite *j*

$A, B, C, \ldots$ - quantities specific to receivers

$j, k, l \ldots$ - satellite-specific quantities

Carrier Phase measurements - Observation model

- It is convenient to convert the carrier phase model into units of range
- Multiply the carrier phase equation by the wavelength

$$L^j_A(T_A) \equiv \lambda_0 \Phi^j_A(T_A)$$
$$= \lambda_0 f_0\left(T_A - T^j\right) + \lambda_0\left(\varphi_{0A} - \varphi_0{}^j - N^j_A\right)$$
$$= c\left(T_A - T^j\right) + \lambda_0\left(\varphi_{0A} - \varphi_0{}^j - N^j_A\right)$$
$$\equiv c\left(T_A - T^j\right) + B^j_A$$

integer number of wavelengths

carrier phase bias (constant)

Pseudorange

Instrumental phase offsets in the satellite and receiver

Carrier Phase measurements - Observation model

Modelling the carrier phase using simplified model for pseudorange

$$L_A^j(T_A) = c\left(T_A - T^j\right) + B_A^j$$
$$= \rho_A^j(t_A, t^j) + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j$$

Pseudorange model

Carrier Phase measurements - Observation model

Modelling the carrier phase using simplified model for pseudorange

$$L_A^j(T_A) = c\left(T_A - T^j\right) + B_A^j$$
$$= \rho_A^j(t_A, t^j) + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j$$

Carrier phase bias

Troposphere delay

Ionosphere delay (the minus sign indicating that the phase velocity actually increases)

Range from satellite To receiver

Receiver and satellite Clock bias

Carrier Phase measurements - Observation model

- True time, t_A, of signal reception is unknown
- True time needs for calculating satellite-receiver range, $\rho_A^j(t_A, t^j)$

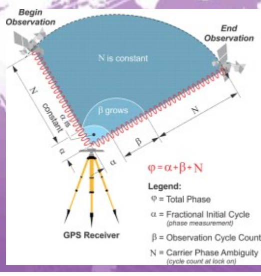
$$t_A = T_A - \tau_A$$

- Receiver clock time, T_A is known (time-tag)

$$L_A^j(T_A) = c\left(T_A - T^j\right) + B_A^j$$
$$= \rho_A^j(t_A, t^j) + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j$$

- Receiver clock bias, τ_A, is not known initially and GPS geodetic software use various approaches to calculate it (Pseudorange point position solution + least-squares technique)
- Satellite clock bias τ^j is obtained from the Navigation Message
- Ambiguities must be resolved to take advantage of high precision phase measurements

Components of the Carrier Phase Observable



Three parts:

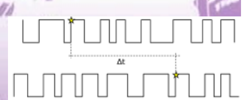
- The fractional initial phase and integer cycle ambiguity N at the first instant of the lock-on do not change during the session (if no cycle slips)
- The number of full phase cycles grows from the moment of lock on until the end of the observation (as the satellite moves from one place to another in its orbit)
- A fixed solution is superior to a float solution

GNSS Measurements – Summary

The distance between receivers and satellites is determined using code measurement and/or carrier phase measurement on the GNSS signal.

Code (Pseudorange) Measurements

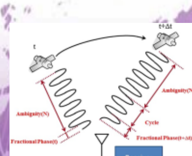
- The time between transmission and reception of the GNSS signal is relatively easy to determine when using code measurements.
- The satellites and GNSS receivers are intended to generate the same code at the same time. By shifting the local code in the receiver until it corresponds to the received code, a time difference is obtained.
- The distance between receiver and satellite can therefore be calculated as the speed of light multiplied by the measured time difference.



GNSS Measurements – Summary

Carrier Phase Measurements

- Solving phase ambiguities, i.e. finding out how many whole wavelengths the distance between satellite and receiver consists of, is the critical part of carrier phase measurement.
- The carrier phase on L1 has a much higher frequency than the C/A code, 1575 MHz, which corresponds to a wavelength of 19 centimetres. Based on the rule of thumb that the signal resolution is about one percent of the wavelength, an individual carrier measurement can in principle be made with an accuracy of about two millimetres!
- Carrier phase measurement is more complicated, both in terms of equipment and method of measurement. Therefore GNSS use the combination of Code and Carrier phase measurements.



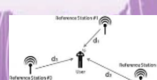
GNSS Measurements – Summary

Comparison Code Vs Carrier phase

	Code measurement	Carrier phase measurement
Time required	Short observation time (seconds)	Short to long observation time (few seconds to hours), depending on application.
Receiver	Simple GNSS receivers	Advanced GNSS receivers
Measurement uncertainty (in plane)	Tens of meters at absolute positioning. Meter level at relative positioning	Centimeter level at relative positioning with determination of integer phase ambiguities.
Sensitivity to signal interruption	Less sensitive, as the measurement period is short.	More sensitive, as determining integer phase ambiguitites requires uninterrupted measurement (sometimes over a long period of time).

GNSS Measurements – Summary

- Code measurement and carrier phase measurement are affected by different sources of error. The impact of the sources of error can be reduced by measuring against many satellites, or by trying to estimate or model the sources of error.
- Positioning of the GNSS receiver in relation to the satellites can be done with one or more receivers. If more than one receiver is used, some of them can be placed over points with an already known position. This is called relative positioning and makes it possible to reduce or eliminate sources of error and thus the measurement uncertainty of the receiver with an unknown position



- Geodetic measurement with GNSS today takes place almost exclusively with **relative carrier phase measurements**, either in real time or with post-processing of the position.

GNSS Positioning

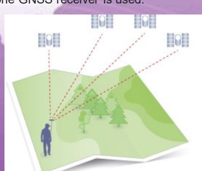
GNSS Surveying Methods

Common requirements of GNSS positioning

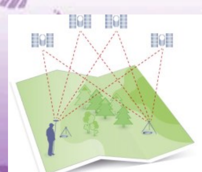
- Clear view of satellites
- Base station requirement
- Single receiver or multiple receivers
- Correction modelling
- Data processing

Absolute and Relative Positioning

- In absolute positioning, the position of the receiver is determined directly towards the GNSS satellites, and only one GNSS receiver is used.

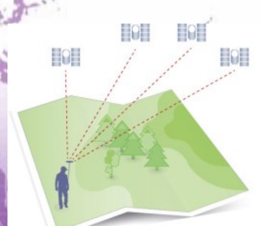


- In relative positioning, the position of the receiver is determined relative to one or more points with known position.



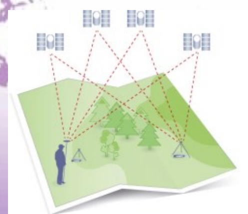
Absolute Positioning

- Receiver position is determined directly in relation to the GNSS satellites
- The measurement is done with only one receiver (Ex. car navigation systems)
- The measurement uncertainty can be relatively large, so rarely used in geodesic surveying
- External information about errors is used in **Precise Point Positioning (PPP)**



Relative Positioning

- The position of the receiver is determined relative to one or more points with known positions
- Requires more than one receiver that simultaneously measure against the same GNSS satellites
- Receiver set up over a known point is called a reference station, **Base station**. Receiver at unknown station is called a **Rover**
- Permanent reference stations with ground-based support systems for relative GNSS positioning (Network RTK)
- Uncertainty at the centimeter level in both real time or with post-processing



Relative Positioning Techniques

Static measurement with post-processing

What is static measurement?

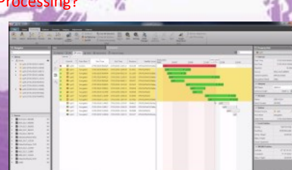
- Set up the GNSS receiver (using tripod) over the point you want to determine the position
- Store measurements over a long period of time
- Measurements are then combined with simultaneously performed measurements at one or more reference stations with a known position
- Mainly used when establishing or supplementing geodetic control networks

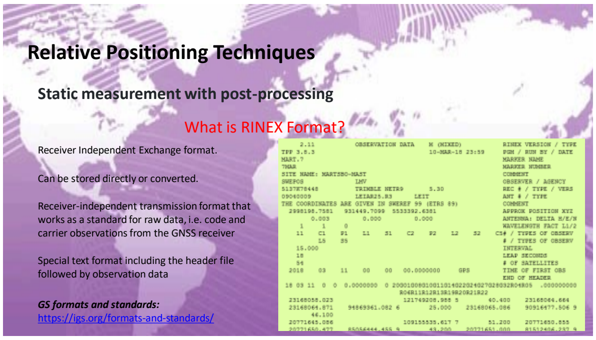
Relative Positioning Techniques

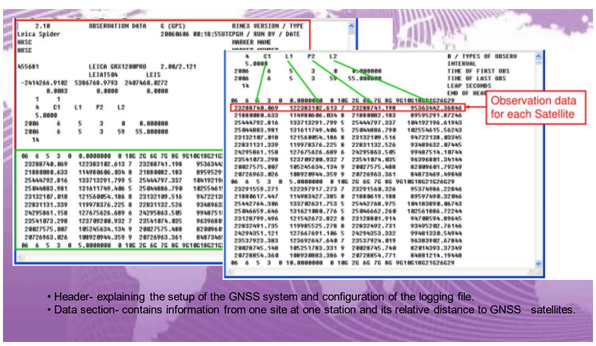
Static measurement with post-processing

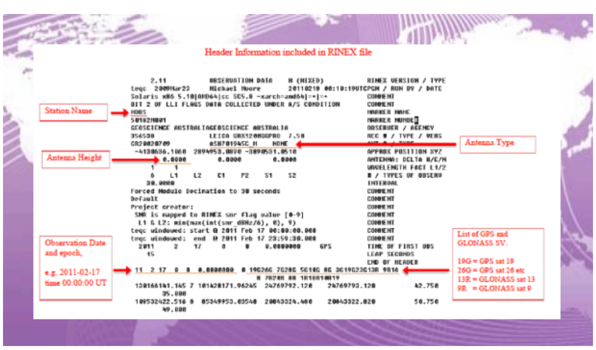
What is Post-Processing?

- GNSS measurements with long observation times are often the most accurate way to determine the position
- Use better orbits and make better estimates of other sources of error (Ex. Precise Epimerids, ionosphere models
- Use processing software with standard or RINEX files




Relative Positioning Techniques
Static measurement with post-processing
What is RINEX Format?
Receiver Independent Exchange format.
Can be stored directly or converted.
Receiver-independent transmission format that works as a standard for raw data, i.e. code and carrier observations from the GNSS receiver
Special text format including the header file followed by observation data
GS formats and standards:
https://igs.org/formats-and-standards/


Observation data for each Satellite
• Header- explaining the setup of the GNSS system and configuration of the logging file.
• Data section- contains information from one site at one station and its relative distance to GNSS satellites.


Header Information included in RINEX file
Station Name
Antenna Height
Antenna Type
Observation Date and epoch,
e.g. 2011-02-17 time 00:00:00 UT
List of GPS and GLONASS SV
19G = GPS sat 19
26G = GPS sat 26 etc
13R = GLONASS sat 13
9R = GLONASS sat 9

RINEX File Types

V123079L.18g	10/27/2018 4:06 AM	18G File	53 KB
V123079L.18n	10/27/2018 4:06 AM	18N File	69 KB
V123079L.18o	10/27/2018 4:17 AM	18O File	139,188 KB

O: **O**bservation file *(.YYo)*

The Observation file provides the following three crucial measurements:

•**Time**: the recorded time of the GNSS receiver for the received signals expressed in GPS time

•**Pseudo-range**: approximate distance (m) from the satellite to the receiver including clock offsets and atmospheric delays

•**Phase**: number of waveforms (ß) measured since locking with the satellite including the fractional initial waveform (α) and assuming no slips (loss of lock commonly caused by power loss, an obstruction, or low signal-to-noise ratio)

RINEX File Types

V123079L.18g	10/27/2018 4:06 AM	18G File	53 KB
V123079L.18n	10/27/2018 4:06 AM	18N File	69 KB
V123079L.18o	10/27/2018 4:17 AM	18O File	139,188 KB

N: GPS **N**avigation file *(.YYn)*

The navigation file contains broadcast ephemeris of the satellites and includes position, velocity, and clock information for the US GPS system.

G: **G**LONASS Navigation file *(.YYg)*

The navigation file contains broadcast ephemeris of the satellites and includes position, velocity, and clock information for the Russian GLONASS system.

Relative Positioning Techniques

DGNSS – Differential GNSS

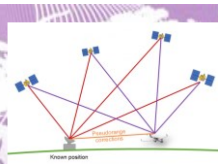
DGNSS is a collective term for measurement using multiple GNSS receivers to reduce position uncertainty.

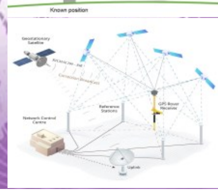
Improves accuracy by using a reference station with known coordinates

comparing the reference station's position with the receiver's measurements, DGPS can eliminate errors caused by atmospheric disturbances, clock inaccuracies, and satellite orbit errors, achieving sub-meter to decimeter accuracy.

Today, DGNSS is mainly used to describe the relative measurement methods based on code measurements

widely used in applications like land surveying, construction, agriculture, and navigation





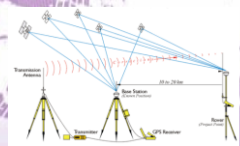
Relative Positioning Techniques

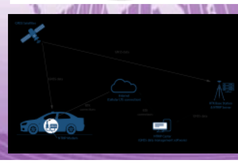
RTK – Real-Time Kinematic

Another name for relative real-time carrier phase measurement

Requires:

- GNSS receivers that can handle carrier phase measurement on several frequencies
- data link for the transmission of RTK corrections between the receivers in real time
- Ex. radio communication or mobile internet.

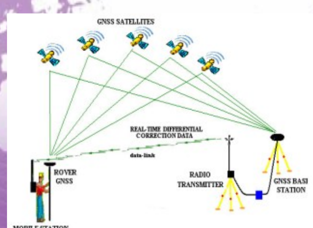




Relative Positioning Techniques

RTK – Real-Time Kinematic

- Real-time method with the lowest measurement uncertainty (few *cm*)
- Phase ambiguities is fixed to the correct integer (fixed solution)
- Initialization takes about ten seconds up to one minute, depending on local conditions
- Can be **Single-station RTK** or **Network RTK**



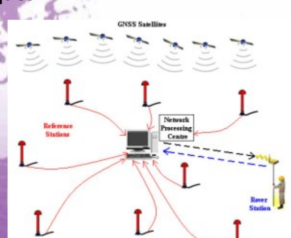
Single-station RTK

Relative Positioning Techniques

Network RTK

Several permanently established reference stations working together to optimize the management of sources of error over a larger coverage area

A special network RTK software is used to manage incoming data from the stations, generating RTK corrections and finally sending custom corrections to the users

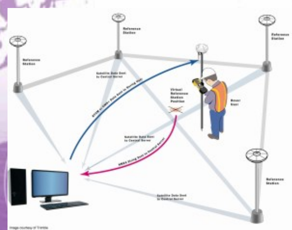


Network-RTK

Relative Positioning Techniques

Network RTK – VRS

- VRS or virtual reference station: the control centre "simulates" a reference station near the rover
- two-way communication for the rover to report its approximate position to the control center, and reference station data is tailored for the simulated reference station.
- Virtual RINEX can be created from data of surrounding reference stations using the same software used for network RTK services.



Relative Positioning Techniques

Advantages and disadvantages of network RTK

Advantages

- user to have only one RTK receiver. A reference station does not need to be established or quality assured by the user
- Good quality in a larger coverage area, unlike single station RTK where the measurement uncertainty increases significantly with the distance to the reference station
- Measurement takes place directly in a uniform and modern reference system adapted for GNSS measurement

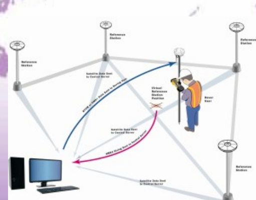
Disadvantages

- Requires working mobile internet, i.e. two-way communication, between service provider and user
- Lack of traceability, as the user does not have access to complete information about the calculation method

Relative Positioning Techniques

Post-Processing of RTK

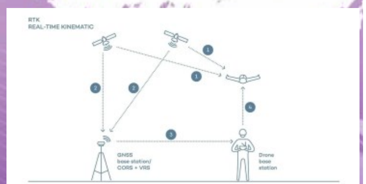
- In post-processing of RTK, virtual RINEX is often used as reference data
- Virtual reference station functions as a reference station in real-time, i.e. provides the necessary correction data
- Collect raw data over a slightly longer period and make regular detail surveys at the points that are to be recalculated later
- Post-process the detail surveys achieveing equivalent quality as with real-time RTK
- Very useful in areas with poor mobile coverage



Relative Positioning Techniques

Post-Processing Kinematic (PPK) Vs. RTK

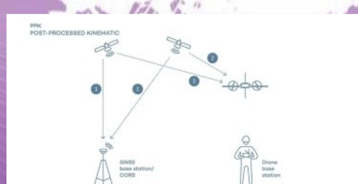
- Mainly PPK and RTK are used to improve and correct the location of drone mapping data and remove the need for GCPs, bringing absolute accuracy down to cm range.
- An RTK drone carries an onboard GNSS RTK receiver that gathers data from satellites and a stationary base (ground) station to more accurately correct image location, in real time as it flies



Relative Positioning Techniques

Post-Processing Kinematic (PPK) Vs. RTK

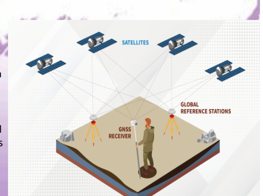
- A PPK drone flies with an onboard GNSS PPK receiver that gathers data from satellites and logs it for retrieval after the flight
- The satellite data from a GNSS receiver on base (ground) station is collected and, after the flight, process base data with rover data to correct satellite signal error, bringing accuracy down to cm range
- No real-time communication , but telemetry



Absolute Positioning Techniques

Precise Point Positioning (PPP)

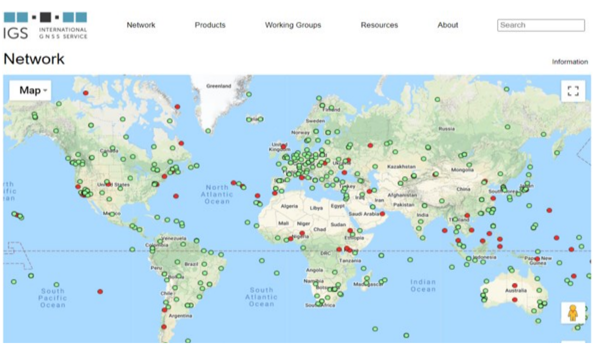
- Originally developed by NASA for both real-time and post-processing applications
- GNSS receiver combined with external information: correction of satellite orbits, clock errors, global or regional modeling of atmospheric sources of error
- No need of nearby reference stations, but a certain global or regional network of reference stations to model the sources of error
- In real-time applications, a communication link to obtain the external correction information – **PPP-RTK**
- Coordinates in the latest ITRF solution



Absolute Positioning Techniques

Precise Point Positioning (PPP)

- Use all the available GNSS constellations (GPS, GLONASS, GALILEO, BEIDOU, QZSS)
- Combine precise satellite positions and clocks with un-differenced, dual-frequency (to remove the first order effect of the ionosphere), pseudorange and carrier-phase GNSS observables. Centimeter-level precision
- Alternative to Differential Global Navigation Satellite System (DGNSS)- not require simultaneous observations from multiple stations
- Require a fairly long convergence time to achieve the utmost performance
- Use of a network of reference stations in order to compute precise estimates of GNSS satellites orbits and clock errors (http://www.igs.org/network)



PPP Benefits

- PPP involves only a single GNSS receiver and, therefore, no reference stations are needed in the vicinity of the user.
- PPP can be regarded as a global position approach because its position solutions refer 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(s)
- PPP reduces labour and equipment cost and simplifies operational logistics 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
- Refers absolute dynamics of the Earth

IGS Products

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

Broadcast Ephemeris

Precise Ephemerids

IGS Products

- IGS Analysis Centers (AC) contribute daily Ultra-rapid, Rapid and Final GPS/GLONASS orbit and clock solutions to the IGS combinations
- GPS/GLONASS orbits and clocks by IGS facilitates a direct link within a globally integrated, reference frame which is consistent with the current International Terrestrial Reference Frame (ITRF)
- Since 2000 the ultra-rapid products available for users
- Since 2013, the IGS Real Time Service (RTS) has been officially launched,
- providing precise orbit/clocks products in real time
- The ultra-rapid and RTS products have since become useful to many other real-time and near real-time users

IGS Analysis Centers (ACs & ACC)

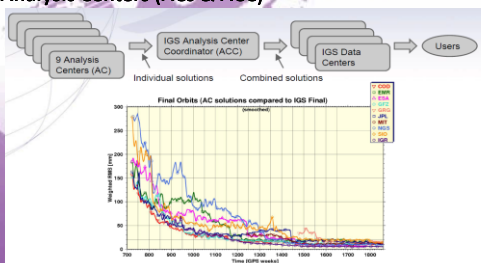
Analysis Center Coordinator (ACC)

Institution	Abbreviation	Country
Geoscience Australia & Massachusetts Institute of Technology	GA/MIT	Australia/USA

IGS Analysis Centers (ACs)

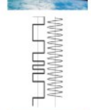
Institution	Abbreviation	Country
Natural Resources Canada	EMR	Canada
Wuhan University	WHU	China
Geodetic Observatory Pecny	GOP-RIGTC	Czech Republic
Space geodesy team of the CNES	GRG	France
European Space Agency/ESOC	ESA/ESOC	Germany
GeoForschungsZentrum	GFZ	Germany
Center for Orbit Determination in Europe	CODE	Switzerland
Jet Propulsion Laboratory	JPL	USA
Massachusetts Institute of Technology	MIT	USA
NOAA/National Geodetic Survey	NGS	USA
Scripps Institution of Oceanography	SIO	USA
U.S. Naval Observatory	USNO	USA

IGS Analysis Centers (ACs & ACC)



How PPP works?

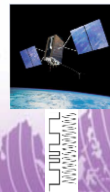
- Precise modelling of GPS satellites
- Precise modelling of GPS signal
- Precise modeling of GPS antenna
- Algorithms

Precise modelling of GPS satellites

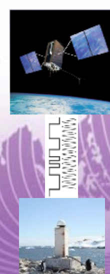
- Geopotential model
  EGM2008 12x12
- Solar radiation pressure model
  Modified CODE model
- Transmission antenna phase center model
  Absolute phase center variation model from IGS
- Eclipsing satellites
  Observations from eclipsing satellites are deleted


Precise modelling of GPS signal



- Tropospheric path delay
  - Saastamoinen model
  - Vienna Mapping Function (VMF1)
- Ionospheric path delay
  - First-order effect is removed using linear combination of dual-frequency phase
  - Higher-order effect is ignored
- Relativistic effect
- Carrier-phase wind-up effect

Precise modelling of GPS antenna



- Metadata book-keeping
  - Antenna type
- Receiver antenna phase center model
  - Absolute phase center variation model from IGS
- Tidal displacements
  - Solid Earth tide
  - Permanent tide
  - Solid Earth pole tide
  - Ocean pole tide
  - Ocean tide loading
  - Ocean tide geocenter
- Data from ~230 globally distributed IGS stations are processed daily

Precise Algorithms

- Basic observables
  - Double-differenced ionosphere-free carrier phase
- Ambiguity resolution
  - Melbourne-Wübbena widelane method
- Adjusted parameters
  - GPS orbit
  - Station coordinates
  - Earth rotation parameters
  - Tropospheric correction parameters
  - Real-valued ambiguities
  - for any ambiguities not fixed
  - Solar radiation
  - pressure model parameters

PPP Software

- GIPSY-OASIS - developed by the Jet Propulsion Laboratory (JPL)
- NRCan PPP - developed by Natural Resources Canada
- magicGNSS - developed by GMV, Spain
- Bernese Software - developed by Astronomical and the Physical Institutes of the University of Bern, Switzerland
- GAPS – developed by the University of New Brunswick (UNB)
- gLAB Software/ NAPEOS – developed by ESA
- RTKLib – open source software

PPP online Services

Submitting RINEX observation files to website, the data will be processed by those services and then the PPP solution is obtained and sent back

GAPS – GNSS Analysis and Positioning Software
http://gaps.gge.unb.ca/index.html

magicPPP
https://magicgnss.gmv.com/

GIPSY
https://apps.gdgps.net/

AUSPOS – Online GNSS processing service
https://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos

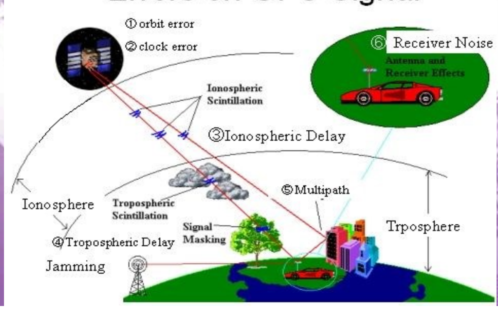
Applications of PPP

Engineering (commercial) and scientific applications

PPP is **feasible** for positioning and navigation in **remote areas** or regions of **low GNSS reference stations**

GNSS Error Sources & Correction Models

Errors on GPS Signal



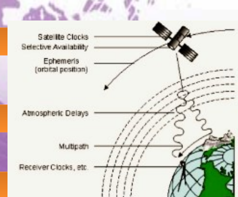
GNSS Errors

GNSS measurements are affected by random and systematic errors which affects the accuracy of measurements

Satellite

Signal Propagation

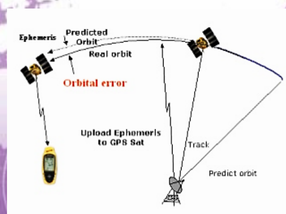
Receiver



Satellite Errors

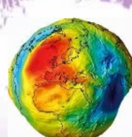
Ephemeris or Orbital error

- Satellite positions are a function of time
- Forces acting on the GPS satellites are not perfect
- Ephemeris errors are differences between true satellite position (real orbit) and position computed using GNSS navigation message (predicted orbit)



Satellite Errors

Forces on GPS satellite



- Earth is not a perfect sphere (or ellipsoid) and hence uneven gravitational potential distribution
- Other space (Astro) bodies attract the satellite, but these are very well modeled
- Not perfect vacuum
- Solar radiation effects (largest unknown error source)

Satellite Errors

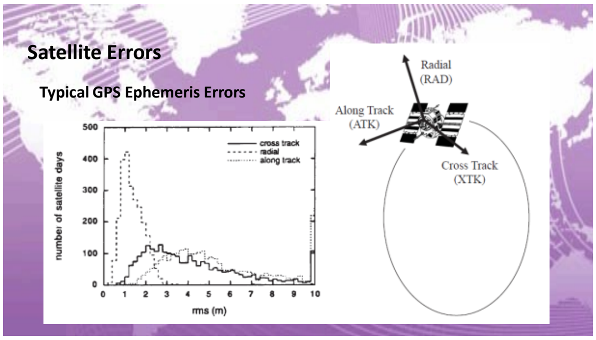
Ephemeris or Orbital error

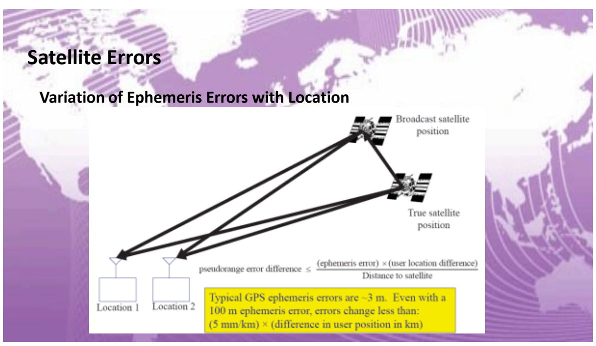
Sources:

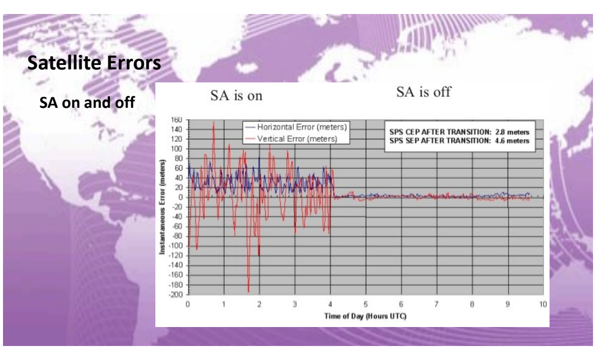
– Selective Availability (SA) (GPS only; this error was never observed and it is now discontinued)
– Control Segment estimation errors
– Age of navigation message data

Estimate ephemeris (orbital) error:

$$\frac{\text{Satellite Position Error}}{\text{Range Satellite}} = \frac{\text{Baseline Error}}{\text{Baseline Length}}$$


Satellite Errors
Typical GPS Ephemeris Errors
number of satellite days
rms (m)
cross track
radial
along track
Radial (RAD)
Along Track (ATK)
Cross Track (XTK)


Satellite Errors
Variation of Ephemeris Errors with Location
Broadcast satellite position
True satellite position
pseudorange error difference ≤ (ephemeris error) × (user location difference) / Distance to satellite
Location 1
Location 2
Typical GPS ephemeris errors are ~3 m. Even with a 100 m ephemeris error, errors change less than: (5 mm/km) × (difference in user position in km)


Satellite Errors
SA on and off
SA is on
SA is off
Horizontal Error (meters)
Vertical Error (meters)
SPS CEP AFTER TRANSITION: 2.8 meters
SPS SEP AFTER TRANSITION: 4.6 meters
Instantaneous Error (meters)
Time of Day (Hours UTC)

Satellite Errors

Satellite and Receiver Clock Errors

- GPS block II and IIA (Legacy satellites) -4 atomic clocks (2-cesium and 2-rubidium)
- Block IIR, IIR-M, IIF (modernized) - Rubidium atomic clocks only
- GPS III satellites (latest modernized) contain Rubidium and Mercury Atomic Frequency Standard clocks.

- Satellite clock error is about 8.64-17.28 nanoseconds per day. The corresponding range error is 2.59-5.18 m

Satellite Errors

Satellite and Receiver Clock Errors

- Satellite clock errors cause additional errors to GPS measurements and are common to all users observing the same satellites

- Can be removed through differencing between the receivers

- Also, by applying the satellite clock correction in the navigation message

Satellite Errors

Satellite and Receiver Clock Errors

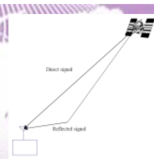
- In contrast, GPS receivers use inexpensive crystal clocks, so the receiver clock error is much larger than the satellite clock error.

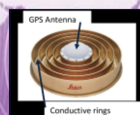
- Can be removed through differencing between the satellites or treating as an additional unknown parameter in the estimation process

Receiver Errors

Multipath

- Signal bounces of a smooth object and hits the receiver antenna
- Significant positional errors result in gravel roads, open water, rock walls, buildings, etc.
- With care, errors can be minimized.
- Multipath seen by two receivers is NOT the same
- The best way to eliminate this error is to construct the observation site with no reflecting surfaces. Another option is to use a chock ring antenna

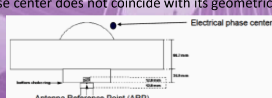




Receiver Errors

Antenna Phase Center Variation

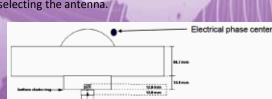
- GPS antenna receives the incoming satellite signal and converts its energy into electric current handled by the GPS receiver
- The point at which the signal is received called **Antenna Phase Center**
- Generally, antenna phase center does not coincide with its geometrical center (Antenna Reference point)



Receiver Errors

Antenna Phase Center Variation

- Antenna phase center varies depending on elevation, azimuth of GPS satellite and signal intensity, and antenna type. This results range error.
- The error is in the order of few *cm* depending on antenna type.
- This error can be neglected most of GPS applications
- Care has to be taken when selecting the antenna.

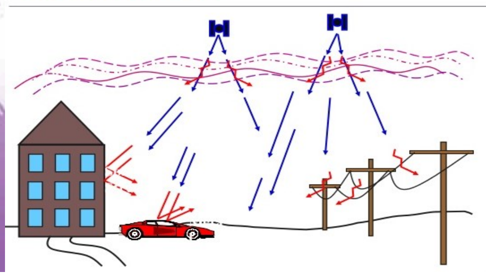


Receiver Errors

Receiver Measurement Noise

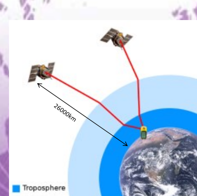
- This results from the limitations of receiver's electronics and a good GPS system should have a minimum noise level.
- Range error due to the receiver measurement noise is of the order of 0.6m, and depending very much on the quality of the GPS receiver.

Signal Propagation or Atmospheric Refraction Errors



Ionosphere

- The upper part of the Earth's atmosphere (50-1000 km). There, ultraviolet and X-ray radiations coming from Sun interact with gas, molecules and atoms resulting gas ionization.
- Electron density is not constant and divided into sub regions/layers vary with time
- Dispersive medium (bend and change speed)



Ionosphere

Ionospheric Refraction

$$\Delta^{Iono} = -\frac{40.3}{f^2} TEC \quad \text{in meters}$$

The TEC is given in TEC units (TECU)

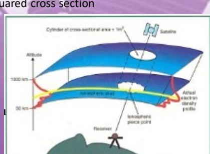
$$1\text{TECU}=10^{16} \text{ electrons per } m^2$$

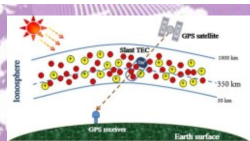
Ex. the delay $\Delta^{\mathrm{Iono}}_{\mathrm{ph}} = 0.18m$ if frequency 1.5GHz and 1 TECU

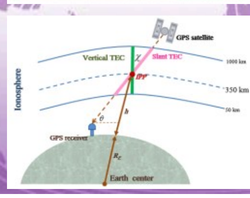
Ionosphere

Total Electron Content (TEC)

TEC is the total number of electrons integrated between two points, along a tube of one meter squared cross section



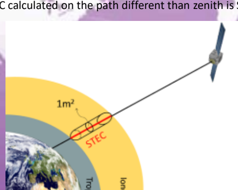


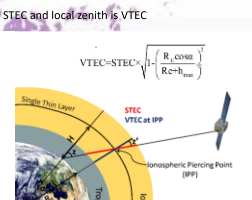


Ionosphere

Slant & Vertical Total Electron Content (STEC & VTEC)

TEC calculated on the path different than zenith is STEC and local zenith is VTEC



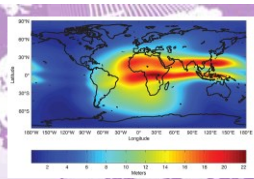


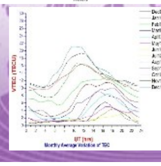
Ionosphere

Total Electron Content (TEC)

TEC depends on number of factors:

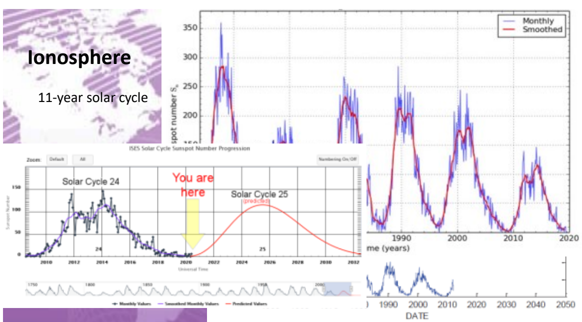
- The time of the day (max in early afternoon and min around midnight)
- The time of the year (higher in winter than in summer)
- The 11-year solar cycle (reach a max value approx. every 11 years)
- The Geographic location (minimum in mid latitude regions and highly irregular in polar and equatorial regions)





Ionosphere

11-year solar cycle



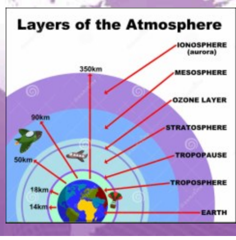
Ionosphere

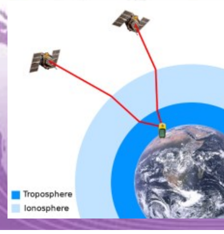
Eliminating the effect of TEC

- Ionospheric modelling (global and local).
- It is difficult to find a satisfying model for the TEC because of the various time-dependent influences.
- The most efficient method is the Elimination of TEC using linear combination of dual frequency measurements (L1 & L2)

Troposphere

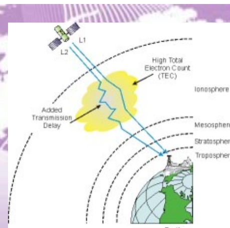
The lowest layer of the atmosphere next to the Earth surface (up to 14km)





Tropospheric Delay

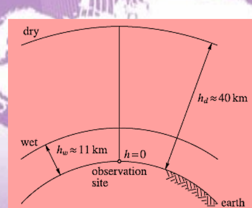
- Tropospheric delays are a factor of atmospheric pressure, temperature and humidity.
- Electrically neutral atmospheric region which means non-dispersive medium w.r.t to frequencies < 15 GHz. So, the propagation is frequency independent. It delays the GPS carrier and codes identically.
- Elimination of the tropospheric refraction by dual-frequency methods is not possible



The effect of the neutral atmosphere (i.e., the nonionized part) is denoted as tropospheric refraction, tropospheric path delay, or simply tropospheric delay.

Tropospheric Delay

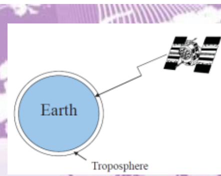
- Tropospheric delays is broken into two components: Dry and Wet
- Dry component results from the dry (hydrostatic) atmosphere and represents 90% of the total delay and can be predicted using mathematical models
- Wet component depends on the water vapour along the GPS signal path - difficult to measure

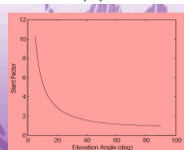


$$N^{\text{Trop}} = N_d^{\text{Trop}} + N_w^{\text{Trop}}$$

Tropospheric Delay

- Vertical delays range from 2-3 m depending on altitude of user and local weather
- Delays for signals along oblique paths may be greater by a factor of 10 for low elevation angles

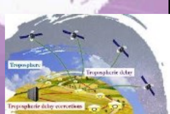




Correcting for Tropospheric Errors

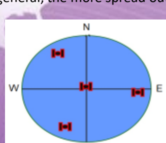
Many correction models:

- Simplest:
  - Use global average weather conditions to determine vertical tropospheric error
  - Apply altitude correction and elevation angle scale factor
  - Residual errors ~25 cm for overhead satellite
- More complicated:
  - Use average local weather (e.g., pressure, temperature, humidity) determined from table lookup
  - Apply altitude correction and elevation angle scale factor
  - Residual errors ~5 cm for overhead satellite
- Most complicated:
  - Use meteorological sensors
  - Residual errors ~3 cm for overhead satellite



Satellite Geometry Measures

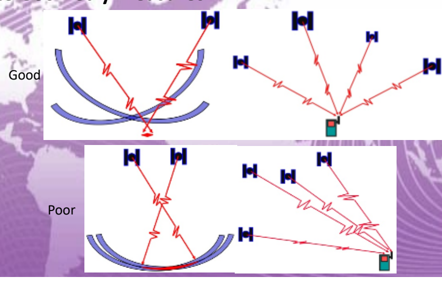
- The overall positioning accuracy of GPS is measured by the combined effect of the unmodeled measurement errors and the satellite geometry
- In general, the more spread out the satellites in the sky better the satellite geometry



Ideal satellite geometry

Poor satellite geometry

Satellite Geometry Measures



Satellite Geometry Measures

- Satellite geometry can affect the quality of GPS signals and accuracy of receiver trilateration
- Dilution of Precision (DOP) reflects each satellite's position relative to the other satellites. The lower the value of the DOP , the better the geometric strength.
- DOP is computed based on the relative receiver-satellite geometry at any instance that requires the receiver and satellite coordinates.
- DOP changes due to movement of satellites (rising or falling) and obstruction between the receiver and the satellite
- GPS receivers can pick best satellites which provide better geometry

Dilution of Precision

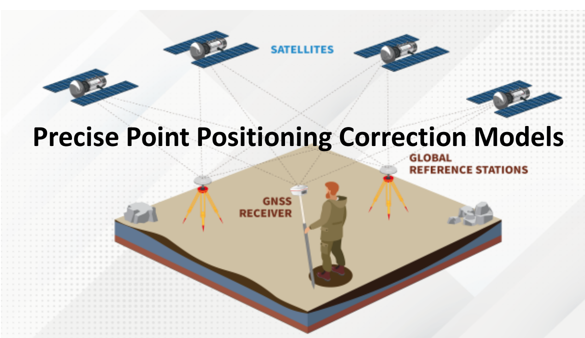
PDOP – Position Dilution of Precision **(commonly used)**
HDOP – Horizontal Dilution of Precision
VDOP – Vertical Dilution of Precision
TDOP – Time Dilution of Precision
GDOP – Geometric Dilution of Precision

- PDOP represents the contribution of satellite geometry to the 3-D positioning accuracy
- PDOP -> (HDOP+VDOP) – satellite geometry effect of horizontal and vertical component accuracy.

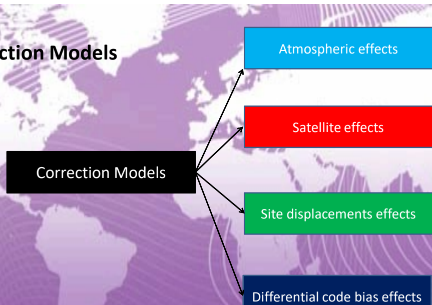
Dilution of Precision

How to check?

QUALITY	PDOP
Very Good	*1-3*
Good	*4-5*
Fair	*6*
Suspect	*>6*



Correction Models



Atmospheric Effects

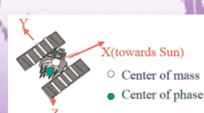
- The propagation of electromagnetic waves needs to be taken into account in precise positioning
- First-order ionospheric effect can be mitigated using the dual-frequency linear combination of ionospheric-free GNSS observables. The higher-order ionospheric effects need to be included into the PPP measurements models
- For tropospheric delay effects, separately account for the hydrostatic (dry) and wet components of the ZTD
- Dry component can be accurately computed from surface pressure, station latitude and height, while the wet one is estimated from the data

Satellite Effects

Satellite Antenna offsets

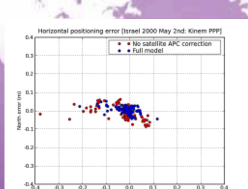
Separation between the satellite center of mass and the phase center of its antenna

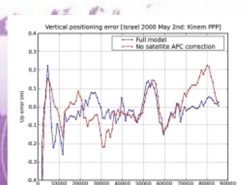
- Force models used for satellite orbit modeling, IGS precise satellite coordinates and clock products refer to the satellite center of mass
- The orbit ephemerides in the GPS broadcast navigation message refer to the satellite antenna phase center



Satellite Effects

Satellite Antenna offsets

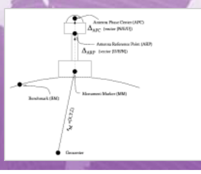


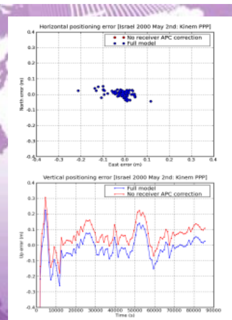


Satellite Effects

Receiver Antenna Phase Center (APC)

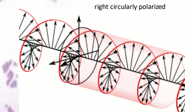
The manufacturers provide technical information on the APC position relative to the ARP





Satellite Effects

Phase wind-up correction



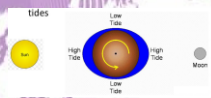
- GNSS satellites transmit Right Hand Circularly Polarized (RHCP) radio waves and therefore, the observed carrier phase depends on the mutual orientation of the satellite and receiver antennas
- Rotation of either receiver or satellite antenna will change the carrier-phase up to one cycle (one wavelength) – phase wind-up effect
- Receiver antenna – fixed (static)-usually north
- Satellite antennas undergo slow rotations as their solar panels are being oriented towards the Sun
- IGS ACs (IGS orbit/clock combined products) apply this phase wind-up correction

Site Displacements effects

- Station undergoes periodic movements (real or apparent) reaching a few *dm* that are not included in the corresponding International Terrestrial Reference Frame (ITRF)
- Most of the periodical station movements are nearly the same over broad areas of the Earth, they nearly cancel in relative positioning over short (<100 km) baselines and thus need not be considered
- However, must considered for solutions consistent with the current ITRF conventions by using a PPP un-differenced approach or a relative positioning approach over long baselines (> 500 km)
- Should add the site displacement correction terms to the regularized ITRF coordinates

Site Displacements effects

Solid earth tides

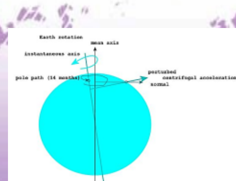


- The periodic vertical and horizontal site displacements caused by tides (due to gravitational forces)
- Consists of a latitude dependent permanent displacement and a periodic part (semi diurnal and diurnal)
- The periodic part is averaged out for static positioning over a 24-h period. The permanent part remains
- Differential (relative) positioning over short baseline (<100km) unaffected

Site Displacements effects

Rotational deformation due to polar motion (polar tides)

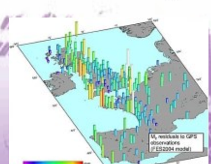
Changes of the Earth's spin axis with respect to Earth's crust, polar motion, causes periodical deformations in the Earth centrifugal potential - *cause periodical station position displacements*



Site Displacements effects

Ocean loading

- Ocean loading is similar to solid Earth tides
- Results from the load of the ocean tides on the underlying crust. Diurnal and semi diurnal periods
- Magnitude of displacement is smaller than solid Earth tides
- More localized, no permanent part & can neglected for stations far from the oceans (> 1000 km)



Differential Code Biases effects

- Systematic errors, or biases, between two GNSS code observations at the same or different frequencies. Required for code-based positioning of GNSS receivers.
- Precise clock products have been generated with the same types of observations, measurements biases are not considered
- If the dual-frequency combined observation in different types of signals, e.g., L2 P(Y)-code and L1 C/A-code, an additional term (Differential Code Bias (DCB)) needs to be introduced in order to translate the satellite clock offset and make it compatible with the employed observations

IGS Formats

IGS Data/product formats

Format name	IGS Product/Sampling	Sampling
RINEX	GNSS Data	30 s
RINEX Clock	Sat. / Station Clock	30 s / 5 min
sp3	Orbits / Clocks	15 min
IGS ERP Format	IGS ERP	1 day
SINEX	Station Pos. / ERP	7 days / 1 day
SINEX Bias	GNSS biases	5 min
SINEX-tropo ext.	Tropo. ZPD	2 h/5 min
IONEX	Iono. maps/Sat DCB	2 h
ANTEX	Ant. Calibr.	-
Site log	Site installation history	-

https://igs.org/formats-and-standards/

Access to Products

GPS Satellite Ephemerides (Orbits) / Satellite & Station Clocks:

ftp://cddis.gsfc.nasa.gov/gnss/products/
ftp://igs.ensg.ign.fr/pub/igs/products/
ftp://gssc.esa.int/gnss/products/
ftp://lox.ucsd.edu/pub/products/

Orbits in files end in *.sp3.Z and the clocks in files end in *.clk.Z

More information on:
https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/clock_products.html
https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/orbit_products.html

Access to Products

Geocentric Coordinates of IGS Tracking Stations

IGS Combined and Analysis Center Position products (positions and velocities) can be found in the standard product directories with filenames that end in *.snx.Z. The station positions and velocity files are stored in Solution Independent Exchange (SINEX) format.

More information on:

https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/station_position_products.html

Access to Products

Earth Rotation

All Earth Rotation products (Ultra-Rapid, Rapid, Final) can be found in the standard product directory having filenames that end in *.erp.Z ;

More information on:

https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/orbit_products.html

Access to Products

Atmospheric Parameters

Final IGS station tropospheric zenith path delay with N, E gradients;

ftp://cddis.gsfc.nasa.gov/gnss/products/troposphere/zpd/
ftp://igs.ensg.ign.fr/pub/igs/products/troposphere/
ftp://gssc.esa.int/gnss/products/troposphere_zpd/

Final Analysis Center station tropospheric zenith path delay with N, E gradients can be found in the product directories having filenames that end in *.tro.Z ;

ftp://cddis.gsfc.nasa.gov/gnss/products/troposphere/sub/
ftp://gssc.esa.int/gnss/products/

Access to Products

Atmospheric Parameters

Rapid and Final ionospheric TEC grid;

ftp://cddis.gsfc.nasa.gov/gnss/products/ionex/
ftp://igs.ensg.ign.fr/pub/igs/products/ionosphere/
ftp://gssc.esa.int/gnss/products/ionex/

More information on:

https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/atmospheric_products.html

Access to Products

Atmospheric Parameters

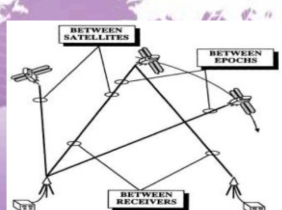
Rapid and Final ionospheric TEC grid;

ftp://cddis.gsfc.nasa.gov/gnss/products/ionex/
ftp://igs.ensg.ign.fr/pub/igs/products/ionosphere/
ftp://gssc.esa.int/gnss/products/ionex/

More information on:

https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/atmospheric_products.html

Linear combinations of Observations



Linear Combinations and Derived Observables

- Both observables (carrier phases and code phases) lead to pseudoranges
  - Code pseudorange measurements are unambiguous, but noisy
  - Carrier phase measurements are very precise, but include integer cycle ambiguity
- Advantage to use all observables, or their linear combinations, in the parameter estimation process
- Unlimited number of possibilities exists, to combine the different observables, and to form derived observables

Differencing Techniques

Meaningful combinations are:

- between observations at different stations (receivers)
- between observations of different satellites
- between observations at different epochs

Advantage:
- Errors that are present in the original observations are eliminated or reduced
- ambiguities of derived observations are easier to solve

Disadvantage:
- Noise level may be considerably increased on combination

Single Differencing

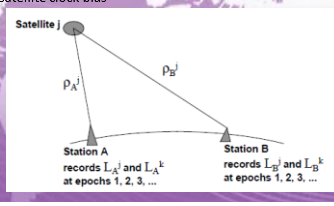
Can be formed between:

- Two receivers
- Two satellites
- Two epochs

Single Differencing

Receiver single differences

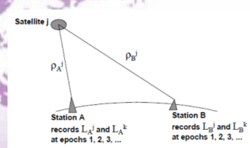
- to eliminate satellite clock bias



Single Differencing

Receiver single differences

$$L_A^j = \rho_A^j + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j$$
$$L_B^j = \rho_B^j + c\tau_B - c\tau^j + Z_B^j - I_B^j + B_B^j$$



$$\begin{aligned}\Delta L_{AB}^j &\equiv L_A^j - L_B^j \\ &= \left(\rho_A^j + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j\right) - \left(\rho_B^j + c\tau_B - c\tau^j + Z_B^j - I_B^j + B_B^j\right) \\ &= \left(\rho_A^j - \rho_B^j\right) + \left(c\tau_A - c\tau_B\right) - \left(c\tau^j - c\tau^j\right) + \left(Z_A^j - Z_B^j\right) - \left(I_A^j - I_B^j\right) - \left(B_A^j - B_B^j\right) \\ &= \Delta\rho_{AB}^j + c\Delta\tau_{AB} + \Delta Z_{AB}^j - \Delta I_{AB}^j + \Delta B_{AB}^j\end{aligned}$$

Single Differencing

Receiver single differences

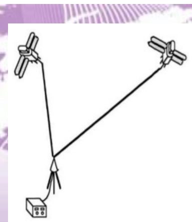
$$\Delta L_{AB}^j = \Delta\rho_{AB}^j + c\Delta\tau_{AB} + \Delta Z_{AB}^j - \Delta I_{AB}^j + \Delta B_{AB}^j$$

- Satellite clock bias is effectively identical
- The atmospheric delay terms are now considerably reduced, and vanish. Also orbital errors.
- The differential troposphere can usually be ignored for horizontal separations less than approximately 30 km
- The differential ionosphere can usually be ignored for separations of 1 to 30 km, depending on ionospheric conditions.
- Disadvantage is that only relative position can be estimated. Also receiver clock bias is still unknown, and very unpredictable.

Single Differencing

Satellite single differences

- The observations of two satellites simultaneously recorded at a single station are differenced
- the receiver clock term cancels

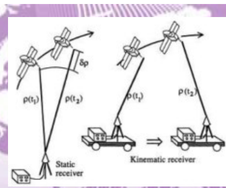


$$\Delta L_A^{jk} = (\rho_A^j - \rho_A^k) + (c\tau_A - c\tau_A) + (c\tau^j - c\tau^k) + (Z_A^j - Z_A^k) - (I_A^j - I_A^k) - (B_A^j - B_A^k)$$
$$= \Delta\rho_A^{jk} + c\Delta\tau^{jk} + \Delta Z_A^{jk} - \Delta I_A^{jk} + \Delta B_A^{jk}$$

Single Differencing

Single differences between two epochs

Frequency at GPS receiver is different than that of transmitted by the satellite due to Doppler effect

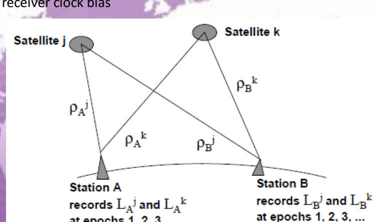


difference between the frequency of the radiation received at a point and the frequency of the radiation at its source, when observer and source are moving with respect to each other (e.g. NGS, 1986)

With single differences between two epochs for the same satellite, the ambiguity term, *N* cancels because the initial phase ambiguity does not change with time (as long as no cycle slips occur)

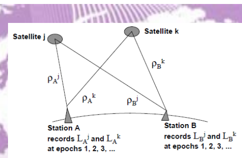
Double Differencing

- To eliminate receiver clock bias



Double Differencing

The single differenced observation equations for two receivers *A* and *B* observing satellites *j* and *k*:

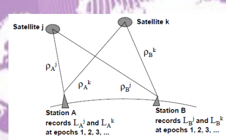


$$\Delta L^j_{AB} = \Delta\rho^j_{AB} + c\Delta\tau_{AB} + \Delta Z^j_{AB} - \Delta I^j_{AB} + \Delta B^j_{AB}$$
$$\Delta L^k_{AB} = \Delta\rho^k_{AB} + c\Delta\tau_{AB} + \Delta Z^k_{AB} - \Delta I^k_{AB} + \Delta B^k_{AB}$$

The double difference phase is defined as the difference between these two:

$$\begin{aligned}\nabla\Delta L^{jk}_{AB} &= \Delta L^j_{AB} - \Delta L^k_{AB} \\ &= \left(\Delta\rho^j_{AB} + c\Delta\tau_{AB} + \Delta Z^j_{AB} - \Delta I^j_{AB} + \Delta B^j_{AB}\right) - \left(\Delta\rho^k_{AB} + c\Delta\tau_{AB} + \Delta Z^k_{AB} - \Delta I^k_{AB} + \Delta B^k_{AB}\right) \\ &= \left(\Delta\rho^j_{AB} - \Delta\rho^k_{AB}\right) + \left(c\Delta\tau_{AB} - c\Delta\tau_{AB}\right) + \left(\Delta Z^j_{AB} - \Delta Z^k_{AB}\right) - \left(\Delta I^j_{AB} - \Delta I^k_{AB}\right) - \left(\Delta B^j_{AB} - \Delta B^k_{AB}\right) \\ &= \nabla\Delta\rho^{jk}_{AB} + \nabla\Delta Z^{jk}_{AB} - \nabla\Delta I^{jk}_{AB} + \nabla\Delta B^{jk}_{AB}\end{aligned}$$

Double Differencing



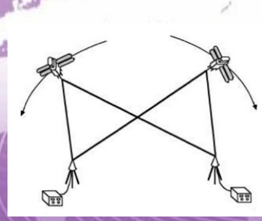
- The receiver clock term vanishes
- free from satellite and receiver clock errors and include only reduced propagation and orbit errors
- The double difference observable is the basic observable in many adjustment models for GPS observations and in many techniques used for the resolution of ambiguities
- Overall, random errors are effectively doubled as compared with the undifferenced observation equation. The motivation for double differencing is to remove clock bias, which would create much larger errors.

Double Differencing

Can be receiver –satellite double differences

Constructed either by:

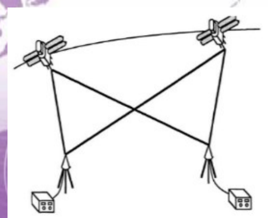
- Taking 2 between receiver single difference observables involving the same pair of receivers but different satellites
- Taking 2 between satellite single difference observables, involving the same pair of satellites but different receivers
- Two results are identical



Double Differencing

Or receiver –time double differences

- Change from one epoch to the next between receiver single difference for the same satellite
- Allows editing cycle slips



Double Differenced Ambiguity

Additional advantage is that the ambiguity is an integer

$$
\begin{aligned}
\nabla\Delta B_{AB}^{jk} &= \Delta B_{AB}^{j} - \Delta B_{AB}^{k} \\
&= \left(B_A^j - B_B^j\right) - \left(B_A^k - B_B^k\right) \\
&= \lambda_0\left(\varphi_{0_A} - \varphi_0^{\,j} - N_A^j\right) - \lambda_0\left(\varphi_{0_B} - \varphi_0^{\,j} - N_B^j\right) - \lambda_0\left(\varphi_{0_A} - \varphi_0^{\,k} - N_A^k\right) + \lambda_0\left(\varphi_{0_B} - \varphi_0^{\,k} - N_B^k\right) \\
&= -\lambda_0\left(N_A^j - N_B^j - N_A^k + N_B^k\right) \\
&= -\lambda_0 \nabla\Delta N_{AB}^{jk}
\end{aligned}
$$

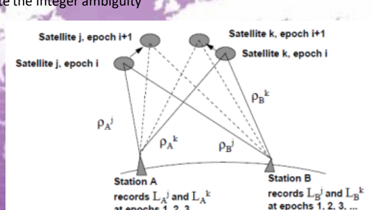
Integer

we can write the double differenced phase observation equation:

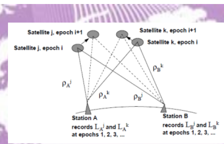
$$\nabla\Delta L_{AB}^{jk} = \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk} - \lambda_0 \nabla\Delta N_{AB}^{jk}$$

Triple Differencing

- to eliminate the integer ambiguity



Triple Differencing



Consider two successive epochs (*i*, *i*+1) of double differenced data from receivers *A* and *B* observing satellites *j* and *k*:

$$\nabla\Delta L_{AB}^{jk}(i) = \nabla\Delta\rho_{AB}^{jk}(i) + \nabla\Delta Z_{AB}^{jk}(i) - \nabla\Delta I_{AB}^{jk}(i) - \lambda_0 \nabla\Delta N_{AB}^{jk}$$

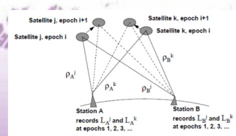
$$\nabla\Delta L_{AB}^{jk}(i+1) = \nabla\Delta\rho_{AB}^{jk}(i+1) + \nabla\Delta Z_{AB}^{jk}(i+1) - \nabla\Delta I_{AB}^{jk}(i+1) - \lambda_0 \nabla\Delta N_{AB}^{jk}$$

The triple difference phase is defined as the difference between these two:

$$\delta(i,i+1)\nabla\Delta L_{AB}^{jk} \equiv \nabla\Delta L_{AB}^{jk}(i+1) - \nabla\Delta L_{AB}^{jk}(i)$$
$$= \delta(i,i+1)\nabla\Delta\rho_{AB}^{jk}(i) + \delta(i,i+1)\nabla\Delta Z_{AB}^{jk}(i) - \delta(i,i+1)\nabla\Delta I_{AB}^{jk}(i)$$

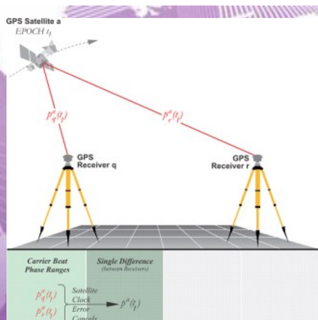
Triple Differencing

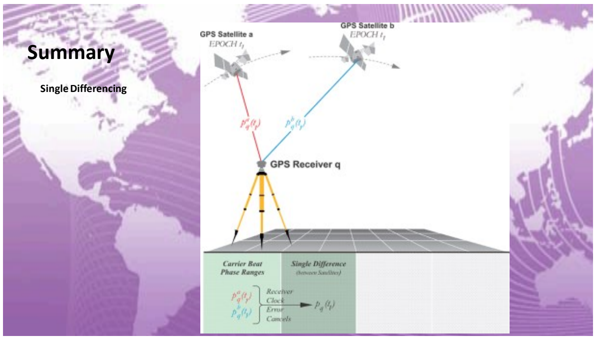
- Integer ambiguity is removed
- Any cycle slips will appear as outliers, and can be removed by conventional techniques (statistical)
- The disadvantage of the triple difference is that it introduces correlations between observations in time (increasing correlations in data has the property of decreasing the data weights)
- Less precise and inappropriate for precise surveys
- The observation equation for triple differences is identical for code and carrier phases

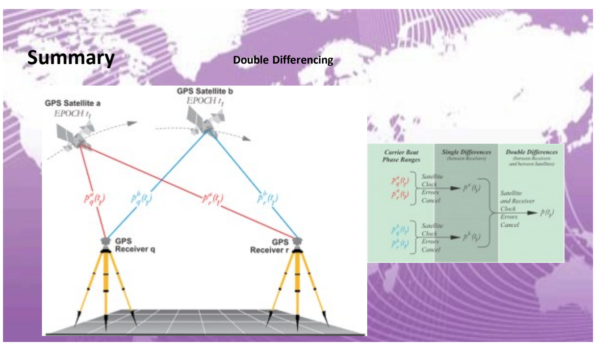


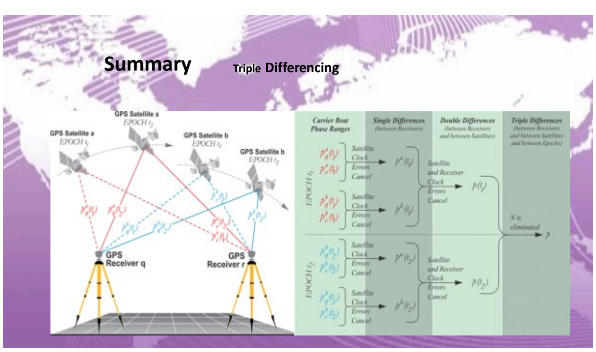
Summary

Single Differencing



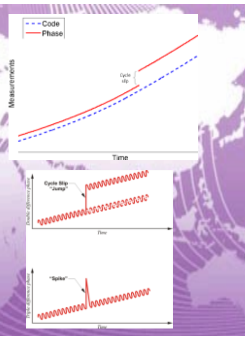

Summary
Single Differencing
GPS Satellite a
GPS Satellite b
GPS Receiver q
Carrier Beat Phase Ranges
Single Difference
Receiver Clock Error Cancels


Summary
Double Differencing
GPS Satellite a
GPS Satellite b
GPS Receiver q
GPS Receiver r
Carrier Beat Phase Ranges
Single Differences
Double Differences


Summary
Triple Differencing
GPS Satellite a
GPS Satellite b
GPS Receiver q
GPS Receiver r
Carrier Beat Phase Ranges
Single Differences
Double Differences
Triple Differences

Cycle Slips

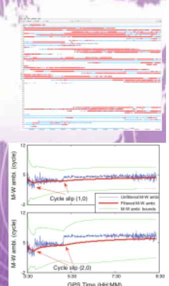
- If the satellite signal is blocked, it cant be tracked anymore.
- When signal is lock again, the fractional part still be the same as if tracking had been continuous.
- However, the integer cycle is discontinuous
- Coded pseudorange measurements are not as affected by cycle slips as are carrier phase measurements



Cycle Slips

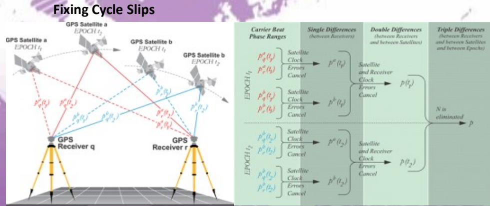
Repairing Cycle Slips

- In post-processing, the location and their size of cycle slips must be determined;
- the data set can be repaired with the application of a fixed quantity to all the subsequent phase observations.
- One approach is to hold the initial positions of the stations occupied by the receivers as fixed, and edit the data manually.
- Another approach is to model the data on a satellite-dependent basis with continuous polynomials to find the breaks and then manually edit the data set a few cycles at a time.
- One of the most convenient of these methods is based on the triple difference. It can provide an automated cycle slip detection system



Cycle Slips

Fixing Cycle Slips



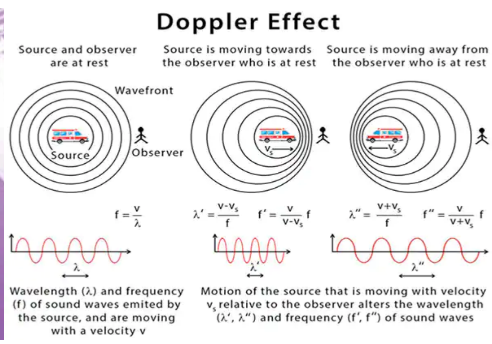
Large residual appears in one of the triple difference's component double differences, it is likely caused by a cycle slip, so the satellite pairs can be sorted until the offending signal is singled-out and repaired.

Doppler Effect

The **Doppler effect** or **Doppler shift** is the change in frequency of a wave in relation to an observer who is moving relative to the wave source.

$$f_o = \frac{v + v_o}{v + v_s} f_s$$

f_o = observer frequency of sound
v = speed of sound waves
v_o = observer velocity
v_s = source velocity
f_s = actual frequency of sound waves



Carrier Phase Ambiguity Resolution

The “Pseudo-range”

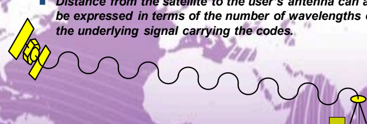
- *Satellite sends binary code*

- *Receiver generates same binary code that it should be hearing from the satellite at a particular time*

- Difference between what it should hear and what it does hear is the time delay
- Range Distance = Time Delay * Speed of Light
- Not the true range; part of the time delay is due to Receiver Clock Offset ~ hence “pseudo-range”

“Carrier Phase” Measurement

- *Distance from the satellite to the user’s antenna can also be expressed in terms of the number of wavelengths of the underlying signal carrying the codes.*



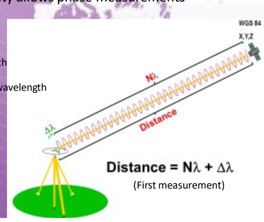
- Wavelength of GPS L1 carrier = 19 cm; L2 carrier = 24 cm
- Fractional part (“phase”) of a given wavelength, can be measured to 1/100 of a wavelength ~ resolution of 2mm;
- Enables position relative to a known point with centimetre accuracy;
- Dual frequency measurements most reliable but accessing L2 carrier signal has required expensive receivers – Will full L2C/L5/L1C signals availability change that?

The “Integer Ambiguity” - N

- The uncertainty of full-number of wavelengths
- Resolving the integer ambiguity allows phase measurements to be related to distance

$\Delta\lambda -$ Partial wavelength

$N\lambda -$ Distance of full-wavelength



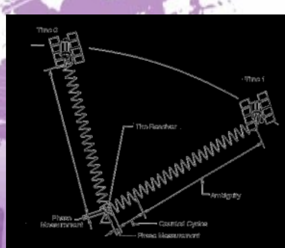
Carrier phase measurement process

- When a receiver is turned on, the fractional part of the phase is observed and an integer counter is initialized
- During signal tracking, the counter is incremented by one cycle whenever the fractional phase changes from 2π to 0
- Thus, at any given epoch, the observed accumulated phase (**Φ**) is the sum of the fractional phase (ϕ) and the integer counter (*n*) along with another term called the **integer ambiguity (N)** – *the number of integer cycles of the carrier that have passed between the satellite and the receiver at the time of initial acquisition*

$$\Phi = \phi + n + N$$

- **Φ** is the total phase, **ϕ** is the fractional initial cycle, **n** is the integer counter and **N** is the **ambiguity**

Carrier phase measurement process



Carrier phase measurement process

- Since **N** is unknown, it needs to be estimated along with the 3-D receiver position in the estimator
- Hence, the solution of **N** revolves around a ***"float"*** value, often close to its true integer value
- To exploit the full potential of the carrier phase measurements, an additional step is required to resolve the float ambiguity estimates to its true integer value. This procedure is known as **ambiguity resolution**.

Ambiguity Resolution – Relative Positioning

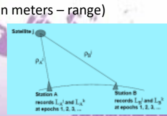
- ✓ **Requirements – Precise Engineering Surveying**
  - 2 stations (baseline), multiple stations (network)
  - Carrier phases from ≥ 4 satellites, then double-differences
  - Use broadcast orbits and clocks
  - Assume values for one station and its clocks
  - Estimate, using weighted least squares, station coordinates, and carrier phase ambiguities
    - ➢ Fix ambiguities to integer values and iterate
  - Achievable precision: < 1cm
    - ➢ or few cm x 10 km using broadcast orbits
  - Can be post-processed or real-time
- ✓ **Process depends on AMBIGUITY RESOLUTION**

Ambiguity Resolution – Relative Positioning

- ✓ **Modeling process**
  - Recall carrier phase observation model (in meters – range)

$$L_A^j = \rho_A^j + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j$$
$$L_B^j = \rho_B^j + c\tau_B - c\tau^j + Z_B^j - I_B^j + B_B^j$$

Carrier phase bias



- Use differencing technique to solve for carrier phase bias

$$\Delta L_{AB}^j = \Delta\rho_{AB}^j + c\Delta\tau_{AB} + \Delta Z_{AB}^j - \Delta I_{AB}^j + \Delta B_{AB}^j$$
$$\Delta L_{AB}^k = \Delta\rho_{AB}^k + c\Delta\tau_{AB} + \Delta Z_{AB}^k - \Delta I_{AB}^k + \Delta B_{AB}^k$$

Two single differenced observations

$$\begin{aligned}\nabla\Delta L_{AB}^{jk} &= \Delta L_{AB}^j - \Delta L_{AB}^k \\ &= \left(\Delta\rho_{AB}^j + c\Delta\tau_{AB} + \Delta Z_{AB}^j - \Delta I_{AB}^j + \Delta B_{AB}^j\right) - \left(\Delta\rho_{AB}^k + c\Delta\tau_{AB} + \Delta Z_{AB}^k - \Delta I_{AB}^k + \Delta B_{AB}^k\right) \\ &= \left(\Delta\rho_{AB}^j - \Delta\rho_{AB}^k\right) + \left(c\Delta\tau_{AB} - c\Delta\tau_{AB}\right) + \left(\Delta Z_{AB}^j - \Delta Z_{AB}^k\right) - \left(\Delta I_{AB}^j - \Delta I_{AB}^k\right) - \left(\Delta B_{AB}^j - \Delta B_{AB}^k\right) \\ &= \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk} + \nabla\Delta B_{AB}^{jk}\end{aligned}$$

Double differenced phase

Ambiguity Resolution – Relative Positioning

- ✓ **Modeling process**
  - Remember:

$$\begin{aligned}\nabla\Delta B_{AB}^{jk} &= \Delta B_{AB}^j - \Delta B_{AB}^k \\ &= \left(B_A^j - B_B^j\right) - \left(B_A^k - B_B^k\right) \\ &= \lambda_0\left(\varphi_{0A} - \varphi_0^j - N_A^j\right) - \lambda_0\left(\varphi_{0B} - \varphi_0^j - N_B^j\right) - \lambda_0\left(\varphi_{0A} - \varphi_0^k - N_A^k\right) + \lambda_0\left(\varphi_{0B} - \varphi_0^k - N_B^k\right) \\ &= -\lambda_0\left(N_A^j - N_B^j - N_A^k + N_B^k\right) \\ &= -\lambda_0\nabla\Delta N_{AB}^{jk}\end{aligned}$$

Integer

  - Each bias $\nabla\Delta B_{AB}^{jk}$ has an integer ambiguity
  - Double difference carrier phase model becomes:

$$\nabla\Delta L_{AB}^{jk} = \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk} - \lambda_0\nabla\Delta N_{AB}^{jk}$$

Ambiguity Resolution – Relative Positioning

✓ **Modeling process**

- Step 1: Least squares "Float" solution

$$\nabla\Delta L_{AB}^{jk} = \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk} - \lambda_0 \nabla\Delta N_{AB}^{jk}$$

  - ➢ Estimate station coordinates, atmospheric delay, and carrier phase ambiguity $\nabla\Delta B_{AB}^{jk}$

- Step 2: Ambiguity resolution
  - ➢ Fix $\nabla\Delta B_{AB}^{jk}$ to nearest integer

- Step 3: Least squares "fixed" solution

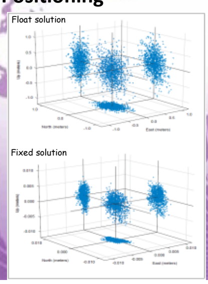
$$\nabla\Delta L_{AB}^{jk} + \lambda_0 \nabla\Delta N_{AB}^{jk} = \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk}$$

Known: ambiguity resolved carrier phase

Ambiguity Resolution – Relative Positioning

✓ **Motivation**

- Resolution of initial phase ambiguity is key to sub-centimeter position accuracy in GPS surveying
- Great precision
- Classical static and rapid-static techniques are used
- Quick initialization requires
  - ➢ Good station-satellite relative geometry
  - ➢ Low observation errors
  - ➢ Reliable algorithum



Ambiguity Resolution – Relative Positioning

✓ **Classical static technique**

- TWO step approach:
  - ➢ First step to estimate station coordinates and real-valued ambiguities
  - ➢ Second step to resolve initial ambiguities to integer values
    - Round real values to nearest integers
    - Use estimated errors to evaluate if resolution to integer is feasible. Ambiguities only fixed if integer value is within an appropriate confidence interval e.g. ±3σ

Ambiguity Resolution – Relative Positioning

✓ **Modern techniques**

Various methods for resolution of ambiguities have been developed and implemented

- Simple Rounding
- Ambiguity Function Method
- Fast Ambiguity Resolution Approach (FARA)
- Least Squares Ambiguity Search Technique
- Fast Ambiguity Search Filter (FASF)
- **Least squares AMBiguity Decorrelation Adjustment (LAMBDA)**

Ambiguity resolution

Success of ambiguity resolution highly depends on

- Quality of modeling
- Estimation process
- Correction of error sources (such as satellite orbit error, atmospheric refraction, multi-path and noise, etc.)

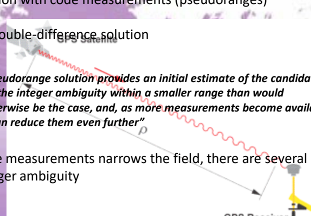
Hence, ambiguity resolution procedure works best on **double-differenced** ambiguity terms

Double-differencing of observations mathematically eliminates the *clock and equipment biases, along with satellite orbit and atmospheric errors*, leaving only the intended integer nature of the ambiguities

The two receivers should be within 20 km of each other in order to maintain the spatial correlation of their observations

Ambiguity resolution

- Initial estimation with code measurements (pseudoranges)
- Subsequent double-difference solution

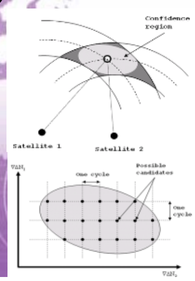


"pseudorange solution provides an initial estimate of the candidates for the integer ambiguity within a smaller range than would otherwise be the case, and, as more measurements become available, it can reduce them even further"

- After the code measurements narrows the field, there are several methods used to solve the integer ambiguity

"Geometric method" of Ambiguity resolution

- The carrier phase data from multiple epochs are processed
- Constantly changing satellite geometry is used to find an estimate of the actual position of the receiver
- Requires a significant amount of satellite motion to succeed, and, therefore, takes time



"Filtering method" of Ambiguity resolution

Independent measurements are averaged to find the estimated position with the lowest noise level

"Search method" of Ambiguity resolution

Search through the range of possible integer ambiguity combinations from which it calculates the one with the lowest residuals

Can provide the probability with certain conditions, that the answer is within given limits

Most GPS receivers use a combination of methods

Nearly all narrow the field by beginning with an initial position established by the code measurements. They then use one or more of methods in combination to come up with the most probable value for the solution of the integer ambiguity

Ambiguity Resolution

- Implications for GPS surveying
  - Increased efficiency resulting from reduced requirement for long data observation sessions (with no loss of precision over short baselines)
  - Kinematic (or RTK with radio link/internet based) surveying now true alternative to total stations
    - Never with poor DOP values
    - Ensure ambiguities are resolved
    - Check during the survey

GNSS Receivers

Objectives

- Recognize the basic functions of the common features of GPS receivers, the antenna, the preamplifier, the RF section, the microprocessor, the CDU, the storage and the power;
- Recognize some of the important issues in choosing a GPS receiver;
- Discuss some of the trends in receiver development;

Common features of GPS receivers

- Many different GPS receivers on the market and they are generally capable of accuracies from sub meter to centimeters.
- Most are also capable of performing differential GPS, real-time GPS, static GPS, etc.,
- Usually accompanied by processing and network adjustment software and so on.
- GPS receivers come in a variety of shapes and sizes
- Most have similar characteristics (common components)

GPS Receiver Schematic

Signal Receiving

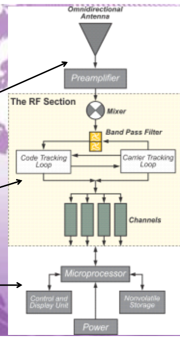
GPS receiver must collect and then convert signals from GPS satellites into measurements of position, velocity, and time. Preamplifier must be efficient since the power received from GPS is low

Signal Processing

Incoming frequency is combined with a signal at a harmonic frequency

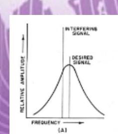
Manage Data collection & Display

Computerized unit that manage data collection, save and display output.



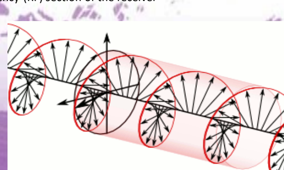
GPS Signal Receiving

- GPS satellite broadcasts its signal across a cone of approximately 28º of arc
- GPS signal has low power
- GPS signal obscured by the variety of electromagnetic noise
- Receiver extract the signal and achieve unambiguous satellite tracking using the correlation techniques
- GPS receiver function cooperatively and iteratively



GPS Antenna

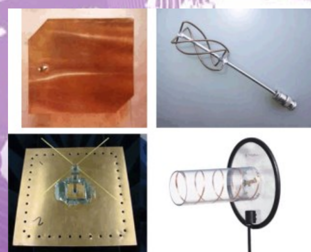
- The antenna collects the satellite's signals and converts the incoming electromagnetic waves into electric currents sensible to the Radio Frequency (RF) section of the receiver
- Several antenna designs are possible in GPS, but antenna efficiency is critical
- GPS antennas must have high sensitivity and high gain
- Designed to collect only the L1 frequency, L1 and L2, or all signals, including L5



Right Hand Circular Polarized Signal

GPS Antenna

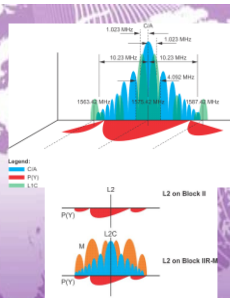
- Wavelengths of the GPS carriers are 19 cm (L1), 24 cm (L2) and 25 cm (L5).
- Antennas that are a quarter or half wavelength tend to be the most practical and efficient. So, GPS antenna elements can be as small as 4 or 5 cm.



Top left: Microstrip patch antenna, Top right: Quadrifilar antenna
Bottom left: Dipole antenna, Bottom right: Helix antenna

GPS Antenna-Bandwidth

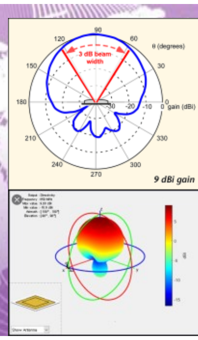
- In general, the larger the bandwidth the better the performance, however, increased bandwidth degrades the signal to noise ratio by including more interference
- L2C signal, like the C/A, has the span of 2.046 MHz
- L5, like the P code, has a bandwidth of 20.46 MHz. L1C signal, its bandwidth would need to be 4.092 MHz
- GPS microstrip antennas operate in a range from about 2 to 20 MHz, so that it is possible to track all of these signals



Power Spectral Density (PSD) Diagrams for L1 and L2

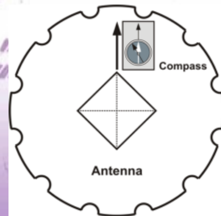
GPS Antenna-Coverage

- Omnidirectional, change in gain (the success of a GPS antenna in collecting more energy from above the mask angle) over a range of azimuths and elevations, nearly a full hemisphere (but not perfectly hemispheric)
- Antenna's gain pattern is specifically designed to reject very low elevation signals
- Equal phase around the antenna's electronic center (phase center), are not perfectly spherical
- A gain of about 3 to 5 *decibels (dB)* is typical for a GPS antenna



GPS Antenna-Orientation

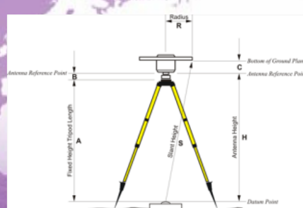
- Antenna phase center is not coincident with its actual physical center (position depends on phase centres at endpoints)
- Phase center changes slightly with the satellite's signal (L1, L2, L5, etc.). In addition, azimuth, intensity, and elevation of the received signal change phase center
- It is fortunate that the phase center shifts are systematic
- To compensate for some of this offset error, antennas are all oriented in the same direction (North) when making simultaneous observations on a network of points



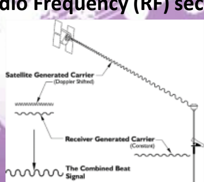
Antenna Oriented to North

Height of Instrument

- Most easily avoided errors
- Correction to be added to make measurement up to the phase center of the antenna
- When Using CORS stations, it is also necessary to know the height of the antenna (available along with the files from the base station)



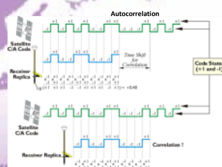
Radio Frequency (RF) section



Incoming frequency is combined with a signal at a harmonic frequency (receiver generated signal)

The two frequencies are multiplied together in a device known as a *mixer*

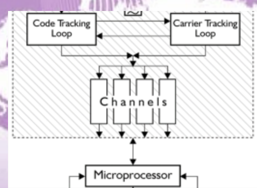
Autocorrelation



Two frequencies emerge and then go through a *bandpass filter,* which removes the unwanted high frequencies and noise from the signal

Results is *intermediate frequency (IF),* or beat frequency signal

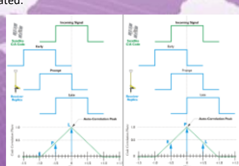
Channels



- Signals from several satellites enter the receiver simultaneously
- Signals are identified and segregated from one another by the *channels* of the RF section
- Channel is hardware, or a combination of hardware and software, designed to separate one signal from all the others (6 channels, 12 channels, or hundreds of channels)
- Frequency from one satellite can have its own dedicated channel, and the channels operate in parallel.
- Once the signal is acquired, it is continuously tracked unless lock is lost.

Tracking loops

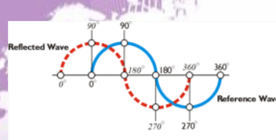
- Dual/multiple frequency receivers have dedicated channels and tracking loops for each frequency. Codes and Carrier tracking loops.
- Code it is generating until the optimum correlation is found between satellite broadcast and receiver generated.



- The incoming signal is in the green at the top.
- The receiver replica is in blue.
- When it is prompt, the replica and the incoming signal are correlated

Tracking loops

- Code's pseudoranges, alone, are not adequate for the majority of applications.
- Next step in signal processing for most receivers involves the carrier phase observable



- Foundation of carrier phase measurement is the mixing the satellite's signal with the replica carrier
- The receiver selects the appropriate beat-frequency with a bandpass filter
- This is basically how a GPS receiver locks on to that carrier and stays locked unless there is a loss of signal or a cycle slip

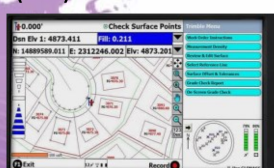
The Microprocessor

- The microprocessor in a GPS receiver is the computer that manages data collection and is the home of the applications
- It controls the entire receiver: the digital circuits, the tracking and measurements
- Produce the position in real time, or near real-time by processing the ranging data, doing reference frame (datum) conversion, and sending the position to the control and display unit (CDU).

GPS Board

Control and Display Unit (CDU)

- GPS receiver will often have a control and display unit
- Facilitate the interaction between the operator and the receiver's microprocessor
- CDU displays status, position data, velocity, DOP
- and time (GPS time or UTC),



- Used to select different surveying methods, waypoint navigation, and/or set parameters such as epoch interval, mask angle, and antenna height.
- CDU varies from receiver to receiver

Storage

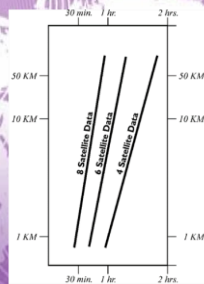
- Most GPS receivers today have internal data logging
- Storage required for a particular session depends on the **length of the session**, the number of satellites above the horizon, the epoch interval, etc.
- Data can be stored in USB or sent to the cloud

Static Session length

- session's duration primarily depends on length of the baseline and satellite geometry

  larger the constellation of satellites, the better the available geometry, the lower the positioning dilution of precision (PDOP), and the shorter the length of the session needed to achieve the required accuracy

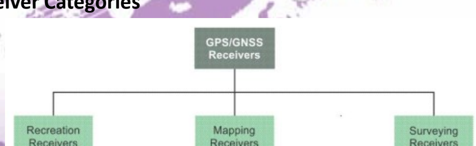
- 8 satellites and 10 km baseline – ½ to 1 hour
- 6 satellites (good geometry) and 10 km baseline – 45 minutes to 1 hour
- 4 satellites and 10 km baseline – 1 to 2 hours



The Power

- GPS receivers operate at low power (9-36 volts DC)
- GPS carrier phase receivers have an internal power supply. Operate 5½ hours or longer on fully charged 6-amp-hour battery. 15 hours without carrier phase observables
- Variety of batteries: Lithium, Nickel Cadmium, and Nickel Metal-Hydride
- Lithium–ion batteries overcome several of the limitations of the others

Receiver Categories



Generally, **single frequency** (C/A code only on L1, L1 carrier phase tracking receivers), **dual-frequency** and **multi-frequency** carrier phase tracking receivers

Receiver Categories

Recreational receivers	Autonomous Horizontal **Precision**	Real-time Corrected Horizontal Network Accuracy	Post-processed Horizontal Network Accuracy
Mapping Receivers	Autonomous Horizontal **Precision**	Real-time Corrected Horizontal Network Accuracy	Post-processed Horizontal Network Accuracy
Mapping (L1 Code)	2 - 10m	0.5 - 5m	0.3 - 15m
Mapping (L1 Code & Carrier)	2 - 10m	0.5 - 3m	0.2 - 1m
Survey Receivers	Autonomous Horizontal **Precision**	Real-time Corrected Horizontal Network Accuracy	Post-processed Horizontal Network Accuracy
Survey	2 - 10 m	> 1 m	> 0.1 m

GNSS Applications

- Agriculture
- Aviation
- Environment
- Marine
- Public safety & disaster relief
- Railway
- Recreation
- Roads & Highways
- Space
- Surveying & Mapping
- Structural monitoring (dams, buildings, etc.)
- Timing

More information: https://www.gps.gov/applications/