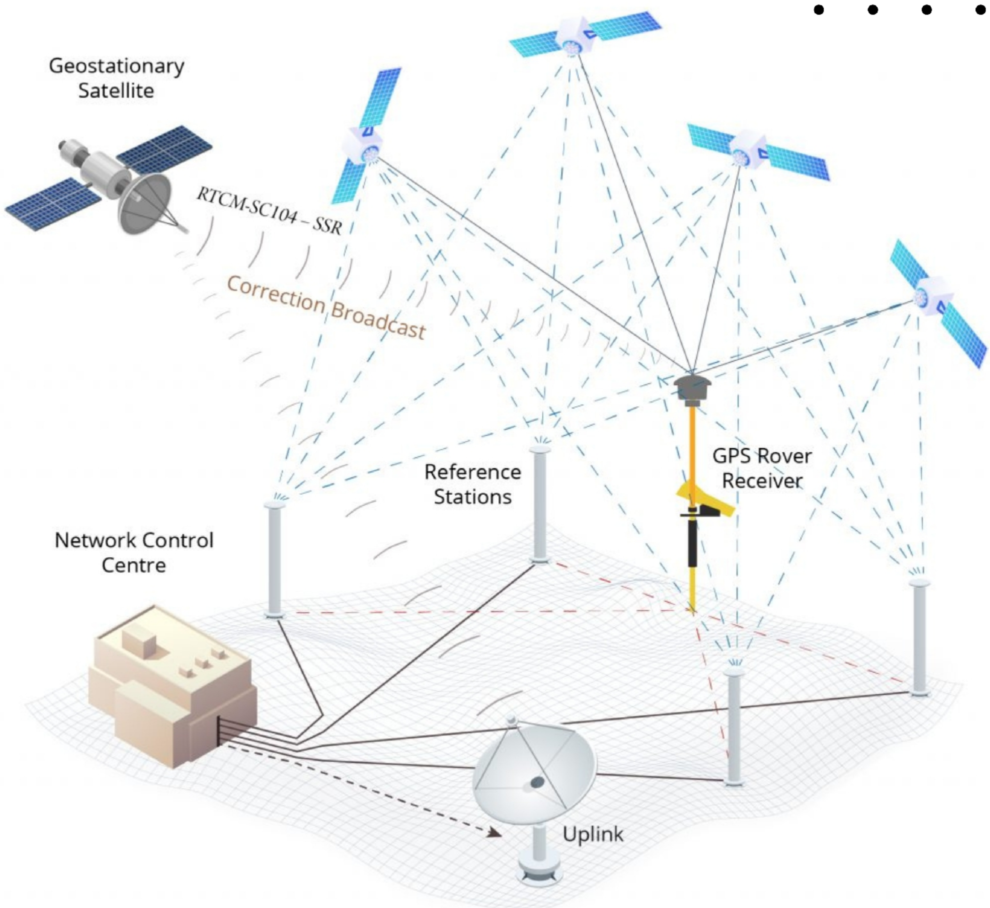
BSc Surveying Sciences
Year II Semester II
Department of Surveying & Geodesy
Faculty of Geomatics
Sabaragamuwa University of Sri Lanka 70140 Belihuloya

COURSE MATERIAL :

FUNDAMENTALS OF SATELLITE BASED POSITIONING & NAVIGATION



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

COURSE OUTLINE

Course	:	**FC 22238 – Fundamentals of Satellite Based Positioning & Navigation**
Programme	:	**BSc in Surveying Sciences – Foundation Course**
Department	:	**Surveying & Geodesy**
Faculty	:	**Faculty of Geomatics**
Contact Hours	:	**150**
Credits	:	**03**
Year	:	**II**
Semester	:	**II**
Synopsis	:	This course introduces students the fundamental aspects of Satellite Based Positioning & Navigation, and is meant for students entering the industry as well as interested in pursuing higher studies in Global Navigation Satellite System (GNSS). This module explains the theoretical and essential practical understanding of the use of GNSS to obtain a position on Earth required by diverse fields related to Earth observation Science.

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

No.	Course Learning Outcome	Programme Outcome	Assessment Methods
1.	Describe the basic concepts of Global Navigation Satellite Systems (GNSS) and how they are used for positioning on Earth. Describe the main components of a satellite navigation system and their functionality.	**P01, P02, P03 & P05**	Multiple Choice quizzes & Final Exam
2.	Understand how traditional surveying principles are applied in GNSS positioning. Explain the principles of trilateration (in 2D) used in GNSS based positioning	**P01, P02, P03 & P05**	Multiple Choice quizzes & Final Exam
3.	Identify GNSS satellites and understand the signal structures used in GNSS systems. Explain how the receiver determines the identity and location of each satellite using navigation messages and signal-matching.	**P01, P02, P03, & P05**	Multiple Choice quizzes &Final Exam
4.	Explain the process for estimating pseudorange using PRN code synchronization. Explain how estimated positions are calculated using pseudorange (trilateration in 3D).	**P01, P02, P03, & P05**	Multiple Choice quizzes & Final Exam
5.	Understand how the physical properties of radio waves are used to improve the precision of pseudorange estimation. Describe the use of wavelengths for precise distance measurement. Explain the use of phase measurement and integer count to obtain precise distance from receiver to the satellite	**P01, P02, P03, &P05**	Multiple Choice quizzes &Final Exam

6.	Describe different potential error sources in GNSS operation and how they are mitigated. Describe the multiple error sources Explain the need of extended observation time to increase the accuracy of GNSS-deduced position	**P01, P02, P03, &P05**	Multiple Choice quizzes &Final Exam
7.	Explain the mathematical concept of differencing (single and double) to mitigate the errors Explain the use of continuous GNSS active relative positioning (CORS) and GNSS Augmentation	**P01, P02, P03, P05, P10 & P11**	Multiple Choice quizzes &Final Exam
8.	Explain the process of converting between Cartesian coordinates and positions in an ellipsoid and orthometric reference frame Explain a reference frame (Datum) and how it is used in GNSS Explain the process of converting between Cartesian coordinates (X,Y,Z) and positions (latitude, longitude, ellipsoid height). Explain why the impotence of the conversion of heights from an ellipsoid to an orthometric reference frame.	**P01, P02, P03 & P05**	Multiple Choice quizzes &Final Exam
9.	Explain the applications of GNSS based positional measurements in land and hydrographic surveying, Geodesy Remote Sensing, GIS and related fields Describe the advanced process of GNSS and Its Applications	**P01, P02, P03, P06, P10 & P011**	Final Exam

10	Ability to apply the knowledge and skills to conduct GNSS observations in the field to determine the position for land surveying and relevant applications. Use different GNSS positioning methods for establishing a geodetic control network and topographic surveys. Ability to use the techniques and skills to understand the modernizations in the field of GNSS and to flexibly adopt to them.		Field and Lab practical reports / presentations

STUDENT LEARNING TIME (SLT)

TEACHING METHODOLOGY

Lectures
Multiple Choice quize / Assignments if necessary
Field and lab reports
Group presentations

WEEKLY SCHEDULE

Week 1	**1.0 Introduction to Principles of Global Satellite Navigation** 1.1 Introduction to GNSS 1.2 History and Traditional Surveying Principles in GNSS Positioning 1.3 Concepts of Trilateration in Two Dimensions

	1.4 Mathematical solution of Trilateration (Using Least Squares) 1.5 How Trilateration works with GNSS 1.6 Segments of GNSS
Week 2	**2.0 GNSS Computational Methods I – Pseudorange measurements** 2.1 Identifying the Satellite and Its Position 2.2 Satellite Orbital Information: Ephemerides 2.3 Using Signal-Matching to Identify and Lock onto a GPS Satellite 2.4 Determining the Pseudorange from the Satellite using
Week 3	2.5 Pseudorange: Definition and Limitations 2.6 Estimating the Position from Pseudoranges 2.7 Mathematical Solution of Trilateration in Three Dimensions (Using Least Squares)
Week 4	**3.0 GNSS Computational Methods II – Carrier Phase measurements** 3.1 The Role of Signal Wavelength 3.2 Estimating the Range based on GPS "Carrier" Frequencies 3.3 How GPS Information is Encoded in the GPS Signal
Week 5/6	3.5 Computation of GPS Wavelengths 3.6 Phase Measurement 3.7 Counting the Number of Signal Cycles (The Doppler Effect) 3.8 The Role of Combining Wavelengths in Signal Processing
Week 6/7	**4.0 GNSS Positioning and Error Sources** 4.1 GPS Satellite and Receiver Clock Errors 4.2 Ionospheric Delay 4.3 Satellite Orbital Errors 4.4 Tropospheric Error 4.5 Multipath Errors
Week 8	4.6 Increasing Accuracy with Increased Observation Time 4.7 Differencing techniques 4.8 Role of Continuous GNSS Active-Relative Positioning Systems such as CORS and VRS 4.9 GNSS Augmentation 4.10 Methods of GNSS positioning (Static, RTK, PPK, Network RTK, Stop and Go)
Week 9	**5.0 Converting GNSS Raw Data into Position** 5.1 Limitations of GPS Positions in an X, Y, Z Coordinate System 5.2 Expressing Positions in an Ellipsoid Model 5.3 Expressing Positions in an Orthometric Reference Surface

Week 10/11	**6.0 Augmentation Systems and Differential GNSS (DGNSS)** 6.1 Global and Local Augmentation Systems 6.2 Differential and Relative GNSS-Based Positioning
Week 12	**7.0 Applications of GNSS and the Role it plays in Sustainable Development** 7.1 Application of GNSS for Land Surveying, GNSS Levelling 7.2 Use of GPS/GNSS for Civil Applications (Navigation)
Week 13/14	**8.0 GNSS Data Processing** 8.1 Introduction to raw GNSS data file structure 8.2 Post-Processing of GPS Location Data using online services 8.3 Hands-on Lab Session using RTKLIB Software 8.4 Processing Sample GNSS Data
Week 15	**10.0 Open Discussion of GNSS in basic applications and GNSS Modernization (Students Presentations)**
Week 16 – 17	**Self-learning and Exam preparation**

GNSS data collection and processing (Land Surveying practical …….GEOP 03):

No. of Hours	Practical Task

06 hours	**2. Basic Measurements with GNSS** 2.1 Basic measurements with different available GNSS receiver types. 2.2 Understand the practical and functional capabilities of different available GNSS receiver types.
18 hours	**3. DGPS observations and processing** 3.1 Practice the differential correction task. 3.2 Establishment of a geodetic control network 3.3 Perform GNSS data post-processing for single baseline and network
06 hours	**4. Real-time Kinamatic observations** 4.1 Practice the real-time Kinamatic correction task. 4.2 Use RTK for practical applications Field and Lab practical presentation
10 hours	**5. GIS data collection (GNSS for mapping)** 5.1 Apply GNNS techniques for GIS data collection and prepare GIS maps Field and Lab practical presentations

REFERENCES

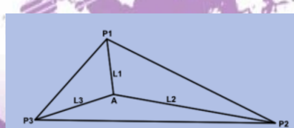
- Strang, Gilbert (1997), Linear Algebra, Geodesy and GPS
- Leick, Alfred (2004), GPS Satellite surveying
- Sickle, Jan Van (2001), GPS for Surveyors
- Seeber, Gunter (2003), Satellite geodesy

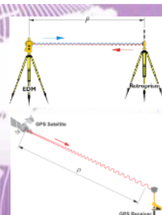
GRADING

Class: Multiple Choice quizzes (x2)	20%
Field and Lab practical reports / presentations (x2)	30%
Final Examination	50%
Total	**100%**

Fundamentals of GNSS

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.

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

- GPS is the most prevalent GNSS

Performance of GNSS

Four (04) criteria:

1.Accuracy: the difference between a receiver's measured and real position, speed or time;

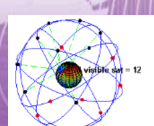
2.Integrity: a system's capacity to provide a threshold of confidence and, in the event of an anomaly in the positioning data, an alarm;

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.

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.



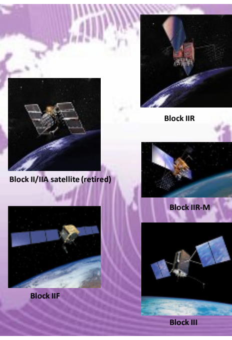
Global Positioning System (GPS)

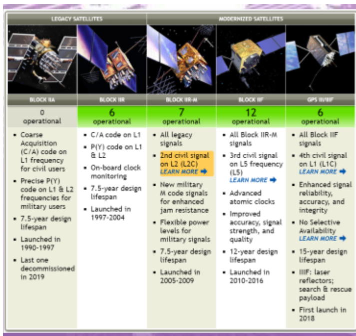
Space segment

- 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





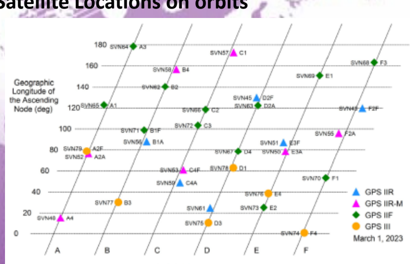
Block	Launch period	Satellite launches				Currently in orbit and healthy
		Success	Failure	In preparation	Planned	
I	1978–1985	10	1	0	0	0
II	1989–1990	9	0	0	0	0
IIA	1990–1997	19	0	0	0	0
IIR	1997–2004	12	1	0	0	7
IIR-M	2005–2009	8	0	0	0	7
IIF	2010–2016	12	0	0	0	12
IIIA	2018–	6	0	4	0	6
IIIF	—	0	0	0	22	0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

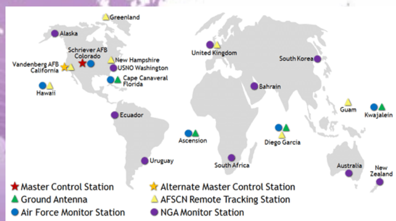
GPS Satellite Locations on orbits



Global Positioning System (GPS)

Control segment

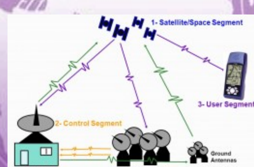
The current Operational Control Segment (OCS) includes a master control station, an alternate master control station, 11 command and control antennas, and 16 monitoring sites



Global Positioning System (GPS)

Control segment elements – Monitor Stations

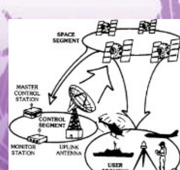
- Track GPS satellites as they pass overhead
- Collect navigation signals, range/carrier measurements, and atmospheric data
- Feed observations to the master control station
- Utilize sophisticated GPS receivers
- Provide global coverage via 16 sites: 6 from the Air Force + 10 from NGA



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

GPS Week Number

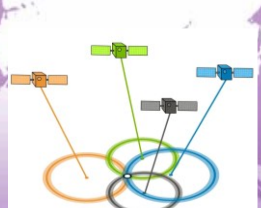
- The GPS date is expressed as a week number
- The week number is transmitted as a ten-bit (2^{10}) field in the navigation messages. it becomes zero again every 1,024 weeks (19.6 years), **GPS Week number rollover**
- GPS week zero started at 00:00:00 UTC (00:00:19 TAI) on January 6, 1980. First rollover: 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.



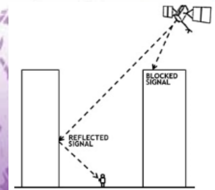
GPS Accuracy cont…

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



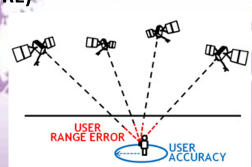
Accuracy and User Range Error (URE)

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.

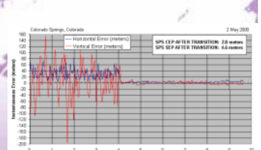
Mostly civilian - single frequency, Military - Dual-frequency

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.



Other GNSS and Augmentation Systems

GNSS

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

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/)

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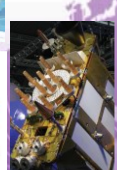


GLONASS-M satellite

Other GNSS

- **Galileo**

Galileo is Europe's Global Navigation Satellite System (GNSS) and it has been operational **since December 2016.** It provides accurate and reliable positioning and timing information which is used in devices such as smartphones

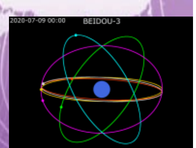
Galileo consists of **24 satellites orbiting Earth at an altitude of 23,000 km**.

https://defence-industry-space.ec.europa.eu/eu-space/galileo-satellite-navigation_en

GALILEO

Other GNSS

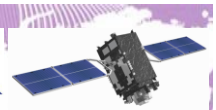
- **BeiDou Navigation Satellite System (BDS)**



- 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 45 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**.

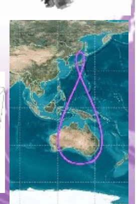
BDS website (beidou.gov.cn)

Other GNSS



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

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").

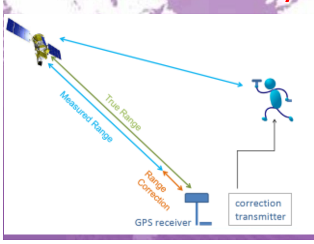
IRNSS provides Standard Positioning Service (SPS) which is provided to all the users and Restricted Service (RS), which is an encrypted service provided only to the authorised users.

IRNSS/NavIC website (isro.gov.in)

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

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

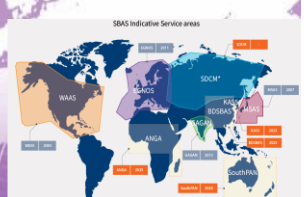
Satellite-based Augmentation Systems (SBAS)

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)



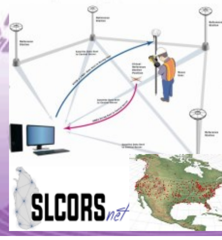
GPS augmentation systems

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)

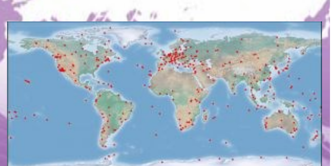
GDGPS is a high accuracy GPS augmentation system developed by the NASA Jet Propulsion Laboratory (JPL) to support the real-time positioning, timing, and determination requirements of NASA science missions.

GPS augmentation systems

International GNSS Service (IGS)

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

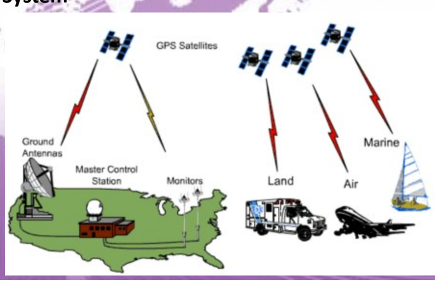
Its mission is to provide the highest quality data and products as the standard for global navigation satellite systems (GNSS) in support of Earth science research, multidisciplinary applications, and education, as well as to facilitate other applications benefiting society.



https://igs.org/products-access/#geocentric-coordinates

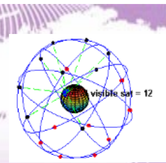
GPS Signals and Data

GPS System



GPS Signals

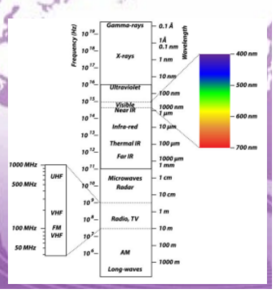
- Broadcast by GPS satellites to enable satellite navigation.
- Satellite constellation is operated by US DOD
- GPS signals include ranging signals, used to measure the distance to the satellite, and navigation messages.
- The navigation messages include **Ephemeris** data, used to calculate the position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



Location: 45°N

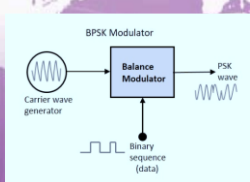
What signal does GPS use?

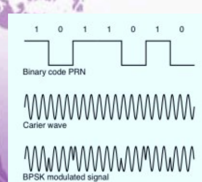
- GPS signal that is carried by radio waves in the microwave part of the electromagnetic spectrum
- Broadcasts a navigation message at 50 bits per second on the microwave carrier frequency of approx. 1600 MHz (L1-1575.42 MHz , L2-1227.6 MHz
- GPS week number and a health report for the satellite so that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



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

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

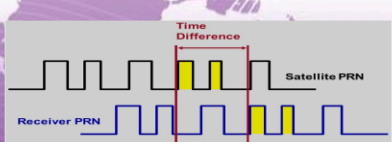
PRN Code	PRN Code Application
L1 C/A	
1 – 63	Reserved (GPS)
64 – 119	Other Augmentation Systems
120 – 158*	Satellite-Based Augmentation Systems (SBASs)
159 – 210	Other RNSS Elements & Applications
L1C	
1 – 63	Reserved (GPS)
64 – 119	Other Augmentation Systems
120 – 158*	Reserved (SBASs)
159 – 210	Other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

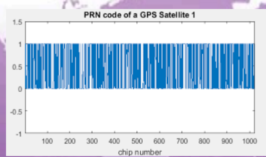
Main functions of these codes are:

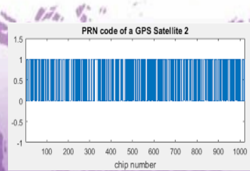
- To provide time delay measurements so the user can determine the distance from receiver's antenna to observed satellite (any code could be used, but the P(Y) code provides a more precise range estimate)



Pseudo-random noise codes

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





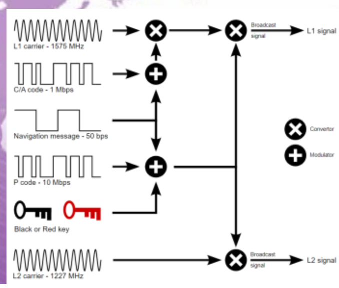
Modulated GPS Signal

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

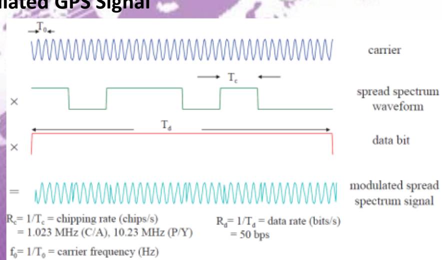
Signal is transmitted primarily by using phase modulation

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

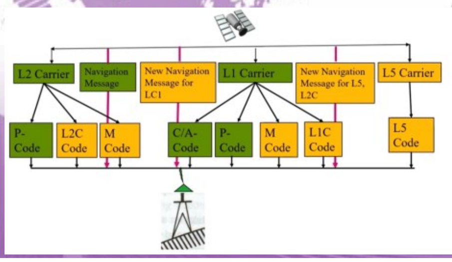
The L2 signal with navigation message and the P-Code which encrypted to generate Y-code



Modulated GPS Signal



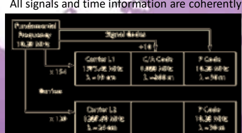
GPS signal structure of the modernized design



GPS Signal Characteristics

Signal components

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



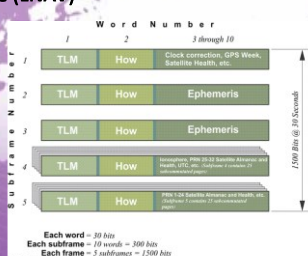
System	Signal	Freq. (MHz)	Wave-Length (m)	Chipping Rate (Mc/s)
GPS	L5	1176.45	0.254	10.23
	L2	1226.70	0.244	1.023
	L1	1575.42	0.190	1.023

	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

Legacy Navigation Message (LNAV)

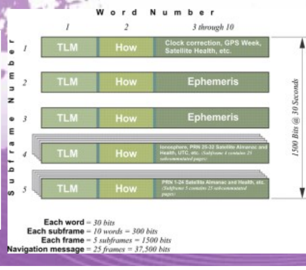
Low frequency signal added to L1 and L2 that gives information about the satellite's orbits, their clock corrections and other system status (Satellite Epimerits)

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)

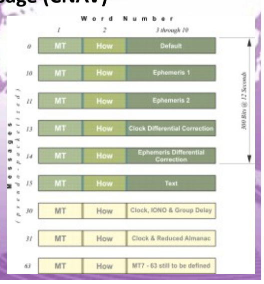
Upgraded version of the LNAV enabling the information of new signals.

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)

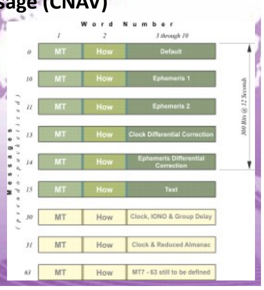
Important changes in the new CNAV message:

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.

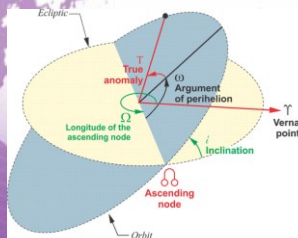
Better interoperability with other global systems (GPS-GLONASS offset is available)

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



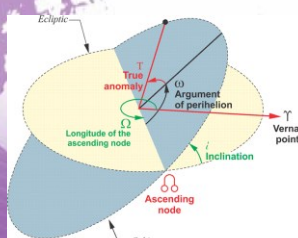
Ephemerides (Keplerian parameters)

- 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



GNSS Measurements

Basic Principles

GNSS Measurements

(Distance between receivers and satellites)

- **Pseudorange measurements** (***Code measurements***)
- **Carrier phase measurements** (***Phase measurements***)

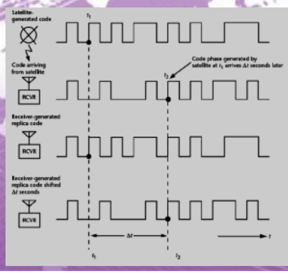
High-accuracy GNSS measurements

- 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 – DGPS

GPS signal transmission and reception

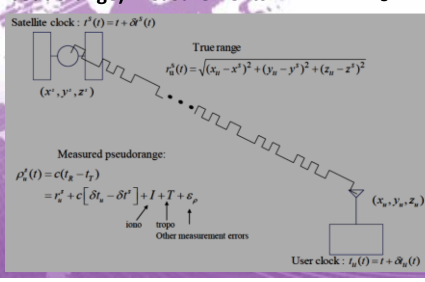
- GPS signals modulated into the carrier waves (L1, L2 and L5) are random binary codes (C/A, P, M, navigation message, etc.) called Pseudo Random Noise codes (PRN codes)
- The GPS signal starts in the satellite as a voltage which oscillates at the fundamental clock frequency of 10.23 MHz
- Separately 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

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***.

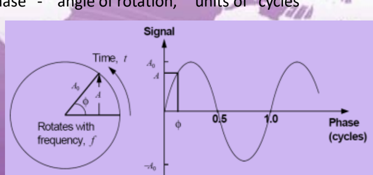
Code (Pseudorange) Measurements - Pseudorange Model



Carrier Phase measurements

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

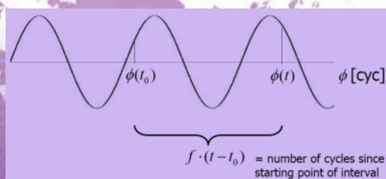
"Phase" - "angle of rotation," units of "cycles"



"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"

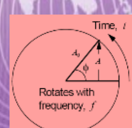
Time - based on some form of periodic motion

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**

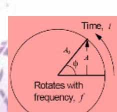
Angles of rotation (Phase) - measure of time

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



Carrier Phase measurements

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

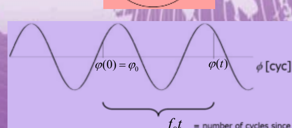


Frequency - Cycles per second
Number of times the line completes a full 360° rotation in one second

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

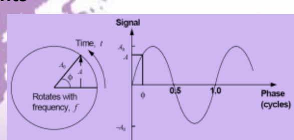
Clock second to be equal a conventional second $(T = t)$ $k = 1/f_0$

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,

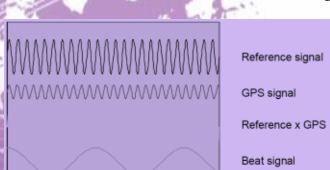
$A(t) = A_0 \sin[2\pi\varphi(t)]$



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

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

Carrier Phase measurements - Carrier Beat Signal



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

Low frequency High frequency

Carrier Phase measurements - Carrier Beat Signal

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

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

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

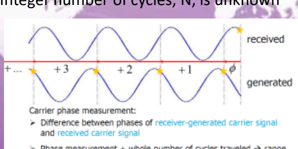
$$f_B \equiv \frac{d\varphi_B}{dt} = f_R - f_G$$

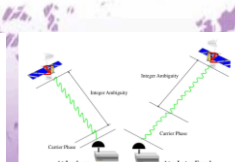
Carrier Phase measurements - Carrier Beat Signal

- 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

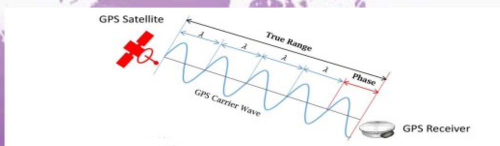




$$\Phi + N = \varphi_R - \varphi_G$$

Carrier Phase measurements - Observation model

How can phase be used to measure distance?



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

GNSS Positioning

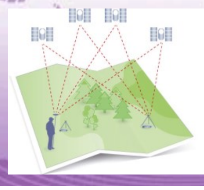
Common requirements of GNSS positioning

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

Absolute and Relative Positioning

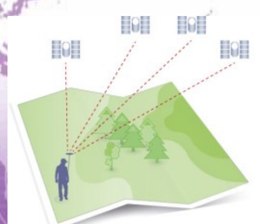
- In absolute positioning, the position of the receiver is determined directly towards the GNSS satellites, and only one GNSS receiver is used.

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



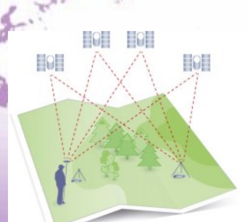
Absolute Positioning

- 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?

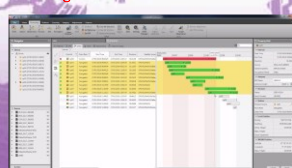
- Set up the GNSS receiver (using tripod) over the point you want to determine the position
- Store measurements over a long period of time
- Measurements are then combined with simultaneously performed measurements at one or more reference stations with a known position
- Mainly used when establishing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



RINEX File Types

V123079I.18g	10/27/2018 4:06 AM	18G File	53 KB
V123079I.18n	10/27/2018 4:06 AM	18N File	69 KB
V123079I.18o	10/27/2018 4:17 AM	18O File	139,188 KB

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

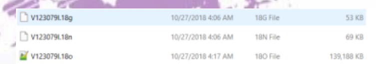
The Observation file provides the following three crucial measurements:

•**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



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 (DGPS)– Differential GNSS (GPS)

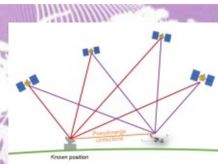
DGNSS is a collective term for measurement using multiple GNSS receivers to reduce position uncertainty.

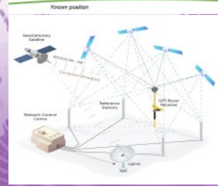
Improves accuracy by using a reference station with known coordinates

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

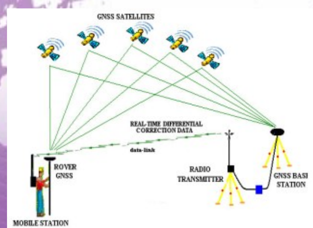
Requires:

- 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**



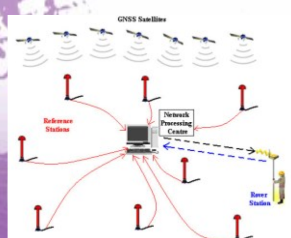
Single-station RTK

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

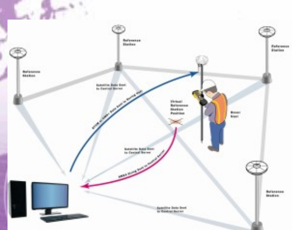


Network-RTK

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

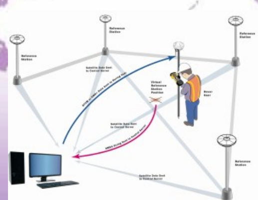
Disadvantages

- 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

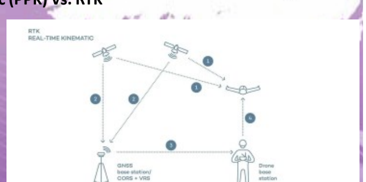
- In post-processing of RTK, virtual RINEX is often used as reference data
- Virtual reference station functions as a reference station in real-time, i.e. provides the necessary correction data
- Collect raw data over a slightly longer period and make regular detail surveys at the points that are to 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

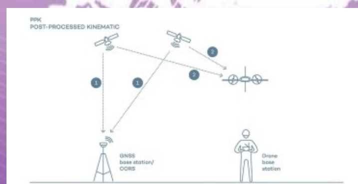
- Mainly PPK and RTK are used to improve and correct the location of drone mapping data and remove the need for GCPs, bringing absolute accuracy down to cm range.
- An RTK drone carries an onboard GNSS RTK receiver that gathers data from satellites and a stationary base (ground) station to more accurately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



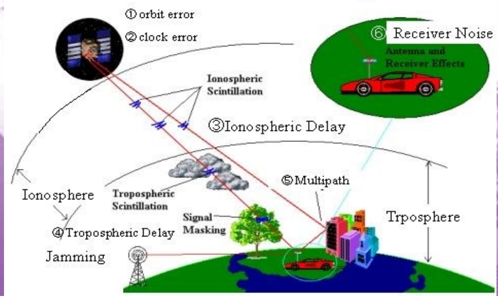
Applications of PPP

Engineering (commercial) and scientific applications

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

GPS Error Sources & Mitigation

Errors on GPS Signal



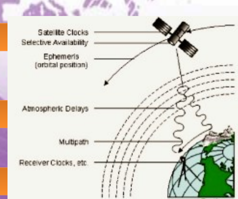
GNSS Errors

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

Satellite

Signal Propagation

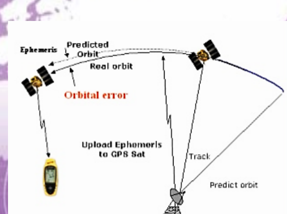
Receiver



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

Ephemeris or Orbital error

Sources:

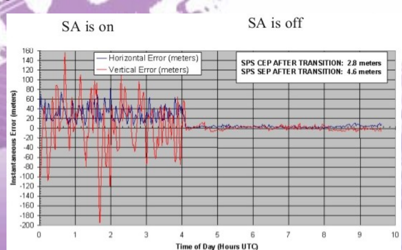
– Selective Availability (SA) (GPS only; this error was never observed and it is now discontinued)
– Control Segment estimation errors
– Age of navigation message data

Estimate ephemeris (orbital) error:

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

Satellite Errors

SA on and off



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.

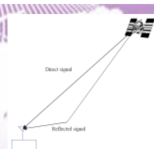
- Satellite clock error is about 8.64-17.28 nanoseconds per day. The corresponding range error is 2.59-5.18 m

Satellite Errors

Satellite and Receiver Clock Errors

- 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

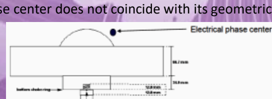
- Signal bounces of a smooth object and hits the receiver antenna
- Significant positional errors result in gravel roads, open water, rock walls, buildings, etc.
- With care, errors can be minimized.
- Multipath seen by two receivers is NOT the same

- 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)

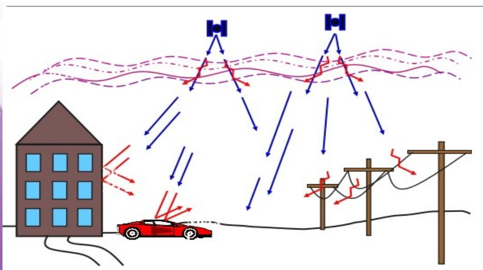


Receiver Errors

Receiver Measurement Noise

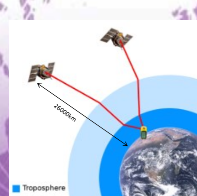
- This results from the limitations of receiver’s electronics and a good GPS system should have a minimum noise level.
- Range error due to the receiver measurement noise is of the order of 0.6m, and depending very much on the quality of the GPS receiver.

Signal Propagation or Atmospheric Refraction Errors



Ionosphere

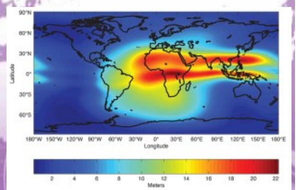
- The upper part of the Earth’s atmosphere (50-1000 km). There, ultraviolet and X-ray radiations coming from Sun interact with gas, molecules and atoms resulting gas ionization.
- Electron density is not constant and divided into sub regions/layers vary with time
- Dispersive medium (bend and change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



Ionosphere

Ionospheric Refraction

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



The TEC is given in TEC units (TECU)

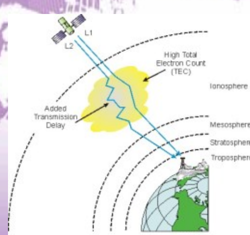
$$1\,\text{TECU} = 10^{16} \text{ electrons per } m^2$$

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

Ionosphere

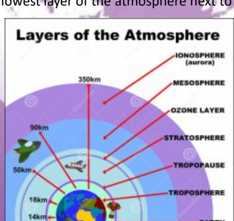
Eliminating the effect of TEC

- 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)



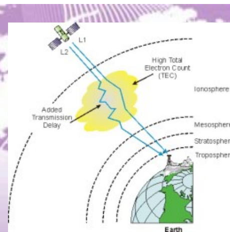
Troposphere

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



Tropospheric Delay

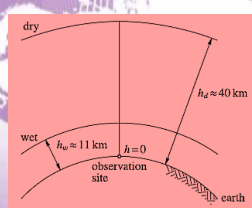
- Tropospheric delays are a factor of atmospheric pressure, temperature and humidity.
- Electrically neutral atmospheric region which means non-dispersive medium w.r.t to frequencies < 15 GHz. So, the propagation is frequency independent. It delays the GPS carrier and codes identically.
- Elimination 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



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

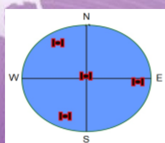
Correcting for Tropospheric Errors

Many correction models:

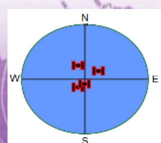
- Simplest:
  - Use global average weather conditions to determine vertical tropospheric error
  - Apply altitude correction and elevation angle scale factor
  - Residual errors ~25 cm for overhead satellite
- More complicated:
  - Use average local weather (e.g., pressure, temperature, humidity) determined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

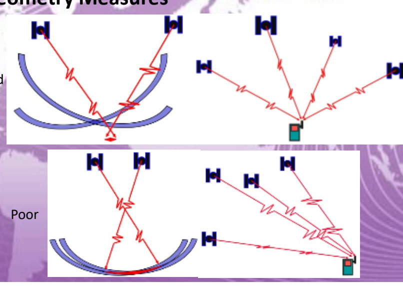


Poor satellite geometry

Satellite Geometry Measures

Good

Poor



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

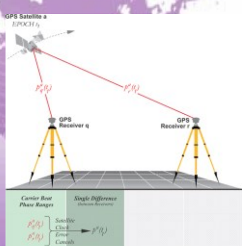
- PDOP represents the contribution of satellite geometry to the 3-D positioning accuracy
- PDOP -> (HDOP+VDOP) – satellite geometry effect of horizontal and vertical component accuracy.

Dilution of Precision

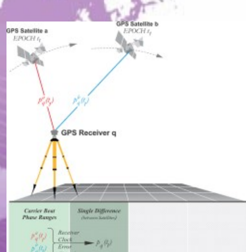
How to check?

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

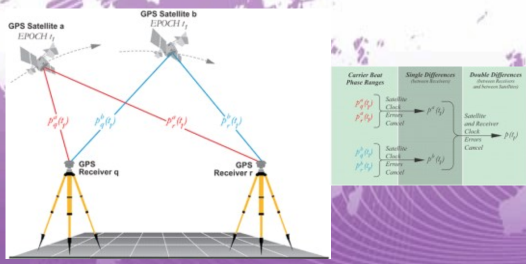
Differencing – Single differencing



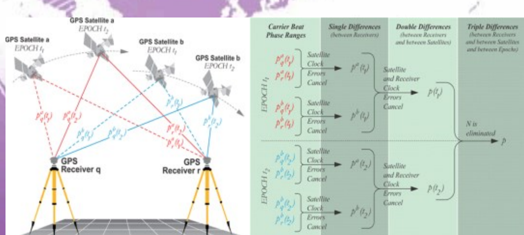
Differencing – Single differencing



Differencing – Double differencing

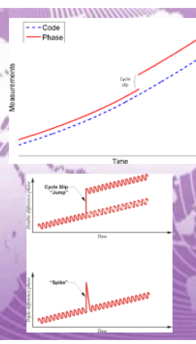


Differencing – Triple differencing



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



GPS Operational Considerations and Applications

GPS Operational Considerations

Quality Assurance and Quality Check (QA/QC)

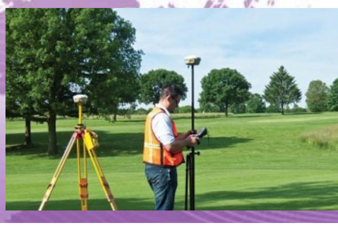
- **Field work**
- **Office work**

Field Work

Periodic equipment calibration and checking

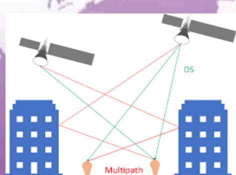
Field Work

Field procedures and training



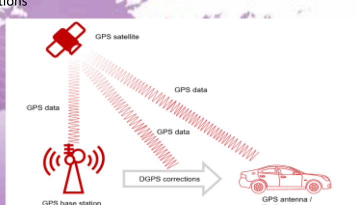
Field Work

Multipath and Signal Obstruction Mitigation



Field Work

Differential Corrections



Field Work

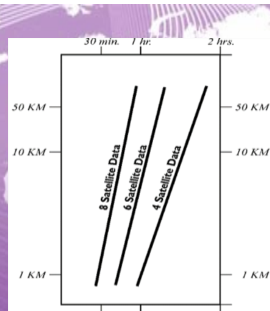
Data Logging and Storage

Field Work

Satellite Geometry Analysis

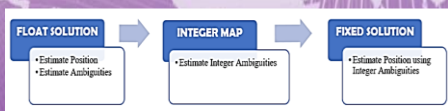
Field Work

Observation time (session length)



Office Work

- Quality Check in Data Processing
- Post-Processing Verification
- Fixed solution not float solution



Office Work

- Error Budget Analysis
- Documentation and Reporting

GPS Applications

- Precision agriculture

GPS Applications

- Aviation

GPS Applications

- Environment

GPS Applications

- Marine navigation

GPS Applications

- Disaster Management

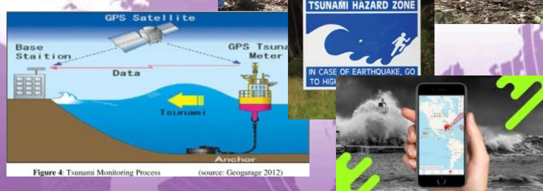
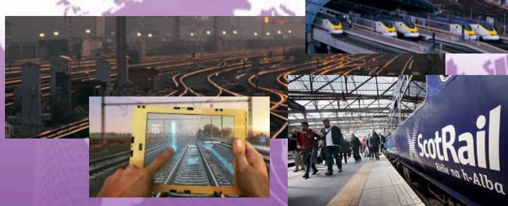


Figure 4: Tsunami Monitoring Process (source: Geogarage 2012)

GPS Applications

- Rail



GPS Applications

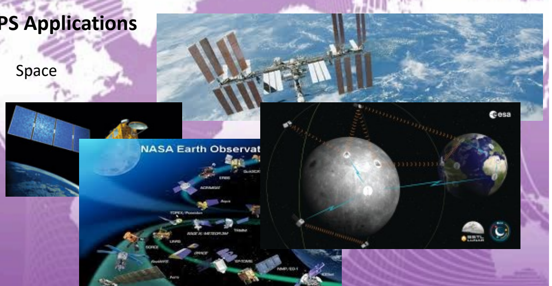
- Road and Highways

GPS Applications

- Recreation

GPS Applications

- Space



GPS Applications

- Surveying and Mapping


GPS Applications
• Timing
GPS time
UTC