An Introduction to GNSS

Presentation Outline

- GNSS Overview

- Basic GNSS Concepts

- GNSS Satellite Systems

- Advanced GNSS Concepts

- GNSS Applications and Equipment

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GNSS Overview

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GNSS Overview

- GNSS (Global Navigation Satellite Systems) started with the launch of the U.S Department of Defense Global Positioning System (GPS) in the late 1970's

- GNSS systems currently include

  - GPS (United States)

  - GLONASS (Russia)

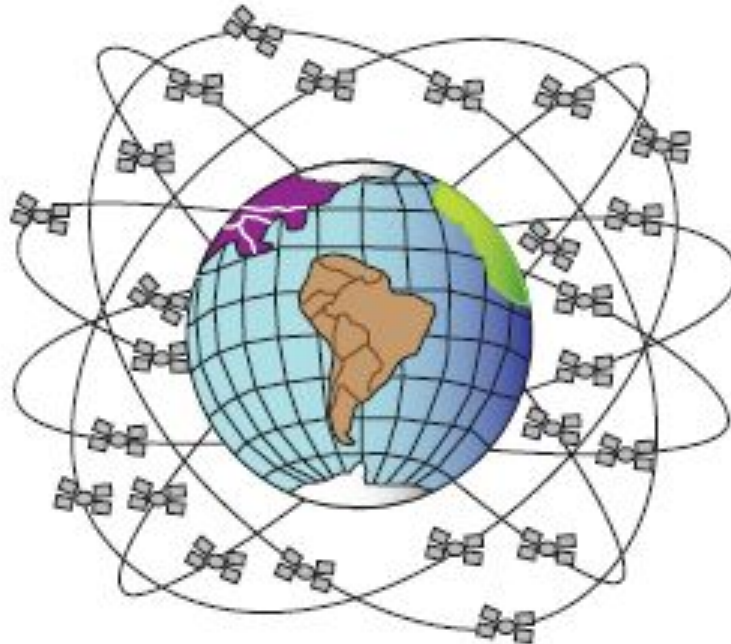 - Galileo (European Union)

  - BeiDou (China)

Architecture

- GNSS satellite systems consists of three major components or "segments:

  - Space Segment

  - Control Segment

  - User Segment

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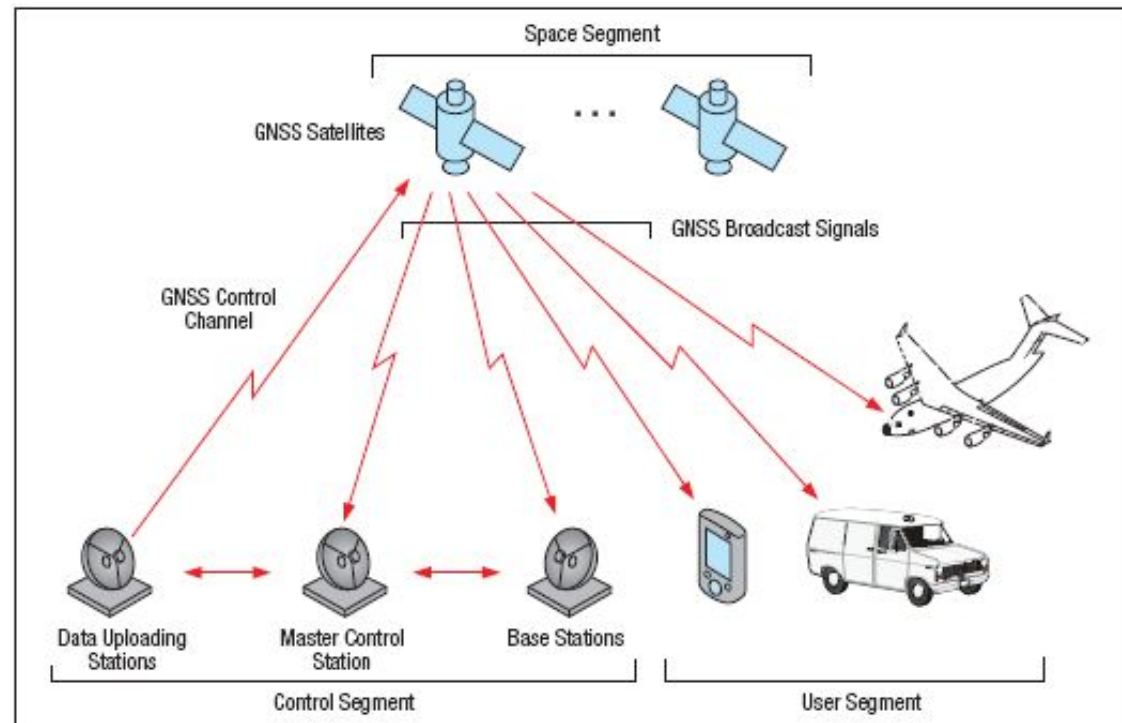
Space Segment

- Consists of GNSS satellites, orbiting about 20,000 km above the earth. Each GNSS has its own constellation of satellites

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Control Segment

- The control segment comprises of a ground-based network of master control stations, data uploading stations, and monitor stations.

- Master control stations adjust the satellites' orbit parameters and on-board high-precision clocks when necessary to maintain accuracy

- Monitor stations monitor the satellites' signal and status, and relay this information to the master control station

- Uploading stations uploads any change in satellite status back to the satellites
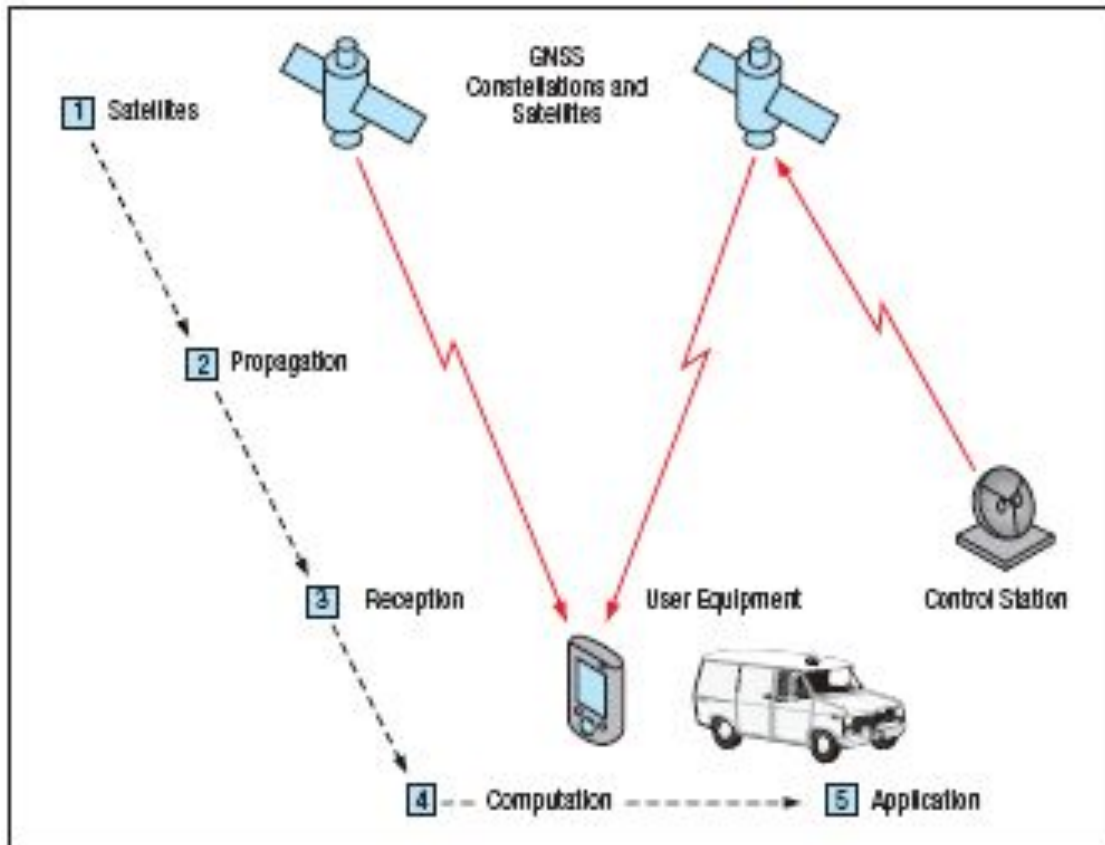
User Segment

- User segment consists of GNSS antennas and receivers used to determine information such as position, velocity, and time

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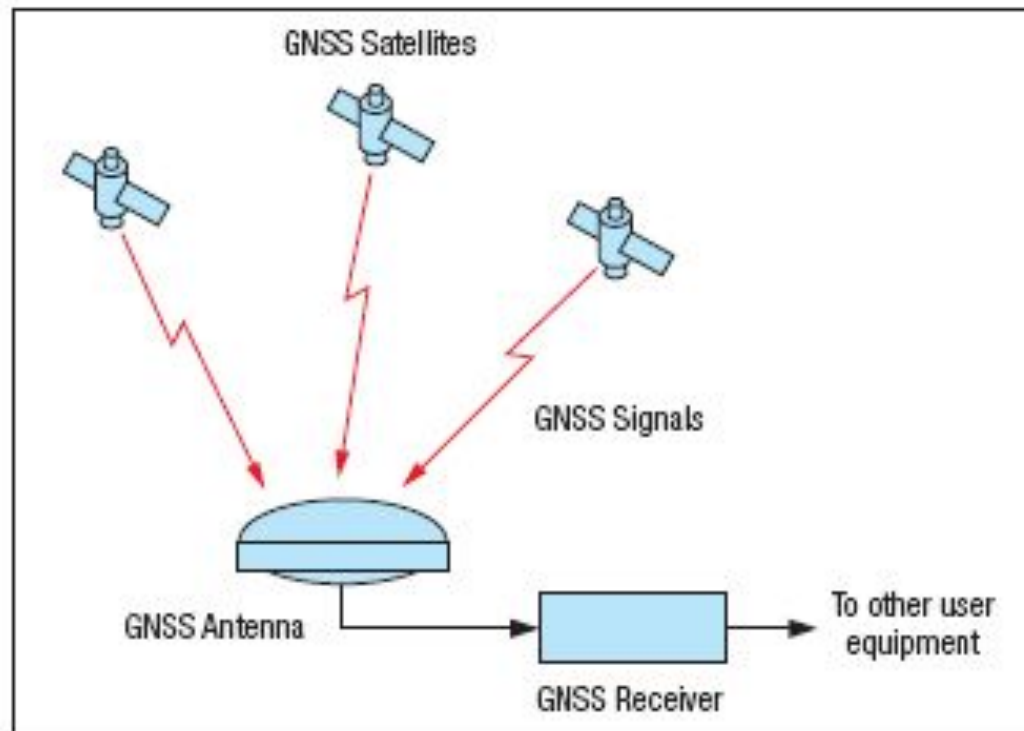
Basic GNSS Concepts

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Basic GNSS Concepts

The above figure shows the steps involved in using GNSS to determine time and position then applying the information.

Satellites

- Multiple GNSS constellations orbiting the earth

  - Beneficial in difficult environment with obstructions to direct line of sight to satellites. Multiple constellations will give more observations

- GNSS satellites know their time and orbit ephemerides very accurately

- Timing accuracy is very important. The time it takes a GNSS signal to travel from satellites to receiver is used to determine distances (range) to satellites

- 1 microsecond = 300m, 1 nanosecond = 30 cm.

- Small deviations in time can result in large position errors

Satellites

- GPS transmits at the following frequencies
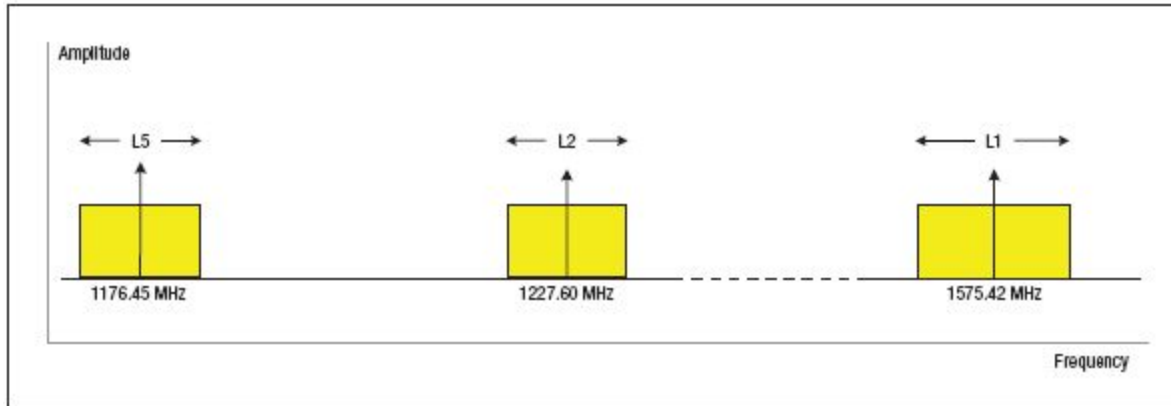
- This frequency band is referred to as the L-band, a portion of the radio spectrum between 1 and 2 GHz

- L1 transmits a navigation message, the coarse acquisition (C/A) code which is freely available to public. An encrypted precision (P) code, called the P(Y) code (restricted access), is transmitted on both L1 and L2.

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Satellites

- Navigation message includes the following information:

  - GPS date and time

  - Satellite status and health

  - Satellite ephemeris data, which allows the receiver to calculate the satellite's position.

  - Almanac, which contains information and status for all GPS satellites

- The P(Y) code is for military use, and provides better interference rejection than the C/A code.

- Newer GPS satellites now transmits L2 C/A code (L2C), providing a second publicly available code to civilian users.

- NovAtel can make use of both L2 carrier and code without knowing how it is coded. This is called semi-codeless technology.

Propagation

- GNSS signals pass through the near-vacuum of space, then through the various layers of the atmosphere to the earth, as illustrated in the figure below:
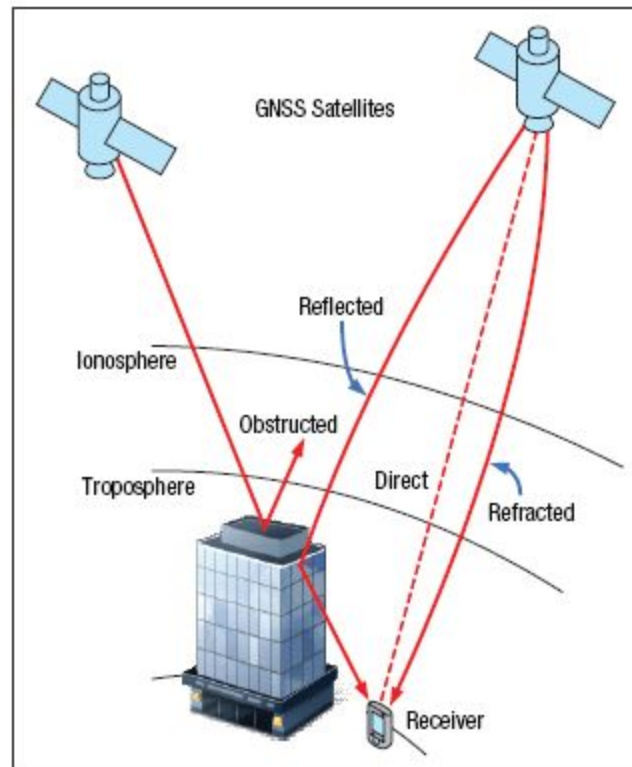
Propagation

- To determine accurate positions, we need to know the range to the satellite. This is the direct path distance from the satellite to the user equipment

- The signal will "bend" when traveling through the earth's atmosphere

- This "bending" increases the amount of time the signal takes to travel from the satellite to the receiver

- The computed range will contain this propagation time error, or atmospheric error

- Since the computed range contains errors and is not exactly equal to the actual range, we refer to it as a "pseudorange"

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Propagation

- The ionosphere contributes to most of the atmospheric error. It resides at 70 to 1000 km above the earth's surface.

- Free electrons resides in the ionosphere, influencing electromagnetic wave propagation

- Ionospheric delay are frequency dependent. It can be virtually eliminated by calculating the range using both L1 and L2

- The troposphere, the lowest layer of the Earth's atmosphere, contributes to delays due to local temperature, pressure and relative humidity

- Tropospheric delay cannot be eliminated the way ionospheric delay can be

- It is possible to model the tropospheric delay then predict and compensate for much of the error

Propagation

- Signals can be reflected on the way to the receiver. This is called "multipath propagation"

- These reflected signals are delayed from the direct signal, and if strong enough, can interfere with the direct signal

- Techniques have been developed whereby the receiver only considers the earliest-arriving signals and ignore multipath signals, which arrives later

- It cannot be entirely eliminated

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Reception

- Receivers need at least 4 satellites to obtain a position. If more are available, these additional observations can be used to improve the position solution

- GNSS signals are modulated by a unique pseudorandom digital sequence, or code. Each satellite uses a different pseudorandom code

- Pseudorandom means that the signal appears random, but actually repeats itself after a period of time

- Receivers know the pseudorandom code for each satellite. This allows receivers to correlate (synchronize) with the GNSS signal to a particular satellite

- Through code correlation, the receiver is able to recover the signal and the information they contain

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Reception

- For each satellite tracked, the receiver determines the propagation time
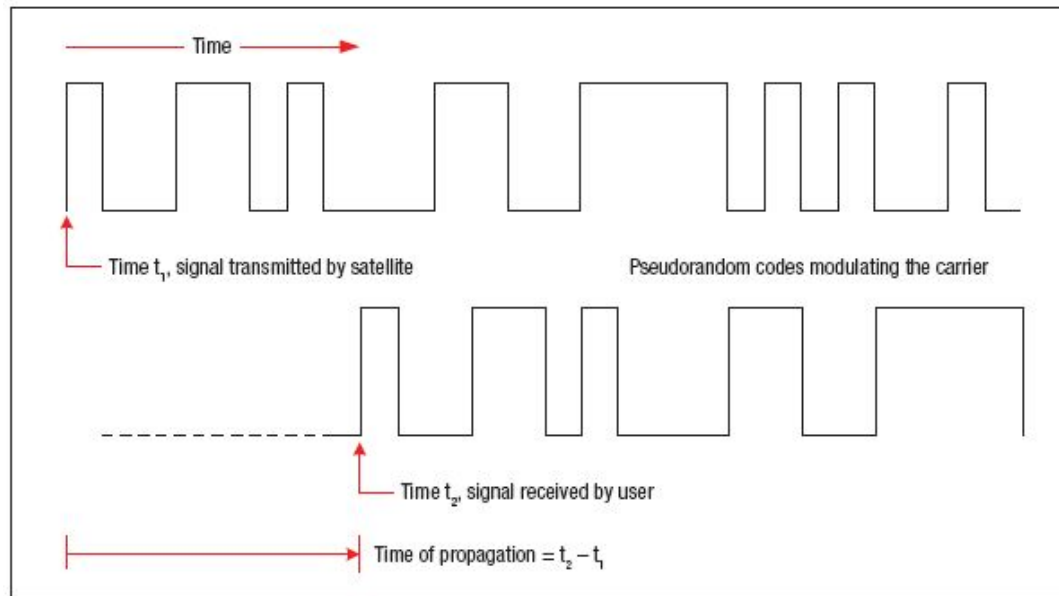
- The above figure shows the transmission of a pseudorandom code from a satellite. The receiver can determine the time of propagation by comparing the transmit time to the receive time

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Computation

- Range measurments from 4 satellites are needed to determine position

- For each satellite tracked, the receiver calculates how long the satellite signal took to reach it, which in turn, determines the distance to the satellite:

  - Propagation Time = Time Signal Reached Receiver – Time Signal Left Satellite

  - Distance to Satellite = Propagation Time * Speed of Light

- Receiver now knows where the satellite was at the time of transmission through the use of orbit ephemerides

- Through trilateration, the receiver calculates its position

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Computation

In a two-dimentional world, here is how position calculation works:

- If receiver acquires two satellites, it has two possible positions:

By knowing the location of Satellites A and B, and your distance to each of them, you know you are at Position 1 or Position 2

D_B, distance to Satellite B

Position 1

D_A, distance to Satellite A

GNSS Satellite B

GNSS Satellite A
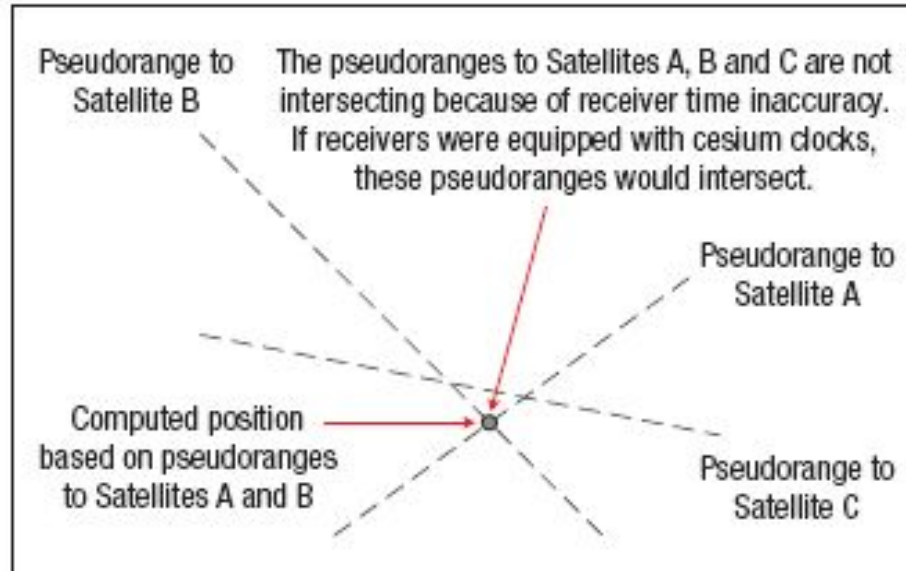
Position 2

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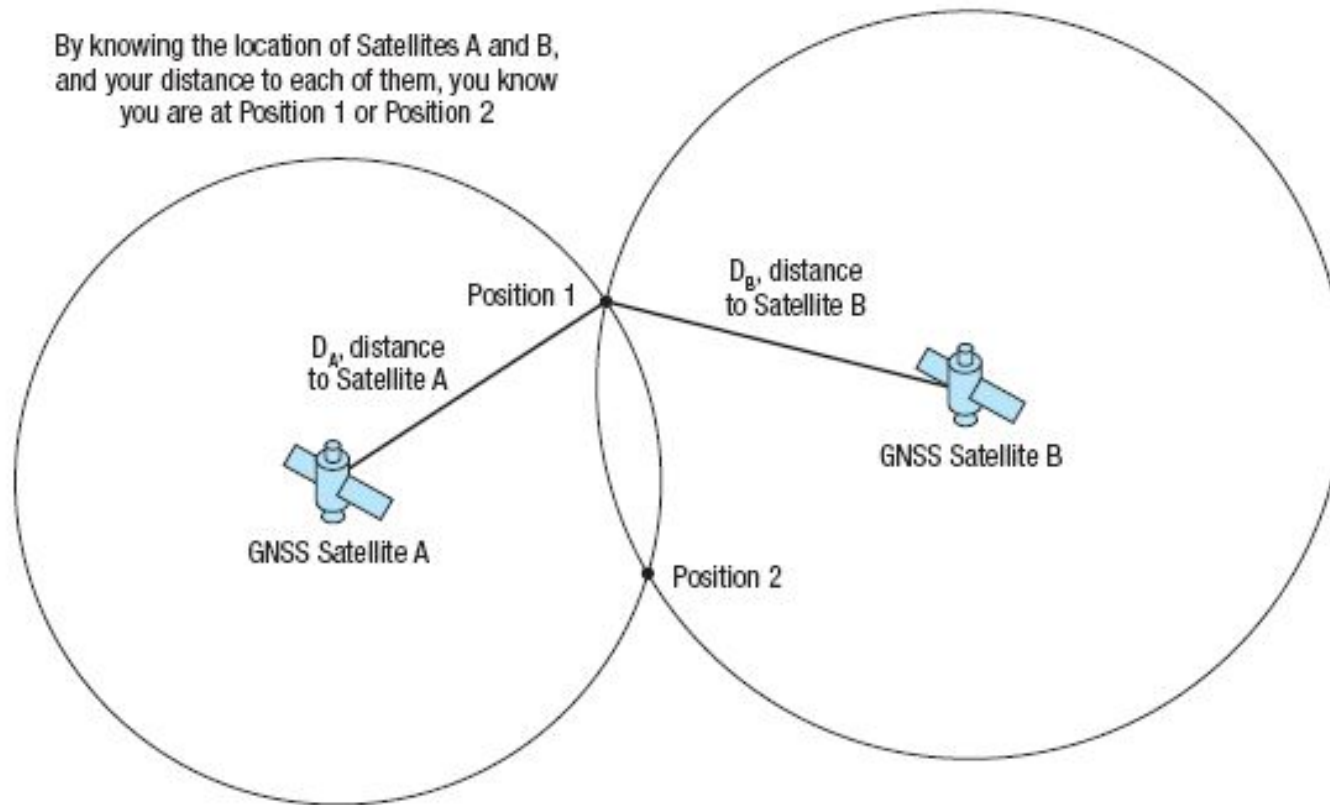
Computation

- Due to receiver clock error, the intersecting points between the range of satellite A and B do not match with the actual position
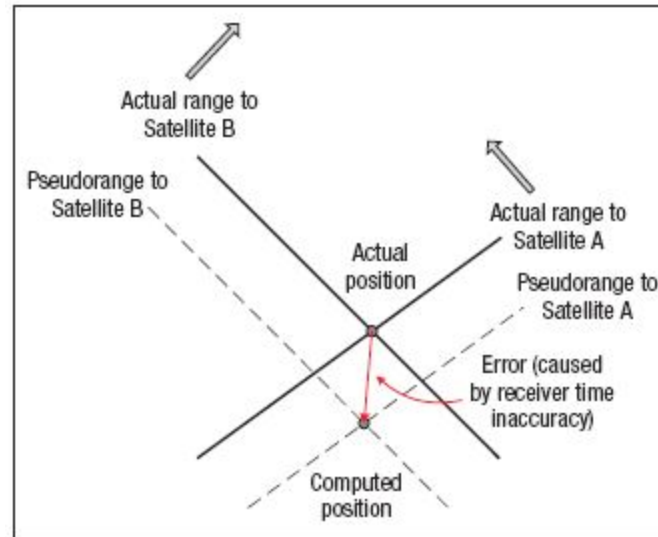
- Receiver clocks are not nearly as accurate as satellite clocks. Their typical accuracy is only about 5 parts per million.

- When multiplied by the speed of light, the resulting accuracy is within +/- 1500 meters

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Computation

- When we now compute the range of the third satellite, the points will not intersect to a single computed position

The pseudoranges to Satellites A, B and C are not intersecting because of receiver time inaccuracy. If receivers were equipped with cesium clocks, these pseudoranges would intersect.

Pseudorange to Satellite B

Pseudorange to Satellite A

Computed position based on pseudoranges to Satellites A and B

Pseudorange to Satellite C

- The receiver knows that the pseudoranges to the three satellites do not intersect due to receiver clock errors

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Computation

- The receiver can advance or delay its clock until the pseudoranges to the three satellites converge at a single point
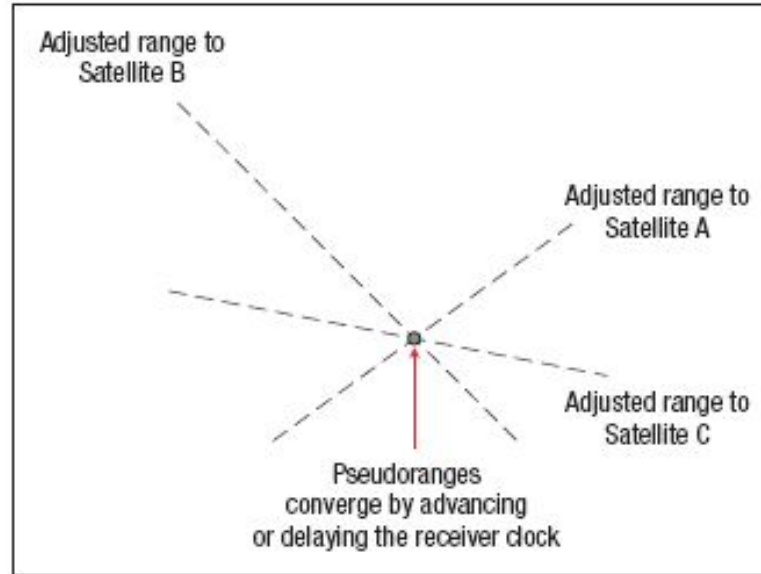
- Through this process, the satellite clock has now been "transferred" to the receiver clock, eliminating the receiver clock error

- The receiver now has both a very accurate position and a very accurate time

- When you extend this principle to a three-dimensional world, we will need the range of a fourth satellite to compute a position

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Computation

- In summary, here are the GNSS error sources that affect the accuracy of pseudorange calculation:

Contributing Source	Error Range
Satellite clocks	±2 m
Orbit errors	±2.5 m
Ionospheric delays	±5 m
Tropospheric delays	±0.5 m
Receiver noise	±0.3 m
Multipath	±1 m

- The degree with which the above pseudorange errors affect positioning accuracy depends largely on the geometry of the satellites being used. This will be discussed later in this training.

GNSS Satellite Systems

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GNSS Satellite Systems

- Currently, the following GNSS systems are operational

  - GPS (United States)

  - GLONASS (Russia)

- The folowing GNSS systems are planned and are in varying stages of development

  - Galileo (European Union)

  - BeiDou (China)

- The following regional navigation satellite systems are planned and are in varying stages of development:

  - IRNSS (India)

  - QZSS (Japan)

GPS

- GPS (Global Positioning System) or NAVSTAR, as it is officially called, is the first GNSS system

- Launched in the late 1970's and early 1980's for the US Department of Defense

- Since the initial launch, several generations, referred to as "Blocks", of GPS satellites have been launched

- GPS was initially launched for military use but opened up to civilian use in 1983

Lockheed Martin

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GPS

- The GPS space segment is summarized in the table below:

Satellites	21 plus 3 spares
Orbital planes	6
Orbit inclination	55 degrees
Orbit radius	26,560 km

- The orbital period of each satellite is approximately 12 hours

- At any point in time, a GPS receiver will have at least 6 satellites in view at any point on Earth under open sky conditions

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GPS

- GPS orbits approximately 26,560 km above the Earth

- GPS satellites continuously broadcast their identification, ranging signals, satellite status and corrected ephemerides (orbit parameters)

- Each satellite is identified by their Space Vehicle Number (SVN) and their PseudoRandom code Number (PRN)

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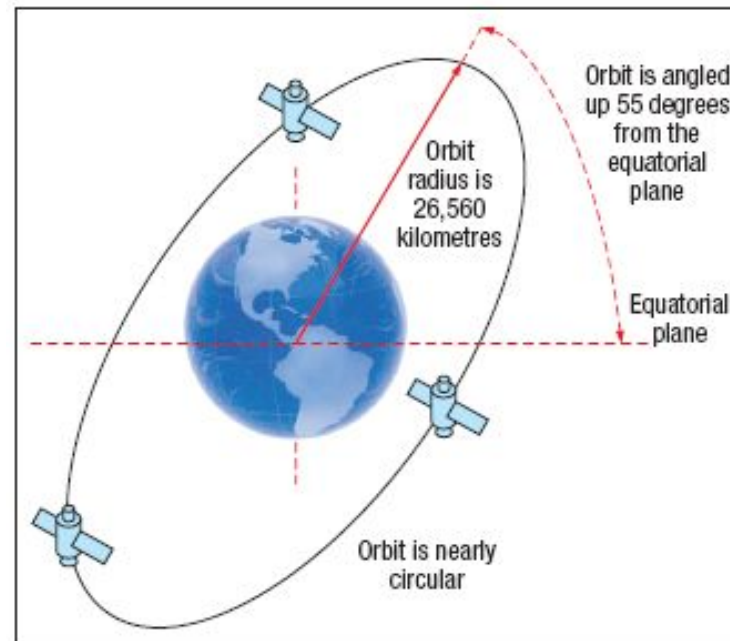
GPS

- GPS signals are based on CDMA (Code Division Multiple Access) technology

- The table below provides further information on different GPS frequencies

Designation	Frequency	Description
L1	1575.42 MHz	L1 is modulated by the C/A code (Coarse/Acquisition) and the P-code (Precision) which is encrypted for military and other authorized users.
L2	1227.60 MHz	L2 is modulated by the P-code and, beginning with the Block IIR-M satellites, the L2C (civilian) code. L2C, which is considered "under development", is discussed below, under "GPS Modernization".
L5	1176.45 MHz	At the time of writing, L5 is available for demonstration on one GPS satellite. The L5 signal is discussed below, under "GPS Modernization".

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GPS

- GPS Control Segment consists of a master control station and a backup master control station, in addition to monitor stations throughout the world

- The monitor stations tracks the satellite broadcast signal and pass them on to the master control station where the ephemerides are recalculated. The resulting ephemerides and timing corrections are transmitted back to the satellites through data up-loading stations

GPS Modernization

- GPS space segment modernization has included new signals, as well as improvements in atomic clock accuracy, satellite signal strength and reliability

- Control segment modernization includes improved ionospheric and trophospheric modelling and in-orbit accuracy, and additional monitoring stations

- Latest generation of GPS satellites has the capability to transmit new civilian signal, designalted L2C

- L2C will be easier for the user segment to track and will provide improved navigation accuracy

- It will also provide the ability to directly measure and remove the ionospheric delay error for a particular satellite, using the civilian signals on both L1 and L2.

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GPS Modernization

- A new GPS L5 frequency (1176.45 MHz) is slowly being added to new satellites

- The first NAVSTAR GPS satellite to transmit L5, on a demonstration basis, was launched in 2009

- L5 signal is added to meet the requirements of critical safety-of-life applications

- GPS satellite modernization will also include a new military signal and an improved L1C which will provide greater civilian interoperability with Galileo

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GLONASS

- GLONASS (Global Navigation Satellite System) was developed by the Soviet Union as an experimental military communications system during the 1970s

- When the Cold War ended, the Soviet Union recognized that GLONASS can be used in commercial applications

- First satellite was launched in 1983, and system declared fully operational in 1993

- GLONASS went through a period of performance decline

- Russia is committed to bring the system back up to operational and set a date of 2011 for full deployment of the system

GLONASS

- The GLONASS constellation provides visibility to a variable number of satellites, depending on your location

- The GLONASS space segment consists of 24 satellites in three orbital planes

- The GLONASS constellation geometry repeats about once every eight days

- GLONASS satellites orbit 25,510 km above the Earth's surface. About 1,050 km lower than GPS satellites

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GLONASS

- The GLONASS control segment consists of the system control center and a network of command tracking stations across Russia

- Similar to GPS, the GLONASS control segment monitors the status of satellites, determines the ephemerides corrections, and satellite clock offsets with respect to GLONASS time and UTC time

- Twice a day, it uploads corrections to the satellites

Designation	Frequency	Description
L1	1598.0625 - 1609.3125 MHz	L1 is modulated by the HP (high precision) and the SP (standard precision) signals.
L2	1242.9375 - 1251.6875 MHz	L2 is modulated by the HP and SP signals. The SP code is identical to that transmitted on L1.

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GLONASS

- GLONASS satellites each transmit on slightly different L1 and L2 frequencies

- GLONASS satellites transmit the same code at different frequencies, a technique known as FDMA (Frequency Division Multiple Access)

- The GLONASS system is based on 24 satellites using 12 frequencies. It achieves this by having antipodal satellites transmitting on the same frequency

GLONASS

- The GLONASS system is based on 24 satellites using 12 frequencies. It achieves this by having antipodal satellites transmitting on the same frequency

Both satellites are transmitting on the same frequency
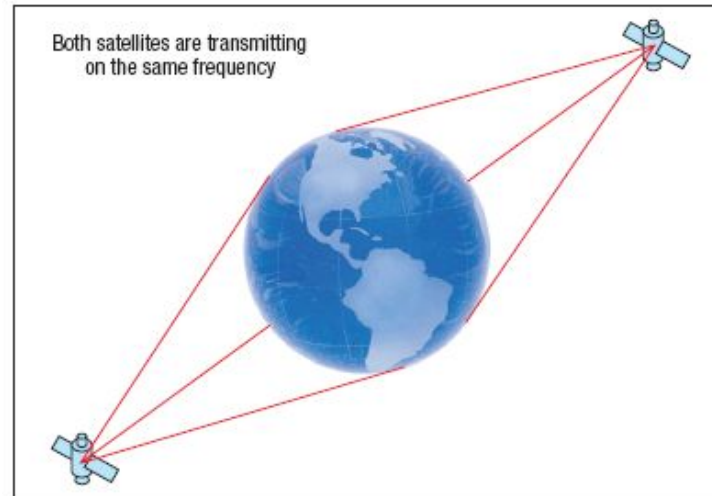
- Antipodal satellites are in the same orbital plane but are separated by 180 degrees. The paired satellites can transmit on the same frequency because they will never appear at the same time in view of a receiver on the Earth's surface

Galileo

- Europe's global navigation system

- Guaranteed global positioning service under civilian control

- Guaranteed availability of service under all but the most extreme circumstances

- Suitable for applications where safety is crucial, such as air and ground transportation

- GIOVE-A and GIOVE-B test satellites are already in orbit

Satellites	27 operational and three active spares
Orbital planes	3
Orbital inclination	56 degrees
Orbit radius	23,616 km

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GNSS Satellite Systems – Galileo

- Once the constellation is operational, Galileo navigation signals will provide coverage at all latitudes

- Two Galileo Control Centres (GCC) will be located in Europe

- Data recovered by a global network of twenty Galileo Sensor Stations (GSS) will be sent to the GCC

- Galileo will provide global Search and Rescue (SAR) function

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Galileo

- Five Galileo services are proposed:

Service	Description
Free Open Service (OS)	Provides positioning, navigation and precise timing service. It will be available for use by any person with a Galileo receiver. No authorisation will be required to access this service. Galileo is expected to be similar to GPS in this respect.
Highly reliable Commercial Service (CS)	Service providers can provide added-value services, for which they can charge the end customer. The CS signal will contain data relating to these additional commercial services.
Safety-of-Life Service (SOL)	Improves on OS by providing timely warnings to users when it fails to meet certain margins of accuracy. A service guarantee will likely be provided for this service.
Government encrypted Public Regulated Service (PRS)	Highly encrypted restricted-access service offered to government agencies that require a high availability navigation signal.
Search and Rescue Service (SAR)	Public service designed to support search and rescue operations, which will make it possible to locate people and vehicles in distress.

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BeiDou

- China's global navigation system

- Initial system will provide regional coverage

- A target of 2015 to begin implementation of GEO and MEO satellites for global coverage

Satellites	35, a combination of 5 GEO and 30 MEO
Orbital planes	6
Orbital inclination	55 degrees
Orbit radius	27,528 km

- Compass will provide two levels of services:

  - Public service for civilian use, and free to users in China

  - Licensed military service, more accurate than public service

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Planned Systems

- IRNSS (India Regional Navigation Satellite System, India)
  - Satellite system to provide regional coverage
  - Planned to launch in 2013

- QZSS (Quasi-Zenith Satellite System, Japan)
  - A three satellite system that will provide regional communication services and positioning information for the mobile environment

Advanced GNSS Concepts

Differential GNSS

- Differential GNSS uses a fixed GNSS receiver, referred to as "base station" to transmit corrections to the rover station for improved positioning

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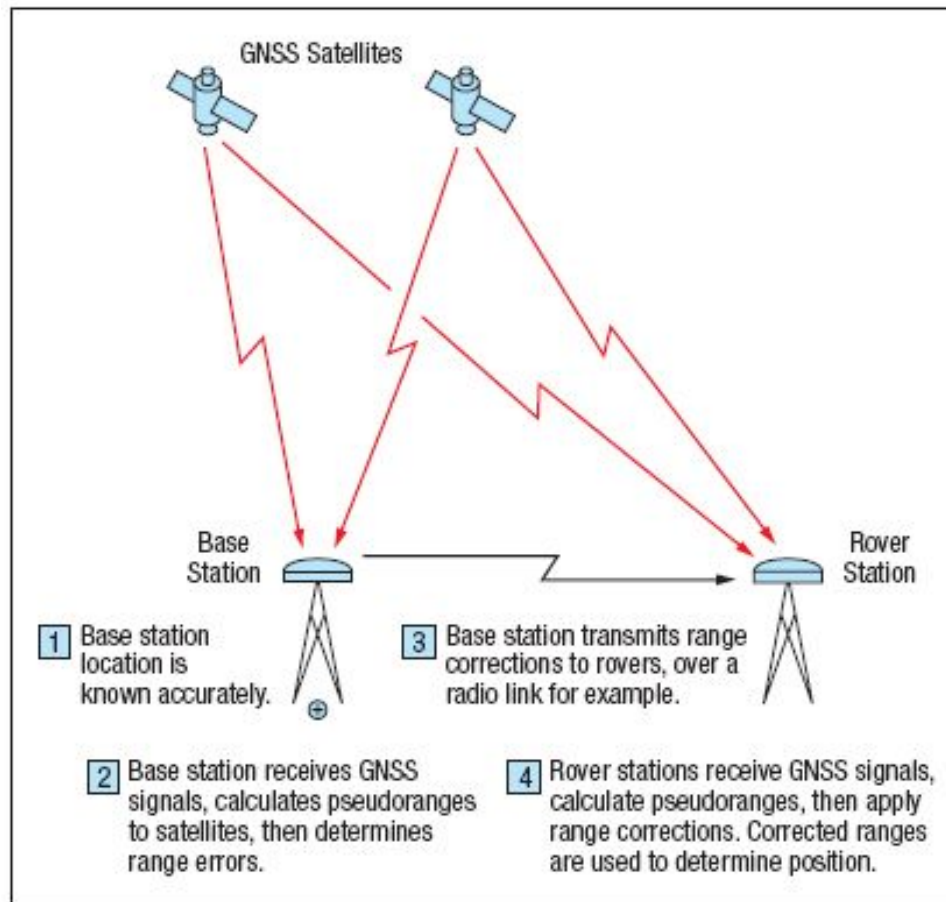
Differential GNSS

- The base station determines ranges to the GNSS satellites by:

    - Using the code-based positioning technique as described earlier

    - Using the precisely known locations of the base station and the satellites, the location of satellites being determined from the precisely known orbit ephemerides and satellite time

- The base station computes the GNSS errors by differencing the ranges measured from the above methods

- The base station sends these computed errors as corrections to the rovers, which will incorporate the corrections into their position calculations

- A data link between the base and rover stations is required

Differential GNSS

- For corrections to be applied, the base and rover must be tracking a minimum of 4 common GNSS satellites (recommend at least 6 common satellites for best results)

- Rover's position accuracy will depend on the absolute accuracy of the base station's known position

- It is assumed that the propagation paths from the satellites to the base and rover stations are similar, as long as the baseline length is not too long

- Differential GPS can work very well with baseline lengths up to tens of kilometers

Satellite-Based Augmentation System

- Satellite-Based Augmentation System (SBAS) is suitable for applications where the cost of installing a base station is not justified, or if the rover stations are spread over too wide of an area

- SBAS is a geosynchronous satellite system that provides services to improve the overall GNSS accuracy

  - Improve accuracy through wide-area corrections for range errors

  - Enhance integrity through integrity monitoring data

  - Improve signal availability if SBAS transmits ranging signals from it satellites

Satellite-Based Augmentation System

- Reference stations receive GNSS signals and forwards them to master station

- Master station accurately calculates wide-area corrections

- Uplink station sends correction data up to SBAS satellites

- SBAS satellites broadcasts corrections
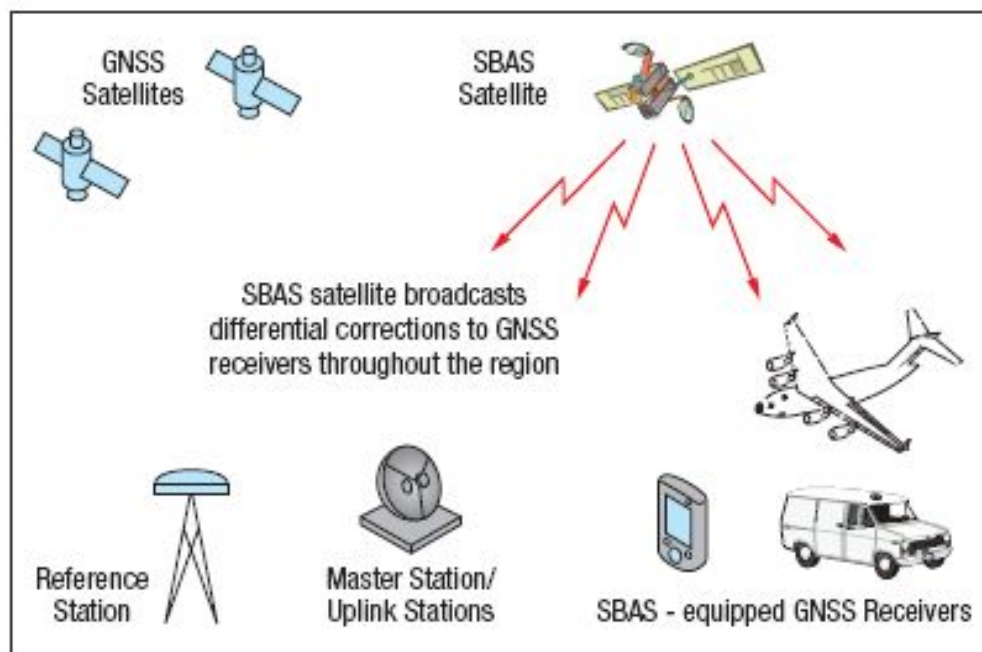
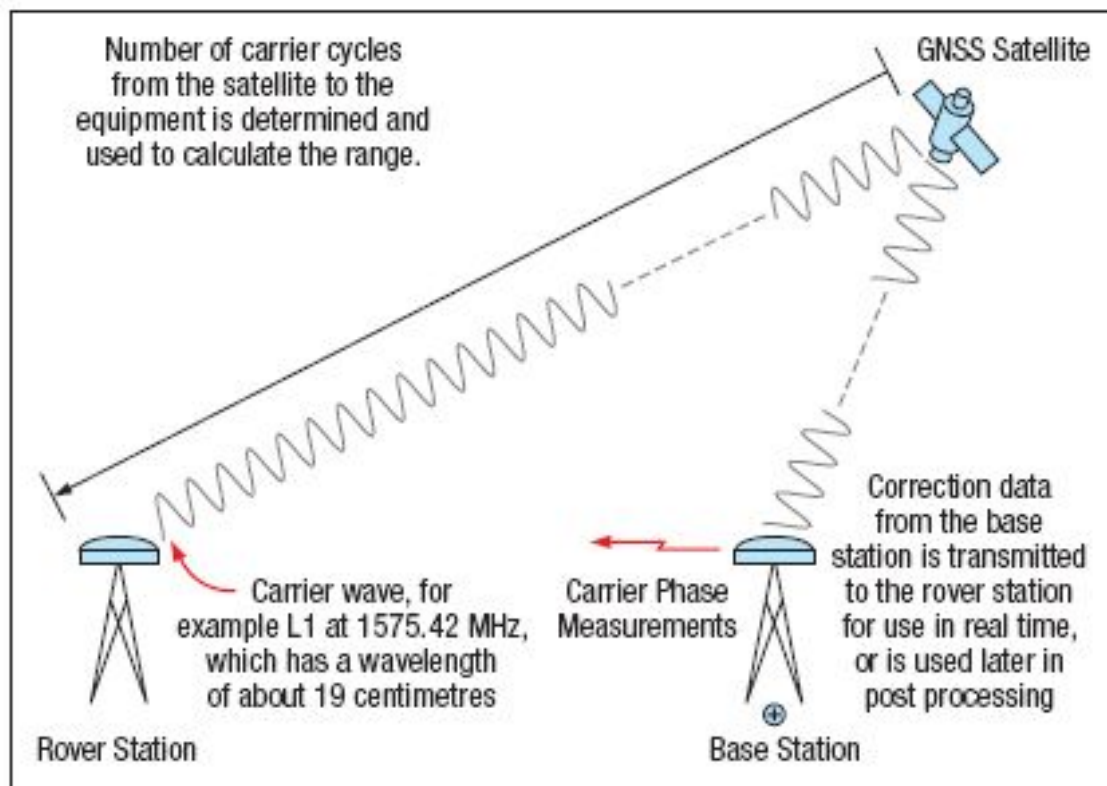# Satellite-Based Augmentation System

- SBAS has two level of services:
    - Free, government-provided SBAS services in GPS frequency (except CDGPS)
    - Commercial SBAS service in a different frequency

- Different free SBAS services are available around the world:
    - Wide Area Augmentation System (WAAS - North America)
    - European Geostationary Navigation Overlay Service (EGNOS)
    - CDGPS (Canada and continental United States)
    - MTSAT Satellite Based Augmentation System (MSAS - Japan)
    - GPS-Aided GEO Augmented Navigation system (GAGAN – India)
    - Satellite Navigation Augmentation System (SNAS – China)

Satellite-Based Augmentation System

- Commercial SBAS system includes OmniSTAR, VERIPOS, and StarFire

- OmniSTAR is a subscription-based service that transmits differential corrections at L-band frequencies close to GPS frequencies

- OmniSTAR provides three levels of services:

  - VBS, providing sub-metre horizontal accuracy

  - XP, providing decimeter accuracy

  - HP, providing sub-decimeter accuracy

- OmniSTAR satellites provide coverage over most of the world's land areas

  - http://www.omnistar.com/chart.html

Real-Time Kinematic (RTK)

- Carrier-based ranging that provides more accurate positioning than through code-base positioning

- Basic idea is to reduce and remove errors from satellites common to both the base and rover

Number of carrier cycles from the satellite to the equipment is determined and used to calculate the range.

GNSS Satellite

Carrier wave, for example L1 at 1575.42 MHz, which has a wavelength of about 19 centimetres

Rover Station

Carrier Phase Measurements

Correction data from the base station is transmitted to the rover station for use in real time, or is used later in post processing
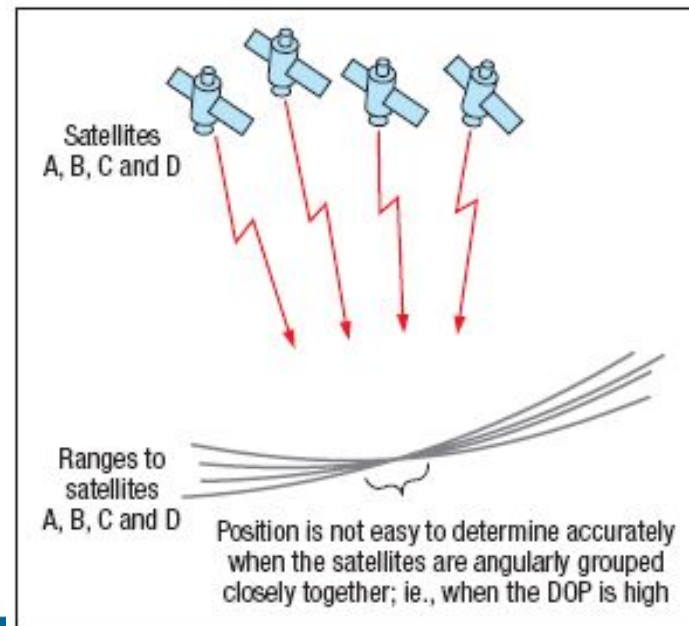
Base Station

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Real-Time Kinematic (RTK)

- The range is calculated by determining the number of carrier cycles between the satellite and the rover station, then multiplying this number by the carrier wavelength

- RTK corrections from a base station is transmitted to the rover to correct for errors such as satellite clock and ephemerides, and ionospheric and tropospheric errors

- A process called "ambiguity resolution" is used to determine the number of whole cycles

- Similar to Differential GNSS, the rover's position accuracy will depend on the base station's accuracy, baseline length, and the quality of the base station's satellite observations

- Virtual Reference Stations (VRS) is a form of Network RTK where there is a wide network of base stations sending out corrections to user stations on demand

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Dilution of Precision (DOP)

- DOP is a numeric value that represents the geometric arrangements of satellites

- The ideal case is to have satellites spread out over the sky

- Good DOP is represented by a low number (approximately 2), and bad DOP is represented by a high number (above 6 is generally unacceptable)

- An example of bad DOP is if all the satellites are clustered in a small area, creating a large area of range intersections

Satellites A, B, C and D

Ranges to satellites A, B, C and D

Position is not easy to determine accurately when the satellites are angularly grouped closely together; ie., when the DOP is high

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Dilution of Precision (DOP)

- A good DOP means the satellites in view are spread throughout the sky

- Area of range intersection is much smaller, positions can be determined more accurately
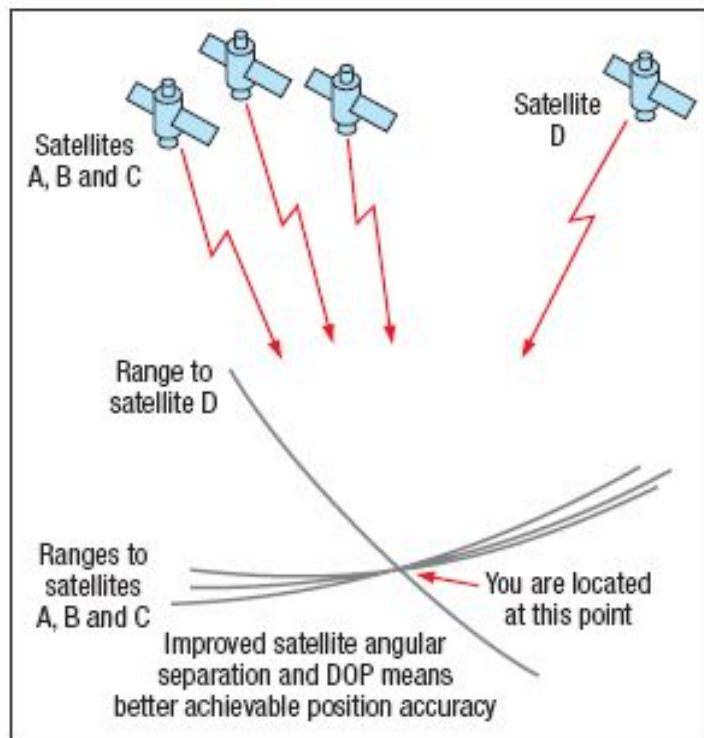
Dilution of Precision (DOP)

- DOP can be expressed as a number of separate elements:

  - HDOP – Horizontal DOP

  - VDOP – Vertical DOP

  - PDOP – Position DOP

- In countries at high latitude (ie. Canada), GNSS satellites are lower in the sky (towards the equator), and having a good DOP is sometimes challanging

- Having multiple constellations and new satellites being launched can provide more observations, improving DOP

- DOP can be predicted using mission planning tools so users can determine the ideal time for their survey

Combined GNSS/Inertial Navigation Systems

- Combination of GNSS and INS will give continuous position, time and velocity information, even in difficult environments where there is limited GPS satellites in view
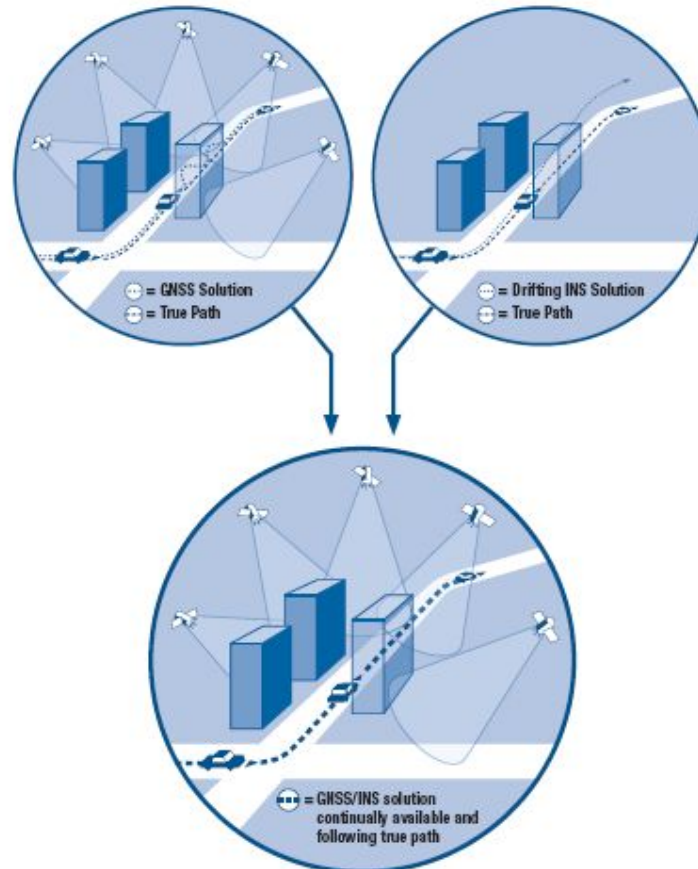
Combined GNSS/Inertial Navigation Systems

- INS uses rotation and acceleration information from an Inertial Measurement Unit (IMU) to compute position over time

- An INS can also solve for full attitude (roll, pitch and heading) measurements

- In absence of external reference such as a GNSS solution, INS solution will drift over time

- When combined, GNSS and INS will provide accurate and reliable navigation solution

- Tightly coupled systems allow the INS to use GNSS data to contain its drift, while the INS solution feeds back into the GNSS solution to improve signal reacquisition and convergence time

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GNSS Data Post-Processing

- For applications where real-time solution is not necessary, raw GNSS data can be collected and stored for post mission processing

- Post-processing does not require a real-time transmission of differential corrections, simplifying hardware configuration

- Users can load data from multiple base stations, or download freely available base station data

- Users can also download PPP data (precise ephemeris and clock data) to process without a base station

- Post-processing can be done on static or kinematic data

GNSS Applications and Equipment

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Applications

Some common GNSS Applications include:

- Transportation

- Timing

- Machine Control

- Marine

- Surveying

- Defence

- Port Automation

Transportation

- Portable navigation devices
- Air, marine, and ground based vehicle navigation

www.boeing.com

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Machine Control

NovAtel Inc.

Thomas Morby, NovAtel Inc.

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Surveying

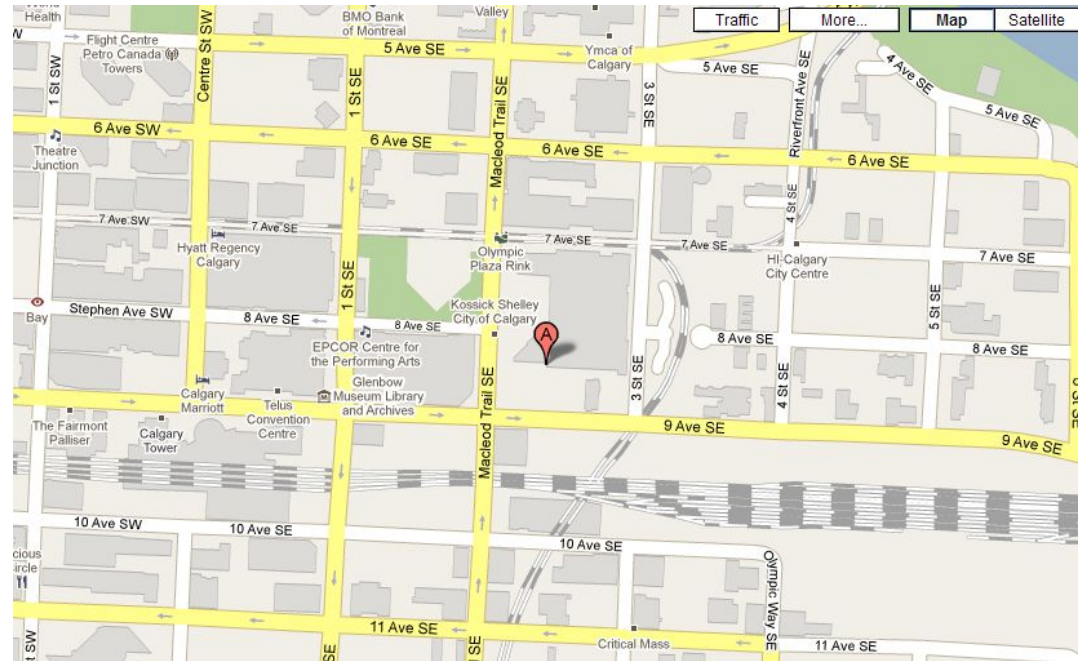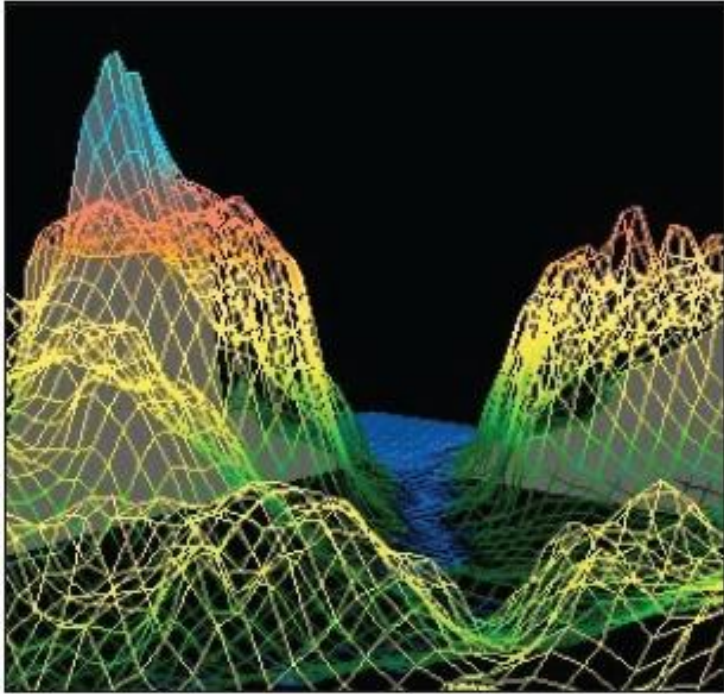Google Street View

GIS

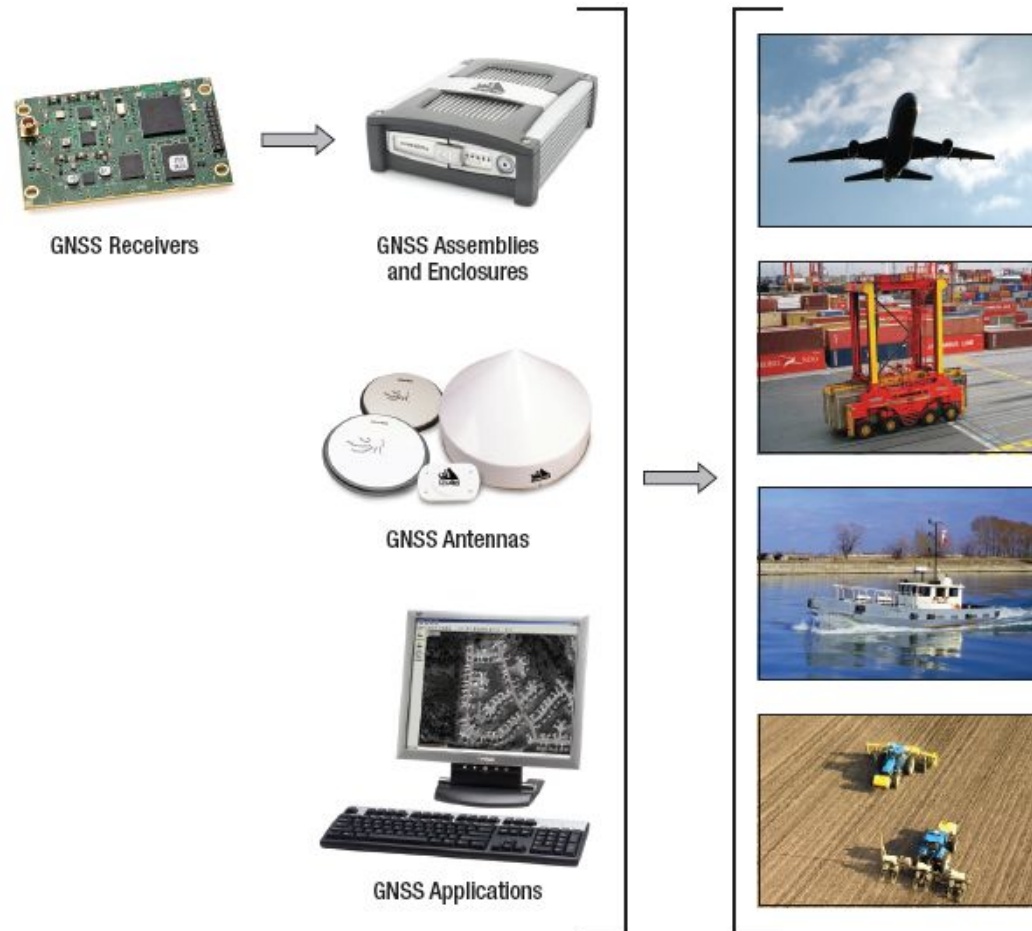Google Map

Port Automation

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Defence

NASA

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Equipment

- There are different types of GNSS equipment available depending on the application and project requirements

GNSS Receivers

GNSS Assemblies and Enclosures

GNSS Antennas

GNSS Applications

Questions?

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