Geospatial Problem Solving

Global Navigation Satellite Systems

Image from NASA:
https://commons.wikimedia.org/wiki/File:Earth_Western_Hemisphere_transparent_background.png#filelinks

AmericaView
Empowering Earth Observation Education
AmericaView.org - Est. 2003

This module will investigate global navigation satellite system or GNSS.

Module Topics

1. How GPS works
2. 3D trilateration
3. Components of the GNSS
4. Position uncertainty and sources
5. Dilation of precision
6. WAAS
7. Post-processing
8. RTK
9. Mission planning

2

These are the topics covered in this module.

Navigation Before GNSS

https://commons.wikimedia.org/wiki/File:USN_Midshipman_takes_a_sextant_reading.jpg

3

Prior to the advent of GNSS, navigation and finding your position on the global was much more complex as we had to rely on the position of the stars and trigonometric surveying techniques.

Now, you can easily find your coordinates using your phone’s built in GPS receiver.

Global Navigation Satellite Systems (GNSS)

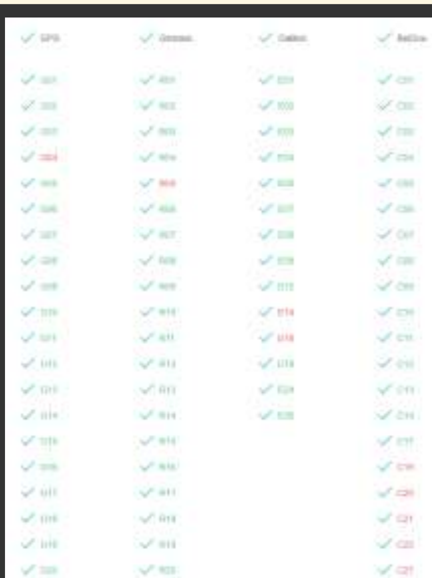
- Satellite-based
- Relative to a datum
- Can be very accurate

- Geodesy = The science of measuring the shape of the Earth and locations on or in the Earth.

4

Geodesy is the science of measuring the shape of the Earth and locations on or in the Earth. GNSS technologies have greatly improved our ability to make measurements on the globe. These technologies rely on satellites, provide coordinates relative to a datum, and can be very accurate.

Global Navigation Satellite Systems (GNSS)



- ❖NAVSTAR = United States
- ❖GLONASS = Russia
- ❖Galileo = European Union
- ❖Compass (BeiDou-2) = China
- ❖QZSS = Japan
- ❖IRNSS = India

http://gnssmissionplanning.com/

5

Different entities have fully functional GNSS systems or are working on developing one.

For example, the United States has the NAVSTAR system, which we commonly just referred to as the GPS system, and Russia has the GLONASS system.

In this module, we will primarily focus on NAVSTAR.

Components of NAVSTAR GPS

https://commons.wikimedia.org/wiki/File:GPS_Satellite_NASA_art-iif.jpg

- Satellite Segment = Constellation of satellites orbiting and transmitting positional signals
- Control Segment = Tracking, communications, data gathering, integration, analysis, and control facilities
- User Segment = Individual with one or more receivers
- GNSS Receiver = A device that records data transmitted by each satellite/process data to 3D coordinates

6

The NAVSTAR systems have three primary components.

The satellite segment is a constellation of satellites that orbit the Earth and transmit positional data. The user segment, such as an individual with a GNSS receiver, can intercept the data transmitted from the satellites to derive a 3D coordinate relative to a datum.

The control segment is responsible for tracking, communication, data gathering, integration, and analysis of the GNSS satellites and data. There are control facilities spread across the globe.

NAVSTAR GPS Satellites

- Altitude ≈ 20,000 kilometers (12,427 miles)
- Orbits = 6
- Daily Orbit = Twice
- Time Above Horizon = 8 or more hours daily
- Typically, there are more than 24 in orbit at one time

https://commons.wikimedia.org/wiki/File:GPS-constellation-3D-NOAA.jpg

7

The NAVSTAR GPS satellites orbit the globe at an elevation of approximately 20,000 kilometers along six different orbital paths.

Each satellite will complete two orbits around the globe daily. At a specific location on the globe, each satellite is viewable for 8 or more hours daily.

Typically, there are more than 24 satellites in orbit at one time just in case some satellites are not operational or there are any issues.

Ground Stations

- Master Station = Colorado Springs
- Number of Stations = 5 tracking stations (Colorado Springs, Hawaii, Ascension, Diego Garcia, Kwajalien)
- Purpose = Observe, maintain, manage, and communication
- Data = Satellite health and status, tracking information, timing
- Master Station Purpose = Synthesizes information and broadcasts navigation, timing, and other data to each satellite/signal for course corrections, changes in operation, or other maintenance

8

Currently the Master Station for NAVSTAR is located in Colorado Springs, Colorado. There are five additional tracking stations spread over the globe.

The main purpose of the control stations is to observe, maintain, manage, and communicate with the satellites. They collect data related to satellite health and status, tracking, and timing.

The master station has additional functions including synthesizing information, satellite course correction, operational changes, and maintenance.

How it Works

https://commons.wikimedia.org/wiki/File:Einstein,_Albert.JPG

- Range Distance = Distance between 2 objects
- Satellite to Receiver
- Range = speed of light X travel time
- Speed of light is a constant
- Also requires timing information
- Relies on radio signals

9

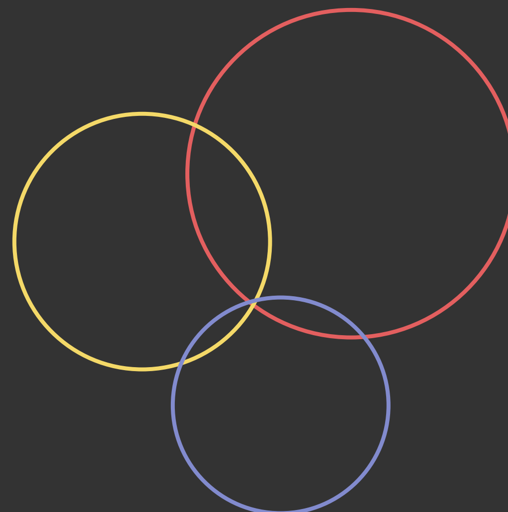
Satellites work by using timing information and our understanding of electromagnetic radiation.

Each satellite sends timing information associated with when the radio waves were transmitted. The receiver then knows when the signal was released and when it was received. So, travel time can be determined.

However, we are really interested in travel distance as opposed to travel time. Luckily, because of the work of Einstein and other scientists, we know that all electromagnetic radiation, including radio waves, travel at a know speed or velocity. So, multiplying this velocity by travel time allows us to calculate a range distance or how far the satellite is from the GNSS receiver.

How it Works: 3D Trilateration

- Need at least 4 overlapping spheres
- Can use three satellites and the Earth
- Generally, more satellites equals greater positional accuracy



10

Distance from one satellite to the receiver is not enough information to find your location, since you could be any direction from the receiver. Imagine that the satellite is located at the center of a sphere with a radius equal to the range distance. The GNSS receiver could be anywhere on the surface of this sphere.

In order to actually estimate your position, the process of 3D trilateration is used to combine range measurements. As demonstrated in the provided image, two circles can intersect at up to two locations. However, three circles can only intersect at one location. So, in 2D space, three range measurements can used to determine your position. However, in 3D space, we must work with overlapping spheres as opposed to circles. You will need 4 overlapping spheres to pinpoint a location.

It is possible to estimate your horizontal location on the Earth using 3 satellites since the datum representing the Earth can be used as the 4th sphere. If you would like to obtain your elevation information along with your horizontal position, you will need measurements from at least 4 satellites.

Generally, more satellites equal greater positional accuracy.

How it works

- ❖Channels = relates to number of satellites that can be detected (12-channel can record up to 12)
- ❖Single Frequency = only picks up L1
- ❖Dual Frequency = picks up L1 and L2
- ❖Ephemeris = data referring to the GPS satellite's position in orbit
- ❖Almanac = data concerning the status of a GPS satellite, which is included in the information being transmitted by the satellite
- ❖C/A Code = the digital code broadcasted on the L1 frequency, which is accessible by all GPS receivers
- ❖P Code = the digital code broadcasted on the L1 and L2 frequencies, which is accessible by the military
- ❖Y Code = an encrypted version of the P code

11

Different signals are made available by the NAVSTAR system.

The number of channels relates to the number of satellites that can be detected. For example, a 12-channel receiver can record information from up to 12 satellites.

Single frequency receivers can only pick up the L1 frequency while dual signal receivers can pick up both L1 and L2 frequencies.

The L1 frequency carries the C/A or coarse acquisition code and is assessable by all civilian receivers. The P code or precise code is broadcasted on the L1 and L2 frequencies and is only assessable by military receivers. The Y code is an encrypted version of the P code and is used to prevent false P code information being sent by hostile forces.

Two sets of data are transmitted from the satellites. The almanac provides data concerning the status of a GPS satellite, its orbit, and its location. The ephemeris data is more precise information about the satellite's location.

GPS Datums

- Location and elevation data are provided relative to a datum and in defined units
- Datum Examples:
  - World Geodetic System 1984 (WGS84)
  - North American Datum 1983 (NAD83)
  - North American Datum 1927 (NAD27)
- It is important to know the datum information!

- Latitude/Longitude
  - Degrees, Minutes, Seconds
  - Degrees, Decimal Degrees
- UTM
  - Easting/Northing
- Elevation
  - Feet
  - Meters

GPS coordinate information is defined relative to a datum or model of the earth. It is important that you know what datum is being used.

Generally, WGS84 is used by the GNSS system. However, this can be changed in the receiver.

Horizontal measurements will be provided in latitude and longitude as degrees, minutes, and second or degrees and decimal degrees. It is also possible to get coordinates relative to a projection, such as a specific UTM zone. If a UTM zone is used, easting and northing measurements will be provided, generally in length units.

Elevation measurements are generally provided in meters or feet relative to a vertical datum. Generally, horizontal measurements are more accurate than elevation measurements.

GIS and GPS

https://geospatial.trimble.com/products-and-solutions/gps-pathfinder-office

How do I get points into my GIS?

1. MxGPS
2. Minnesota DNR Garmin Application
3. Conversion Software
4. Manipulate waypoints in Excel
5. Display XY Data
6. Trimble Software

https://www.dnr.state.mn.us/mis/gis/tools/arcview/extensions/DNRGarmin/DNRGarmin.html

Things to Consider

❖ Must know your datum and units
❖ Must define datum and units correctly
❖ May need to manipulate data

13

There are many tools available for getting GPS measurements into your GPS. Some examples are provided here. Note that some tools are free, such as the Minnesota DNR Garmin Application.

When importing GPS data into your GIS, it is important to know your datum and units.

You may need to manipulate the data to prepare it to be used in your GIS.

Types of Data

- Waypoints = individual, unconnected point locations (x, y, z)
- Tracks = points connected to form lines
- Routes = a series of points that you want to navigate between

14

Different types of data can be collected by GPS units.

Waypoints represent individual point measurements with x, y, and z coordinates.

Tracks are points that are connected to form a line feature.

Routes are points that you want to navigate between but are not connect to form a line.

Positional Uncertainty

- There is noise/error/uncertainty with all range measurements
- Spheres will not meet at a single point
- Fuzziness

15

All measurements have some uncertainty or error, including GNSS measurements. There is noise, error, and uncertainty with all range measurements.

Because of this uncertainty, 2 overlapping spheres, representing the range distances from 2 satellites, will not overlap at a discrete point but as an area. More than 2 spheres will overlap as a volume. So, there will be some fuzziness or uncertainty in the measurements.

Sources of Uncertainty

- Ionospheric and atmospheric delays
- System operation delays
  - Satellite tracking
  - Time and signal delays
  - Loss of sync
- Receiver
- Reflection of signals (multipath)
- Topography
- Canopy cover
- Weather
- Lack of satellite reception
- Movement

16

Measurement uncertainty arises from a variety of factors.

Radio waves travel at a defined speed in a vacuum. However, this speed will vary when outside of the vacuum of space, such as in the atmosphere. So, there will be atmospheric delays that produce uncertainty in the range measurements. There can also be interference from the ionized gases in the ionosphere.

There can be issues with the system operation, such as satellite tracking, time and signal delays, and loss of sync. If you don't know where the satellite is with a high level of accuracy, then this will translate to measurement errors.

There can be issues with receivers.

All electromagnetic radiation, including radio waves, can bend, bounce, and reflect. So, signals picked up by a receiver may not have simply been transmitted straight to the GNSS receiver. Instead, they may have bounced off of nearby topography or buildings, which will artificially lengthen the range distance measurements.

Topography and canopy cover can impact the number of satellites being received. If you are using a GNSS receiver in a canyon or incised valley, satellites near your local horizon may not be viewable as they are masked by the topography. So, you may receive data from a smaller number of satellites. This can also happen in cities where satellite signals are being blocked by tall buildings.

Weather conditions also have an impact, as weather impacts atmospheric delays and interference. Generally, higher quality data can be collected on clear days in comparison to cloudy or stormy days.

Generally, the more satellites that are being collected, the better the measurements, so lack of satellite reception can impact the quality of the collected measurements.

One way to improve GPS measurements is to average data over time. However, this is not possible when you are moving.

Accuracy vs. Precision

- **Accuracy** = agreement with truth
- **Precision** = agreement with other measurements

17

Before we move on, I want to provide a discussion of the difference between accuracy and precision. Since we often use these terms interchangeably colloquially, this can be a bit confusing.

Accuracy represents agreement with truth or the correct measure. Here, we are concerned with whether or not your measurements agree with the correct value on average.

In contrast, precision had to do with whether your data agree with each other or how repeatable your measurements are. This has nothing to do with agreement with the correct value.

The difference here is often explained with a target where the bull's eye represents the correct answer.

The example on the left represents an archer that is not accurate but precise. So, he or she is missing the bull's eye, but each arrow hits in nearly the same place. So, he or she is consistent even if the bull's eye is missed.

The next example shows a pattern that is less precise but accurate. There is more spread in the pattern, or the archer is less consistent, but the average position would be near the bull's eye.

The third example is neither accurate nor precise since the archer is not consistent and the average location would not be near the bull's eye.

The last pattern is both precise and accurate.

As a GNSS-related example, imagine you are collecting GPS measurements at a location. If you get close to the same coordinates each time you take a measurement, then the measurements are precise but not necessarily accurate, as there could be some systematic error or calibration issue.

Measuring Uncertainty based on Satellite positon: Dilution of Precision

- A measure of positional precision
- Horizontal Dilution of Precision (HDOP)
- Vertical Dilution of Precision (VDOP)
- Positional Dilution of Precision (PDOP)
- PDOP = Ratio of the volume of a tetrahedron created by the four most widespread, observed satellites to the volume defined by the ideal tetrahedron
- Generally, better precision is obtained when the satellites are more spread out in the local sky
- Lower PDOP is better
- DOP spikes are bad

http://gnssmissionplanning.com/

18

It is possible to estimate GNSS data precision based on dilution of precision.

More precise data are generally provided when the satellites are more spread out in the local sky. To calculate dilution of precision, we compare the ratio of the volume of a tetrahedron created by the four most widespread, observed satellites to the volume defined by the ideal tetrahedron. The more clustered the satellites are, the lower the precision.

Here, I will differentiate three dilution of precision measurements: HDOP, VDOP, and PDOP.

HDOP, or horizontal dilution of precision, only considers the horizontal coordinate measurements. Elevation is not included.

VDOP, or vertical dilution of precision, only considers the vertical or elevation measurement. Horizontal measurements are not considered.

PDOP, or positional dilution of precision, considers both horizontal and vertical measurements.

Generally, PDOP will be worse than HDOP or VDOP because it is incorporating precision issues for both the horizontal and vertical measures.

VDOP will generally be worse than HDOP because elevation is generally measured with lower precision than horizontal coordinates.

Because DOP is based on the position of the satellites, and the satellites are on fixed orbital paths, it is possible to estimate the DOPs prior to a field collection. This can help you plan for data collections.

Lower DOP is better. DOP spikes are bad or represent time periods when the position of the satellites will cause reduced measurement precision.

You should try to avoid collecting data during DOP spikes.

Increasing Precision

- Collect multiple stationary measurements
  - Not an option for moving objects
  - Can get statistics
- Make use of GLONASS
- Use WAAS enabled unit
- Utilize Differential Correction
  - Post-Processing
  - Real-Time Differential GPS, Real-Time Kinematic (RTK)
  - Using error data provided through cellular networks

https://www.ngs.noaa.gov/OPUS/

19

Many methods are available to potentially increase the precision or quality of our GNSS data.

For example, for a stationary object it is possible to collect multiple measurements and average the results. In fact, when a high quality, survey-grade GPS is placed at a location for at least two hours the measurement will have very little error and will be considered truth.

Having access to more satellites can also improve measurements. Some receivers are capable of communicating with the NAVSTAR and GLONASS constellations, thus potentially increasing the number of measurements that can be collected.

We will discuss more complex methods in the following slides including WAAS, post-processing, and real-time kinematic surveys.

Wide Area Augmentation System (WAAS)

- Satellite-Based Augmentation System (SBAS)
- U.S. Federal Aviation Administration
- Real-time accuracies for single fixes
- Within 4-7 meters
- Can average multiple fixes for increased accuracy
- Correlated relative to broadcasted correction data from ground stations
- Only for NAVSTAR GPS (US System)
- Most handheld units are WAAS enabled
- For real-time needs

https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/howitworks/

20

WAAS, or the Wide Area Augmentation System, is a type of SBAS, or Satellite-Based Augmentation System.

It was originally developed by the US Federal Aviation Administration for aviation and air traffic control purposes and provides real-time corrections, which is very important for air traffic control.

Precision can be increased to 4 to 7 meters using this method. Note that some sources will suggest less than 4 meters.

It works by collecting error information at ground control stations. This error information is then transmitted to satellites that then re-broadcast the correction information.

WAAS-enable receivers can collect this information and use it to correct GNSS measurements in real time.

Currently, WAAS is only designed to work with the NAVSTAR system. However, other SBAS systems are available.

Most handheld units, especially those designed for use with NAVSTAR, are WAAS-enabled.

WAAS is generally used if there is a need for real-time correction; however, post-processing can provide better results.

Post-Processing

- Based on comparison to noise or error at known points (a differential correction)
- Correction applied after raw GPS data are collected
- Can be correct relative to established GPS points (OPUS points from the National Geodetic Survey or CORS data)
- Can be corrected relative to you own base station
- Not useful if you need precise data ahead of time
- Requires specialized software
- Can now correct using cell phone signals

https://www.ngs.noaa.gov/OPUS/

21

Post-processing required that data be corrected after a collection back in the office.

Similar to WAAS, it relies on a differential correction relative to error estimates at ground stations. You can use established base stations or establish your own using survey-grade GPS receivers.

This is not useful if you need real-time correction. However, the results are generally better than using WAAS.

Note that not all receivers are capable of this, including most handhelds units, since raw GPS data must be collected then post-processed. This requires access to specialized software.

It has become possible to perform post-processing in the field using correction information made available through cellular networks. This will require a cellular signal.

Continuously Operating GPS Reference Stations (CORS)

- Highly accurate/precise reference locations for comparison

https://geodesy.noaa.gov/CORS/

Different ground networks are available that can be used to model error and differentially correct GNSS measurements.

One example is the Continuous Operating Reference Stations, or CORS.

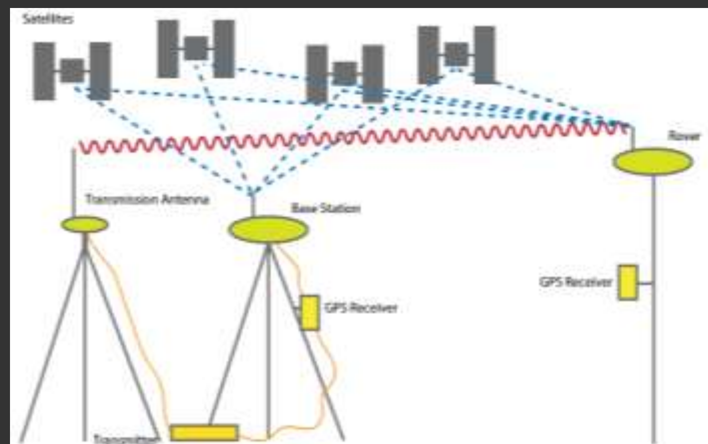
CORS offers a network of GNSS ground stations across the United States and in some other countries.

The correction data can be accessed via the internet to post-process your data.

Again, specialized software and hardware are required.

Real-Time Kinematic (RTK)

- GPS data are collected with a rover
- Correction are made using a base station
- Corrections are transmitted from base station to rover



23

Another form of post processing is real-time kinematic, or RTK, surveys.

In the case of RTK surveys, a base station is established. A second GNSS receiver is then used to collect data as a rover. The roving GNSS receiver collects data relating to its distance from the base station in 3D space.

Back in the office, the base station data are post-processed and corrected. The x, y, and z measurements from the rover are then converted to coordinate using the corrected base station data.

RTK relies on quality x, y, z positional measurements relating to the distance between the base station and rover in combination with post-processed base station data.

Base Stations

https://commons.wikimedia.org/wiki/File:CORS_spicewood_lcrh.jpg

- Survey-grade quality GPS unit
- If GPS data are continuously collected at a location for at least two hours, the location is considered a highly precise/accurate reference location

24

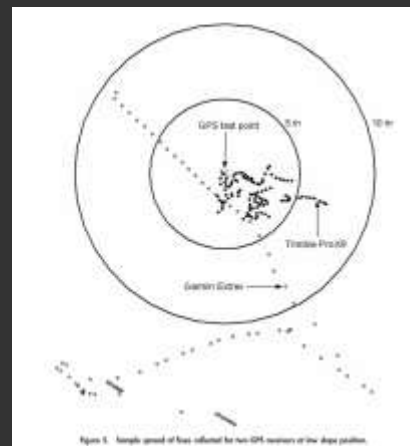
A GNSS base station is a survey-grade GNSS receiver that collects information at a location for an extended period of time.

These stations can be installed semi-permanently with regular maintenance.

If GPS data are continuously collected at a location for at least two hours, the location is considered to be a highly precise/accurate reference location and can be used as ground truth or to correct other measurements.

Accuracy Comparisons

- Horizontal measurements are more accurate/precise than vertical
- One report:
  - Non-corrected = < 10 m horizontal
  - WAAS = 0.3 – 2 m horizontal
  - RTK = 0.05 – 0.5 m horizontal
  - Post-Processed = 0.02 – 0.25 m horizontal
- Accuracy varies with collection conditions
- Depends on project needs and budget



Danskin, S.D., Bettinger, P., Jordan, T.R., and C. Cieszewski (2009). “A comparison of GPS performance in a southern hardwood forest: exploring low-cost solutions for forestry applications.” *Southern Journal of Applied Forestry*, 33(1): 9-16.

25

This slide provides some comparisons for different types of GNSS data. Note that this is just one report and other findings may vary.

Non-corrected GPS data can generally provide horizontal measurements within 10 meters of the correct location. WAAS can improve this to be potentially within 2 meters. Sub-meter accuracy can generally be obtained using post-processing or RTK.

The quality of data that can be or needs to be collected will depend on the project needs and budget. Not all applications require sub-meter accuracy.

Mission Planning

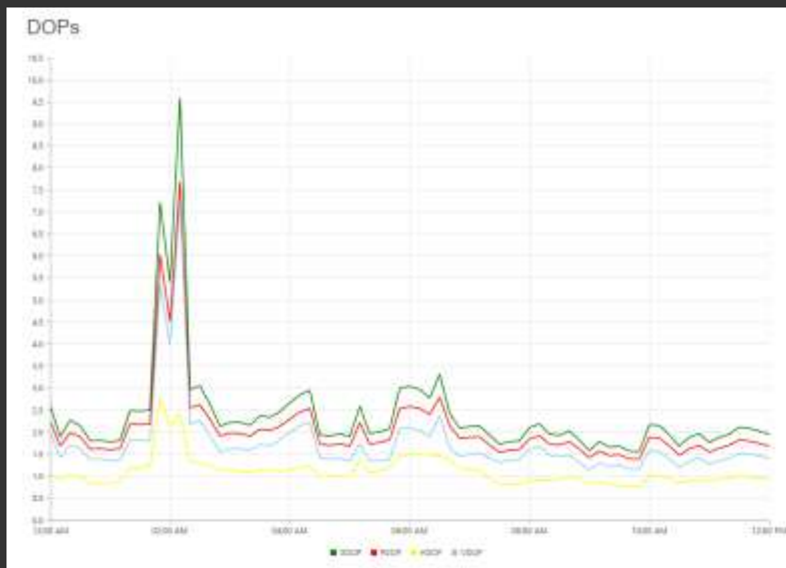
- Since we know where the satellites will be ahead of time, we can plan ahead of data collections.
- I like this software: http://gnssmissionplanning.com/

26

As mentioned above, we can measure DOP prior to a data collection since we know where the satellites will be ahead of time along their fixed orbital paths. This allows us to plan for data collections.

There are many software tools available for GNSS planning. Here, I will demonstrate the Navmatrix tool that is provided as a web interface.

DOP

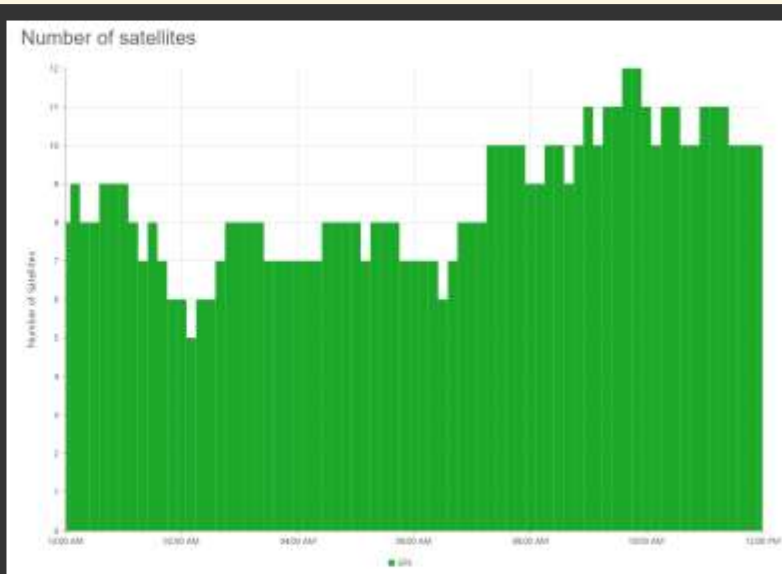


27

This graph represents DOPs over a certain time period. Note that you want to avoid collecting data during DOP spikes, such as 2 AM in this example.

Generally, PDOP will be higher than VDOP, which will be higher than HDOP.

Number of Satellites



28

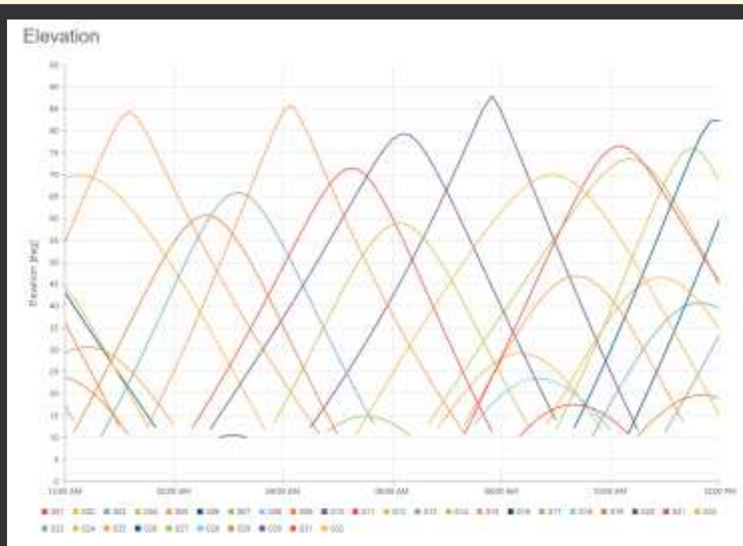
This graph shows how many satellites are potentially visible during a certain time period. This is only showing results for the NAVSTAR system.

If you compare this to the DOP graph, you should see a correlation between DOP and the number of satellites. More satellites generally reduces DOP or improves the precision.

Satellite Visibility

This graph shows over what time period each satellite in the constellation is observable at this location during the specified time period.

Satellite Elevation



30

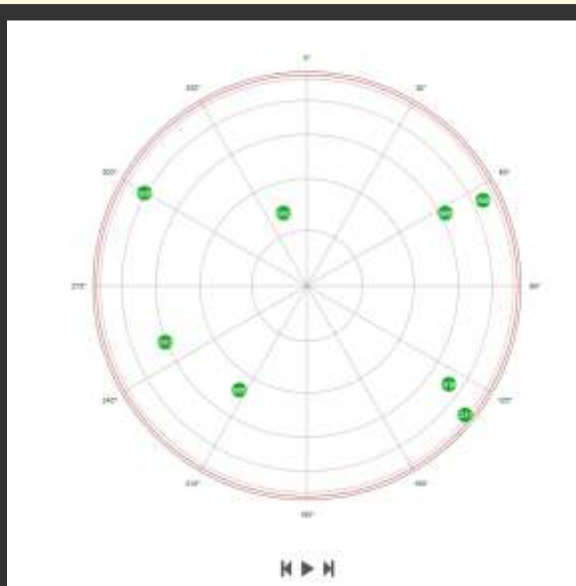
This graph shows the height of each satellite in the local sky.

Note that satellites tend to come into view at the horizon, move higher into the sky and closer to the zenith, then fall out of view after passing beneath the horizon again.

As satellites leave the view or local sky, more satellites pass into view.

Note in this graph that it is assumed that satellites that are within 10 degrees of the horizon will not be viewable due to topographic effects. So, the graphs stop at 10 degrees as opposed to the horizon or 0 degrees.

Sky Plot



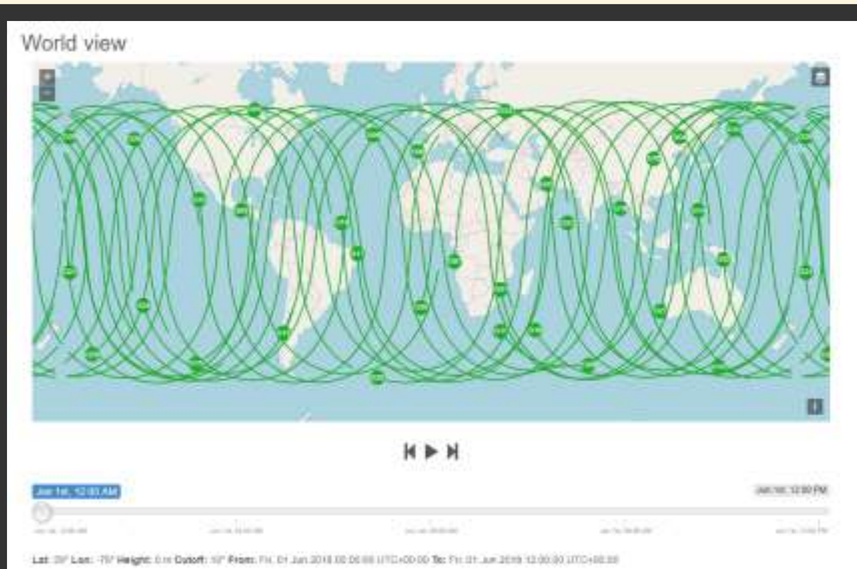
31

The sky plot represents the local sky or the dome over the receiver. The outside markings represents the compass direction or azimuth in which the satellite is being viewed while the radiating circles represent the angle above the horizon.

The center point represents the zenith or point directly above the receiver. The outer margin represents the horizon. So, a 3D dome is represented as a 2D graph. The location of an object in the local sky can be defined using the direction in which to look, or the azimuth, and the height above the horizon, or altitude. This graph provides both measurements.

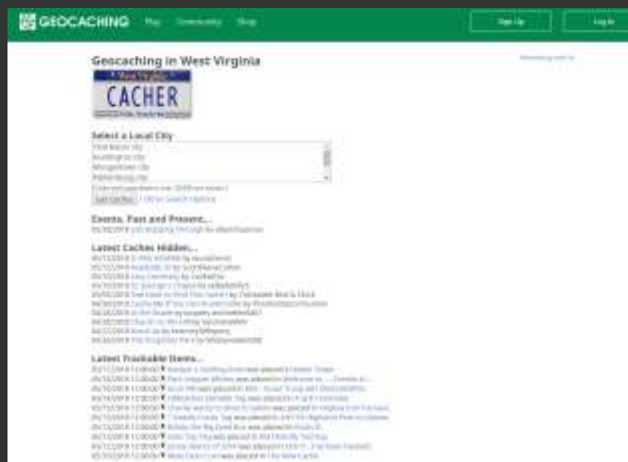
This graph will play as a video to show how satellites move through the local sky at the defined location throughout the defined time period.

Sky Orbit



You can also view satellite orbits as a video at the global scale.

Geocaching



https://www.geocaching.com

33

A fun application of GNSS is geocaching in which you search for hidden treasures using your handheld GNSS or phone.

Here is a link to a website that provides a list of geocache locations in different areas.

This is the end of this lecture module.

Please return to the West Virginia View Webpage for additional content.

Thanks! Hope you found this useful.