Lecture 14.01 The Global Positioning System (GPS)

LaACES Student Ballooning Course

What is GPS?

- GPS (Global Positioning System) is a constellation of satellites that orbit the Earth
- Each satellite completes two orbits a day in one of six orbits
  - Orbits designed so there are 6 satellites in view from most places on Earth
- A GPS device allows a user determine his/her position by receiving the signals from multiple satellites

GPS Satellite Constellation

- There are currently 31 operational satellites in the 24-slot constellation (6 orbits x 4 slots)
- These satellites orbit in 1 of 6 orbital planes
  - These planes have an altitude of ~ 20,200 km
  - Each satellite orbits the Earth twice a day
- In 2011, the Air Force completed the "Expandable 24," a constellation expansion. 3 planes expanded to allow an extra satellite became part of the constellation baseline. GPS is now, effectively, a 27 slot constellation

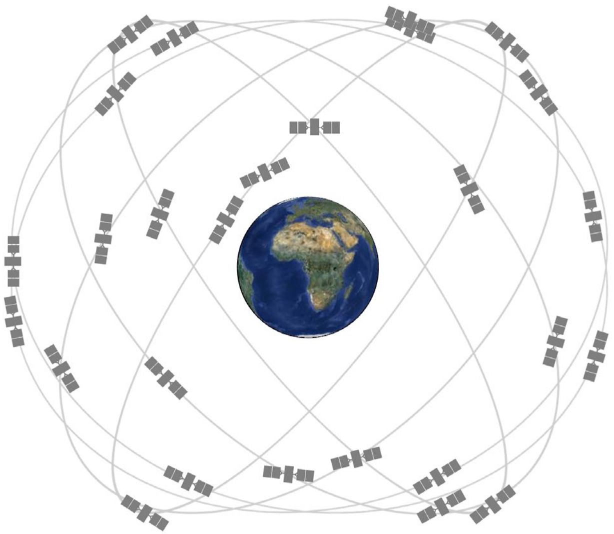

Figure 1: Shown is 24-slot satellite constellation. This configuration ensures that GPS users can view 4+ satellites from almost any point on the planet

Motivations Behind GPS

- World War II and the Cold War provided the justification for countries to research, develop, and deploy various navigational systems
- Some predecessors to our current GPS include: LORAN, Decca, Sputnik 1, TRANSIT, SECOR, Timation satellite, and OMEGA
- Development of these systems were driven by the military. Better systems were needed for missile accuracy and navigation for ships, submarines, and aircrafts

GPS History

- 1973: GPS project launched
  - Created/owned by the United States government, operated by the Air Force
  - Cold War arms race justified the billions of dollars to research, develop, deploy, and operate a constellation of navigational satellites
    - Ballistic missile submarines needed accurate fixes of their positions before launching.
    - Intercontinental ballistic missiles and strategic bombers required a more accurate and reliable navigational system
  - Inventors: Roger L. Easton (Naval Research Laboratory), Ivan A. Getting (Aerospace Corporation), Bradford Parkinson (Applied Physics Laboratory)
- 1978: First satellites launched into orbit
- 1995: Full constellation of satellites in orbit

Selective Availability

- In the 1990s, the US government degraded GPS accuracy for civilians on a global scale (Selective Availability)
  - President Clinton turned off Selective Availability in May 2000
  - According to the US government, they have no intention to ever use Selective Availability again
- Civilian Restrictions
  - Receivers capable of operating above 18 km and 515 m/s or that are designed / modified for use with missiles require a State Department export license
    - These devices are classified as weapons
    - Disabling operations above the limits exempts the receiver from a weapon classification

Non-US Positioning Systems

- Russia – GLONASS (Global Navigation Satellite System)
  - Global coverage since 2000s. Currently being restored to full availability
- European Union – GALILEO
  - 30-satellite system to be completed by 2020
- China – BeiDou Navigational Satellite System
  - Global coverage since December 27, 2018
- Japan – QZAA (Quasi-Zenith Satellite System)
  - Currently only 4 satellites in orbit – regional coverage
- India – NAVIC (Navigation with Indian Constellation)
  - Currently 7 satellites in orbit – regional coverage

Different countries' systems can be added to GPS devices

Multi-Constellation devices are called GNSS

More available satellites = quicker and more accurate fixes

How Does GPS Work?

- Trilateration used by GPS receivers to calculate their position
- GPS satellites broadcast radio signals that include their location and time
  - Satellites' time is very accurate due to atomic clocks onboard
- GPS devices receive these signals and use the arrival time to calculate the distance between themselves and a satellite
  - $D = \text{speed of light} * (t_{received} - t_{transmitted})$

Figure 2: Shown are three satellites. For the trilateration example, we will assume these are the satellites observed by a GPS receiver

Trilateration

- All of the possible points from a single location create a circle
- For satellite 1, we can draw a circle with radius D1 around it. The GPS receiver must be somewhere on the circle
    - Same process for satellites 2 and 3
- Since the GPS receiver must be somewhere on each circle, the intersection of these circles is the receiver's position

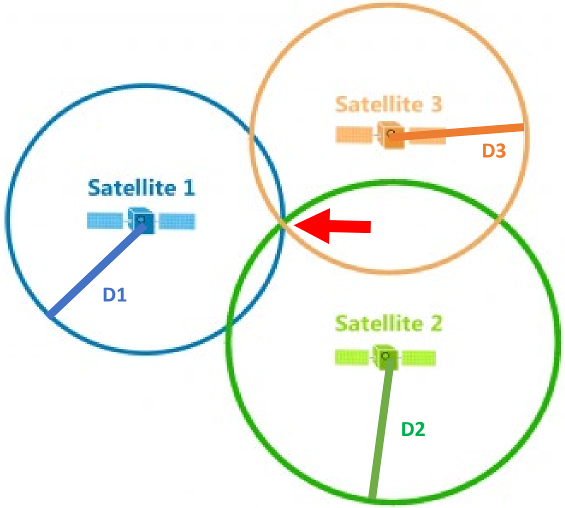

Figure 3: Shown are the circles that represent the distance from each satellite. The intersection of the three circles, as shown by the red arrow, is the location of the GPS receiver

Trilateration Continued

- We live in a 3D world, so each satellite is actually in the center of a sphere, not a circle
  - The intersection point of all spheres is the position of the GPS receiver, but there are 2 intersection points with 3 spheres
- To achieve a fix in all dimensions, a GPS receiver must be receiving information from 4 satellites

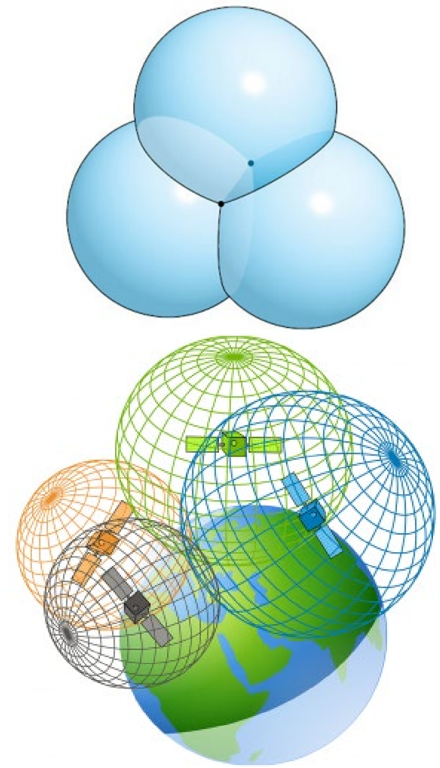

Figure 4: Top – The intersection of 3 spheres is two points, not one point. This means 3 satellites are not enough to obtain a 3D fix
Bottom – Shown are the spheres that represent the distance from each satellite. It is the intersection of 4 spheres that give a GPS receiver its position

Finding Your Position Summary

- GPS receivers get time and location information from satellites. By calculating the distance from themselves to each satellite, a receiver can find their position
- With 3 satellites in view, a GPS receiver can determine its latitude and longitude.
  - This is called a 2D fix
- With 4 satellites, a GPS receiver can find its latitude, longitude, and altitude
  - This is called a 3D fix

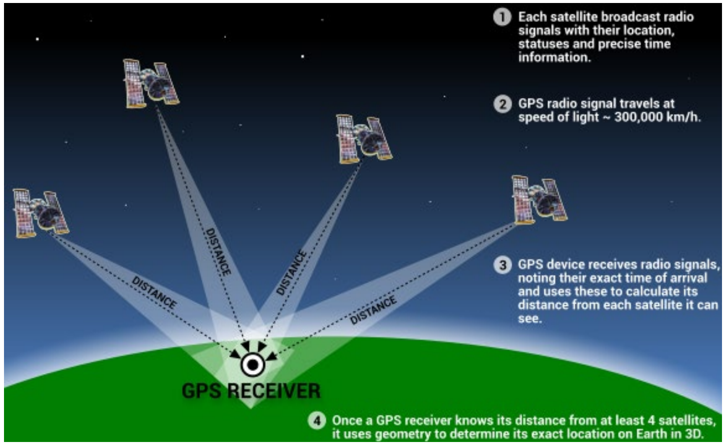

Figure 5: A GPS receiver needs 4+ satellites in view in order to calculate its latitude, longitude, and altitude. Once the receiver knows its position, it can calculate other information like speed or distance to destination

GPS Accuracy

- Although GPS satellites are required to broadcast their signals with a certain accuracy, a device's accuracy depends on a variety of factors
  - Clock Errors
  - Atmospheric Conditions
  - Satellite Geometry
  - Signal Blockage
  - Receiver Quality
- Most smartphone GPS are accurate to within 4.9m (16ft). This accuracy gets worse near large objects, such as buildings and trees
- High precision GPS receivers can be accurate to within a few centimeters

Clock Errors

- Satellite clock errors: GPS satellites have atomic clocks on board. These are extremely accurate but can drift. This drift produces errors
  - The errors are minimized by calculating clock corrections at monitoring stations. These monitoring stations transmit their corrections + the GPS signal to GPS receivers
- Receiver clock errors: GPS receivers don't have atomic clocks; they have quartz crystal clocks. These are less stable and less accurate
  - The error from this clock is eliminated by comparing the arrival times of two satellites whose transmission times are known exactly.

Atmospheric Conditions

- Changes in atmospheric conditions affect the speed of GPS signals as they pass through different layers of the atmosphere
  - The transmission can slightly bend like light trough a prism
  - These speed changes result in errors in position and time
  - When a satellite is directly overhead, these errors are minimized. Satellites near the horizon have a longer atmospheric path for their signals, so these errors are greater

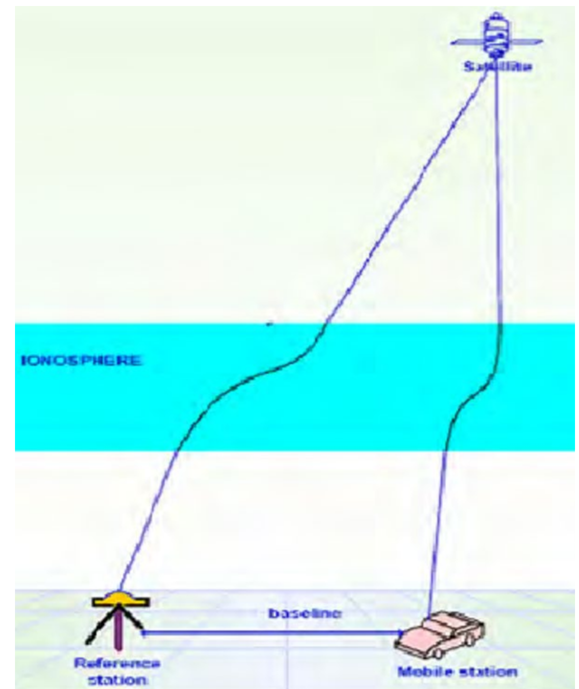

Figure 8: Shown is an exaggerated view of the GPS signal path. Traveling through the atmosphere causes delays and deflections of the GPS signal

Atmospheric Conditions: Ionosphere

- In the ionosphere(layer of charge particles in atmosphere), GPS signals are both deflected and delayed. Due to the varying density of the ionosphere, the delays and deflections aren't consistent over the signal's path
- Based off ionosphere models, GPS monitoring stations calculate and transmit corrections to satellites. This removes about 75% of ionosphere errors
- The ionosphere delay of a signal depends on the signal's frequency. By measuring the delay in multiple frequency bands, the dispersion error can be calculated

Atmospheric Conditions: Troposphere

- The delay caused by the troposphere depends on temperature, pressure, humidity, and the locations of the receiver and transmitter
  - It is not frequency dependent. This means, unlike ionosphere errors, using multiple frequencies cannot remove this error
- Hydrostatic component
  - Dry gases in the troposphere cause errors. The error varies with temperature and pressure, but can be calculated using ideal gas laws
- Wet component
  - Water vapor and clouds also cause delays. The delay is small (10s of cm) but varies fast and is harder to model

Satellite Geometry

- Geometric Dilution of Precision (GDOP) is error caused by viewing satellites that are too close together
- Figure 6 shows an example of this principle
  - In A, someone has measured their distance from two landmarks, and then drawn circles with corresponding radii around the landmarks. Their position is the intersection of the circles
  - In B, they have included error bounds in their circles. Their position is anywhere within the green shaded region
  - C is the exact same as B, but the landmark positions have changed. Because of the landmarks' positions, the error of the user's position has increased drastically

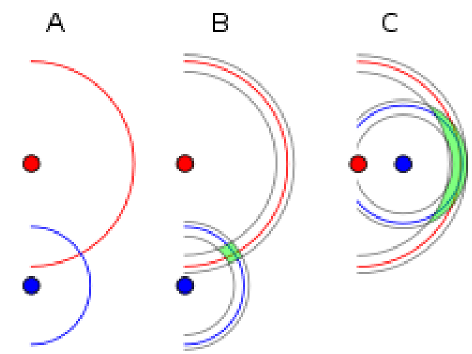

Figure 6: Shown is an example of DGOP. A user knows the distances between themselves and two landmarks (red and blue dots)

A) By drawing circles around the landmarks corresponding to the known distances, the user can pinpoint their location as the circles' intersection
B) There are errors associated with the distance measurements. This means there is uncertainty in the user's position. The user's position is somewhere in the green shaded area
C) With poorly positioned landmarks, the area containing the user's position in can grow. This is Geometric Dilution of Precision

Signal Blockage

- Satellite signals can be blocked by buildings, bridges, trees, etc.
- Using GPS underground or indoors can also degrade the signal
  - Having difficulty inside? Move the receiver closer to a window
- Reflected signals also cause errors; this is called multipath. The original signal is blocked, but the receiver receives a reflected signal
- Less common signal degradation culprits: radio interference, solar storms, satellite maintenance

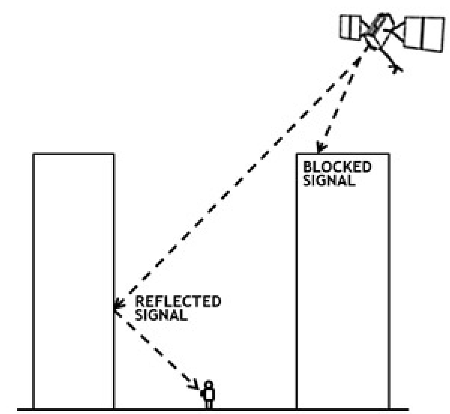

Figure 7: Shown is an example of multipath. The real GPS signal is blocked from the receiver by a tall building. Another GPS signal is reflected off a second building and is then received by the user. Using this signal would result in incorrect position information for the receiver

Receiver Quality

- GPS receivers that use more than one frequency result in more accurate positions than receivers only utilizing one frequency
- Military receivers use dual-frequency
- Most civilian receivers only utilize one frequency for GPS signals
  - Dual-frequency GPS receivers are available for civilian use, but they are expensive. This has the effect of limiting the civilian use of dual-frequency GPS receivers to mostly professional applications

Differential GPS (DGPS)

- DGPS is a system that provides corrections to position data. By using a fixed, known position of a GPS base station, a receiver can adjust real time GPS signals to eliminate errors
  - This can result in accuracies on the centimeter level
  - DGPS corrections are only applicable for positional data
- Useful for surveying work

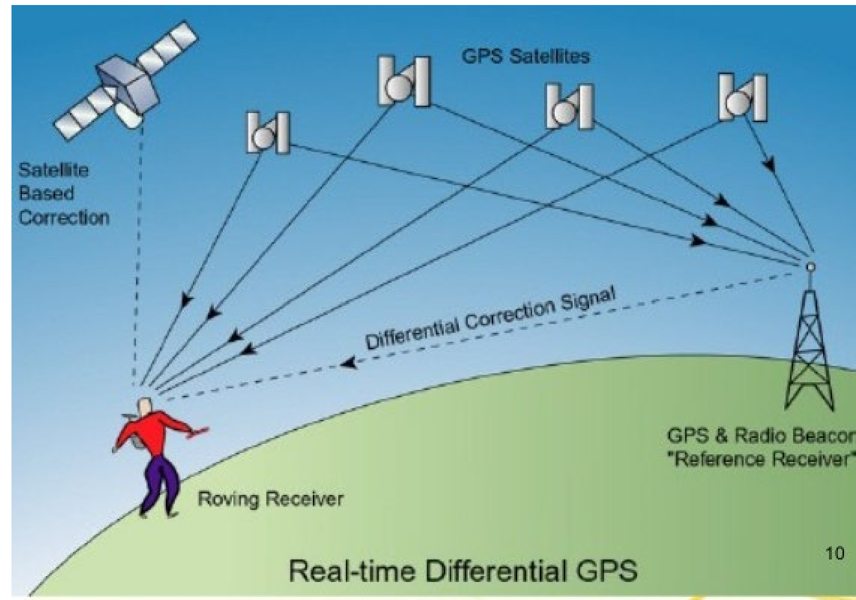

Figure 9: Shown is a caricature of DGPS. A receiver uses the normal 4 satellites to calculate its position. Then, signal from a beacon with a fixed, known location is used to help eliminate errors

GPS Applications

- Location
- Navigation
- Tracking
- Mapping and Surveying
- Time Synchronization

GPS Communication

- GPS signals encode data for receivers. A receiver can request specific types of information. The standard format for the transmitted information is a National Marine Electronics Association (NMEA) sentence
- NMEA Sentences are text strings with predefined data in a certain order separated by commas
- There are multiple NMEA sentences. The main 6 are: RMC, GGA, GLL, VTG, GSA, and GSV

NMEA Sentences: Information provided

- RMC – Recommended Minimum
  - Time, status, latitude, longitude, speed, track angle, data, magnetic variation
- GGA – Essential data
  - Time, latitude, longitude, fix quality, number of satellites being tracked, HDOP, altitude, height of geoid, time since last DGPS update, DGPS station ID number
- GLL – Geographic Latitude and Longitude
  - Latitude, longitude, time, status
- VTG – Velocity Made Good
  - True track, magnetic track, ground speed
- GSA – GPS DOP and active satellites
  - Fix status, PRNs of satellites used for fix, PDOP, HDOP, VDOP
- GSV – Satellites in View
  - Number of satellites in view, satellite PRN number, elevation, azimuth, SNR

NMEA Sentence: GGA Layout

$GPGGA,hhmmss,llll.ll,a,yyyy.yy,a,x,xx,x.x,x.x,M,x.x,M,x.x,xxxx*hh

0 , 1 , 2 ,3, 4 ,5,6,7, 8, 9,10,11,12,13,14 15

1. hhmmss.ss Time of fix hh:mm:ss UTC
2. llll.ll Latitude: ll degrees 07.038 minutes
3. a Direction. N = North. S = South.
4. yyyy.yy Longitude: 11 degrees 31.000 minutes.
5. a Direction. E = East. W = West.
6. x Fix quality: 0 = no fix. 1 = GPS fix. 2 = Differential GPS fix. 4 = Real-Time Kinematic (RTK) fixed integers. 5 = RTK float integers. 6 = Dead reckoning. 7 = Manual input mode. 8 = Simulator. 9 = WAAS.
7. xx Number of satellites being tracked
8. x.x Horizontal dilution of position
9. x.x Altitude
10. M Meters (units for 9)
11. x.x Relationship between geoid and WGS84 ellipsoid
12. M Meters (units for 11)
13. x.x Time (seconds) since last DGPS update
14. xxxx DGPS station ID number
15. *hh Checksum

NMEA Sentence: RMC Layout

$GPRMC,hhmmss,A,llll.ll,a,yyyy.yy,a,x.x,x.x,ddmmyy,x.x,a,A*hh

1. hhmmss.ss Time of fix hh:mm:ss UTC
2. A Signal status. A = Active Signal. V = Void, no signal.
3. llll.ll Latitude: ll degrees 07.038 minutes
4. a Direction. N = North. S = South.
5. yyyy.yy Longitude: 11 degrees 31.000 minutes
6. a Direction. E = East. W = West.
7. x.x Speed over ground, knots
8. x.x Track angle (degrees, True)
9. ddmmyy Date of fix
10. x.x Magnetic variation 20.3 degrees
11. a Magnetic variation direction
12. A Positioning system mode indicator. A = autonomous. D = differential. E = estimated. M = manual input. N = data not valid.
13. *4A Checksum