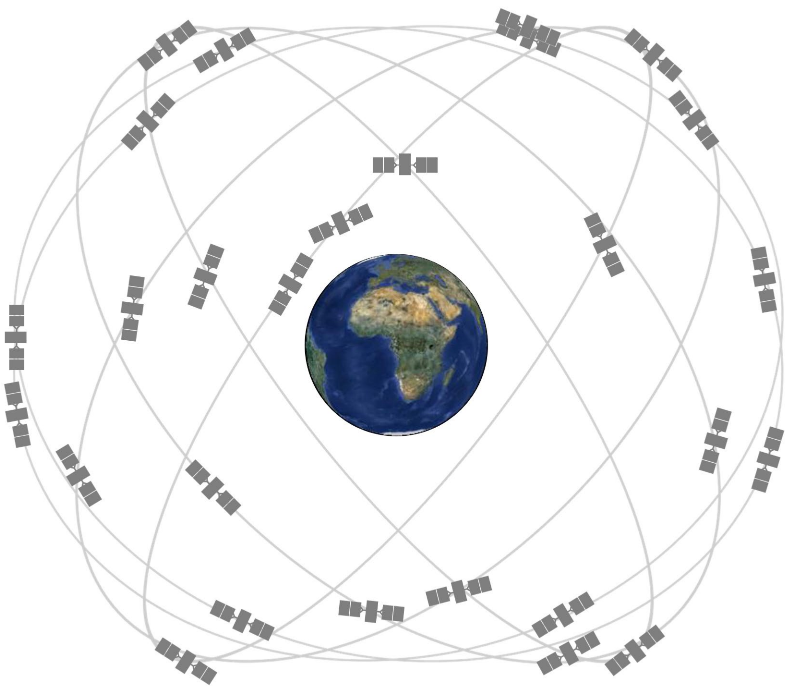
The Global Positioning System (GPS)

What is GPS?

- GPS (Global Positioning System) uses a constellation of satellites that orbit the Earth
- A GPS receiver receives highly precise timing signals from these satellites and calculates its position in 3-dimensional space (Latitude, Longitude, and Altitude)

GPS Satellite Constellation

- Minimum operation of the GPS system is a 24-slot constellation (6 orbits x 4 slots)
  - Normal operation is 31 active satellites
- These satellites orbit in 1 of 6 orbital planes
  - These planes have an altitude of ~20,000 km
  - Each satellite orbits the Earth twice a day (12-hour orbit)
- The current status of the constellation, along with status messages, can be viewed online
  - https://www.navcen.uscg.gov/gps-constellation



The 24-slot satellite constellation. This configuration should ensure at least 6 satellites are visible form any point on Earth

GPS Operation Restrictions

- Civilian Restrictions
  - Receivers capable of operating above 18 km **AND** 515 m/s could be used as weapons guidance and require a State Department export license
  - A GPS should disable itself when it exceeds these limits
  - Some receivers would shut themselves off with either condition, leading to failure during balloon flights
  - A balloon payload will travel below the speed limitation, so receivers should function throughout the flight
  - We have occasionally seen the Adafruit GPS fail at 10 km, but this seems to be unrelated

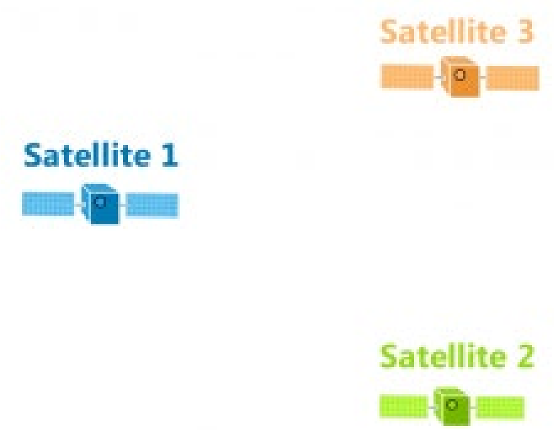
Other Satellite Positioning Systems

- Russia – GLONASS (Global Navigation Satellite System)
  - Global coverage since the 2000s
- European Union – GALILEO
  - 25 - Active satellites as of 2025
- 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

- Multi-Constellation receivers use the term **Global Navigation Satellite System** (GNSS)
- Because of technology improvements, even inexpensive receivers like the Adafruit GPS can receive multiple constellations

How Does GPS Work?

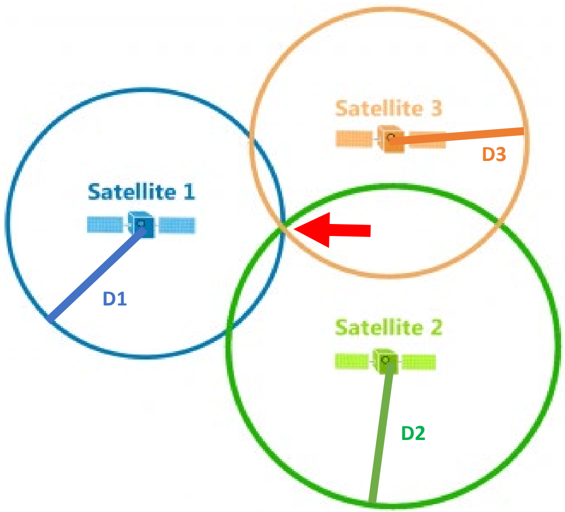
- GPS satellites broadcast radio signals that include their location and time
  - Satellites' time is very accurate due to atomic clocks onboard
- GPS devices receive these signals and use the arrival time to calculate the distance between themselves and a satellite
  - So the distance D from the orbiting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



Each Satellite broadcasts its location and time of broadcast

Trilateration

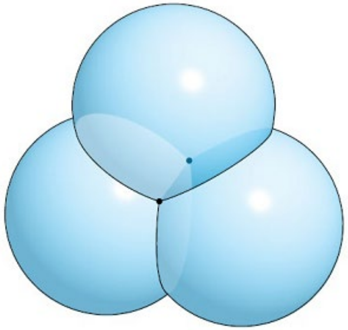
- For each satellite, draw a circle of radius D around it
- The GPS receiver must be somewhere on the circle
  - The same process is repeated for all actively tracked satellites
- Since the GPS receiver must be somewhere on each sphere, the intersection of these circles is the receiver's position

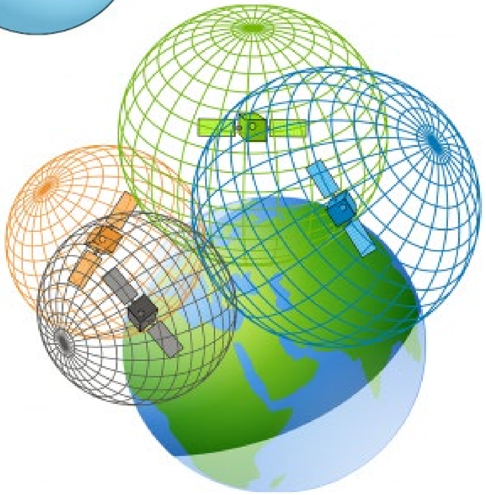


The circles represent the distance from each satellite. The intersection of the three circles, as shown by the red arrow, is the location of the GPS receiver

Trilateration Continued

- In 3D, so each satellite is the center of a sphere, not a circle
  - The intersection point of 3 spheres has two possible positions
- To achieve a fix in 3 dimensions, a GPS receiver must track 4 satellites at a minimum
- With 3 satellites in view, a GPS receiver can determine its latitude and longitude by assuming it is "close" to the surface of the Earth
  - 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





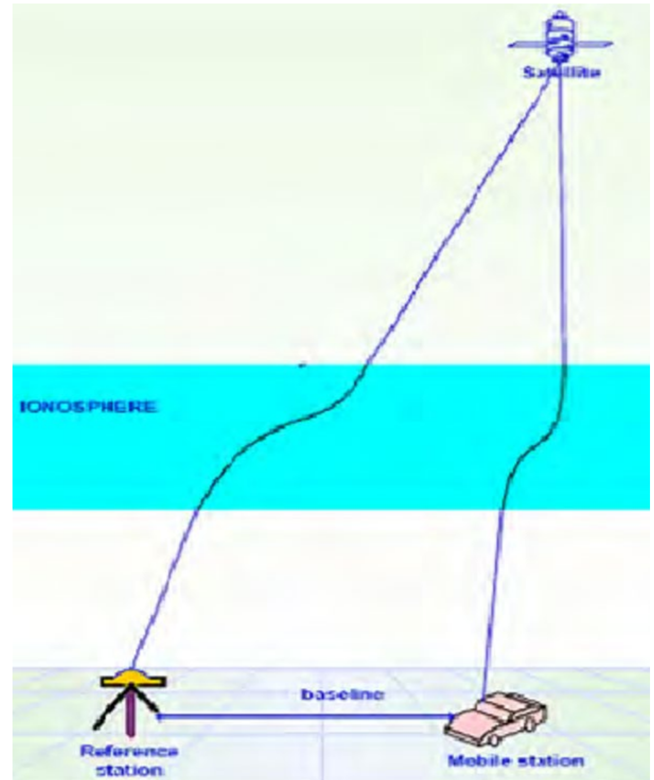
Top – The intersection of 3 spheres is two points, not one point. This means 3 satellites are not enough to obtain a 3D fix
Bottom – Shown are the spheres that represent the distance from each satellite. It is the intersection of 4 spheres that give a GPS receiver its position

GPS Accuracy

- Because GPS requires such precise timing, the accuracy of position is by
  - Atmospheric Conditions
  - Clock Errors
  - Signal Blockage and Multipathing
  - Satellite Geometry (Dilution of Precision)
- Most smartphone GPS are accurate to within ~5m (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

Atmospheric Conditions

- The GPS signal is not traveling through a vacuum to the receiver but has to travel through the layers of the atmosphere
- In the ionosphere(layer of charged particles in the atmosphere), signals of different frequencies are deflected or travel at slightly different speeds
  - These effects can be measured by ground stations and corrections broadcast to receivers
- In the troposphere (lowest region of the atmosphere) changes in humidity and air pressure also cause slight variations in signal speed
  - These are localized to specific weather between a satellite and receiver, so are difficult to correct



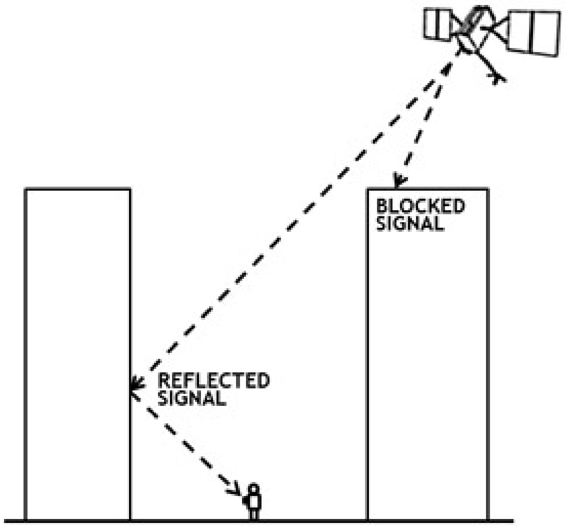
Shown is an exaggerated view of the GPS signal path. Notice that the delay can be measured by a reference station and a correction broadcast to a mobile receiver

Clock Errors

- Satellite clock errors: GPS satellites have atomic clocks on board
  - These are extremely accurate but can drift over time
  - The errors are minimized by calculating clock corrections at fixed 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
  - The accuracy of these clocks varies from receiver to receiver
  - The error from this clock can be corrected by comparing the arrival times of two satellites whose transmission times are known exactly

Signal Blockage

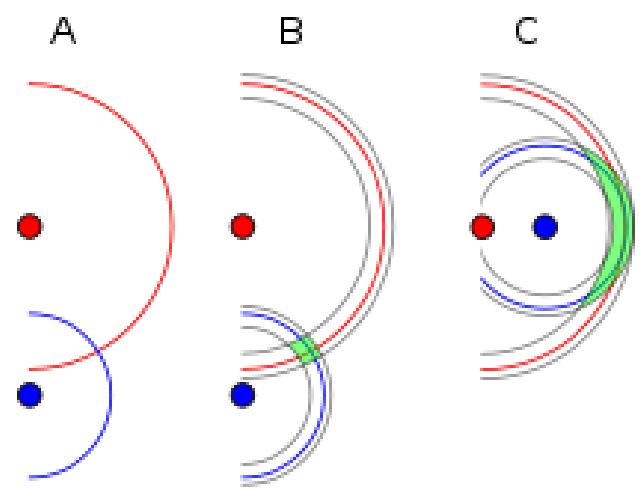
- The signal has to get to the receiver to be used
- Satellite signals can be blocked by buildings, bridges, trees, etc.
- Reflected signals also cause errors; this is called multipath. The original signal is blocked, but the receiver receives a reflected signal, and the reflected signal's path will be longer
- Using GPS indoors or near buildings, the signal will be degraded
  - Having difficulty inside? Move the receiver closer to a window
  - This is not a concern during flight, but receiving signals in the lab can be a challenge



The direct GPS signal is blocked from the receiver by a tall building. Another GPS signal is reflected off a second building and is then received. This effect is greatly exaggerated in the picture.

Satellite Geometry

- These effects cause uncertainty
- Geometric Dilution of Precision (DOP) is an error caused by the position of the satellites
- The figure shows this effect
  - In A, someone has measured their distance from two satellites and draws circles with corresponding radii
  - In B, error causes the circles to have thickness, but because of the position of the receiver, the possible region (in green) is small
  - In C, the distance error is the same, but now the overlapping region is much larger, so the positions are less well known



An example of DOP. A user knows the distances between themselves and two satellites (red and blue dots)

A) With perfect precision, the user knows their exact position.

B) For a given error, the circles gain some thickness. In B, there is a small region of uncertainty

C) In C, the same error give a much larger Dilution of Precision, solely do to the location

GPS Receiver Output

- The standard output for a GPS receiver is an ASCII text string over UART
- The standard format for the transmitted information is a National Marine Electronics Association (NMEA) sentence
  - Usually spoken Knee - Mah
- Each NMEA Sentence is a text string of predefined data in order, separated by commas
  - Different NMEA sentences will have different information
- Starts with a $ and ends with <CR><LF>
- Several references are available online giving the format
  - https://cdn.sparkfun.com/assets/a/3/2/f/a/NMEA_Reference_Manual-Rev2.1-Dec07.pdf

Common NMEA Sentences: Information provided

There are many different NMEA sentences but here are the most common (with GGA

- RMC – Recommended Minimum
  - Time, status, latitude, longitude, speed, track angle, date, 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
- GSV – Satellites in View
  - Number of satellites in view, satellite PRN number, elevation, azimuth, Signal Strength

Notice how is we want a date AND an altitude we need both GGA and RMC

Example NMEA Sentence: GGA Layout

$GPGGA,002153.000,3342.6618,N,11751.3858,W,1,10,1.2,27.0,M,-34.2,M,,0000*5E

$GPGGA,hhmmss,llll.ll,a,yyyy.yy,a,N,xx,H.H,A.A,M,g.g,M,S.S,IIII*hh

1 , 2 , 3 ,4, 5 , 6, 7,8, 9, 10, 11,12,13,14,15 16

1.	GPGGA	Message ID, indicates GGS. For a GNSS fix (GPS + other constellations) will be GNGGA
2.	hhmmss.ss	Time of fix hh:mm:ss UTC
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.	N	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. Ours will be 0, 1 or 2
8.	xx	Number of satellites being tracked (0 to 12)
9.	H.H	Horizontal dilution of position as unitless number
10.	A.A	Altitude above Mean Sea Level (MSL)
11.	M	Meters (units for altitude)
12.	g.g	Relationship between geoid and WGS84 ellipsoid, this is a correction for the earth not being a sphere
13.	M	Meters (units for 11)
14.	S.S	Time (seconds) since last DGPS update, this is a position correction from a ground station
15.	III	DGPS station ID number, an ID for the ground station used in the correction
16.	*hh	Checksum in hex, this is the result of a checksum calculation on the previous bytes in the string, by repeating the calculation you can verify you did not miss any characters in the string