Before GPS we had “follow the stars.” sextant, chronometer, and radio such as Loran. First satellite navigation was TRANSIT.
The Four Basic Functions of GPS

• Position and coordinates
• Distance and direction between two waypoints
• Travel progress reports
• Accurate time measurements
An Early Satellite Navigation System – TRANSIT (1964 to 1968)

TRANSIT (aka NAVSAT & NNSS)

Location for naval Polaris ballistic missile submarines.

Based upon Doppler shift with 150 MHz and 400 MHz signals.

By 1968 TRANSIT had 36 satellites in polar orbits.

A satellite moves at 17,000 mph.

The Global Positioning System (GPS), originally NAVSTAR GPS, is a satellite-based radio-navigation system owned by the United States government and operated now by the United States Space Force. It is one of the global navigation satellite systems (GNSS) that provides geolocation and time information to a GPS receiver anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites. Obstacles such as mountains and buildings block the relatively weak GPS signals. Five ground stations support GPS.
GPS is a World-Wide Radio-Navigation System

A World-wide radio-navigation system using “man-made stars” \textit{(i.e., satellites)} for referencing positions on the Earth, calculating position (accurate to matter of meters). Can also determine speed, bearing, tacking, distance to destination and sunrise and sunset times.

“Man-made stars” for navigation

Signal’s “time-of-flight” used to find distance.

GPS Receiver

The Global Positioning System (GPS) is a constellation of at least 24 artificial satellites. The GPS satellites are uniformly distributed in a total of six orbits such that there are four satellites per orbit. There are two full orbits per day for each satellite. Satellite altitude is 12,472 miles. Each satellite has its own PR code.

As of February 2020 there were 31 operational satellites in GPS. Orbit time is 11 hours, 57 minutes, & 57.26 seconds.

http://learntoflyblog.com/2016/02/01/aircraft-systems-gps/
Using Trilateration for Determining Position

Trilateration uses distances and not angles (triangulation).

Satellites signals are synchronized

Three satellites work but four satellites are better.

https://gisgeography.com/trilateration-triangulation-gps/
Measuring distance With GPS PRN Signals

Distance = Speed of Light • Time Difference

Trilateration Requirements

- To triangulate, a GPS receiver measures distance using the travel time of radio signals.
- To measure travel time, GPS receiver needs very accurate timing.
- Along with distance, receiver need accurate data on where satellites are in space.
- System will also need to correct for any delays the signal experiences as it travels through atmosphere.

History of GPS Introduction

The need for a very accurate navigation system came out of the Cold War – the Pentagon begins a feasibility study in the 1960s. Military needs are the motivation for GPS.

In 1963 Aerospace Corporation completed a study of a proposed GPS system for the military (it was approved).

The NAVSTAR program receives funding beginning in 1973 by the Department of Defense.

The first four GPS satellites are launched in 1978.

In April 1995, the 24th satellite is launched and the GPS system becomes fully operational.

In 1989 Magellan Corporation introduces a commercial hand-held GPS navigation receiver (Magellan NAV 1000).

In 2004 Qualcomm developed an “Assisted GPS” to use cellular networks to give a more accurate position.
Space, Control and User Segments of GPS

https://www.slideshare.net/chintanmehta007/how-gps-works-14291595
Space Segment: GPS Block IIR(M) Satellite

Each satellite weights about 2000 pounds. Seventeen feet across solar panels. Transmit signal is 50 Watts. A 10-year lifetime for each satellite before replacement.

Control Segment: Monitor Stations

- Track GPS satellites as they pass overhead
- Collects navigation signals, range/carrier measurements, and atmospheric data
- Feeds observations to the master control station
- Utilizes sophisticated GPS receivers
- Provides global coverage from 16 sites: 6 from the U. S. Space Force plus 10 from NGA

https://www.gps.gov/systems/gps/control/
Control Segment: 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

https://www.gps.gov/systems/gps/control/
Control Segment: Ground Antennas

- Send commands, navigation data uploads, and processor program loads to the satellites
- Collects telemetry
- Communicates 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

https://www.gps.gov/systems/gps/control/
Control Segment: Locations

https://www.gps.gov/systems/gps/control/
User Segment: GPS Receivers


General Information in GPS Signals

The GPS signal has two components:

1. **Ephemeris Data** – Contains status of the satellite, current date and time. This data is constantly transmitted from each satellite and is essential for position determination.

2. **Almanac Date** – Tells GPS receivers where each satellite is located at any time of the day. Each satellite transmits almanac data showing the orbital information of that satellite.
GPS satellites, each of which has at least two onboard cesium and as many as two rubidium atomic clocks.

The relative times are mathematically transformed into three absolute spatial coordinates and one absolute time coordinate. GPS Time (GPST) is a continuous time scale and theoretically accurate to about 14 ns. However, most receivers lose accuracy in the interpretation of the signals and are only accurate to 100 ns. The GPST is related to but differs from TAI (International Atomic Time) and UTC (Coordinated Universal Time). GPST remains at a constant offset with TAI (TAI – GPST = 19 seconds) and like TAI does not implement leap seconds. Periodic corrections are performed to the on-board clocks in the satellites to keep them synchronized with ground clocks. The GPS navigation message includes the difference between GPST and UTC. As of July 2015, GPST is 17 seconds ahead of UTC because of the leap second added to UTC on 30 June 2015. Receivers subtract this offset from GPS Time to calculate UTC and specific time zone values.
Atomic Clocks are the Ultimate in Accuracy

Physicists discovered that atoms of specific elements oscillated at exactly the same rate. In 1967, the atomic clock timing standard was determined to be exactly 9,192,631,770 oscillations per second (Cesium 133 atom resonant frequency).

The 3 types of atomic clocks include cesium, hydrogen, and rubidium.

**Cesium Atomic Clocks** - cesium atomic clocks employ a beam of cesium atoms. The clock separates cesium atoms of different energy levels by a magnetic field.

**Hydrogen atomic clocks** - Maintain hydrogen atoms at the required energy level in a container with walls of a special material.

**Rubidium Atomic Clocks** - The simplest and most compact of all atomic clocks. They use a glass cell of rubidium gas that changes its absorption of light at the optical rubidium frequency when the surrounding microwave frequency is just right.
Atomic Clock Example

The Bliley AR133 Series is a multifunctional Rubidium Standard designed to provide precision timing and reference frequency. It is one of the smallest atomic standards available without sacrificing performance.

AR133 Key features include:

- Long Term Stability $5 \times 10^{-11}$/month
- -150 dBC/Hz phase noise @ 10kHz
- $5 \times 10^{-12}$ ADEV @ 100sec
- 8.25W steady-state power
- 3”x3” (77mmx77mm) package

https://resources.bliley.com/ar133-series-rubidium-frequency-atomic-clock
Atomic Clock Stability Improvement

What is the state of the art in time stability?

Ans. Instability of $10^{-17}$ over an hour-long measurement

https://physics.stackexchange.com/questions/516265/why-is-there-a-moores-law-for-atomic-clocks
GPS Carriers for Signal Transmission

**L1 (1575.42 MHz)** carries the C/A code (Course Acquisition code) and the P code (Precision code)

**L2 (1227.60 MHz)** carries the P code (Precision code)

L3 (1381.05 MHz) is used by the Defense Support Program to signal detection of missile launches, nuclear detonations, etc.

L4 (1379.913 MHz) is used for additional correction to the part of the atmosphere from solar radiation

L5 (1176.45 MHz) is used as a civilian safety-of-life signal

Note: L2 signal is $154 \times 10.24$ MHz and L1 is $120 \times 10.24$ MHz.
Two Main GPS Carrier Signals

The GPS satellites transmit signals on **two carrier frequencies**. The **L1 carrier** is **1575.42 MHz** and carries both the **status message** and a **pseudo-random code** for timing.

The **L2 carrier** is **1227.60 MHz** and is used for the more precise **military pseudo-random code**.

[Diagram of GPS signal processing]

http://wireless.ictp.it/school_2001/lab0/GPS/PRC.HTM
The L1 GPS Signal

The transmitted L1 signal uses binary phase shift keying.

https://gssc.esa.int/navipedia/index.php/File:GPS_Signals.png
Pseudo-Random Codes in GPS

Pseudo-Random Codes (Two types)

The first pseudo-random code is called the C/A (Coarse Acquisition) code. It modulates the L1 carrier. It repeats every 1023 bits and modulates at a 1MHz rate. Each satellite has a unique pseudo-random code. The C/A code is the basis for civilian GPS use.

The second pseudo-random code is called the P (Precise) code. It repeats on a seven-day cycle and modulates both the L1 and L2 carriers at a 10MHz rate. This code is intended for military users and can be encrypted – when encrypted it's called the "Y" code.

Navigation Message

There is a low frequency signal added to the L1 codes that gives information about the satellite's orbits, their clock corrections and other system status. Frequency is 50 Hz.
Time Standards

Universal Coordinated Time (UTC)

- Greenwich Mean Time (GMT)
- GPS Time + T(sec)
- Zulu Time (military)

Local Time: AM and PM (adjust for local time zone)

Military time
(local time on a 24-hour clock)
Universal Coordinated Time Standard

Coordinated Universal Time (or UTC) is the primary time standard by which the world regulates clocks and time. It is within about 1 second of mean solar time at 0° longitude. It is effectively a successor to Greenwich Mean Time (GMT).

The current version of UTC is defined by the International Telecommunications Union Recommendation (ITU-R TF.460-6), Standard-frequency and time-signal emissions, and is based on International Atomic Time (TAI) with leap seconds added at irregular intervals to compensate for the slowing of the Earth's rotation.

UTC is used in many Internet and World Wide Web standards. UTC is 7 hours ahead of Mountain Standard Time (Santa Rosa, CA).

Clock: [https://time.is/UTC](https://time.is/UTC)

GPS Time Accuracy

The position calculated by a GPS receiver relies on

Current time,
Satellite position, and
Time delay for the signal.

The GPS signal in space will provide a “worst case” accuracy of 7.8 meters at a 95% confidence limit.

GPS time is accurate to about 14 nanoseconds. But this is degraded by transmission and receiver errors.

Higher accuracy is available today by using GPS in combination with augmentation systems. These can enable real-time positioning to within a meter.

https://www.slideshare.net/jawadali19252/gps-ppt-33758814?next_slideshow=1
Origin of Errors When Using GPS

The sum of possible errors can result up to ± 50-100 meters from the actual position of the GPS receiver.

1. Satellite clock: One nanosecond of inaccuracy in a satellite results in about 1/3 meter (~ 1 foot) of error in measuring the distance to the satellite. (Atomic clocks on satellite)
2. Receiver clock: Any error in the receiver’s clock directly results in distance error.
3. Atmospheric propagation: Speed of signal in the ionosphere and troposphere can introduce errors up to 30 meters.
4. Multi-path signals: Can introduce an error up to about one meter.
Source of Errors in GPS

**Ionosphere:** Electrically charged particles 80 to 120 miles above Earth affects the speed of electromagnetic waves. The change in the speed depends upon the frequency so the L1 and L2 signals propagate at different speeds.

**Tropospheric water vapor:** Affects attenuation of signal at all frequencies. Difficult to correct for this effect.

**Multipath propagation:** Reflected waves near the receiver affect the reading of the time of flight.

**Poor visibility:** Due to trees and other obstacles. This is why GPS is not well received indoors.

**Noise:** Combined effect of PRN noise and receiver noise.
Limitations in GPS Use

GPS satellite signals are weak; it doesn’t work well in indoors (in buildings), underwater and under trees.

Highest accuracy requires line-of-sight satellite-to-receiver; it generally doesn’t work as well in urban environments. Errors can result in GPS readings where obstacles interfere with the GPS signals.

The Department of Defense (DoD) can at any time shut down the GPS system (i.e., degrade performance or completely shut it off) for any reason.

Some GPS receivers are sensitive to low battery voltage as the battery ages.
Other GPS Systems in the World

In addition to the U.S. GPS system, other countries are deploying their own GPS systems.

**Russia:** GLOSNASS (Global Navigation Satellite System)
- Fully operational; comparable to GPS

**European Union:** Galileo Positioning System
- Now fully operational; better accuracy than GPS

**India:** Indian Regional Navigation Satellite System (IRNSS)
- Presently only seven operational satellites up

**China:** BeiDou Navigation Satellite System (BDS)
- Operational with 33 satellites; Better accuracy x 3
Assisted or Augmented GPS for Cellular Phone Use

**Assisted GPS** or **Augmented GPS** is a system that often significantly improves the startup performance (i.e., time-to-first-fix (TTFF)) of a GPS satellite-based positioning system. A-GPS is extensively used with GPS-capable cellular phones, as its development was accelerated by the U.S. FCC's 911 requirement to make cell phone location data available to emergency call dispatchers.

https://en.wikipedia.org/wiki/Assisted_GPS
Assisted or Augmented GPS for Cellular Phone Use

When you use assisted GPS this whole process is much faster. Cellular network towers have GPS receivers and those receivers are constantly pulling down satellite information and computing the data. This data is then passed on to the cellular phone (when requested) since the relevant satellites to your location are already identified and all GPS computations can be handled by 3rd party computers. The result to the end user is:

- Faster location acquisition
- Less processing power is required by your device
- Saves battery life
- Location acquisition indoors or in non-optimal environmental settings

https://www.windowscentral.com/gps-vs-agps-quick-tutorial
Antennas in a 3G Mobile Phone

GSM & W-CDMA Antenna

GPS Antenna

Wi-Fi & Bluetooth Antenna

Good antenna design is essential for good GPS reception.

https://pdfs.semanticscholar.org/8f1c/fb96c209eaa17ce7bc8463e95740f7959be3.pdf
Questions
Custom Antennas for Modern Mobile Phones

http://www.amphenol-tm.com/home-page/