Introduction to GPS
Global Positioning System

A military (DOD) based system designed to provide the information necessary to determine your location accurately anywhere in the world...
Why did DOD developed GPS?

- Cold war missile (ICBMs) defense
- Take out enemy missiles/silos with precision
- To do this accurately, must know launching position
  - Land-based ICBMs -- generally no problem
  - Submarine-based ICBMs are a special case
    - Sub has ascend to near-surface depth
    - Rapidly fix exact position from anywhere
    - Then Launch

- The result...Navigation changed forever
U.S. GPS

**NAVigation System Timing And Ranging NAVSTAR**

- 24 Operational satellites (6 spares)
- Orbiting at ~22,000 km altitude
- 6 different orbital planes each with 4 satellites
Russian GPS

Global’naya Navigatsionnaya Sputnikovaya Sistema GLONASS (Sep. 24, 1993)

24 Operational satellites

Orbiting at ~19,100 km altitude

3 different orbital planes each with 8 satellites
Indian GPS

Indian Regional Navigational Satellite System (IRNSS)

7 satellites

Soon to be operational (2011-2013)

Orbiting at ~24,000 km altitude
European GPS

GALILEO constellation (EU & ESA)

Not yet operational (2014-2019)

Provides a global SAR capability; each satellite equipped with transponders to relay distress signals to SAR coordinators and then back to the user

30 planned satellites in orbit with 3 spares

Orbits will be at ~23,222 km altitude
Other Countries Developing GPS

**COMPASS** (a.k.a. Beidou-2, BIG DOPPLER, or BD2)
- Chinese GPS constellation
- 5 satellites operational; 30 more planned

**DORIS**, Doppler **Orbitography and Radio-positioning Integrated by Satellite**
- French precision NAV system

**QZSS**, Quasi-Zenith Satellite System, Japan’s proposed
- 3 satellite regional time transfer GPS system
GPS replaces LORAN & TRANSIT

**LORAN:**
- **LOng RAnge Navigation**
- Ground-based radio triangulation method with continuous position fixes, accurate to ~300 meters.
- Limited coverage (Lat, Lon)

**TRANSIT:**
- Doppler shifts; 16 or less fixes per day. Sub-meter accuracy in ~3 days (central tendency).
- Worldwide coverage (Lat, Lon, Ht)
- For POLARIS ballistic missile subs and ships
Global Positioning System (GPS)

Continuous Position Fixes

Worldwide coverage

Latitude/Longitude/Height

Centimeter to 5-meter accuracy in seconds
GPS has 3 Segments

**Space Segment** – as discussed, 24 sats w/ 6 spares

**User Segment** – all of us with receivers, phones, etc.

**Control Segment** –
6 ground stations located around the world.

Maintain proper sat functioning
GPS has 3 Segments

Control Segment

Consists of...

- Master control station (MCS)
- Alternate MCS
- 4 dedicated ground antennas
- 6 dedicated monitor stations
  - Falcon AFB
  - Hawaii
  - Cape Canaveral
  - Ascension Island
  - Diego Garcia
  - Kwajalein Atoll
...GPS has 3 Segments

Space Segment Description

24 Satellites
6 planes w/ 55° orbits
Each plane has 4 SVs
20,200 km orbit
1 revolution / 12 hours

Very high orbits for...
Accuracy
Survivability
Coverage
- 1972, USAF Central Inertial Guidance Test Facility (Holloman AFB)
  - Flight tests of prototype GPS receivers using ground-based pseudo satellites
  - Developed to overcome limitations of former NAV systems
- 1978-1989, 11 Block I satellites launched (no signal degradation)
  - 1978 first US experimental Block I GPS SV launched
  - 1983, Soviet interceptor aircraft shot down civilian airliner (KAL007) that strayed into prohibited airspace due to NAV errors (269 killed).
  - Pres. Regan vowed to make GPS available for civilian use.
- 1985, US launched ten more Block I SVs to validate concept
  - Command & control turned over to 2nd Satellite Control Squadron (2SCS)
- 1989-1997, Block II/IIA
  - 1989, 1st modern BLK II SV launch
  - 1990-91, 1st GPS use in war (Gulf 1)
  - 1993 (Dec), full constellation achieved (24 in orbit)
  - 1996, Pres. Clinton declares GPS dual use
  - Signal degraded until Spring 2000
- 2000 (May 1st) SA turned off → 1996 Clinton exec. order
- 2004, US Gov signs agreement with ESA for cooperation with planned GALILEO GPS
- 2004 (Nov), Qualcomm announces “assisted GPS” for use in mobile phones
- 2011 (16 July), Block II F-2 launched from Cape Canaveral
User Segment

You, plus...
pretty much everyone else
What’s an Atomic Clock?

All clocks count ticks or pulses of a “resonator”

Pendulum clocks, the pendulum is the resonator at one swing per second...tracked/counted by gears

Digital clocks use oscillations of the power source (60 cycles per second in US) or oscillations of a quartz crystal as the resonator...tracked electronically.

Atomic clocks use the resonance frequency of atoms as the resonator....regulated by the frequency of the microwave electromagnetic radiation emitted or absorbed by the quantum transition (energy change) of an atom or molecule

Accurate to ~\(1/9,000,000,000\)th of a second...

...Way-accurate!!

Loses only 1 second / 10,000 years

From very big to very small
Trilateration

A position is calculated by knowing:
The location of, and
calculating the distance to,
a group of satellite vehicles (SV’s)

The SV’s act as precise reference points
2D-Trilateration

Say you’re totally lost. Someone tells you that you are 625 mile from Boise, ID

Circle of distances away from Boise
2D-Trilateration

Say you’re totally lost. Someone tells you that you are 625 mile from Boise, ID

*Circle of distances away from Boise*

You ask someone else and they know you are 690 miles from Minneapolis, MN

*Only 2 possible locations*
2D-Trilateration

Say you’re totally lost. Someone tells you that you are 625 mile from Boise, ID

Circle of distances away from Boise

You ask someone else and they know you are 690 miles from Minneapolis, MN

Only 2 possible locations

When asked, a third person knows you are 615 mile from Tucson, AZ

Now, you know precisely where you are
3D-Trilateration is Similar...

One SV...

The receiver knows it is $X$ distance from $SV_1 \implies$ a sphere of possibilities
3D-Trilateration

Two SVs...

If the receiver generates spheres for 2 SVs it knows its position is narrowed down to where the spheres intersect ➔ a ring

The two spheres overlap in a ring of possible receiver positions.
Three SVs...
The receiver produces a third sphere that intersects the “ring” in only 2 points.
3D-Trilateration

Three SVs... 3rd sphere narrows receiver location down to 2 possible locations.

GPS receiver can just ignore the point in space or, better yet, ...

Get help from a 4th satellite to reduce possible locations to a single point....sort of...

More on error later.
Ground Example

A train leaves the station at 9:00 A.M. Traveling 5 miles per hour.

How far from the station is it at 11:00 A.M.?

Answer: 10 miles
GPS Example

A signal leaves a satellite at 9:00:00.000 A.M. traveling at 186,282.397 miles per second.

How far is it from the satellite at 9:00:00.065 A.M.?

\[ \Delta t = 0.065 \text{ seconds} \]

Answer: 12,108.36 miles
GPS Signal

How do we know when the signal left the SV?

- Receivers & SV’s use the same code
  - Coarse/Acquisition code or C/A code
  - A.k.a. Pseudorandom noise (PN or PRN code)
    - 1,023 bit deterministic sequence
    - Transmitted @ 1.023 megabits per second (Mbit/s)
    - Sequence repeats every millisecond
    - Sequences only match up (or strongly correlate) when they are exactly aligned
- Receiver uses code to determine time since transmission

Measures time distance between same part of code
GPS C/A Signal – Code Lock
C/A code & Carrier Modulation

Modulation of a data signal onto a carrier signal.

AM radio → Amplitude modulation

FM radio → Frequency modulation

← Digital data → (e.g., C/A code)

GPS C/A Code Chips (Rows = PRN Signal Numbers 1-32)
Military GPS Signal: P-code

P-code is also a PRN; but each SV’s P-code is...
- $6.1871 \times 10^{12}$ bits long (~720.213 gigabytes)
- Repeats once a week @ 10.23 Mbits/s
- Extreme length increases correlation & eliminates range ambiguity
- Each SV transmits a unique portion of P-code ($2.35 \times 10^{14}$ bits)

To prevent unauthorized P-code use or interference (*Spoofing*)
- P-code encrypted by a modulation sequence with W-code
- Result = anti-spoofing Y-code a.k.a $\rightarrow$ P(Y)-code
- Details of W-code are kept secret.
GPS Position Solution

\[
(X_1 - U_x)^2 + (Y_1 - U_y)^2 + (Z_1 - U_z)^2 = (SL (T_1 - C_b))^2
\]

\[
(X_2 - U_x)^2 + (Y_2 - U_y)^2 + (Z_2 - U_z)^2 = (SL (T_2 - C_b))^2
\]

\[
(X_3 - U_x)^2 + (Y_3 - U_y)^2 + (Z_3 - U_z)^2 = (SL (T_3 - C_b))^2
\]

\[
(X_4 - U_x)^2 + (Y_4 - U_y)^2 + (Z_4 - U_z)^2 = (SL (T_4 - C_b))^2
\]

\[\begin{align*}
X_i & \quad Y_i & \quad Z_i \\
U_i & \quad U_i & \quad U_i \\
SL & & \\
T_i & & \\
C_b & &
\end{align*}\]

- \(X_i\), \(Y_i\), \(Z_i\): Coordinates of the \(i^{th}\) satellite
- \(U_i\), \(U_i\), \(U_i\): Rover coordinates to be determined
- \(SL\): Speed of Light (186,282.397 miles / second)
- \(T_i\): Time necessary to receive a signal from the \(i^{th}\) satellite
- \(C_b\): Clock bias (error) of the rover (~1/9,000,000,000th of a second)
Three Methods of Positioning

- Autonomous (least accurate)
- Differential (mid-level accuracy)
- Phase Differential (most accurate)
Autonomous Positioning

Receiver is used to collect real-time locations

– No corrections are applied to locations
  • Locations off by as much as **100 m** if SA is active
  • Locations off by as much as **5-6 m** if SA **not** active
  • Accuracy depends on degree of Selective Availability
    – How much is Falcon AFB distorting the signals?

--When SA is off--
CEP (50%) = 1.67m
2dRMS (98%) = 4.06m
Differential GPS: Post Processing

- Corrections are applied to positions after returning from field
- Uses data collected simultaneously by a base station
- Gives sub-meter to 5 meter accuracy

Get Base Station Coords afterward
Differential Correction: Real-Time

- Correction is applied while still in field
- Makes use of additional signals being broadcast by a known ground station

Compare/Correct to Base Real-Time
Phase Differential Correction

- C/A (PRN) Code-correlating with differential correction $\rightarrow$ 2-3 m accuracy
- To achieve higher accuracies (cm-mm scales) $\rightarrow$ Codeless techniques using 2 carrier signals (L1 & L2)
  - L1: 1575.62 MHz (GeoXT) $\lambda = 19.03$ cm ($\lambda = c/f$)
  - L2: 1227.60 MHz $\lambda = 24.42$ cm
- Eliminates effects of both clock and atmospheric errors
- Doppler Phenomenon – waves (e.g. L1 & L2) moving through a medium are affected (phase shift) in proportion to the wavelength.
- L1 & L2 have different wavelengths ($\lambda$) $\rightarrow$ different phase shifts
- Amount of atmosphere & the effects on signal travel time are precisely estimated
  - L1-L2 Phase processing in the field $\rightarrow$ 10-100 cm
  - L1-L2 Phase processing with base station $\rightarrow$ 5 mm
SV’s location is transmitted to the SV by ground control

- SV then relays its location to your receiver
- If a SV fails to maintain proper orbit, adjustments are uploaded
- If problem exists, control segment deems the SV unhealthy
Almanac Messages

• Almanac is a set of parameters used to calculate the rough location of each SV
  – Each SV broadcasts Almanac data for all other SVs
  – Valid for several months

• Almanacs are used for:
  – Rapid SV acquisition
    • Almanac data (and current time) indicates to the rover which SV’s to “look” for ….given the rover’s roughly approximated ground position.
    • With this info, the appropriate SV’s can be selected for the initial search.
  – Pre-mission planning
    • Predict good/bad SV geometry in advance (more on this later)
Ephemeris Messages

- Ephemeris is a set of parameters (orbital & clock correction data) used to determine exact location of SV
- Each SV broadcasts only its own ephemeris... every 30 sec.
- Ephemeris only considered valid for 30min.
- Ephemeris used for
  - Calculating a GPS position
- When rover initially locks on a SV, the receiver display shows “hollow” signal strength.
  - Because ephemeris data has yet to be completely collected
- Once ephemeris is collected from all locked-on SV’s in turn
  - Signal strength turns “solid” black
Selective Availability (SA)

- Errors introduced to reduce User Range Accuracy (URA)
  - Discourages hostile use
  - Largest source of error ➔ autonomous GPS...100m 2dRMS
  - Sum of two component effects...
    - Epsilon - ephemeris “fibbing”
      - US Gov. fibs a bit about the NAVSTAR SV(s) location(s)
    - Dither - clock variations (every several min. & few sec.)
      - Lies about time “frame” C/A code was sent from SV’s

CEP (50%)
How Accurate Is GPS?

• That Depends on some variables...
  • Time spent at a geographic Location
  • Design of receiver (antenna design)
  • Relative position of satellites
  • Rover configuration settings (sky mask, PDOP allowed
  • Correction methods (none, post-process, real-time)
More on Accuracy Later

• Will discuss...
  • DOP’s: Dilution of Precision Measures
  • UERE: User Equivalent Range Error