EESC 9945

Geodesy with the Global Positioning System

Class 1: *Introduction*

1. Class meeting time
2. Overview of term
3. Term Project: Point positioning
4. Introduction to the Global Positioning System

Aim of Class

To introduce the principles of the use of the Global Positioning System, including:

- GPS components (segments)
- GPS observations
- Using GPS observations to estimate positions

Emphasis is for geoscience user of GPS, not necessarily for geodesists

Slides from Classes

- Available at http://www.ldeo.columbia.edu/~jdavis/eesc9945.htm soon after class

Course Outline

- Introduction
- Satellite orbits
- GPS constellation
- GPS observables
- Propagation medium
- Point positioning using pseudorange
- Relative positioning using carrier-beat phase (2 classes)
- Terrestrial reference frames
- Positioning using stochastic filtering (2 classes)
- GPS errors

Term Project (for credit): *Point positioning using Coarse Acquisition Code*

- Can work in teams of 2–3
- Overall goal of project is to write code to calculate Earth-fixed positions using pseudorange (similar to navigation devices)
- Can use any computer programming language (including MATLAB)
- Project will have four sub-goals; each sub-goal has one subroutine to develop:
  1. Due 15 Feb: Read broadcast ephemerides in RINEX format for 24-hour block and return Cartesian coordinates for all satellites for closest epoch
  2. Due 1 Mar: Calculate Earth-centered Cartesian coordinate for GPS satellite given broadcast ephemeris for specific epoch
  3. Due 29 Mar: Read GPS observations in RINEX observation file and return list of observed satellites and ionosphere-free pseudorange observables
  4. Due 26 Apr: Use observables and satellite coordinates in least-squares solution for site position
- Further details next week
- **This week's assignment: E-mail me team members before next class**

Course Topics

- Satellite orbits
  - What are the motions of artificial satellites?
  - How is their position described?
  - How do we translate between Keplerian satellite ephemerides and Earth-centered Cartesian coordinates?
  - Where can we obtain GPS ephemerides and what is their format?

Course Topics

- GPS Constellation
  - How many satellites are there and how do we label them?
  - How are they configured within this constellation?
  - How are GPS satellites controlled and how do they keep time?
  - What is the signal broadcast by the GPS satellites?

Course Topics

- GPS Observables
  - What are the phase and pseudorange observables?
  - Models for these observables

Course Topics

- Propagation medium
  - How do the ionosphere and neutral atmosphere impact propagation of the GPS observations?
  - How do we deal with these effects?

Course Topics

- Point positioning using pseudorange
  - Point positioning
  - How do we estimate the point position of the GPS receiver using least squares and the pseudorange observable?

Course Topics

- Relative positioning using carrier-beat phase
  - Relative positioning
  - What are the phase observables used in relative positioning?
  - Data processing considerations
  - Orbit estimation

Course Topics

- Terrestrial reference frames
  - Definition
  - Relevance to GPS
  - How do we establish reference frames?

Course Topics

- Stochastic filtering
  - Dynamic systems
  - Stochastic systems
  - Prior constraints and sequential least squares
  - The Kalman filter

Course Topics

- GPS errors
  - What are the main sources of error impacting GPS?

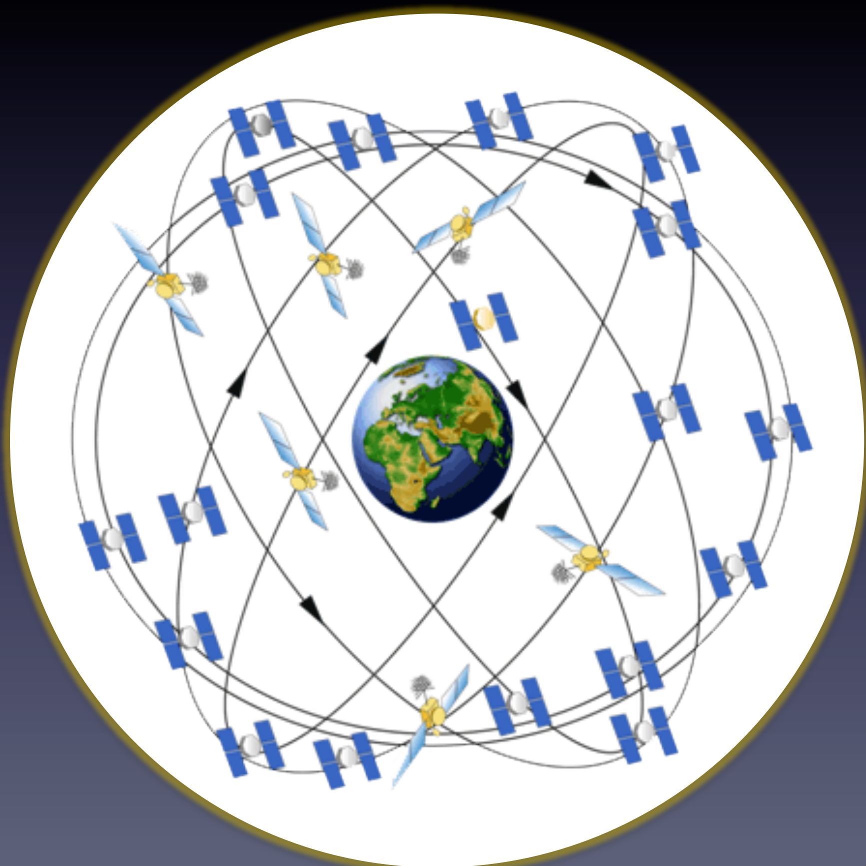
The Global Positioning System (GPS)

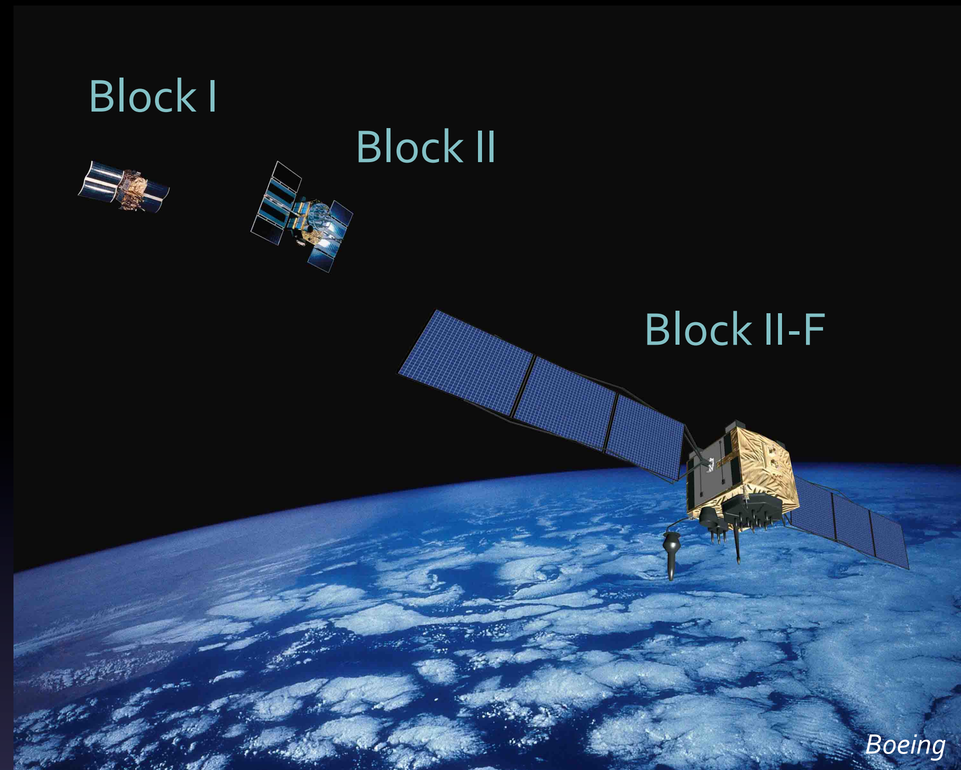
- *The* Global Positioning System (GPS) is *a* Global Navigational Satellite System (GNSS)
- US Department of Defense
- Operational 1993
- Some web sites:
  - http://www.gps.gov (Main government GPS portal; includes Civil GPS Service Interface Committee)
  - http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=5311 (DoD Joint GPS Directorate)
  - http://igscb.jpl.nasa.gov (International GNSS Service Central Bureau)
- Other Global Satellite Navigational Systems:
  - GLONASS (Russia, 1995)
  - Galileo (Europe, 2019)
  - Beidou/Compass (China, 2020)

The Global Positioning System

Three Segments:

1. **Space segment**



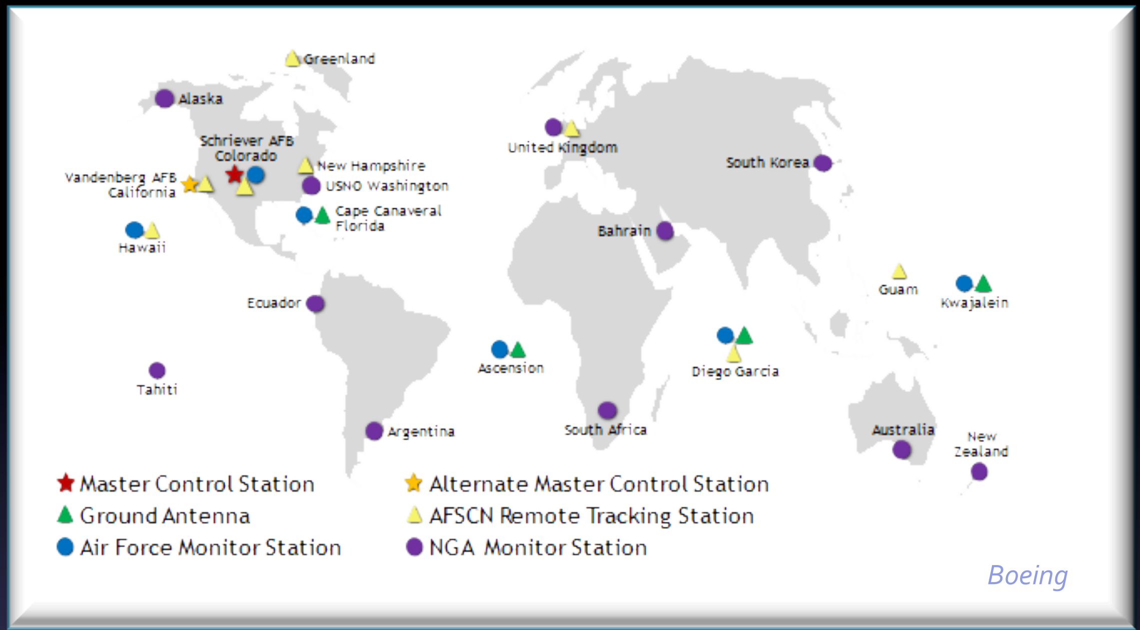


- Official constellation name: **NAVSTAR** (**Nav**igation **S**ignal **T**iming **a**nd **R**anging)
- 31 usable satellites (1/15/2013)
- 20,000 km altitude
- Arranged in six orbital planes (4–6 SV each)
- 24-hr geosynchronous orbits
- Multiple satellite designs (blocks) in use at one time
- Constellation monitored by USNO (tycho.usno.navy.mil/gps.html)

The Global Positioning System

Three Segments:

1. Space segment
2. **Control segment**



- Monitor health of satellites
- Uplink to satellites (commands, data)
- Performs solutions and uploads ephemerides and clocks to SVs

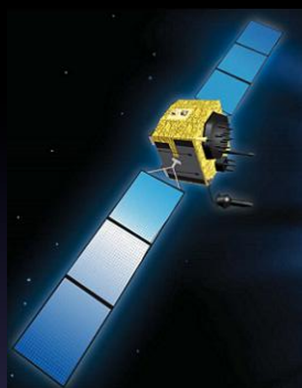
The Global Positioning System

Three Segments:

1. Space segment
2. Control segment
3. **User segment**
    1. Science
    2. Agriculture
    3. Aviation
    4. Civilian navigation
    5. Surveying
    6. Recreation
    7. Space
    8. Timing

GPS is a Timing System

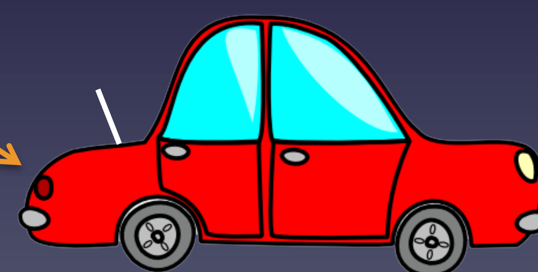
GPS Satellite #24



"The current time at satellite #24 is 10:00:00.00"

Radio signal

Time for the signal to reach us: 0.080 000 000 seconds
Speed of light: 299 792 458 m / s
Distance to #24: 299 792 458 x 0.08 = 23,983.39664 km



At 10:00:00.08, your GPS receiver hears
"The current time at satellite #24 is 10:00:00.00"

Time Systems

- TAI (International Atomic Time)
  - Time kept by atomic frequency standards
  - *Second* is 9,192,631,770 cycles of radiation from transition between two hyperfine levels of Cesium-133 ground state
- UTC (Universal Coordinated Time)
  - Atomic time scale that gives mean solar time
  - Sometime called "Greenwich Time" since predecessor was GMT (Greenwich Mean Time)
  - Offset from TAI by leap seconds
- GPS time
  - Runs with TAI, except offset: TAI = GPS + 19 s
  - GPS time and UTC agreed on 1980 January 6.0 (*GPS standard epoch*)
  - Therefore, GPS time and UTC time disagree by the number of leap seconds since 1980 January 6.0
  - GPS time is often measured in weeks and seconds of week since GPS standard epoch

Time and Frequency

- Time is now measured using a frequency standard
- The phase of a uniformly running frequency standard is $\phi(t) = 2\pi f_\circ t + \phi_\circ$
- An error in the frequency therefore causes a time-dependent error in the phase of $\delta\phi(t) = 2\pi\delta f(t)t$
- This is known as a *clock error*

GPS Clock Errors

- The GPS satellites carry on-board atomic clocks (Cs at first, Rb for latest SVs)
- The clocks are maintained (clock corrections uploaded) by monitoring by the GPS ground segment
- GPS receivers also have accurate clocks and can also be connected to external 1 pps source
- The differences between the clock readings and the "true" time measured in a common system are the clock errors:

$$t(\mathrm{rec}) = t + \delta_r \qquad t(\mathrm{sat}) = t + \delta^s$$

GPS Clock Errors

- The *observed* propagation time of a GPS signal from SV to Rxr is the receive time *measured by the receiver* minus the transmit time measured by the satellite:

$$\tau_{\text{obs}} = t_r(\text{rec}) - t^s(\text{sat}) = t_r + \delta_r - t^s - \delta^s = \tau_{\text{true}} + \delta_r - \delta^s$$

- Thus, clock errors bias the estimates of the propagation time
- The electrical path length between transmitter and receiver is related to the propagation time by $\rho = c\tau$ where c is the speed of light in vacuum

Pseudorange

- Assuming travel through vacuum, the *pseudorange* is the observed geometric range, i.e., the true range biased by clock errors:

$$\rho(t) = c\tau_{\mathrm{true}} + c\,(\delta_r - \delta^s) = |\vec{x}^s(t-\tau) - \vec{x}_r(t)| + c\,(\delta_r - \delta^s)$$

- The pseudorange is sometimes called the *code observable* for reasons we will discuss several classes from now

Suggested Background Resources

Hoffman-Wellenhof, B., H. Lichtenegger, and E. Wasle (2008), *GNSS – Global Navigational Satellite Systems*, Springer.

Leick, A. (2004), *GPS Satellite Surveying*, 3rd ed., Wiley.

Parkinson, B. W., J. J. Spliker, Jr. (eds.) (1996), *Global Positioning System: Theory and Applications, Volumes I and II*, Progress in Astronautics and Aeronautics, Vols. 163 & 164, American Institute of Aeronautics and Astronautics.