GEOS F493 / F693
Geodetic Methods and Modeling

– Lecture 02: GPS Overview, Coordinate Systems–

Ronni Grapenthin
rgrapenthin@alaska.edu
Elvey 413B
(907) 474-7286

September 09, 2019

GPS Overview

- 1973: Architecture approved
- 1978: First Block-I satellite launched
- 1983: Korean Air 007 shot down after straying into USSR air space
- 1983: Pres. Reagan mandated civilian use of GPS
- 1985: 10 Block-I satellites in orbit for concept test
- 1995: Full Operational Capability (FOC)
- 2000: Selective availability turned off

GPS Block-I, *NASA*

GPS Overview

- 2005: Begin modernization, First Block IIR-M broadcasts L2C signal
- 2010-2015: 10/12 Block IIF satellites launched, broadcast L5 signal
- 2018 (?) Block III launches: new signals – Military (M-code), L1C, increased signal power, laser retro-reflectors for orbit tracking,
- total satellite launches: 72, only 2 failures! `https://en.wikipedia.org/wiki/List_of_GPS_satellites`

GPS Block-IIIA, *NASA*

GPS Primary Uses

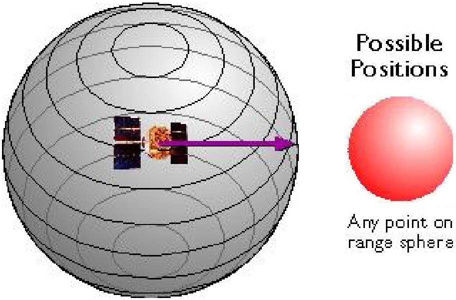
Navigation

real-time, meter accuracy (sub-meter in differential mode)

Surveying

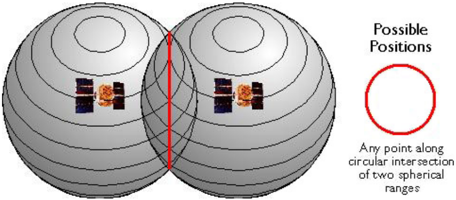
post-processing, multi-receiver, millimeter accuracy

GPS Positioning (in a Nutshell) – Ranging



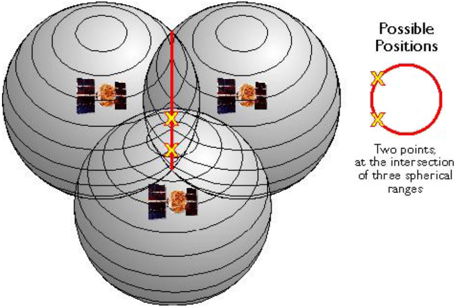
https://www.e-education.psu.edu/geog482spring2/c5_p18.html

GPS Positioning (in a Nutshell) – Ranging



https://www.e-education.psu.edu/geog482spring2/c5_p18.html

GPS Positioning (in a Nutshell) – Ranging



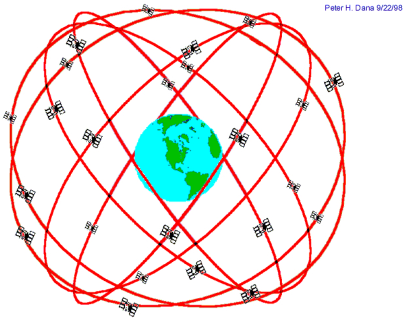
https://www.e-education.psu.edu/geog482spring2/c5_p18.html

System Architecture

- Space Segment – satellites
- Control Segment – management of satellites
- User Segment – Civil and military receiver development

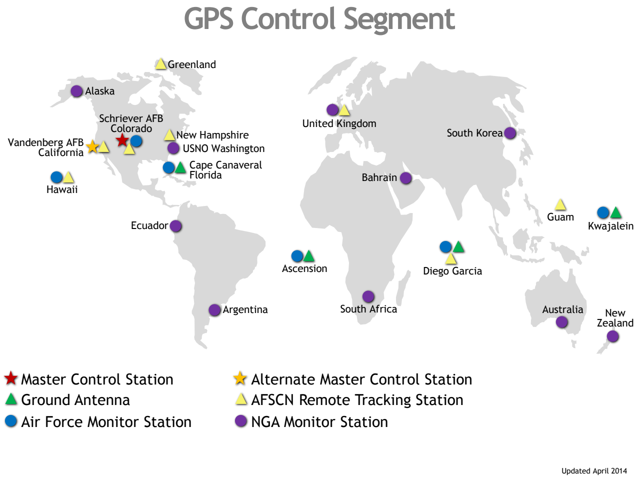
System Architecture: Space Segment

- Baseline constellation 24 satellites, 6 orbital planes, 55° inclined
- Period ≈ 12 hours, stationary ground tracks
- Currently 32 satellites operational
- Constellation Status / Outages: `http://www.navcen.uscg.gov/`
- E.g. `http://navcen.uscg.gov/?Do=constellationStatus`



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

System Architecture: Control Segment



gps.gov

Master control station (Colorado) operates system, sends commands

System Architecture: Control Segment

- monitor orbits, satellite health
- maintain GPS time (currently 18 s ahead of UTC)
- predict ephemerides, clock parameters
- update satellite navigation messages
- maneuver satellite: maintain orbit

local	2015-08-23 21:06:20	Sunday	day 235	timezone UTC-6
UTC	2015-08-24 03:06:20	Monday	day 236	MJD 57258.12939
GPS	2015-08-24 03:06:37	week 1859	97597 s	cycle 1 week 0835 day 1
Loran	2015-08-24 03:06:46	GRI 9940	349 s until	next TOC 03:12:09 UTC
TAI	2015-08-24 03:06:56	Monday	day 236	36 leap seconds

http://www.leapsecond.com/java/gpsclock.htm

System Architecture: Control Segment

- each satellite visible at min 2 monitor stations
- monitor stations operated remotely from MCS
- equipment: GPS receivers w/ cesium clocks, met instruments, comms to satellites
- GPS time based on atomic clocks on satellites and monitor stations
- satellite clock time offset, drift, drift rate part of navigation message, allows clock sync

System Architecture: User Segment

Coordinate Systems 1/11

What’s your coordinate system?

Coordinate Systems 2/11

- need 2 coordinate systems
- one in which user position is fixed – rotates with Earth
- another spaced-fixed/inertial to express satellite motion – Earth rotates
- transformations (rotations) link the coordinate systems

Coordinate Systems 3/11 – CTRS

Coordinate system in which user position is fixed:

- rotates with the Earth: conventional terrestrial reference system (CTRS)
- use cartesian coordinate system
- define origin at center of mass
- z-axis is axis of rotation
- x-axis goes through intersection of equatorial plane and reference median
- y-axis makes it right-handed

Coordinate Systems 3/11 – CTRS

Coordinate system in which user position is fixed:

- rotates with the Earth: conventional terrestrial reference system (CTRS)
- use cartesian coordinate system
- define origin at center of mass
- z-axis is axis of rotation
- x-axis goes through intersection of equatorial plane and reference median
- y-axis makes it right-handed

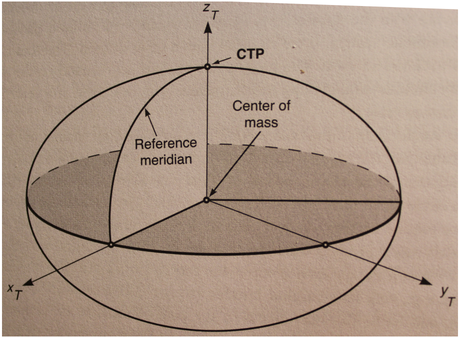
Easy, right?

Coordinate Systems 3/11 – CTRS

Coordinate system in which user position is fixed:

- rotates with the Earth: conventional terrestrial reference system (CTRS)
- use cartesian coordinate system
- define origin at center of mass
- z-axis is axis of rotation
- x-axis goes through intersection of equatorial plane and reference median
- y-axis makes it right-handed

Easy, right?



Misra and Enge, 2011, GPS–Signals, Measurements, and Performance

Coordinate Systems 4/11 – CTRS

What are potential issues?

Coordinate Systems 4/11 – CTRS

What are potential issues?

- *polar motion*: pole of rotation moves, roughly circular, several meters/year
- use conventional terrestrial pole (CTP) – average of polar motion between 1900-1905
- *center of mass*: where is it?

Coordinate Systems 4/11 – CTRS

What are potential issues?

- *polar motion*: pole of rotation moves, roughly circular, several meters/year
- use conventional terrestrial pole (CTP) – average of polar motion between 1900-1905
- *center of mass*: where is it?

Actually,

- CTRS is *realized* through a set of points
- need consistent coordinates from measurements
- measurements have errors
- *realize* coordinate frame that fits data best (e.g,least-squares)
- World Geodetic System 1984 (WGS84) one such realization
- GPS positions in WGS84 ECEF coordinate frame
- Scientists use ITRF (International Terrestrial Reference Frame)

Coordinate Systems 5/11 – CIRS

Coordinate system which is space-fixed

- Earth within: conventional inertial reference system (CIRS)
- express forces, acceleration, velocity, position vectors
- inertial reference system defined as stationary / constant velocity in space
- define origin at Earth's center of mass
- z-axis is axis of rotation
- x-axis in equatorial plane pointing to vernal equinox (intersection of equatorial plane w/ plane of rotation around sun)
- y-axis makes it right-handed

Coordinate Systems 5/11 – CIRS

Coordinate system which is space-fixed

- Earth within: conventional inertial reference system (CIRS)
- express forces, acceleration, velocity, position vectors
- inertial reference system defined as stationary / constant velocity in space
- define origin at Earth's center of mass
- z-axis is axis of rotation
- x-axis in equatorial plane pointing to vernal equinox (intersection of equatorial plane w/ plane of rotation around sun)
- y-axis makes it right-handed

Again . . . easy, right?

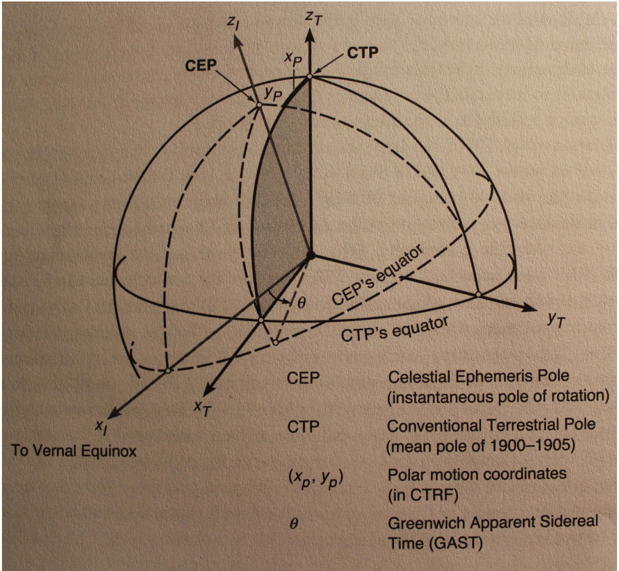


Figure 4.2 Inertial and terrestrial reference systems.

Misra and Enge, 2011, GPS–Signals, Measurements, and Performance

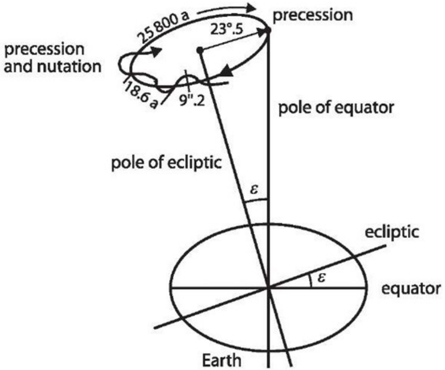
Coordinate Systems 7/11 – CIRS

What are potential issues?

Coordinate Systems 7/11 – CIRS

What are potential issues?

- *varying speed around sun*: think as inertial coord sys over short time
- *axis of rotation not fixed*: precession (26 kyrs), nutation (18.6 yrs)
- well understood – can be traced to any epoch



source: `http://what-when-how.com`

Coordinate Systems 8/11

Cartesian coordinates not intuitive to convey position
(Any guess where we are: X=-1353856.8945, Y=314830.6876, Z=-6205742.1059)

- How about curvilinear coordinates: latitude, longitude, height?
- Earth is rough, need smooth model; easy to characterize: ellipsoid
- origin Earth's center of mass
- z-axis = axis of revolution of ellipsoid
- need to specify semi-major/minor axis (*a*,*b*), or flattening $f = (a - b)/a$
- WGS84: $a = 6378137.0m$, $1/f = 298.257223563$

Coordinate Systems 9/11

- *geodetic latitude,* ϕ: angle in meridian plane, between equatorial plane and line that's normal to tangent at P
- *geodetic longitude,* λ: angle in equatorial plane, between reference meridian and meridian plane through P
- *geodetic height,* h: measured along normal to tangent at P; no physical meaning!

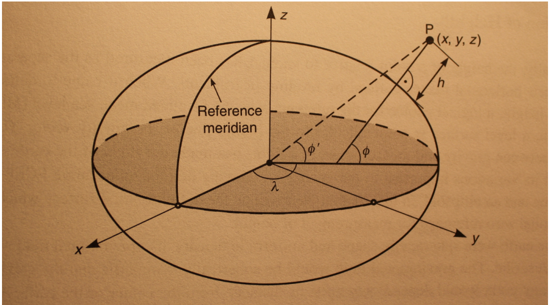


Figure 4.4 Cartesian (x, y, z) and ellipsoidal (ϕ, λ, h) coordinates. Geocentric latitude is denoted as ϕ'. We denote a right angle as ⊾.

Misra and Enge, 2011, GPS–Signals, Measurements, and Performance

Coordinate Systems 10/11 – HEIGHTS

- first definition of absolute height relative to mean sea level (MSL)
- recall previous slide: height measured along normal to level surface (tangent at P)
- perpendicular to gravity vector! ...understanding gravity is important!
- all points with same value of gravity potential: *equipotential surface*
- equipotential surface with best fit to MSL is *geoid*
- orthometric height $H = h - N$, shown on topo maps.

Coordinate Systems 11/11 – HEIGHTS

- orthometric height $H = h - N$, shown on topo maps.

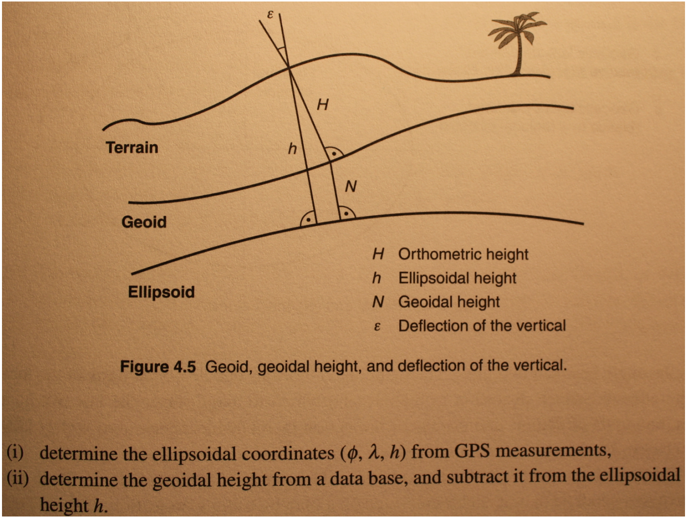


Figure 4.5 Geoid, geoidal height, and deflection of the vertical.

(i) determine the ellipsoidal coordinates (ϕ, λ, h) from GPS measurements,
(ii) determine the geoidal height from a data base, and subtract it from the ellipsoidal height h.

Misra and Enge, 2011, GPS–Signals, Measurements, and Performance