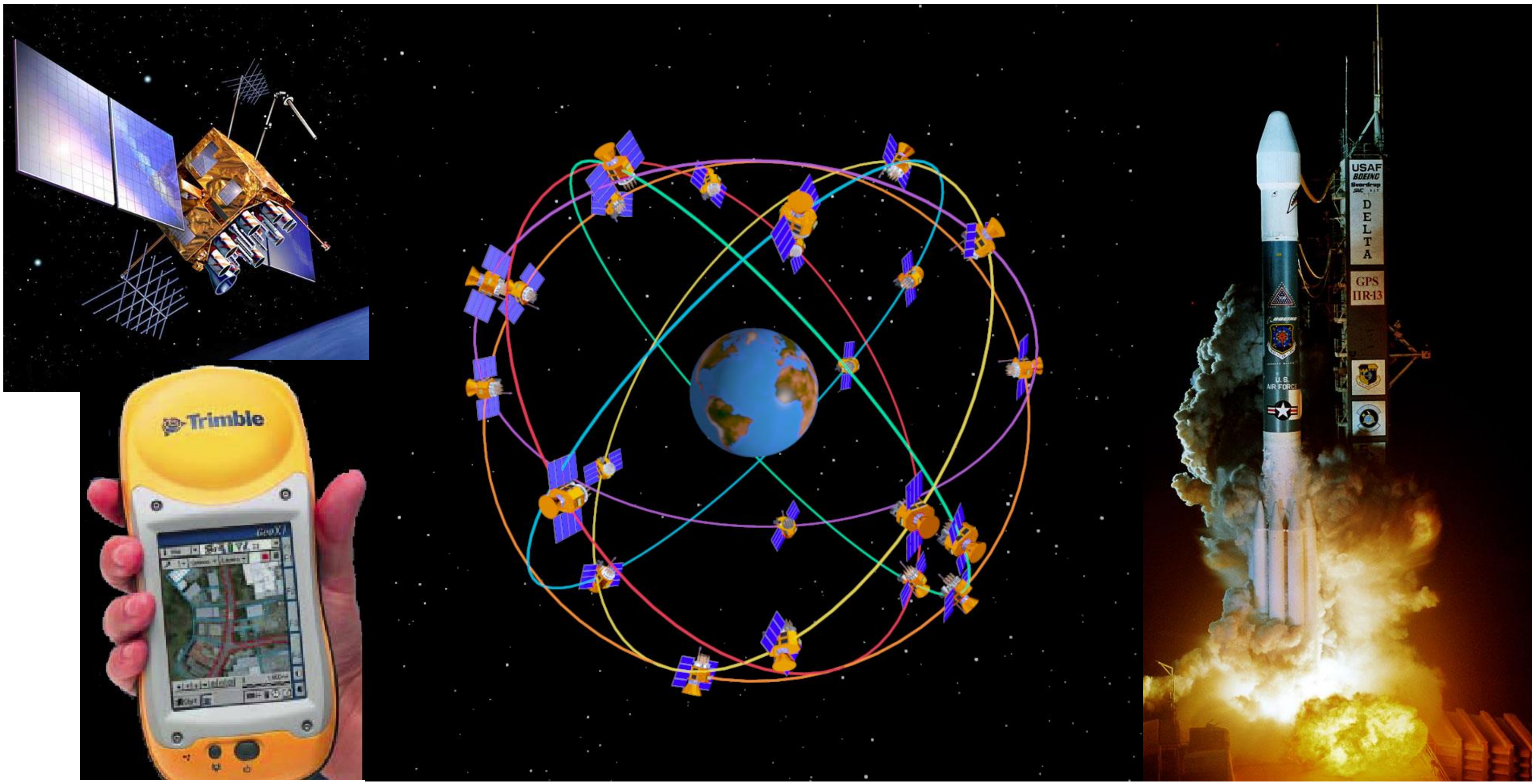
The Global Positioning System (GPS) & Global Navigation Satellite System (GNSS)



GPS Facts of Note

- US DoD navigation system
  - First launch on 22 Feb 1978, fully operational in 1994
  - ~$15 billion (?) invested to date
- 24 (+/-) Earth-orbiting satellites (SVs)
  - 24 primary, 7 spares; 32 presently in orbit
  - Altitude of 20,200 km
    - In 6 orbital planes inclined 55^o to equator, spaced 60^o apart
    - Orbital period of 12 hrs
  - 6 to 12 SVs visible at all times anywhere in the world
- EU Galileo, Russian Fed. GLONAS systems

GPS Milestones

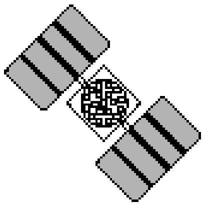
- 1978: First 4 satellites launched
- 1983: GPS declassified
- 1989: First hand-held receiver
- 1991: S/A activated
    - DGPS now essential for surveying and mapping
- 1994: GPS constellation fully operational
    - (My first hand-held receiver)
- 1995-1996: First hand-held, “mapping-grade” receivers (DGPS-enabled, w/data dictionary)
    - (DGS gets 2, and buys 2 more 3 years later)

GPS Milestones, cont.

- 1996-1998: GPS on a microchip
    - (UT senior thesis student completes first geo. map with DGPS)
- 1997: First $100 hand-held receiver
- 1999: USCG DGPS service operational
    - Free real-time DGPS for areas near waterways
- 2000: S/A off
    - Detailed mapping with an inexpensive receiver now possible
        - DGS buys 10 WAAS-enabled e-Trex receivers
        - DGS begins teaching GIS/GPS course
- 2003: FAA commissions WAAS
    - Free national DGPS coverage
        - DGS/CNS purchases 35 more WAAS e-Trex
        - DGS purchases 3 tablets with internal WAAS GPS and GeoXT
        - 2008: DGS buys 10 mapping grade handhelds (Trim.Nomads)

GPS Segments

- **Space** – Satellites (SVs).



- **Control** – Ground stations track SV orbits and monitor clocks, then update this info. (ephemeris, clock corrections) for each SV, to be broadcast to users (“almanac”). Control Facility at Schriever Air Force Base, CO.

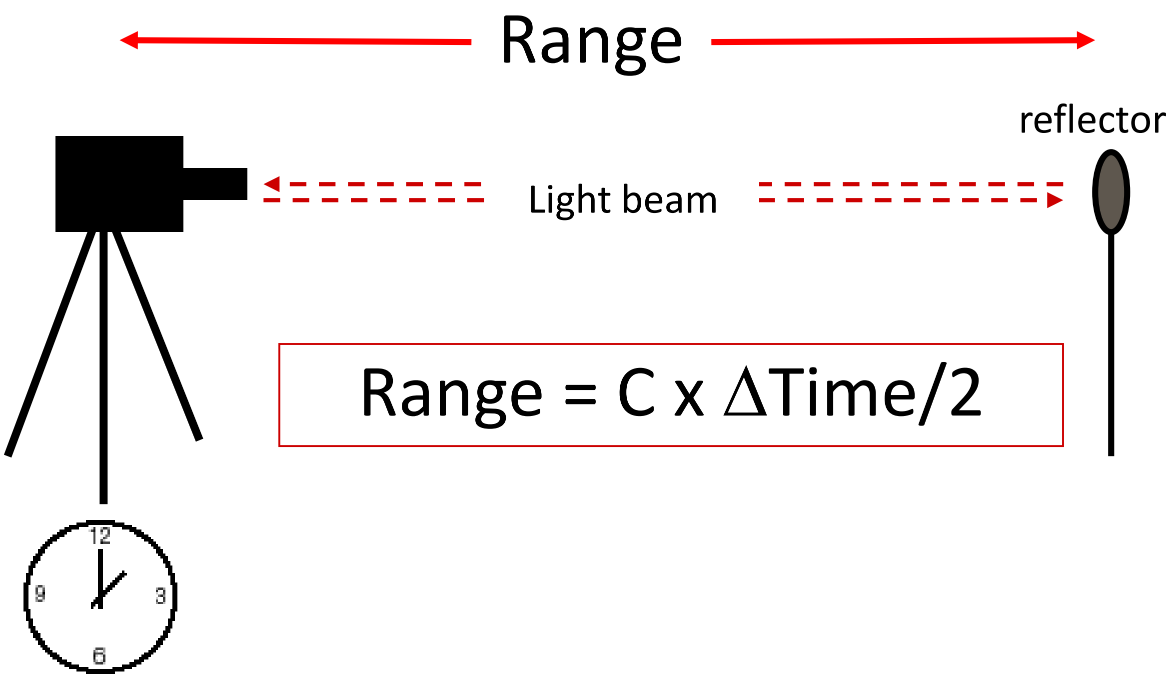
- **User** – GPS receivers convert SV signals into position, velocity and time estimates.

Ranging Techniques

- Two-way ranging: “Active”
  - Electronic Dist. Measuring devices (EDMs)
  - Radar, Sonar, Lidar
- One-way ranging: “Passive”
  - GPS

Ranging techniques

- Two-way ranging (EDM)



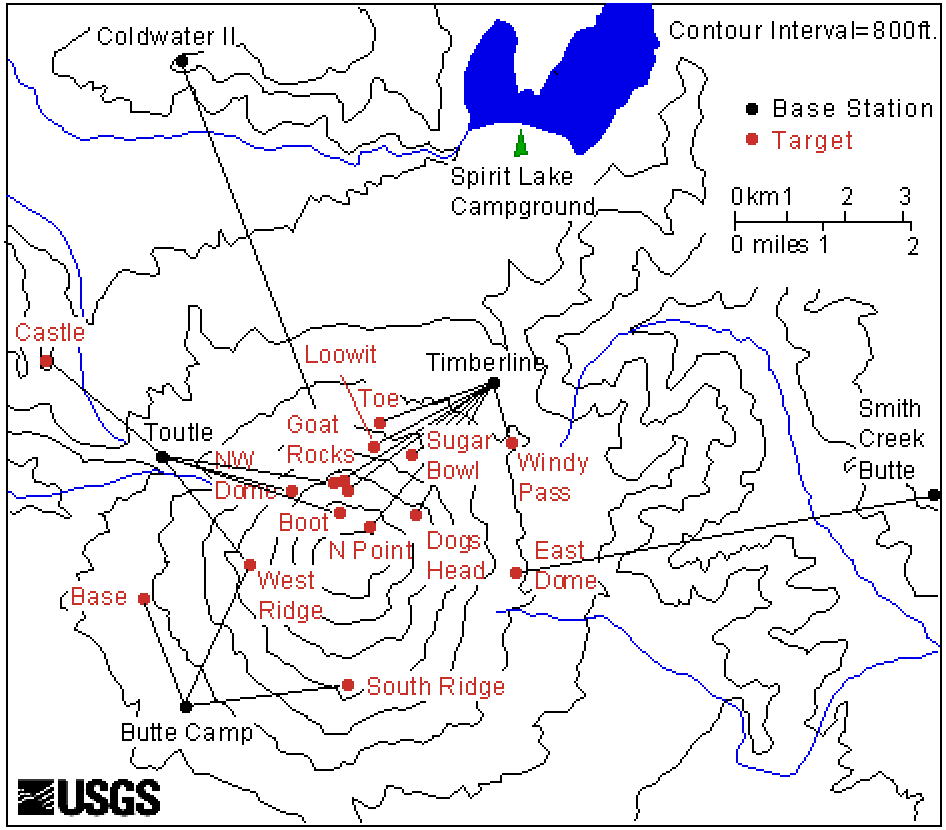
$$\text{Range} = C \times \Delta\text{Time}/2$$

Two-way Ranging: Electronic Distance Measuring (EDM) Instrument

EDM:

laser source/receiver

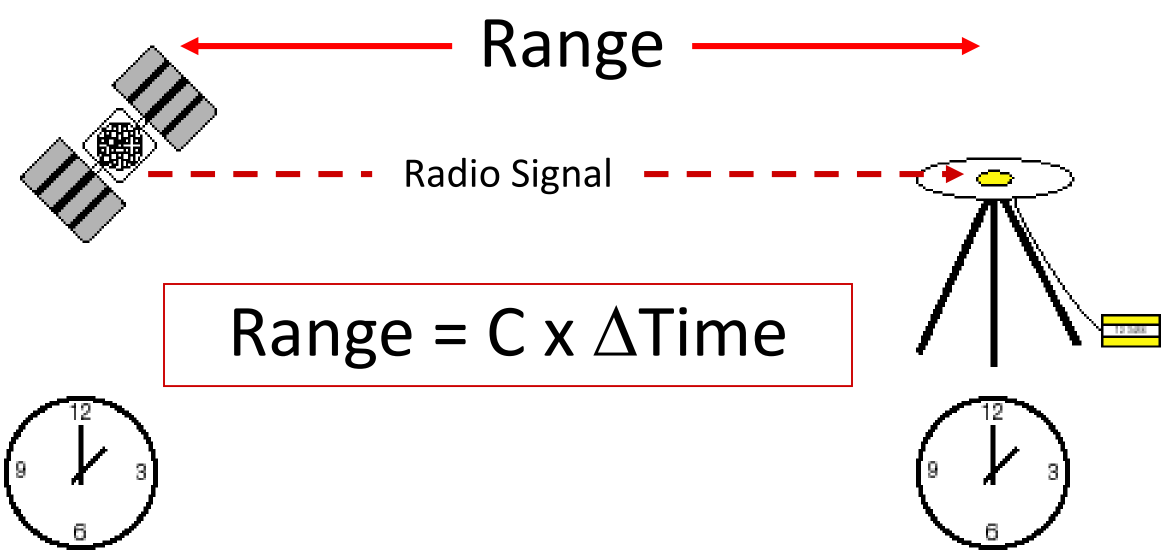
Retroreflector (“target” mirror)

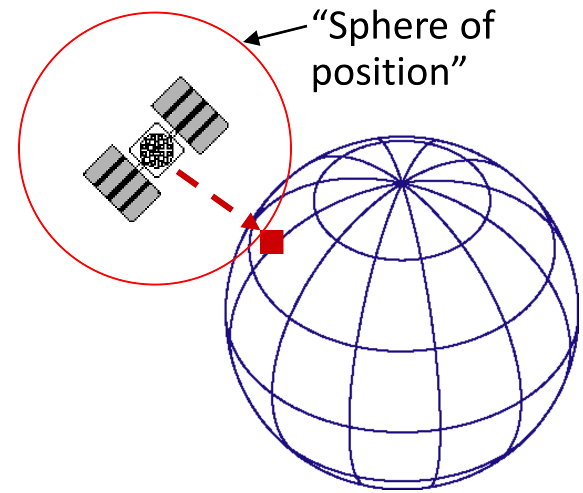


Mt. Saint Helens Monitoring Prior to 1980 Eruption

Ranging techniques

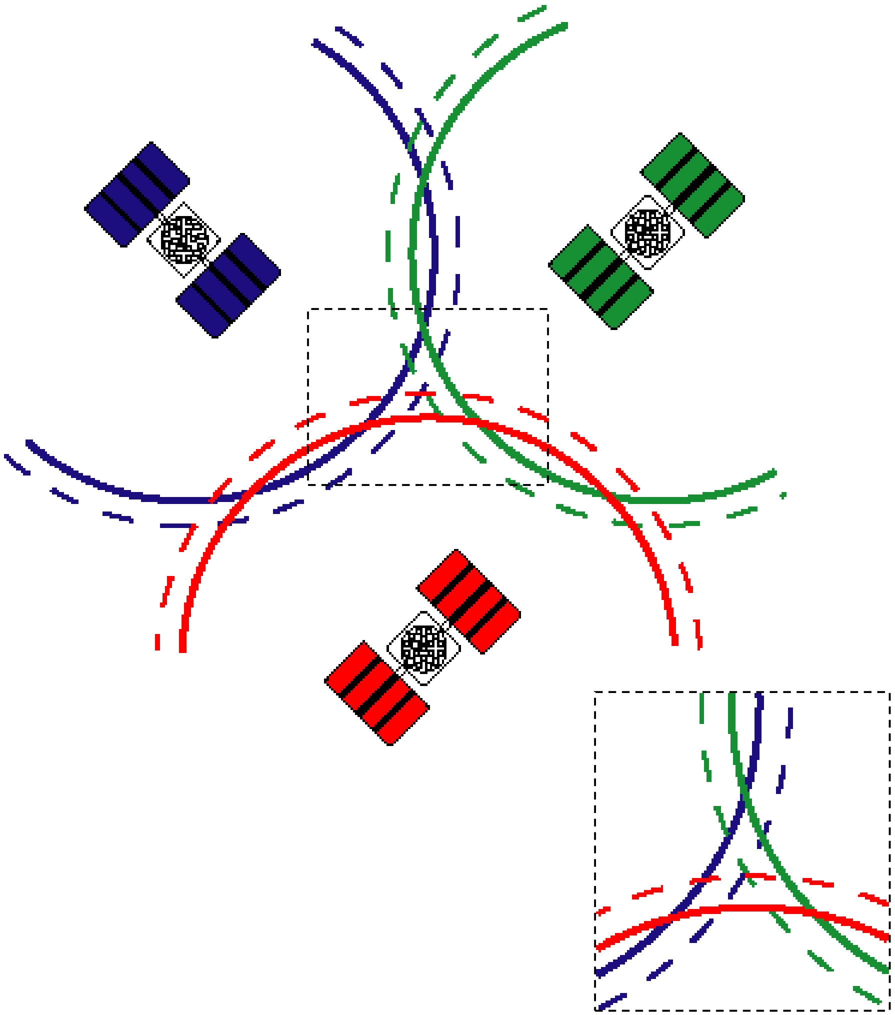
- One-way ranging with GPS





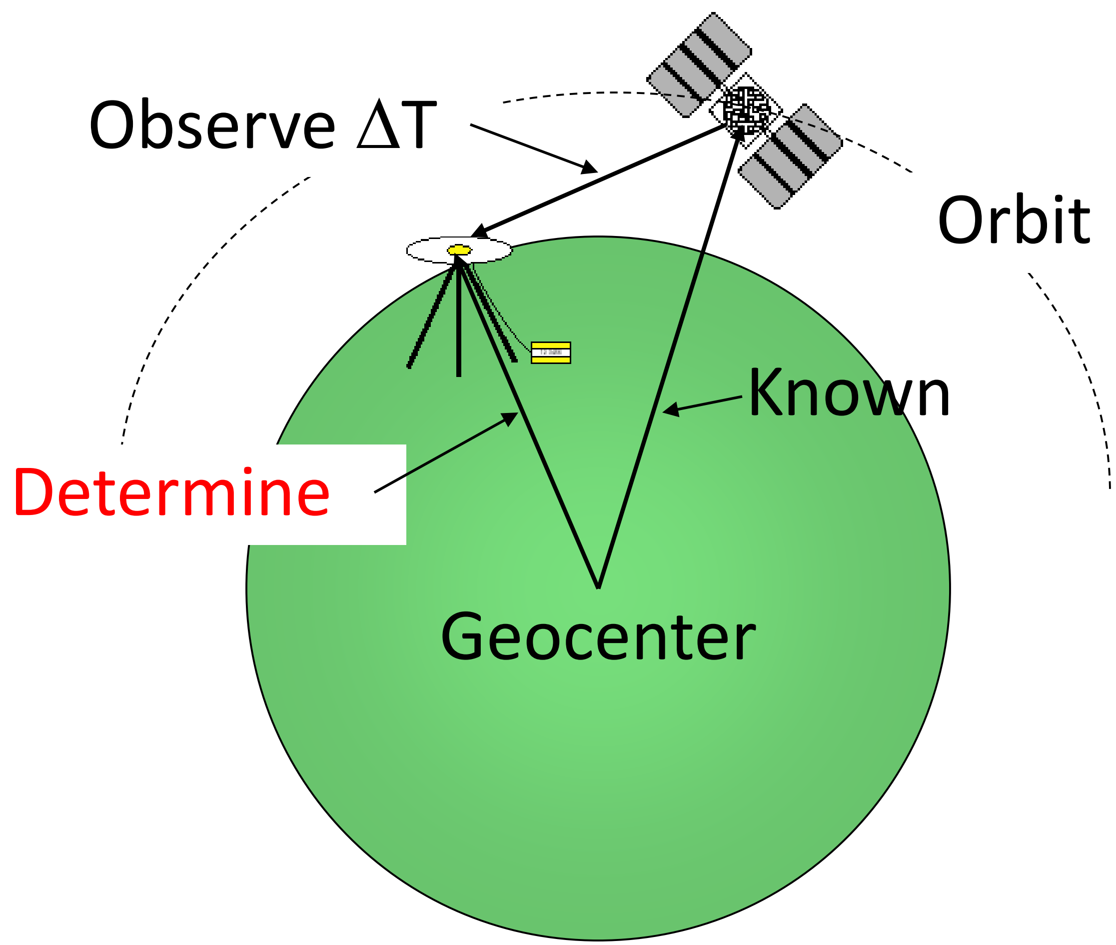
1 microsecond error = ~ 300 meters
1 nanosecond error = ~ 1 foot

How are SV and receiver clocks synchronized?



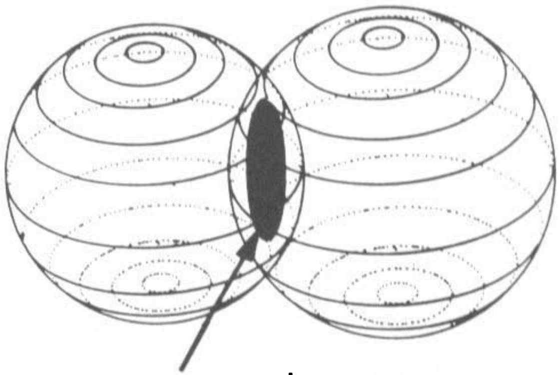
- Clock errors will cause spheres of position (solid lines) to miss intersecting at a point.
- Adjust receiver clock slightly forward will cause larger ΔT(=larger sphere; dashed) and intersection at point.
- Requires 4 SVs, not 3 as shown, for clock error & X, Y, Z

Satellite Positioning

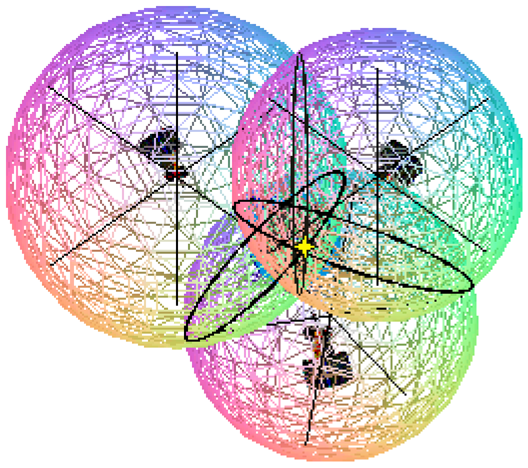


3-D (X, Y, Z) One-way Ranging

- Intersection of 2 spheres of position yields circle
- Intersection of 3 spheres of position yields 2 points of location
  - One point is position, other is either in space or within earth's interior
  - With earth ellipsoid (4th sphere)
    - Get receiver clock synchronized and X & Y but no Z
- Intersection of 4 spheres of position yields XYZ and clock synchronization



Two spheres



Three spheres

Determine Position by:

1) Downloading almanac (ephemeris info., SV health, etc.) Takes 12.5 minutes for full message.
2) Synchronize receiver clock/measure ΔT to 4 satellites = *pseudorange*
3) Account for error sources (see below) by modeling = **range**
4) Calculating intersection and compute X, Y, Z w.r.t. to center of selected reference ellipsoid
5) Converting to coordinates of interest

How is ΔT measured?

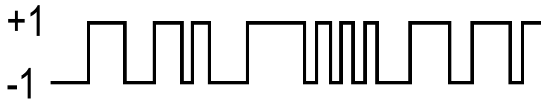
- By using broadcast signals ("codes")
  - Code solutions
    - Less precise, easiest to achieve

OR

- By using carrier cycles
  - Carrier-phase solutions
    - More precise, more difficult to achieve

Broadcast Signals - Codes

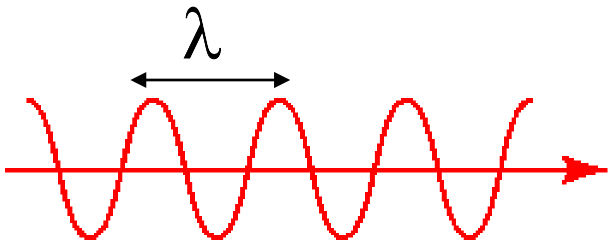
- Coarse acquisition (C/A) code
  - Civilian access, least accurate;
  - Each SV broadcasts unique C/A code
    - 1023 bits/millisecond, binary, pseudorandom
  - Receiver generates same codes



- Precise or protected (P) code
  - Authorized users only, more accurate (5-10 m absolute)
  - Code requires algorithm “seed” that is classified
  - P code for each satellite reset weekly
- Y code
  - Military use only
  - Code algorithm is encrypted
- Status message – satellite health, status and orbit info

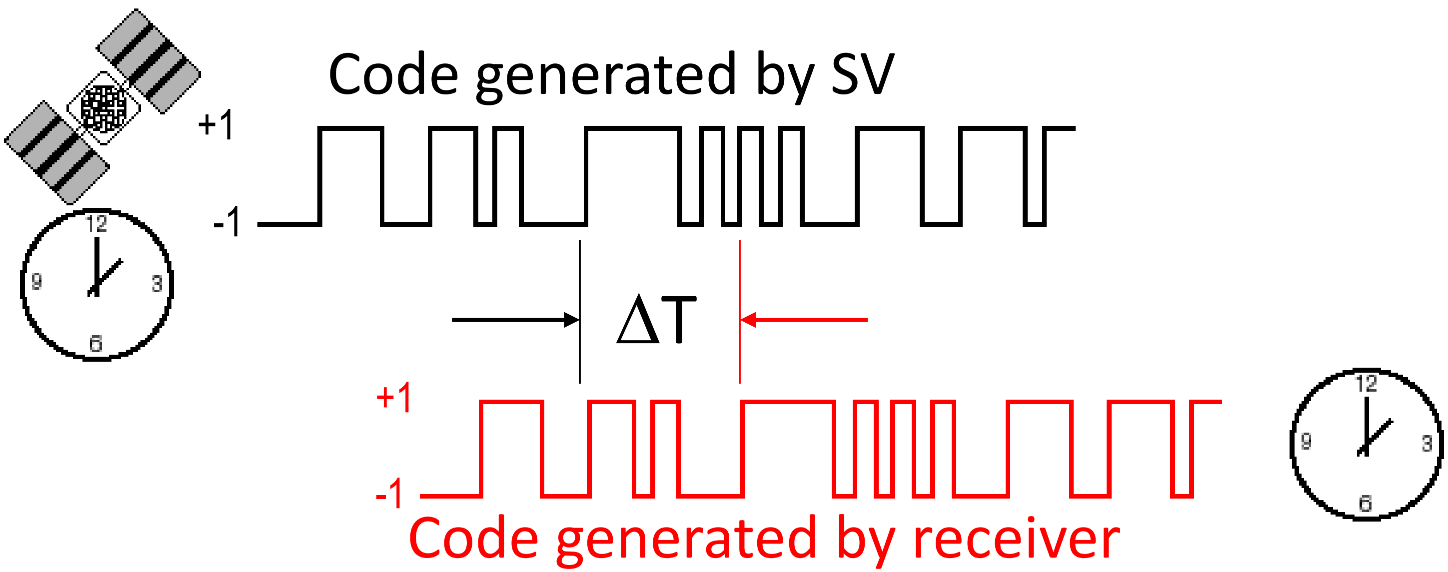
Signal "Carrier"

- Radio waves with following characteristics:
  - L1 (&L1c): frequency = ~1575 MHz with λ = 19 cm
    - Carries C/A code and status message, modulated at 1 MHz
    - Carries P code modulated at 10 MHz
  - L2 (&L2c): frequency = ~1228 MHz with λ = 24 cm
    - Carries P code
- Fundamental precision in positioning limited by ability to determine phase of carrier (to ~ $0.01\lambda = 1$ or 2 mm)

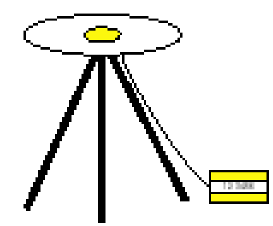


ΔT Code solutions

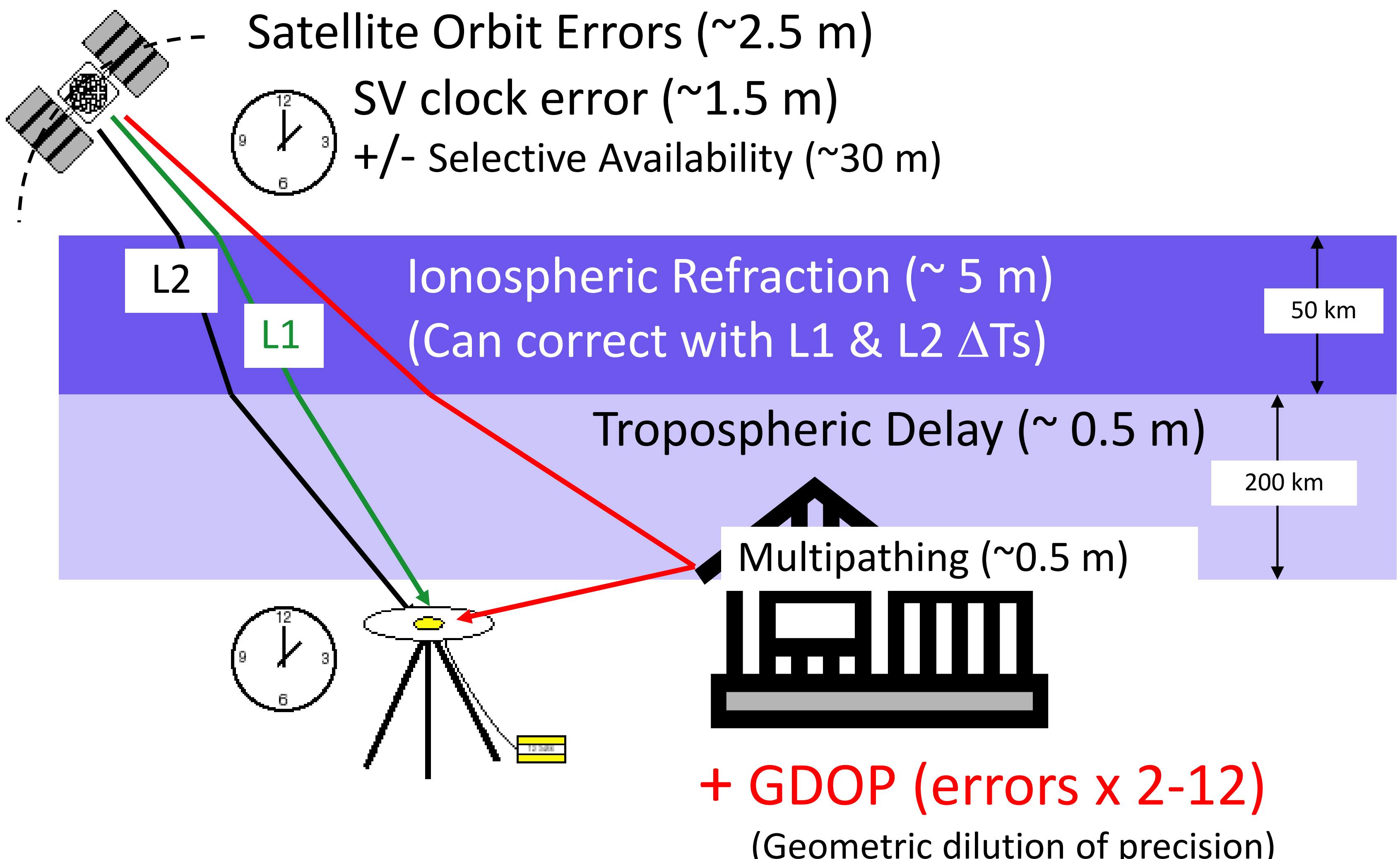
- Compare offsets in satellite and receiver codes to arrive at ΔT



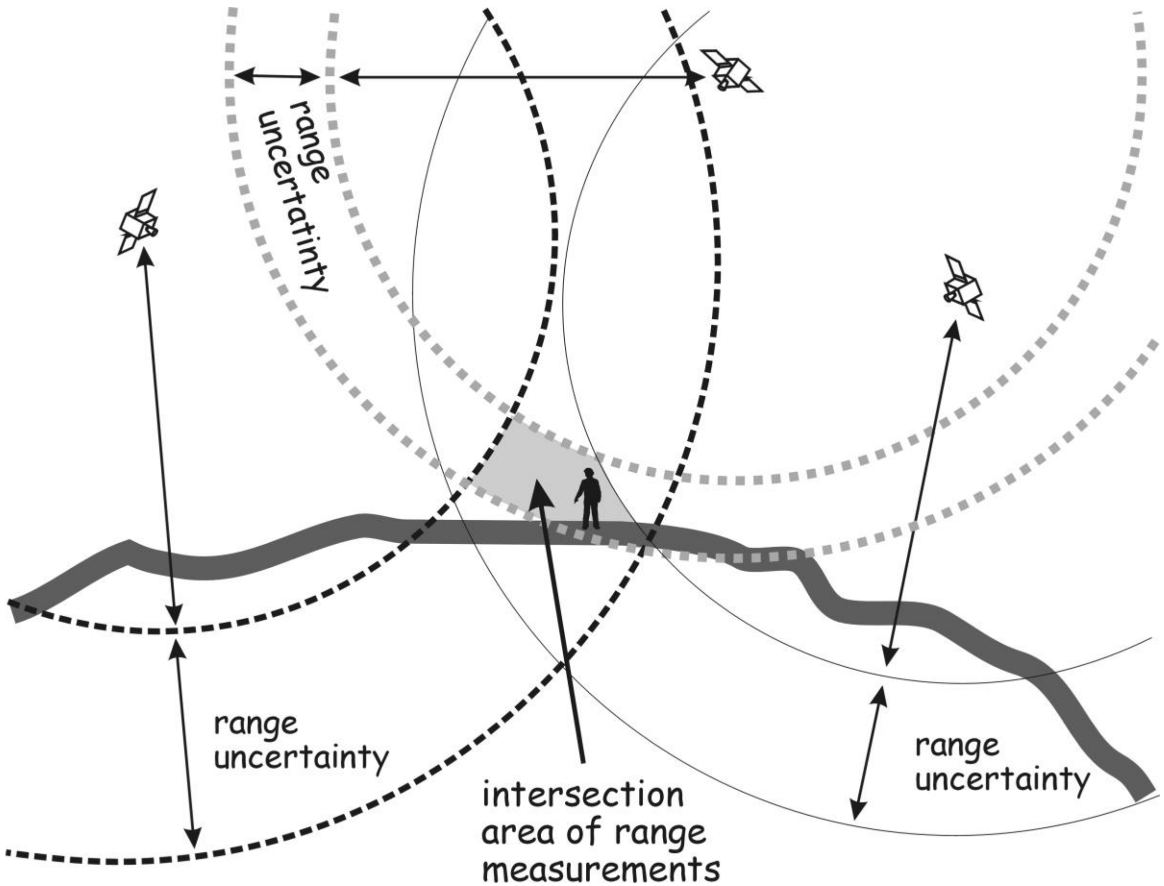
$$\text{Pseudorange} = C \times \Delta T$$



Sources of Error

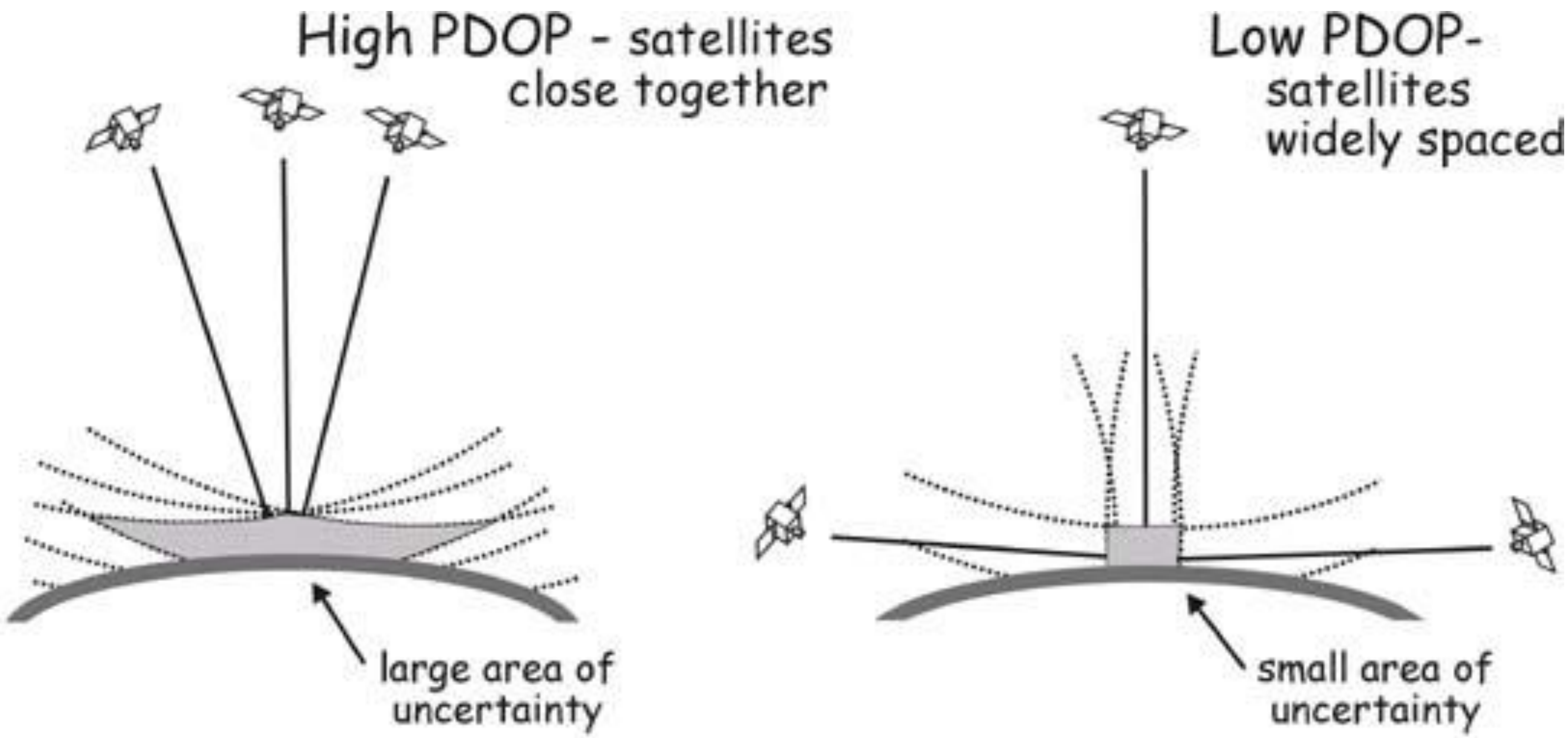


Range Uncertainties-DOPs



From Bolstad, Fig. 5-11

Geometric Dilution of Precision (GDOP)

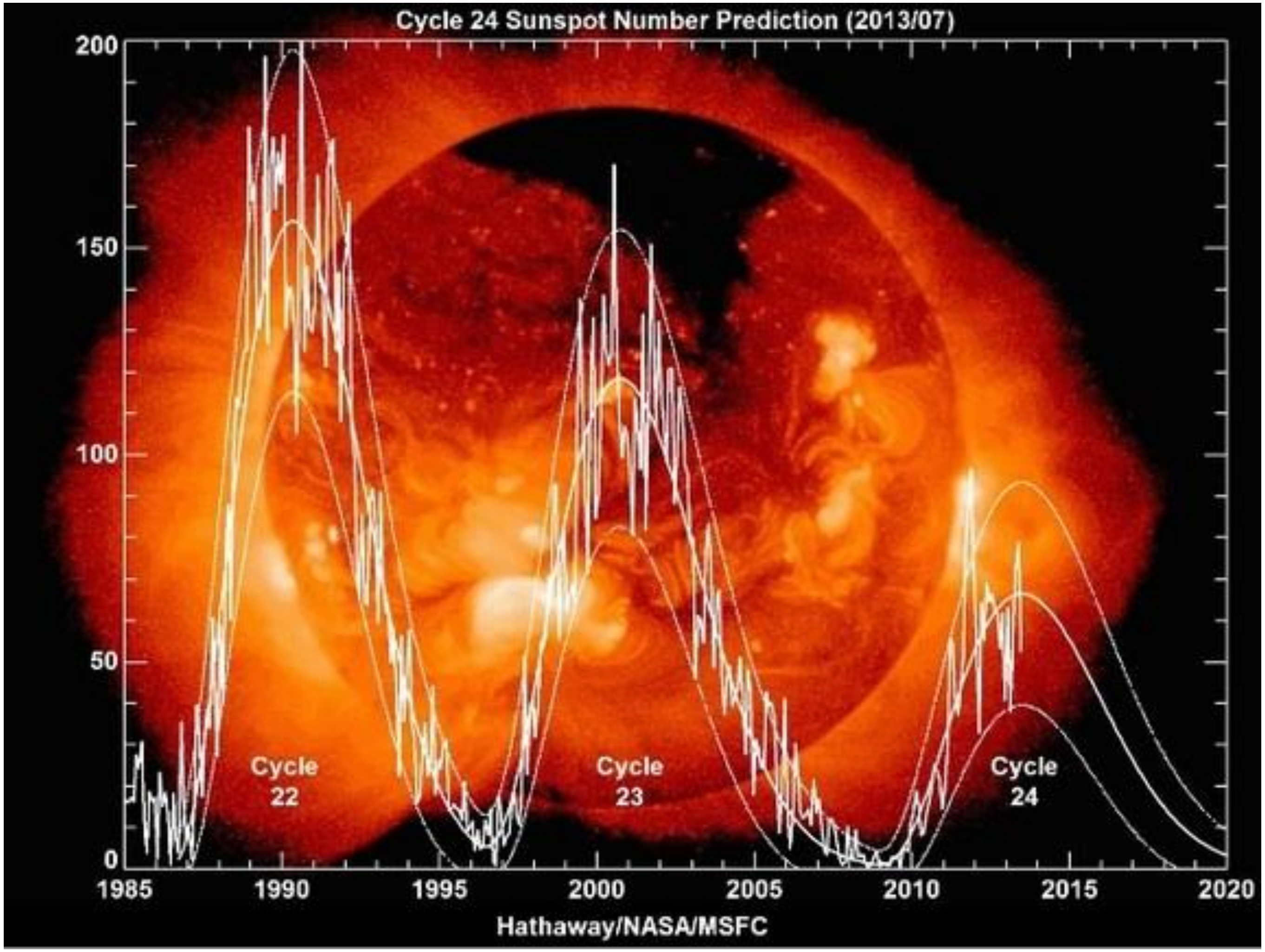


From Bolstad, Fig. 5-10

Summary of Error Sources (m)

Source: Trimble Navigation.	Standard GPS	DGPS
SV Clocks	1.5	0
Orbit (Ephemeris)	2.5	0
Ionosphere	5.0	0.4
Troposphere	0.5	0.2
Receiver Noise	0.3	0.3
Multipath	0.6	0.6
S/A	30 (0)	0
2-D Accuracy	~10-15m	2.8

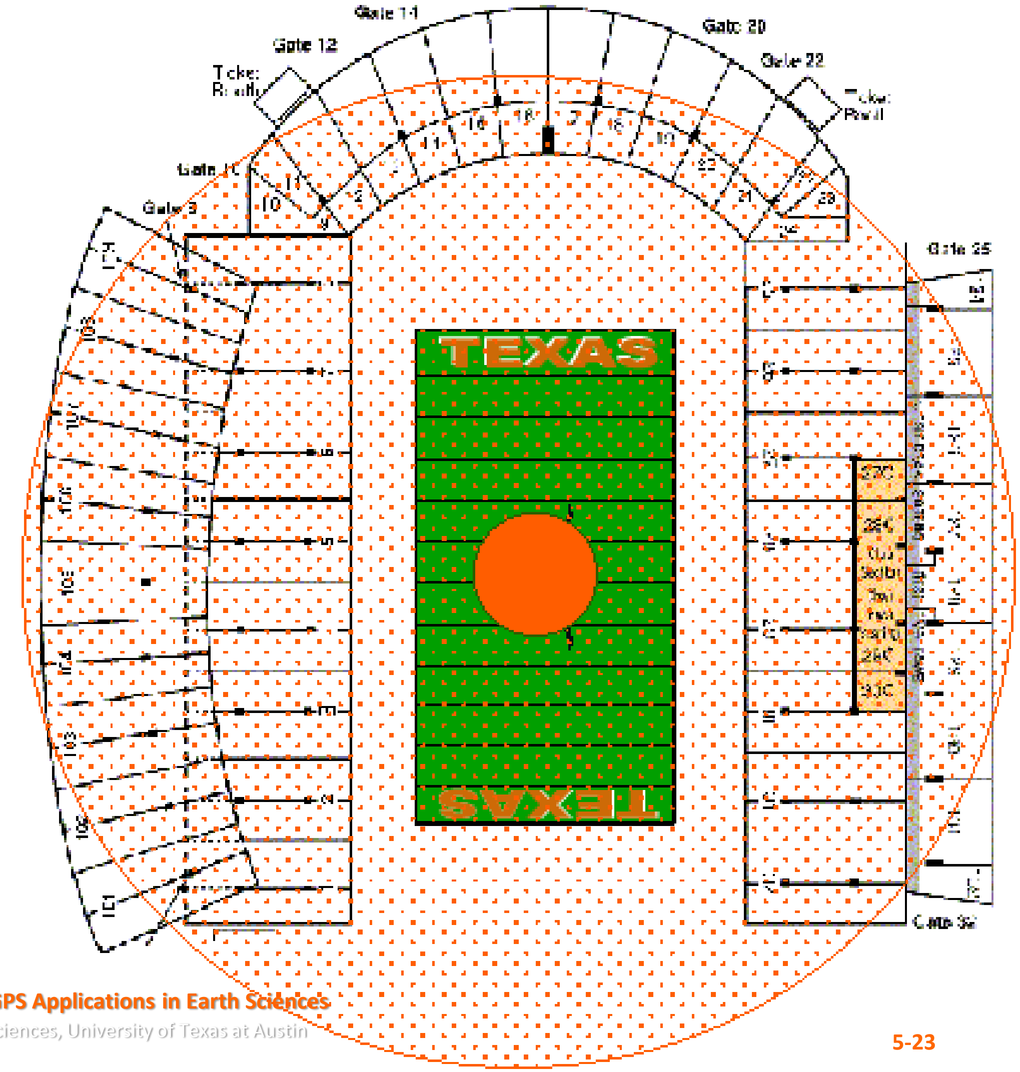
Solar Sunspot Cycle – 2014 maximum



Comparison with S/A on & off

- S/A on: I'm in the stadium but am I on the field or in the stands?

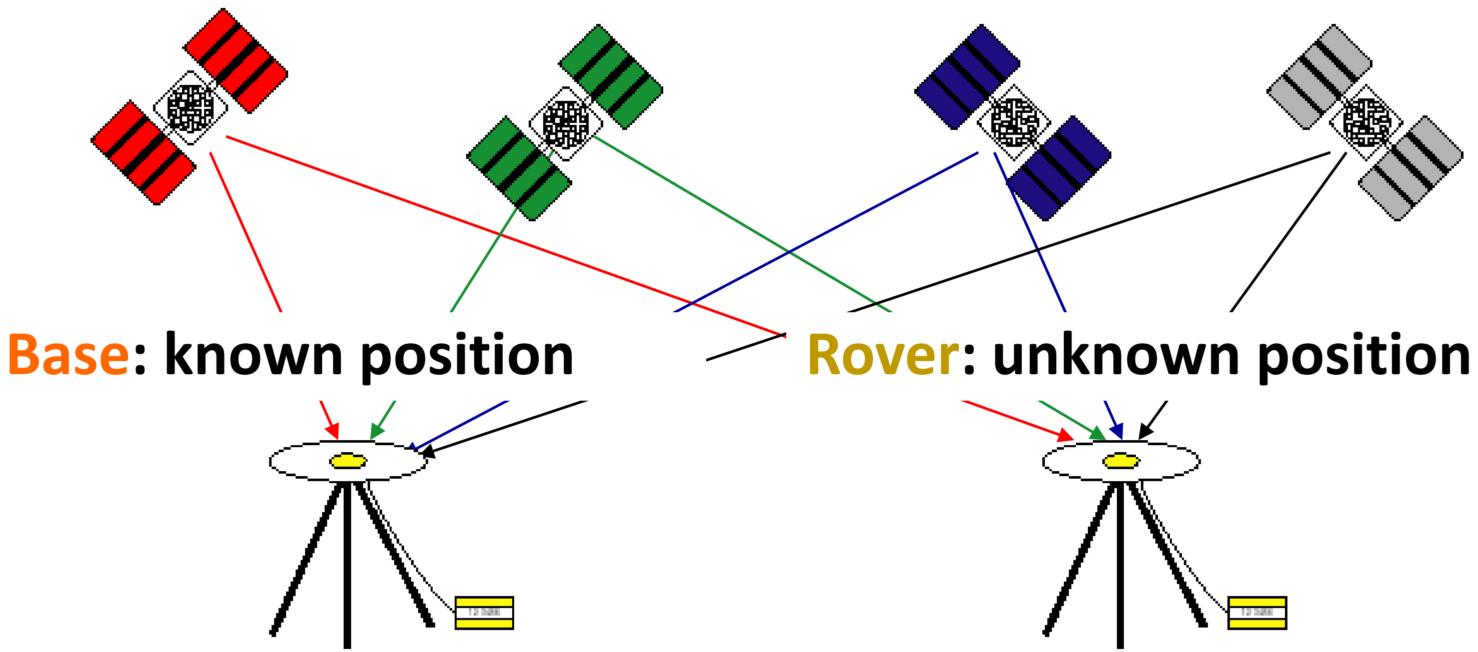
- S/A off: Which yard marker am I on?



Differential GPS (DGPS)

- Requires two receivers
  - One receiver (base) is established at known position
  - Second receiver (rover) occupies unknown position(s)
- Common errors are eliminated by combining data from both receivers
- Most accurate results from use of *carrier* (L1, L2) *phase* DGPS (<cm)

Differential GPS Positioning



- Base station pseudoranges compared to known position; differences are errors common to both receivers.
- Base computes pseudorange corrections for rover.
- Apply correction to rover data, either in real time (+/-6 seconds) or long afterwards.

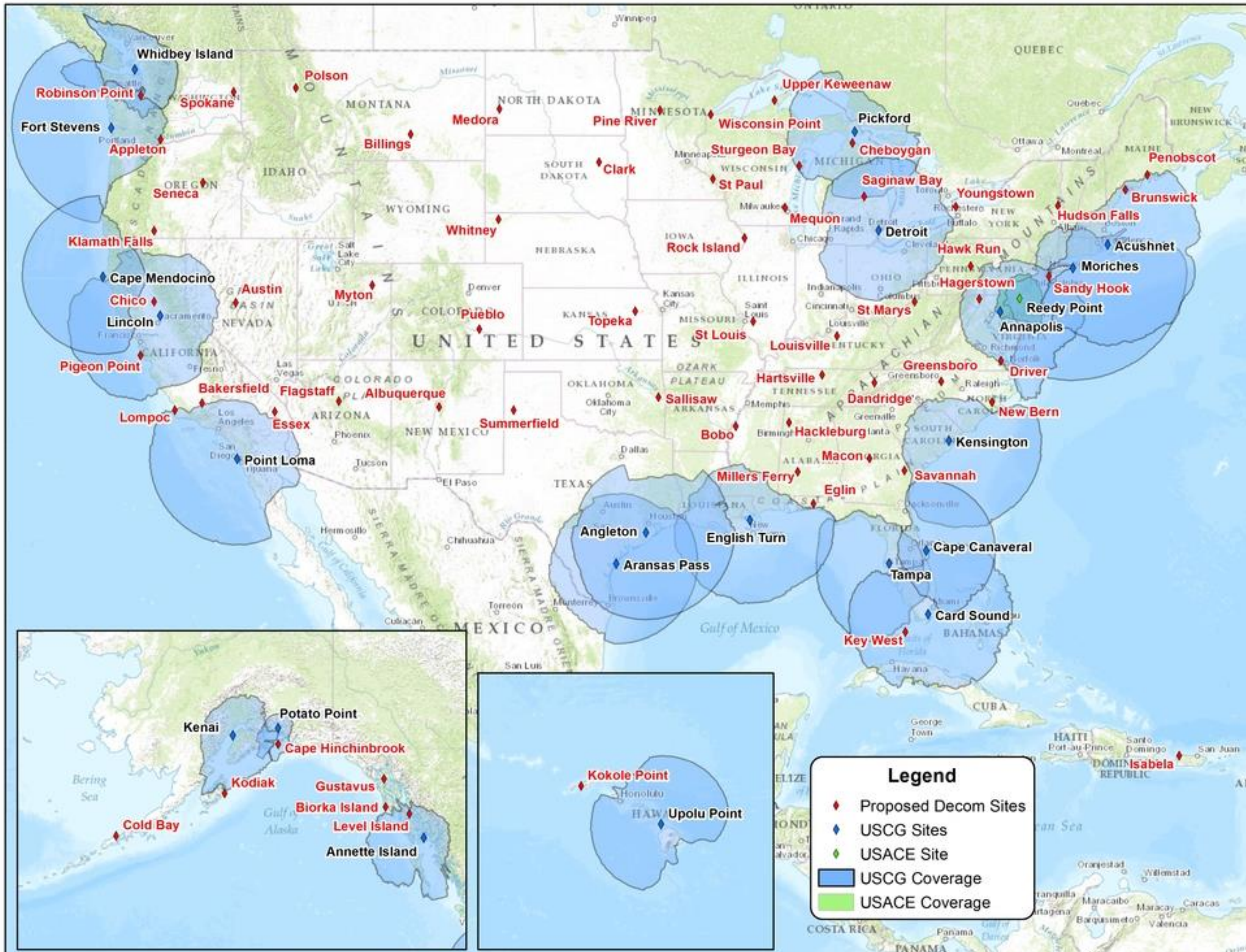
Base Station Correction Data Availability:

1. Real-time, via telemetry
   - Auxillary antenna connected to GPS receiver to receive broadcast corrections in real-time:
   - Ground-based augmentation Services (GBAS)
     - Base station and broadcaster set up on site (JSG equipment)
     - US Coast Guard (US Nationwide Differential GPS System; NDGPS)
   - Satellite-based augmentation services (SBAS)
     - WAAS, EGNOS, Commercial Services – OmniSTAR
2. After the fact, "**post-processing**"
   - Base station data combined with rover data after collection
   - CORS – continuously operating reference system (data from a network of base stations stored for download)

Important Developments, DGPS

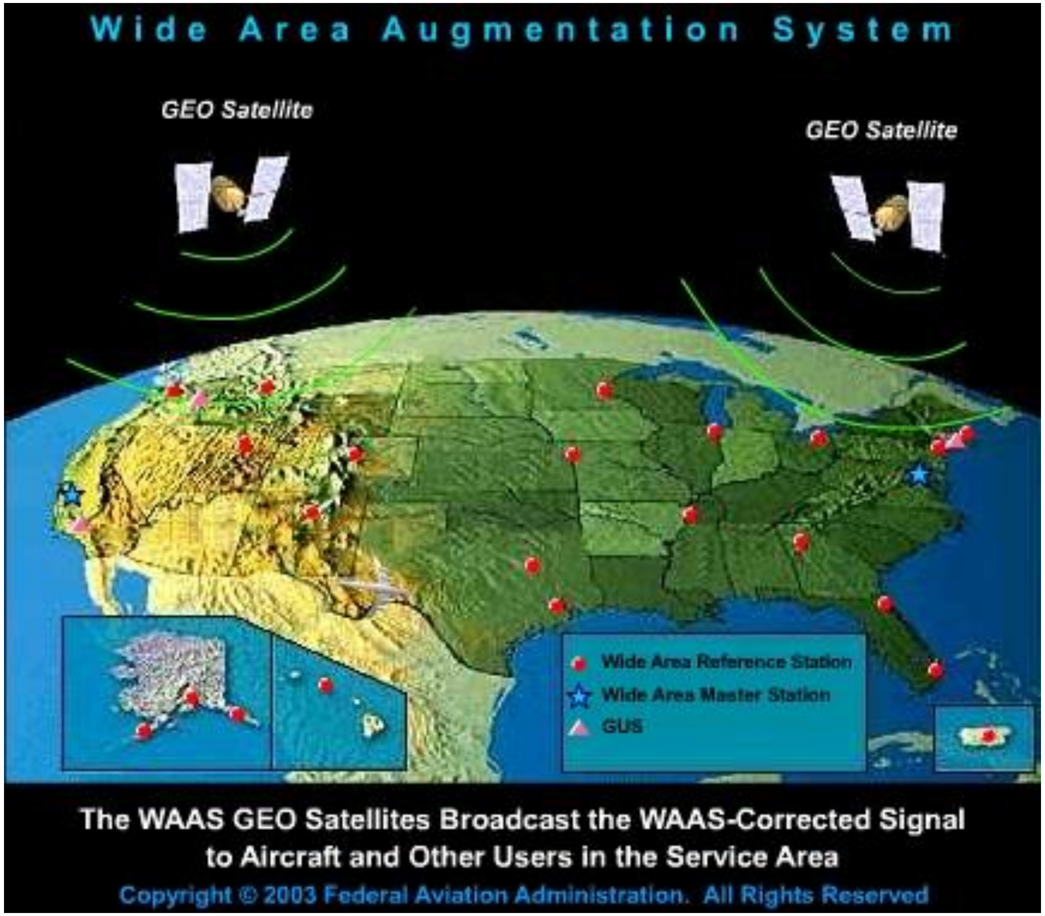
- USCG DGPS beacon service (1999; NDGPS) now decommissioned
- Deactivation of Selective Availability (S/A) (2000)
- Satellite Based Augmentation Systems (SBAS)
  - Commissioning of US FAA Wide Area Augmentation System (WAAS) (2003)
  - European Union - EGNOS (2009)
  - OmniSTAR – Commercial service, global coverage

2020 Decommissioning of NDGPS Sites

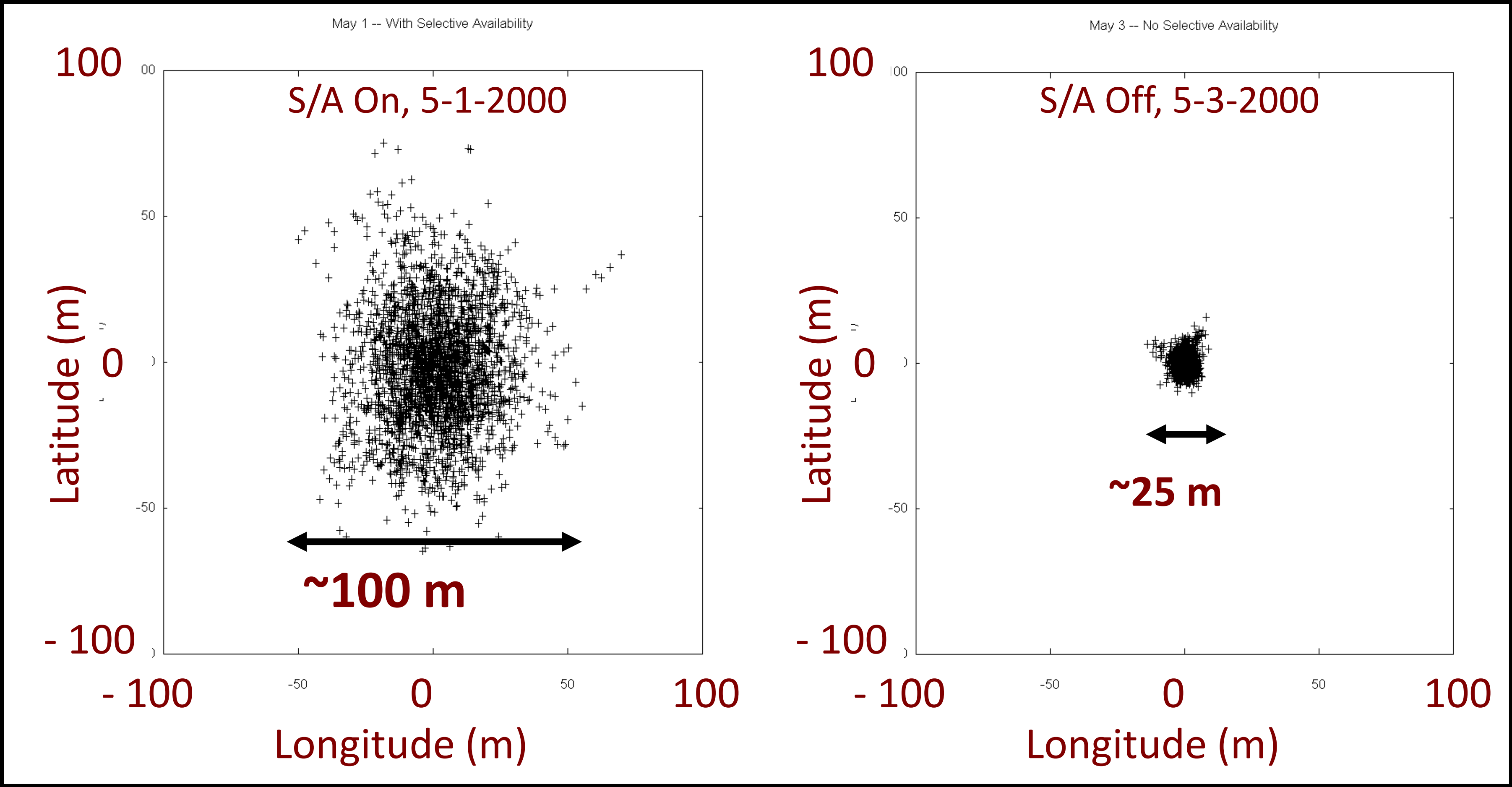


2003 Commissioning of WAAS

- DGPS corrections broadcast from geostationary satellites



Deactivation of Selective Availability



High Accuracy GPS

“Carrier-phase” DGPS

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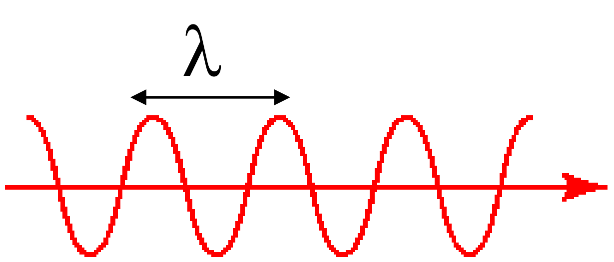
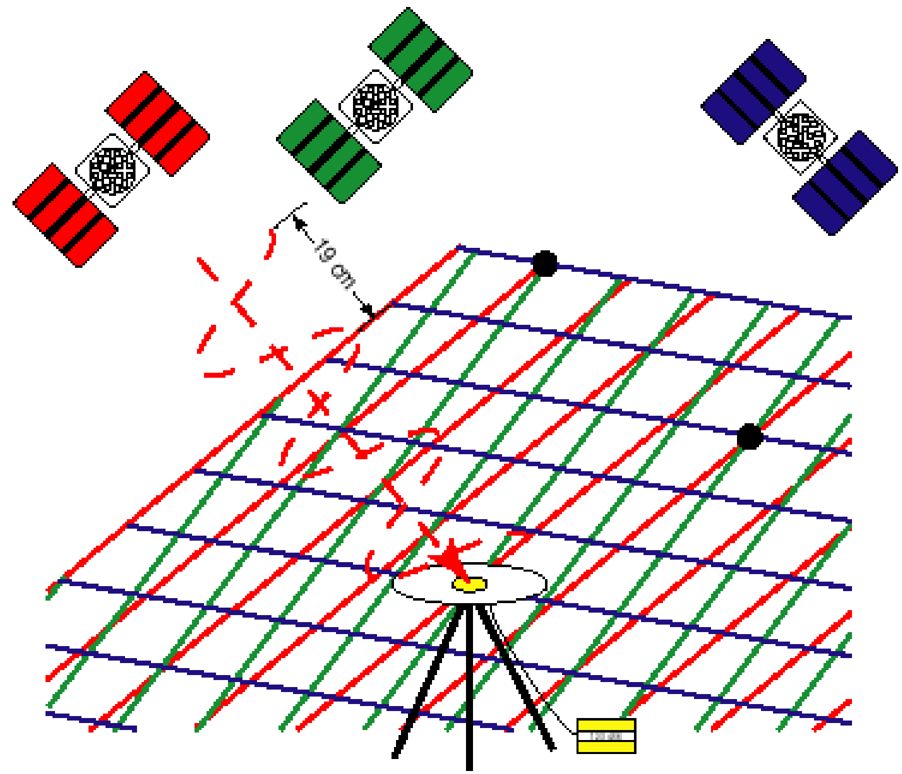


DGPS Carrier-Phase Solutions

- Use 19 cm wave as ruler to measure # of cycles (& phase of cycle) from each satellite
- Ruler is not labeled; track phase from several SVs and find intersection(s) of coincident phases.
- Know approx. position of antenna from code-phase DGPS; eliminates ambiguity.
- Passage of waves and motion of SVs need to be known
    - Cycle Slips

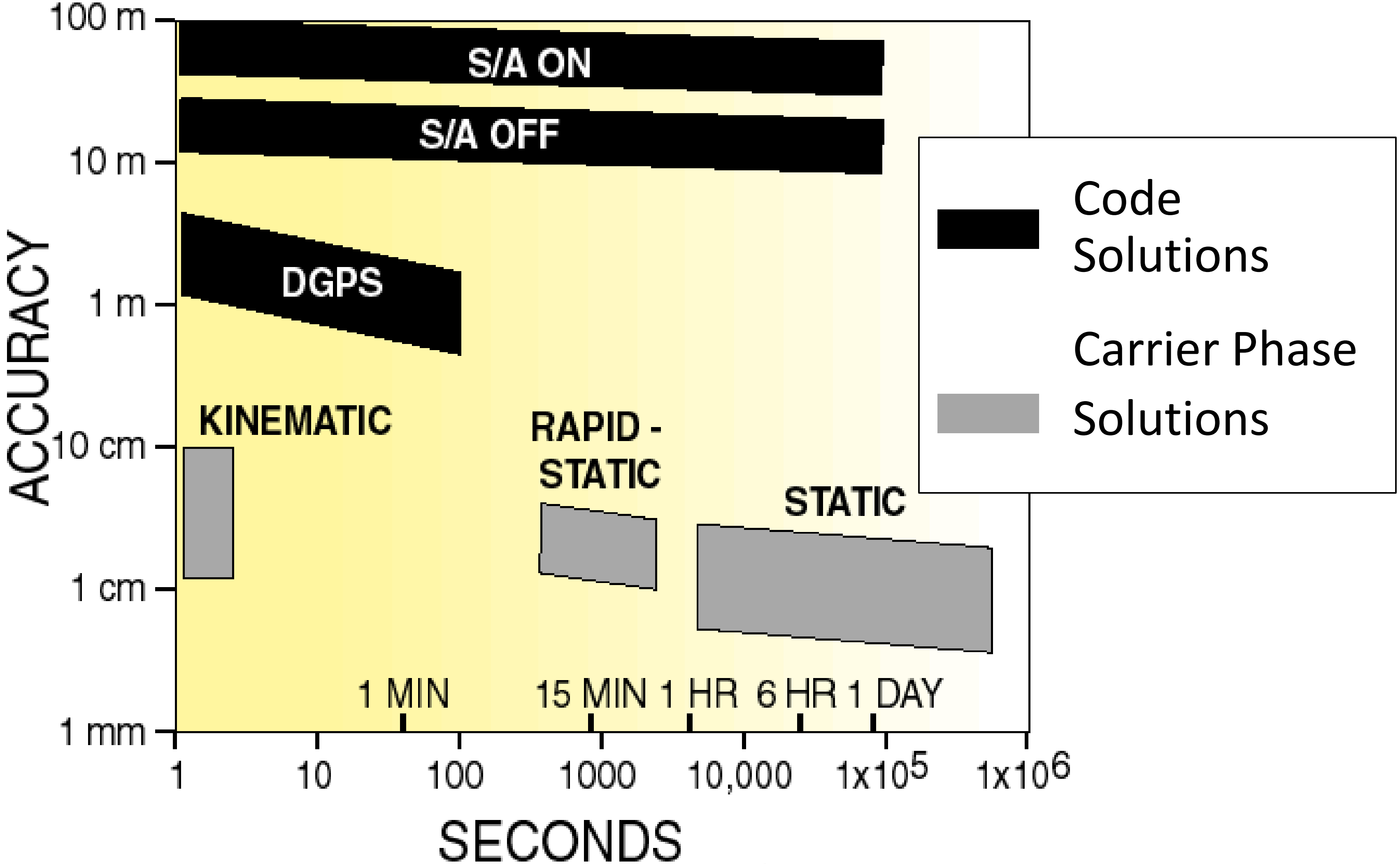


- Sub-centimeter precision possible

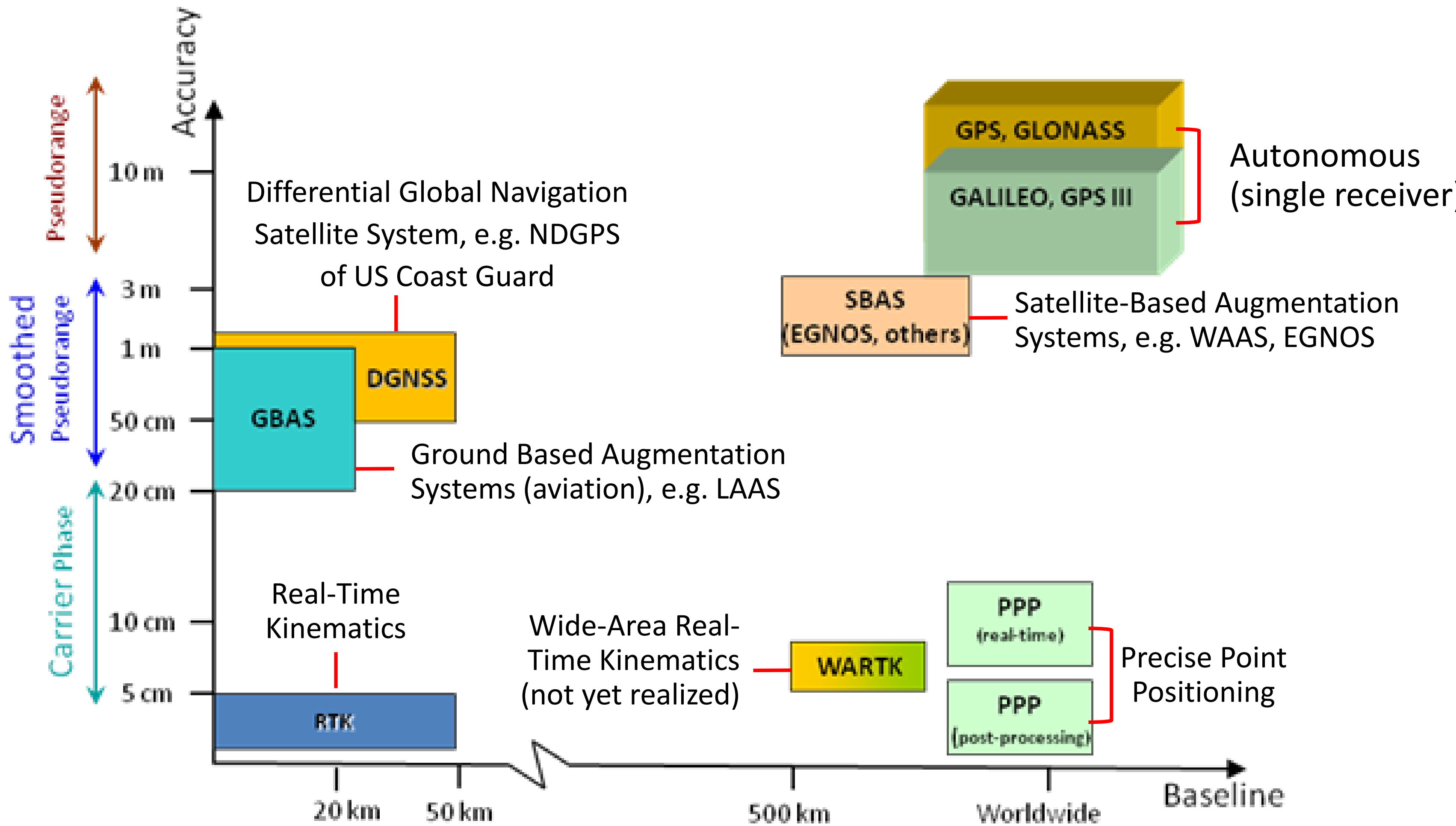
Types of Carrier-phase Solutions

- Static: “Rover” is stationary and collects data for several hours
- Rapid Static: Rover is stationary and collects for 5-20 minutes
- Kinematic: Rover collects on the move

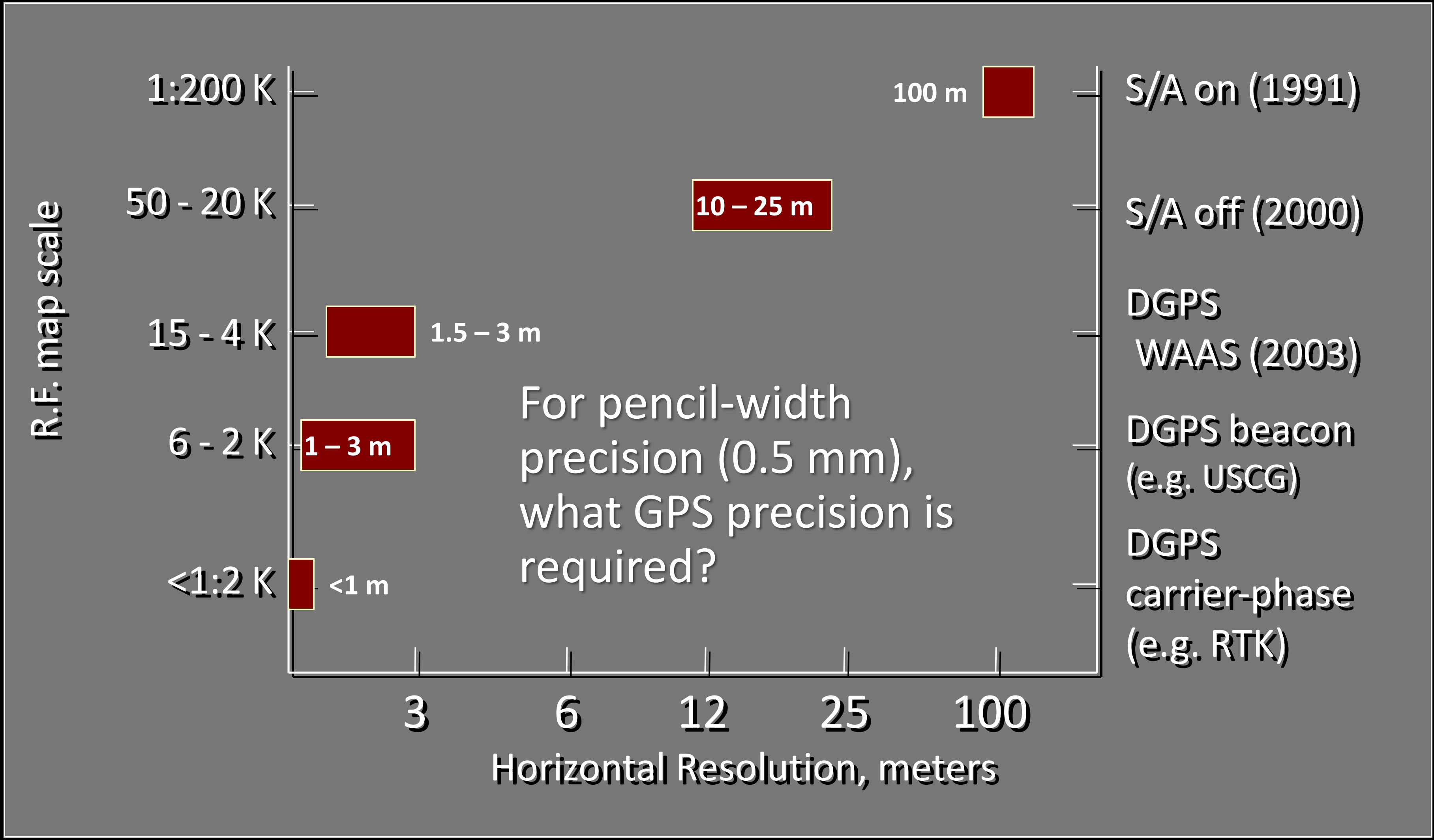
Accuracy of Code vs. Carrier Phase Solutions



GPS Accuracy – Generic Terminology



GPS Precision and Map Scales



GPS Resolution and Map Scales