12.S56 GPS: Where Are You?
Fall 2008

12S56 GPS

GPS Original Design

- Started development in the late 1960s as NAVY/USAF project to replace Doppler positioning system
- Aim: Real-time positioning to < 10 meters, capable of being used on fast moving vehicles.
- Limit civilian ("non-authorized") users to 100 meter positioning.

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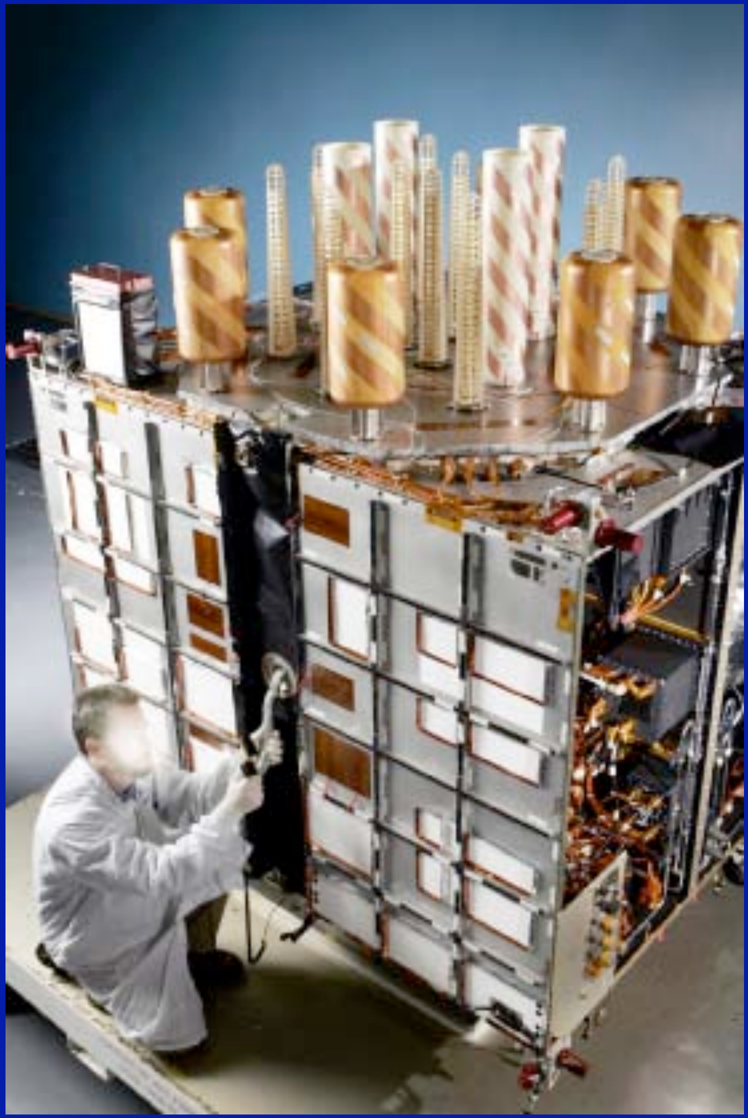
GPS Design and performance

- Aim: Real-time positioning to < 10 meters, capable of being used on fast moving vehicles, but by use of carrier phase measurements, millimeter level positioning, averaged over 24-hours is possible
- Innovations
  - Multiple satellites (originally 21, now ~28-32). Up to 10 simultaneously visible.
  - All satellites transmit at same frequency and thus can be observed with narrow band (inexpensive) receiver.
  - Spread-spectrum transmission binary code used.
  - Dual frequency band transmission:
    - L1 ~1.575 GHz, L2 ~1.227 GHz
    - Corresponding wavelengths are 190 mm and 244 mm
  - Differential positioning allows many errors to cancel to a large degree (e.g. satellite orbital errors) allowing mm and sub-mm positioning (24-hour average) and 3-20 mm kinematic positioning (~1-second average).
- Continuous time operation possible at specific locations.



GPS Block IIRM satellite
1100 kg weight

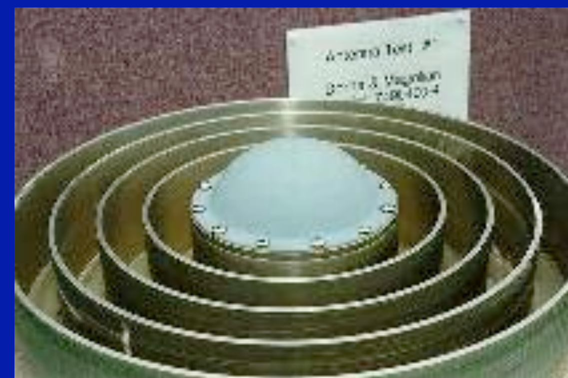
Courtesy of Lockheed Martin. Used with permission.

From http://www.lockheedmartin.com/

GPS Receivers and Antennas (Geodetic)

Image removed due to copyright restrictions.

Units weight ~1kg and are ~10cm per side



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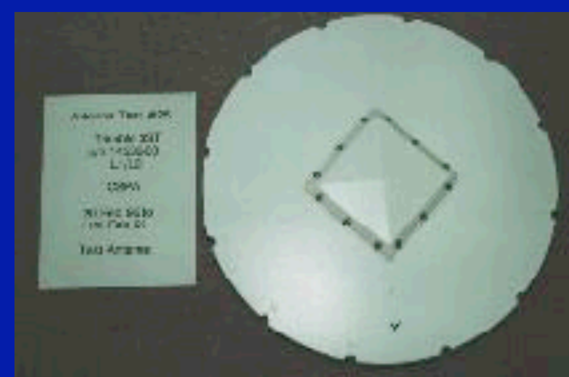

Choke rings and ground plane suppress multipath

http://www.leica-geosystems.com/
http://www.trimble.com/
http://corp.magellangps.com/
http://www.topconpositioning.com/

Courtesy of National Geodetic Survey.

Styles of Monuments

Image removed due to copyright restrictions.

Drilled braced monument considered most stable

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Courtesy of Commonwealth of Australia (Geoscience Australia). Used with permission.

High-wind situations

Specifics of GPS signal

- GPS transmits at two frequencies
  - L1 1575.42 MHz (2x77x10.23 MHz)
  - L2 1227.60 MHz (2x60x10.23MHz)
  - Wavelengths L1 ~190 mm; L2 ~244 mm
- Codes:
  - Course acquisition code (C/A) Chip rate (rate at which phase might change) 1.023 MHz
  - Precise positioning code (P code) 10.23 MHz
  - Y-code (Antispoofing code) also 10.23 MHz derived by multiplying P-code by ~20KHz code (highly classified)

Specifics of GPS

- Code lengths:
  - C/A code is 1023 bits long
  - P-code is 37 weeks long (2×10^{14} bits in code)
  - Only one P-code, satellites use different weeks from same code (P-code repeats each week)
  - As far as we know Y-code never repeats (again classified)
- Data message: Implemented by changing sign of code at rate of 50 bits/second (low data rate)

Specifics of GPS

- 10.23 MHz is fundamental frequency in GPS
- All radiofrequencies and codes generated from the same 10.23MHz crystal whose long term stability is controlled by Cesium or Rubidium clock (older satellites)
- The following graphics show schematically the construction of the GPS signal

Measurement usage

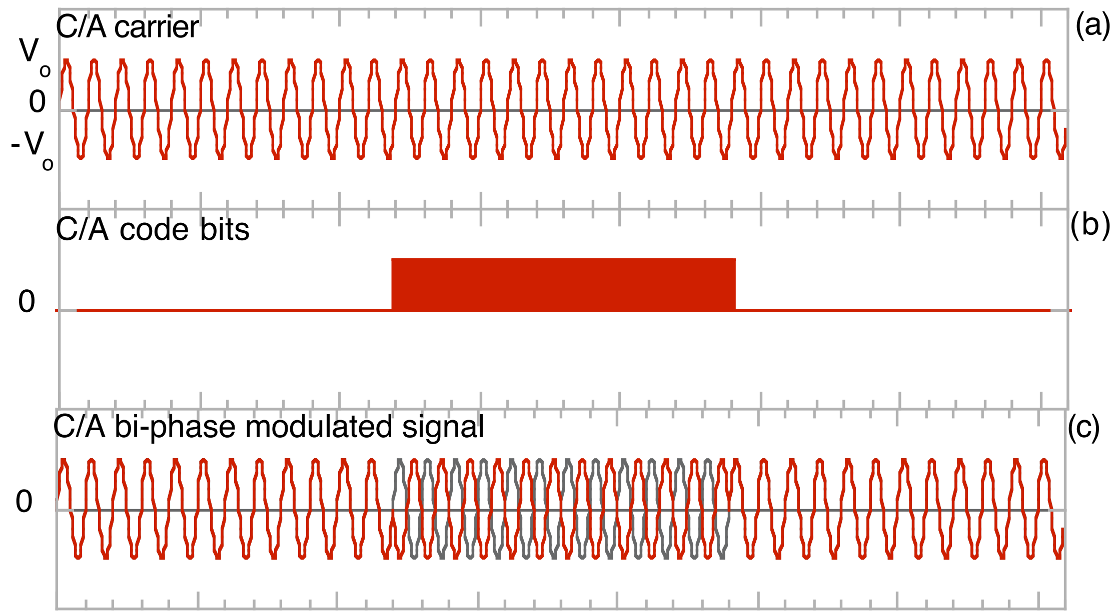
- “Spread-spectrum” transmission: Multiple satellites can be measured at same time.
- Since measurements can be made at same time, ground receiver clock error can be determined (along with position).
- Signal

$$V(t,\vec{x}) = V_o \sin[2\pi(ft - \vec{k}.\vec{x}) + \pi C(t)]$$

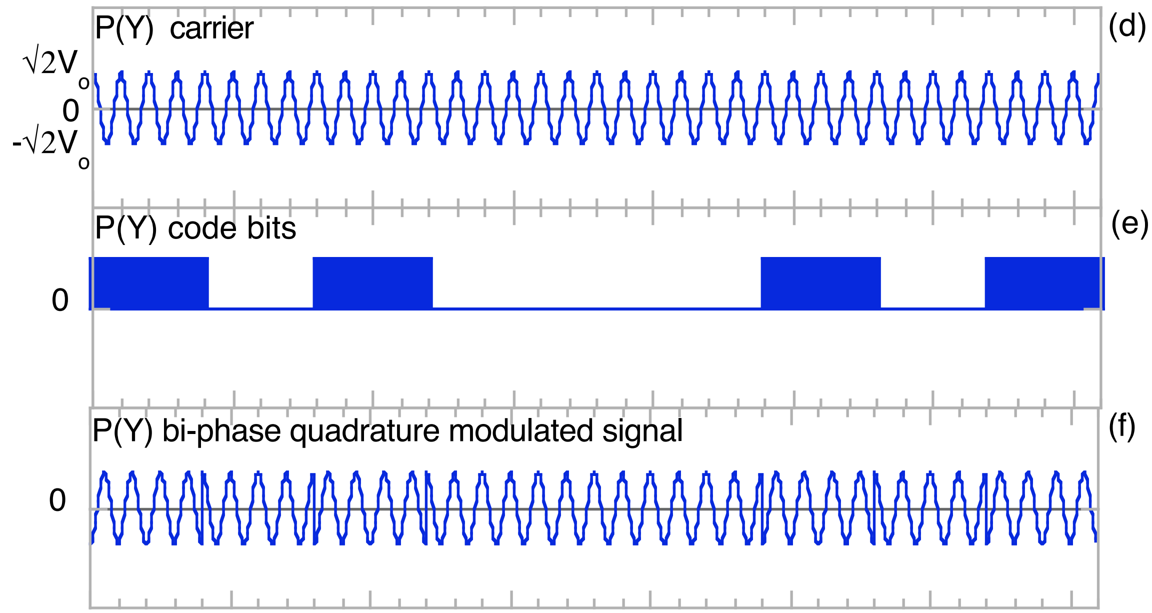
$C(t)$ is code of zeros and ones (binary).

Varies discretely at 1.023 or 10.23 MHz

CA Code Modulation

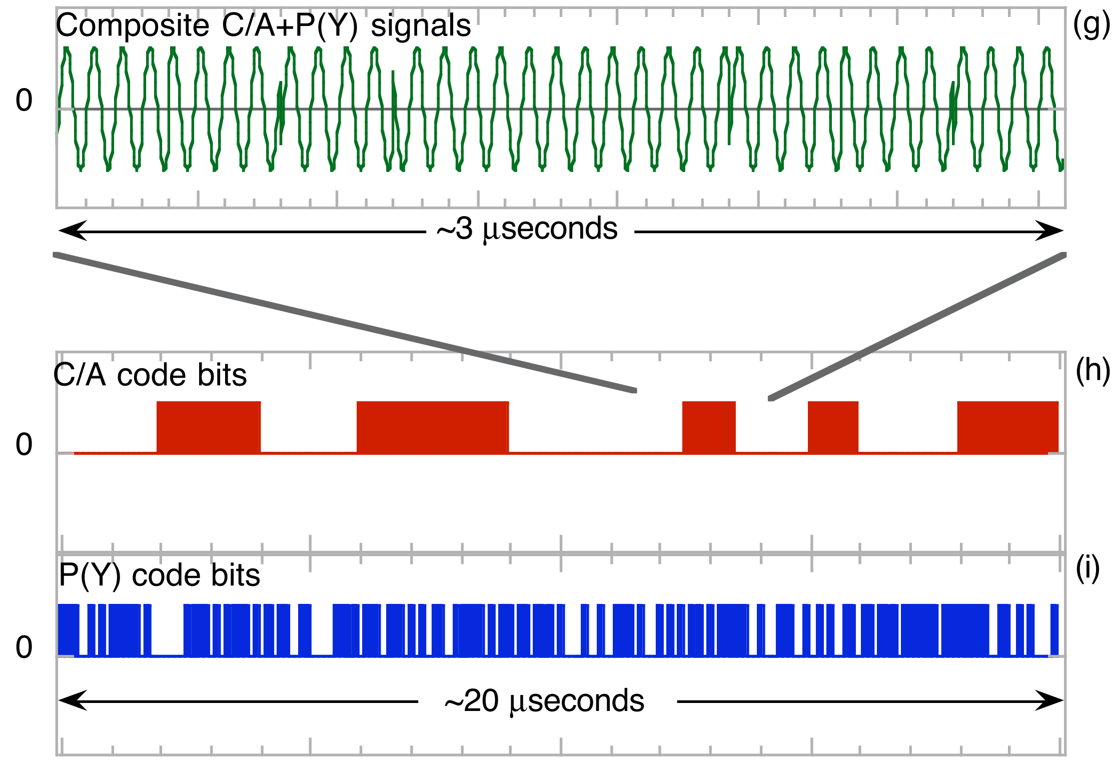


P-Code generation



P-code rate should 10 times higher than C/A code

Composite: Sum of C/A and P code



Composite GPS signal

- Last few slides show construction of composite signal
- There are sets of phase reversals on the L1 signal: C/A code at rate of 1.023 MHz and the P(Y) code add 90^o out of phase at a rate of 10.23 MHz
- How do you the GPS signal if you don’t know both codes (since each reverses the sign and should average to zero)? Answer next slide

Measurements

- Since the C(t) code changes the sign of the signal, satellite can be only be detected if the code is known (PRN code)
- Multiple satellites can be separated by “correlating” with different codes (only the correct code will produce a signal)
- The time delay of the code is the pseudo-range measurement.
- These times delays are called pseudo-range because they include errors in the ground receivers clocks (bad clocks) and satellites clocks (good clocks that can be modeled reasonable well: a few meters of position)

Position Determination (perfect clocks).

Image removed due to copyright restrictions.

- Three satellites are needed for 3-D position with perfect clocks.
- Two satellites are OK if height is known)

Image removed due to copyright restrictions.

Position determination: with clock errors: 2-D case

- Receiver clock is fast in this case, so all pseudo-ranges are short

Measurements

- Measurements:
  - Time difference between signal transmission from satellite and its arrival at ground station (called “pseudo-range”, precise to 0.1–10 m)
  - Carrier phase difference between transmitter and receiver (precise to a few millimeters)
  - Doppler shift of received signal
- All measurements relative to “clocks” in ground receiver and satellites (potentially poses problems).

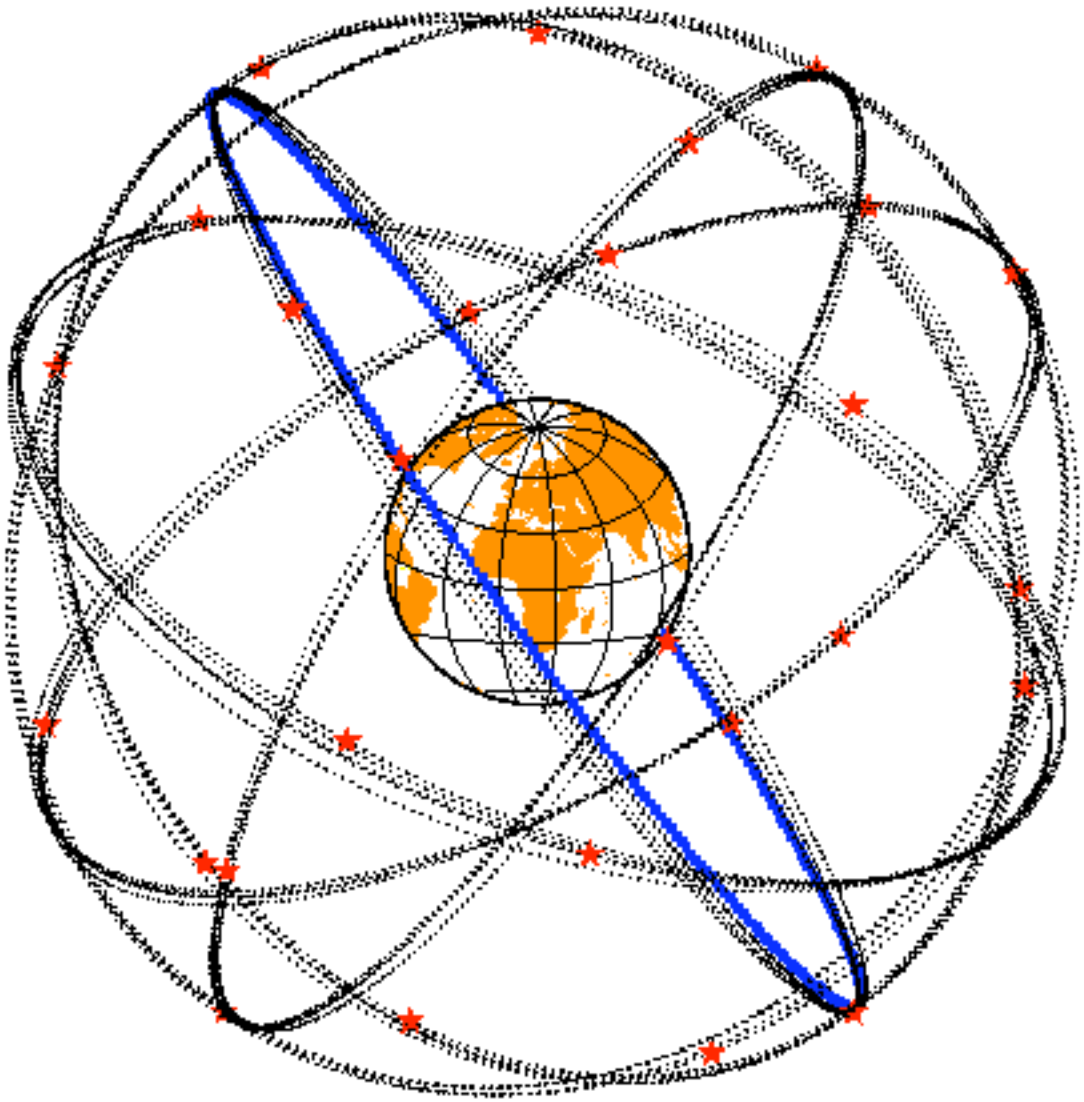
Positioning

- For pseudo-range to be used for "point-positioning" we need:
  - Knowledge of errors in satellite clocks
  - Knowledge of positions of satellites
- This information is transmitted by satellite in "broadcast ephemeris"
- "Differential" positioning (DGPS) eliminates need for accurate satellite clock knowledge by differencing the satellite between GPS receivers (needs multiple ground receivers).

Satellite constellation

- Since multiple satellites need to be seen at same time (four or more):
  - Many satellites (original 21 but now 28-32)
  - High altitude so that large portion of Earth can be seen (20,000 km altitude —MEO)
  - Orbital Period is 12 sidereal hours
  - Inclination ~55 degrees
  - Six orbital planes (multiple satellites in each plane)

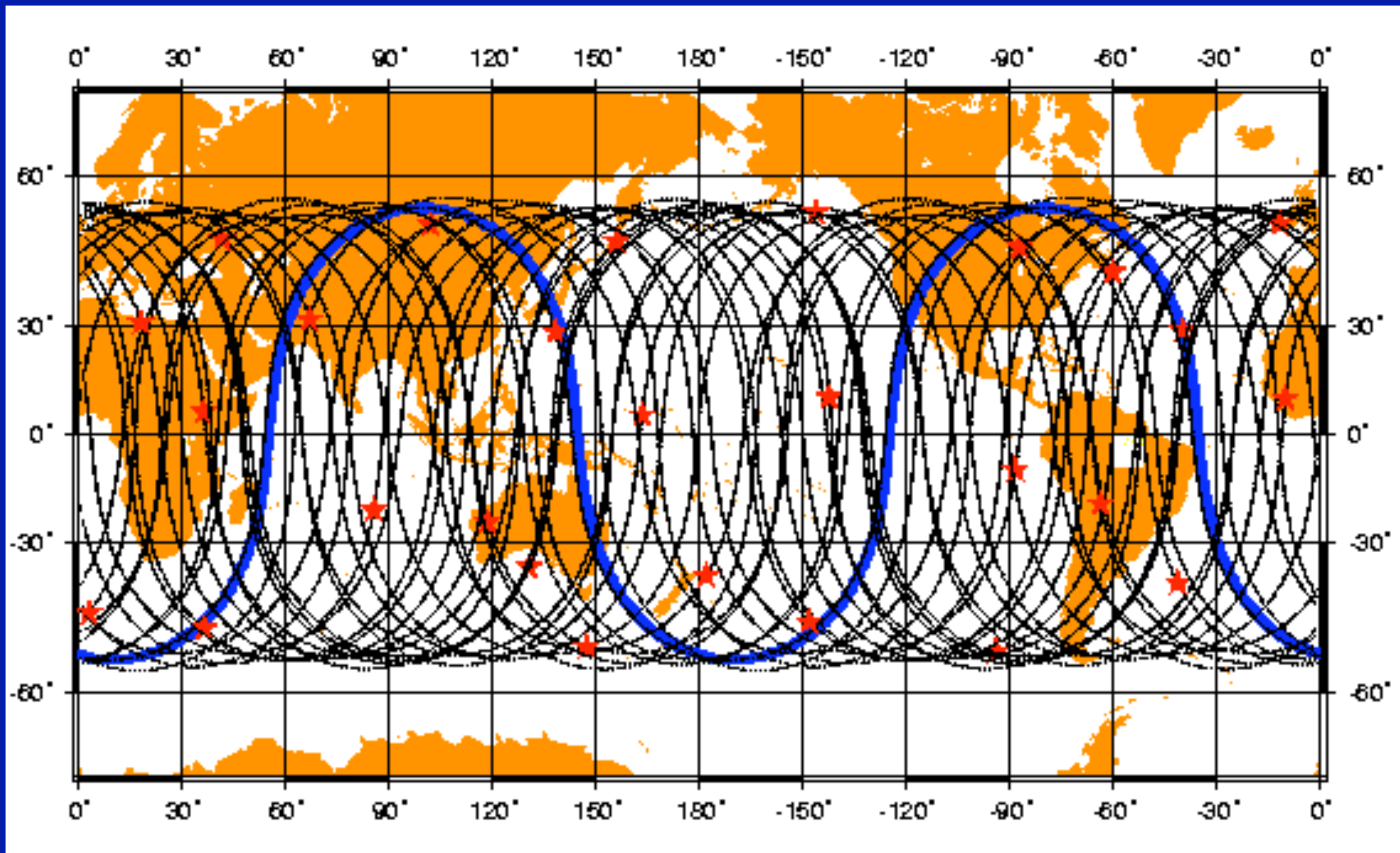
Current constellation



- Relative sizes correct (inertial space view)
- “Fuzzy” lines not due to orbit perturbations, but due to satellites being in 6-planes at 55º inclination.

Ground Track

Paths followed by satellite along surface of Earth.



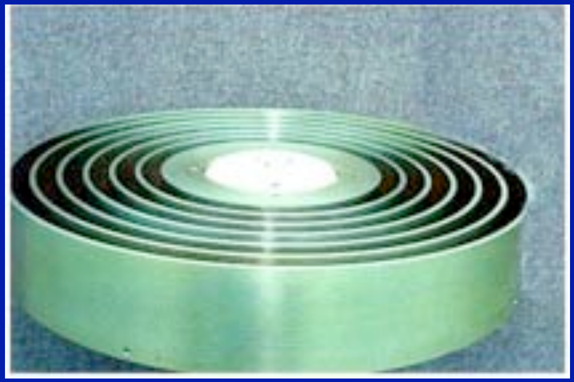
Pseudo-range accuracy

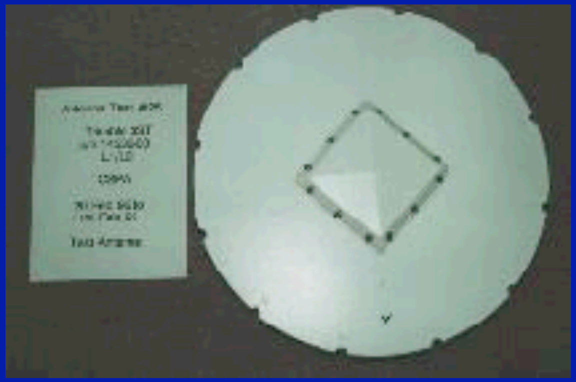
- Original intent was to position using pseudo-range: Accuracy better than planned
- C/A code (open to all users) 10 cm-10 meters
- P(Y) code (restricted access since 1992) 5 cm-5 meters
- Value depends on quality of receiver electronics and antenna environment (little dependence on code bandwidth).

GPS Antennas (for precise positioning)

Nearly all antennas are patch antennas (conducting patch mounted in insulating ceramic).

- Rings are called choke-rings (used to suppress multi-path)





Courtesy of National Geodetic Survey.

Positioning accuracy

- Best position accuracy with pseudo-range is about 20 cm (differential) and about 5 meters point positioning. Differential positioning requires communication with another receiver. Point positioning is “stand-alone”
- Wide-area-augmentation systems (WAAS) and CDMA cell-phone modems are becoming common differential systems.
- For Earth science applications we want better accuracy
- For this we use “carrier phase” where “range” measurement noise is a few millimeters (strictly range change or range differences between sites)

Carrier phase positioning

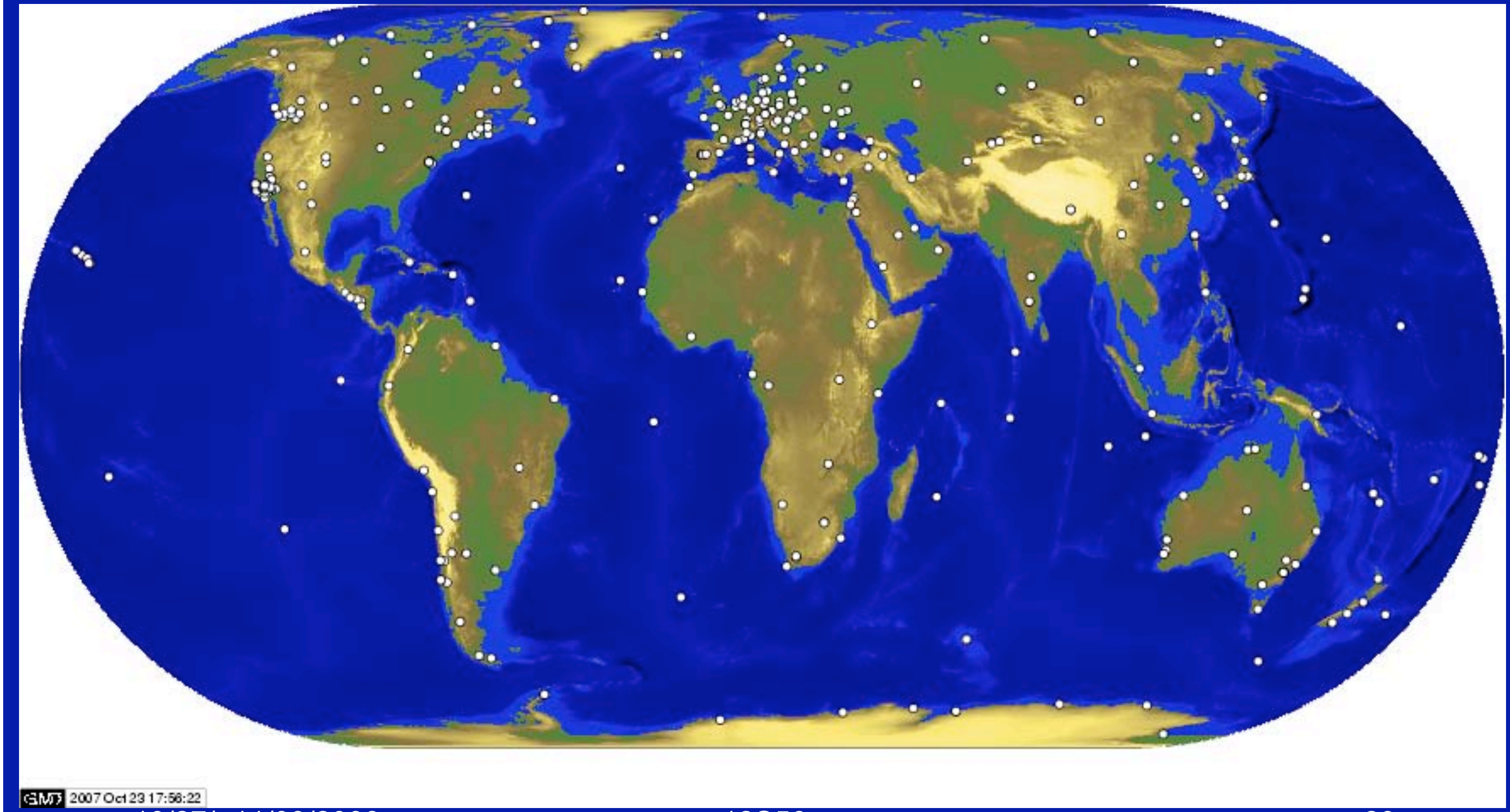
- To use carrier phase, need to make differential measurements between ground receivers.
- Simultaneous measurements allow phase errors in clocks to be removed i.e. the clock phase error is the same for two ground receivers observing a satellite at the same time (interferometric measurement).
- The precision of the phase measurements is a few millimeters. To take advantage of this precision, measurements at 2 frequencies L1 and L2 are needed. Access to L2 codes in restricted (anti-spoofing or AS) but techniques have been developed to allow civilian tracking of L2. These methods make civilian receivers more sensitive to radio frequency interference (RFI)
- Next generation of GPS satellites (Block IIF) will have civilian codes on L2. Following generation (Block III) will have another civilian frequency (L5).

Phase positioning

- Use of carrier phase measurements allows positioning with millimeter level accuracy and sub-millimeter if measurements are averaged for 24-hours.
- Examples:
  - The International GPS Service (IGS) tracking network. Loose international collaboration that now supports several hundred, globally distributed, high accuracy GPS receivers. (http://igscb.jpl.nasa.gov)
  - Applications in North America: Plate Boundary Observatory (PBO) http://pboweb.unavco.org/

IGS Network

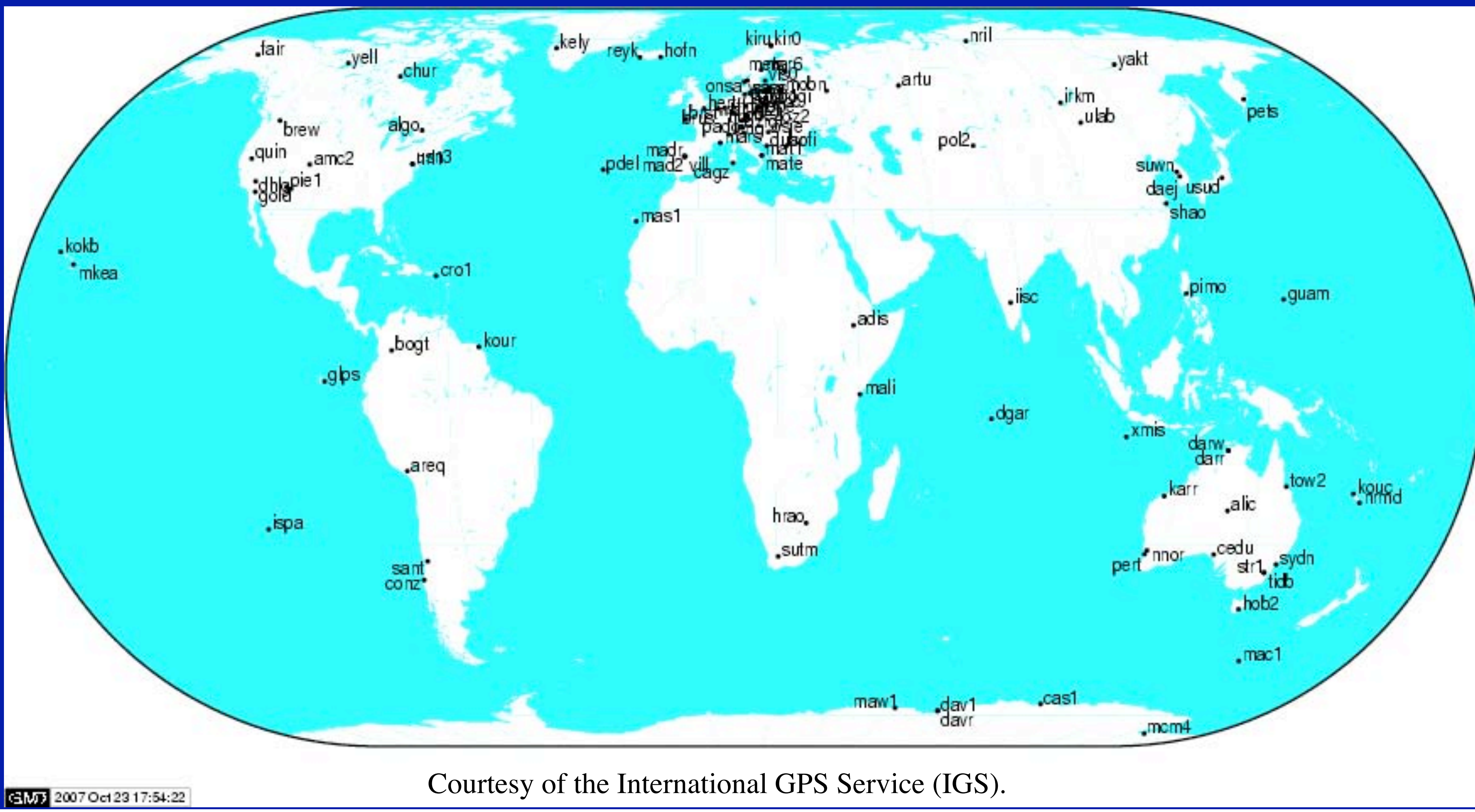
Currently over 400 stations in network



Courtesy of the International GPS Service (IGS).

IGS network

- Stations in the IGS network continuously track GPS satellites and send their data to international data centers at least once per day. All data are publicly available.

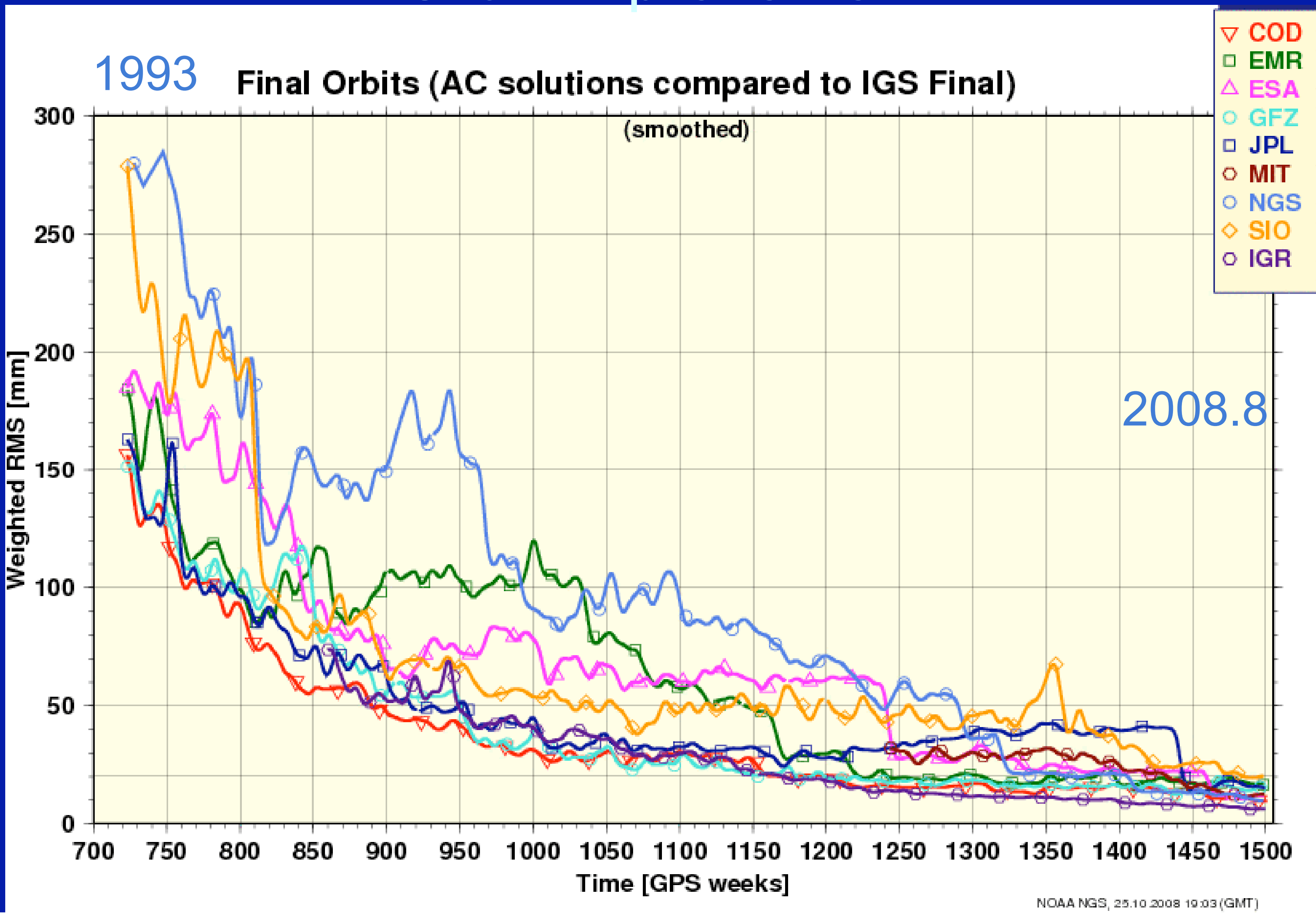


Courtesy of the International GPS Service (IGS).

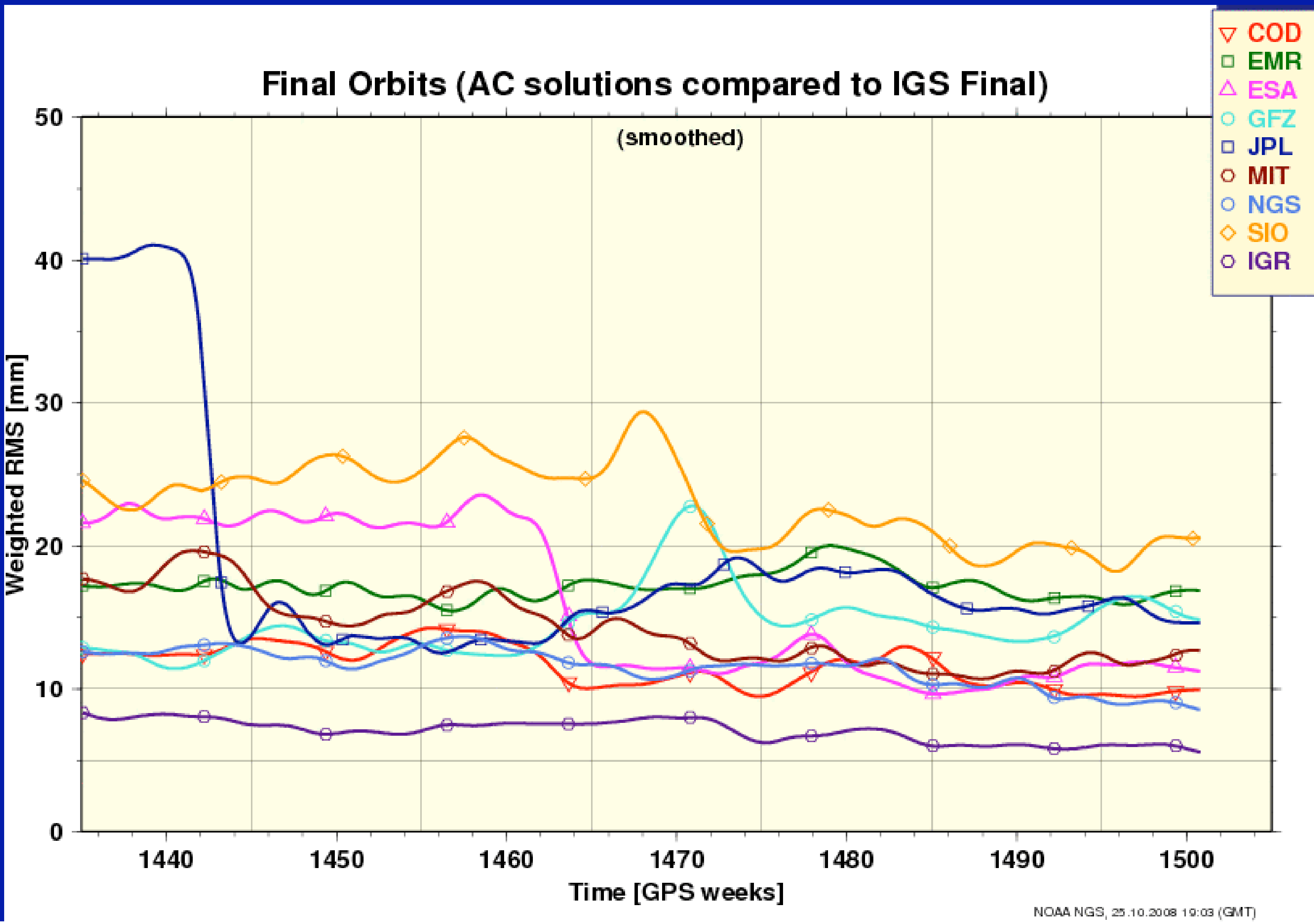
Uses of IGS data

- Initial aim was to provide data to allow accurate determination of the GPS satellite orbits: Since IGS started in 1994, orbit accuracy has improved from the 30 cm to now 2-3 cm
- From these data, global plate motions can be observed in “real-time” (compared to geologic rates)
- Sites in the IGS network are affected by earthquakes and the deformations that continue after earthquakes. The understanding of the physical processes that generate post-seismic deformation could lead to pre-seismic indicators:
  - Stress transfer after earthquakes that made rupture more/less likely on nearby faults
  - Material properties that in the laboratory show pre-seismic signals.
- Meteorological applications that require near real-time results

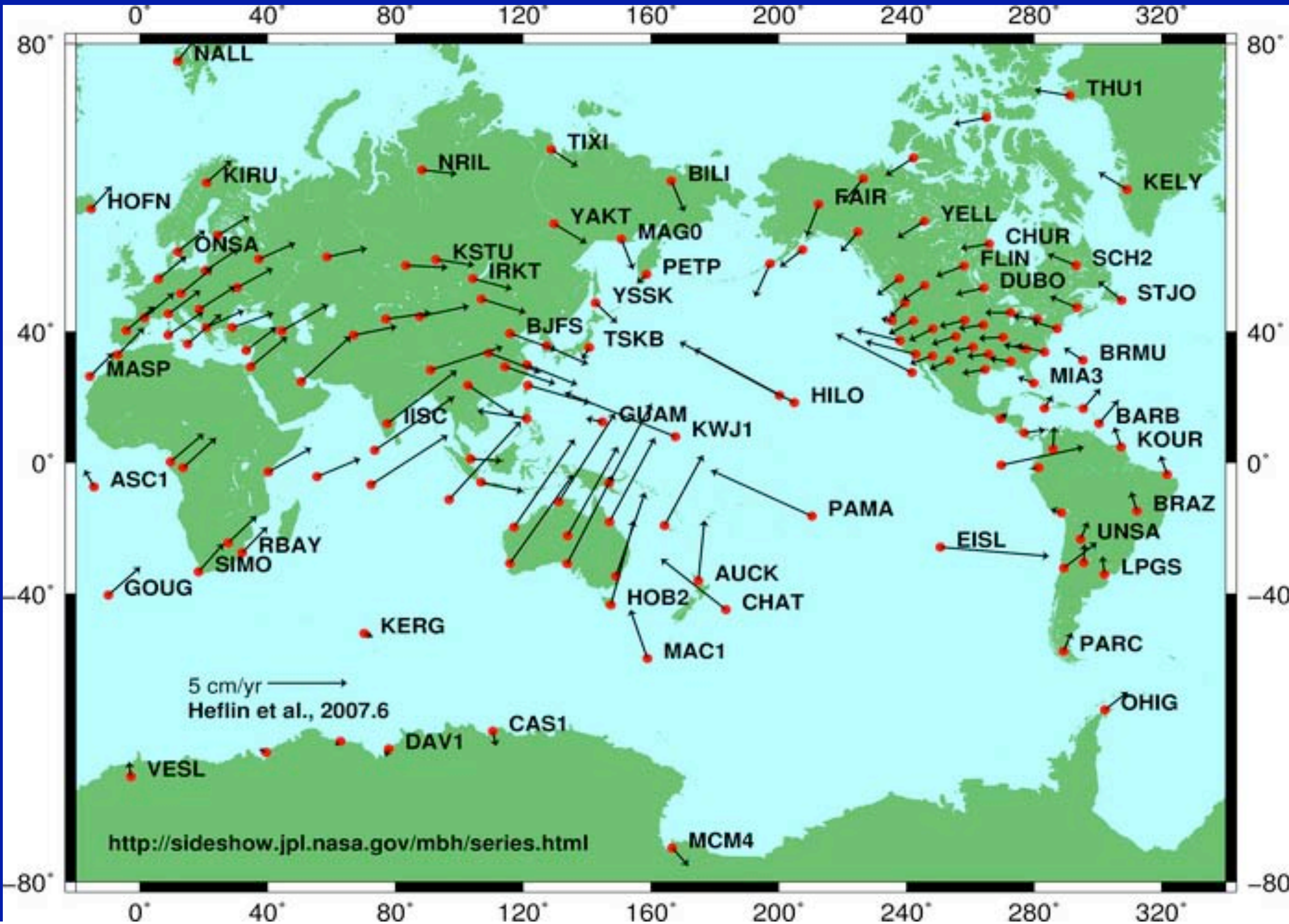
Orbit Improvement



Recent Orbit quality

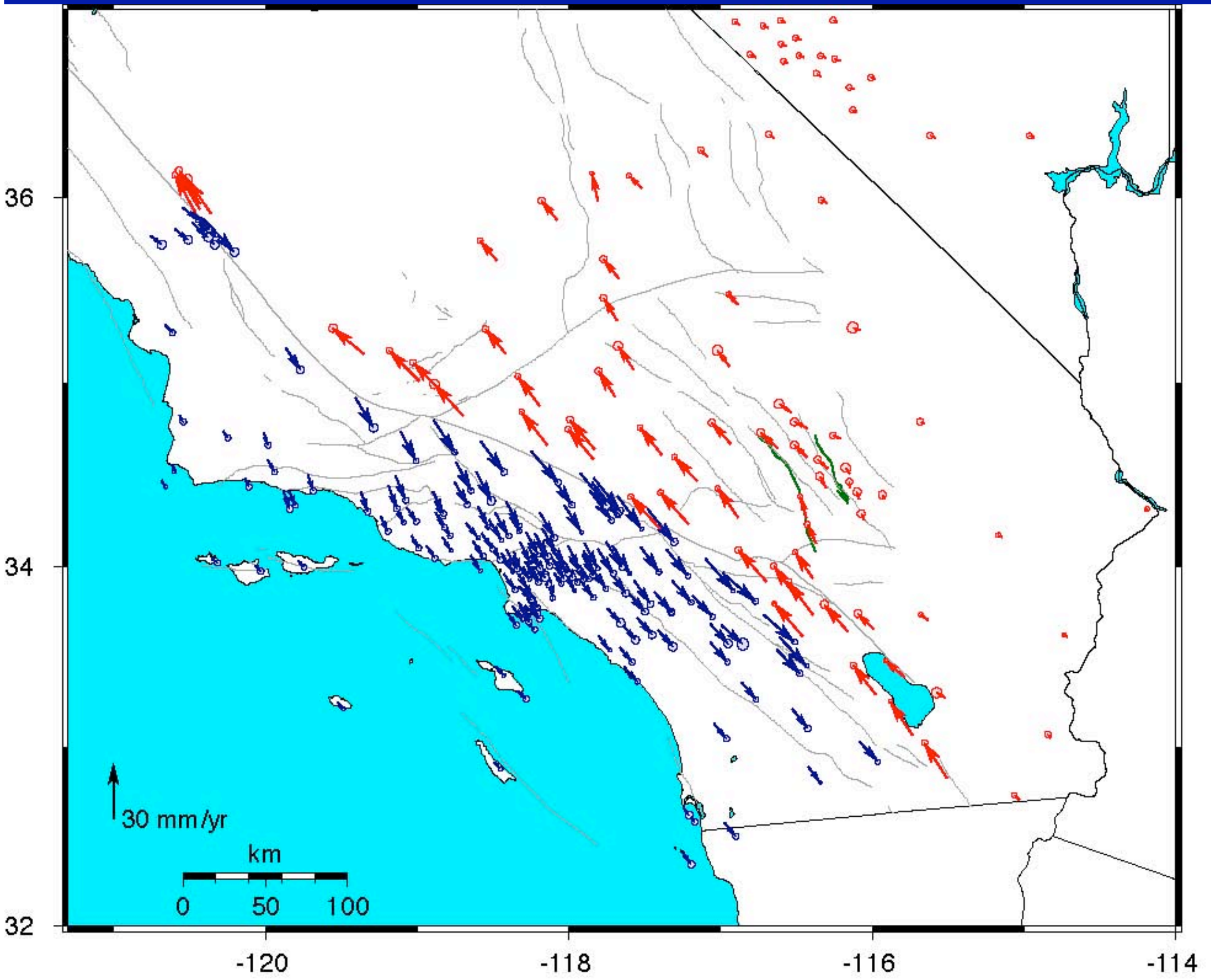


Global Plate Motions



Motions in California

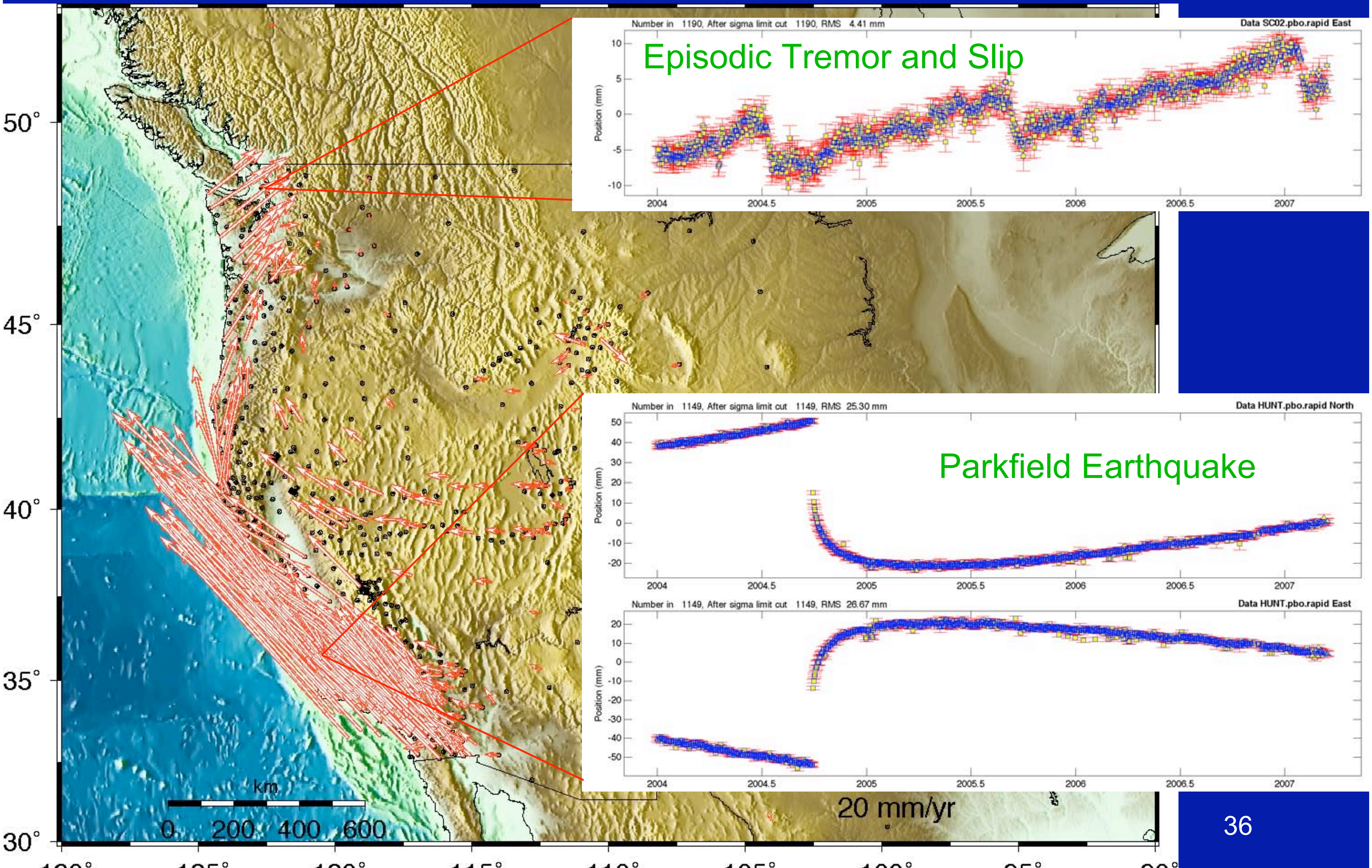
Red vectors relative to North America;
Blue vectors relative to Pacific



Motion across the plate boundary is ~50 mm/yr.

In 100-years this is 5 meters of motion which is released in large earthquakes

Types of motions in Western US



CONCLUSIONS

- GPS, used with millimeter precision, is revealing the complex nature and temporal spectrum of deformations in the Earth.
- Programs such as Earthscope plan to exploit this technology to gain a better understanding about why earthquakes and volcanic eruptions occur.
- GPS is probably the most successful dual-use (civilian and military) system developed by the US
- In addition to the scientific applications, many commercial applications are also being developed.