Applications of the Global Positioning System

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Overview

- Original design of the Global Positioning System (GPS)
- Use by "non-authorized" users
- Applications to:
  - Tectonic studies
  - Meteorology
  - Other applications

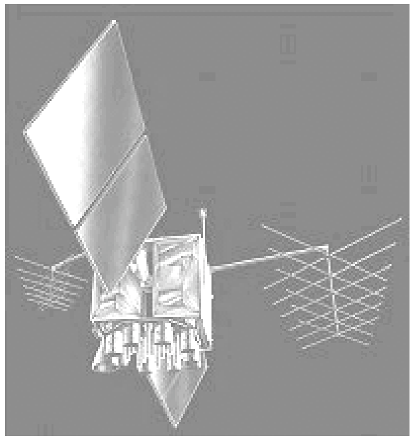
GPS Original Design

- 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.

GPS Design

- Innovations:
  - Use multiple satellites (originally 21, now ~28)
  - All satellites transmit at same frequency
  - Signals encoded with unique "bi-phase, quadrature code" generated by pseudo-random sequence (designated by PRN, PR number): Spread-spectrum transmission.
  - Dual frequency band transmission:
    - L1 ~1.5 GHz, L2 ~1.25 GHz

Latest Block IIR satellite (1,100 kg)



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).

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 or 10 MHz

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.

Position Determination (perfect clocks).

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

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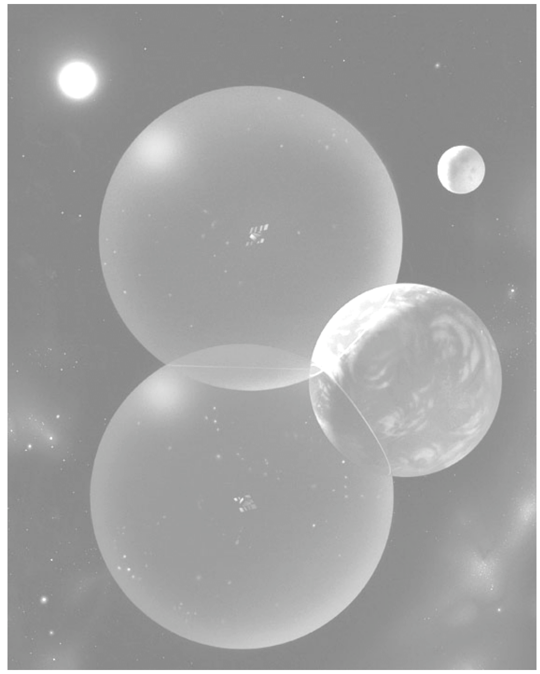

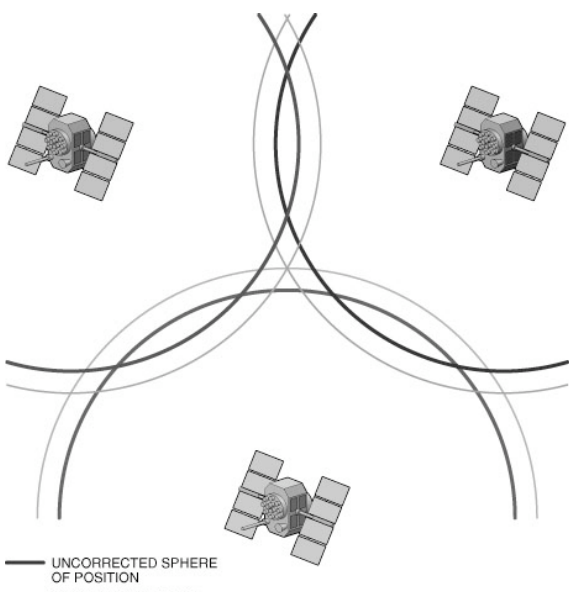

Position determination: with clock errors: 2-D case

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

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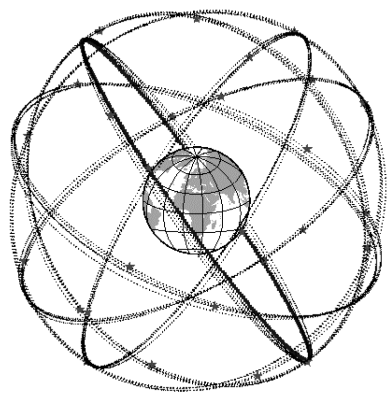
Positioning

- For pseudo-range to be used for positioning 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.

Satellite constellation

- Since multiple satellites need to be seen at same time (four or more):
  - Many satellites (original 21 but now 28)
  - High altitude so that large portion of Earth can be seen (20,000 km altitude —MEO)

Current constellation



• Relative sizes correct (inertial space view)

• "Fuzzy" lines not due to orbit perturbations, but due to satellites being in 6-planes at 55° inclination.

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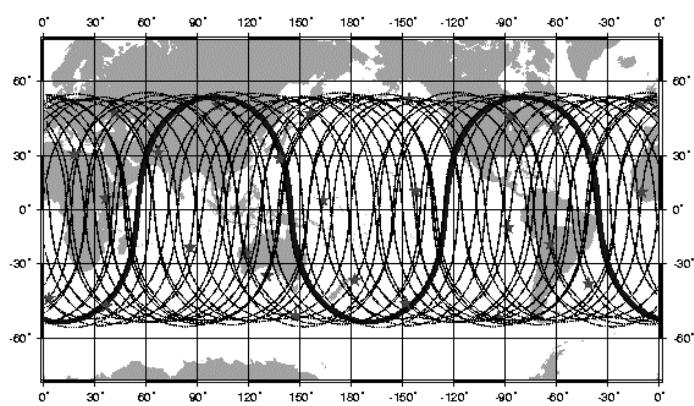
Ground Track

Paths followed by satellite along surface of Earth.



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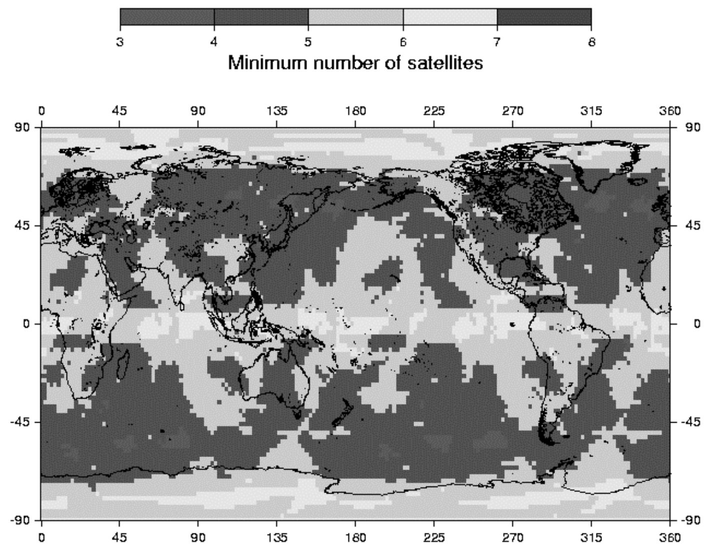
Satellite Availability (smallest number above 15° minimum elevation)



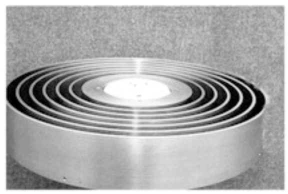
Pseudo-range accuracy

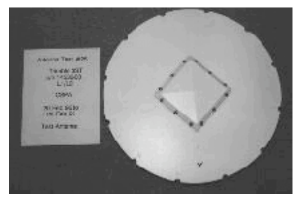
- Original intent was to position using pseudo-range: Accuracy better than planned
- C/A code (open to all users) 10 cm-10 meters
- P(Y) code (restricted access since 1992) 5 cm-5 meters
- Value depends on quality of receiver electronics and antenna environment.

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)





Positioning accuracy

- Best position accuracy with pseudo-range is about 20 cm (differential) and about 5 meters point positioning.
- For Earth science applications we want better accuracy
- For this we use “carrier phase” where “range” measurement noise is few millimeters

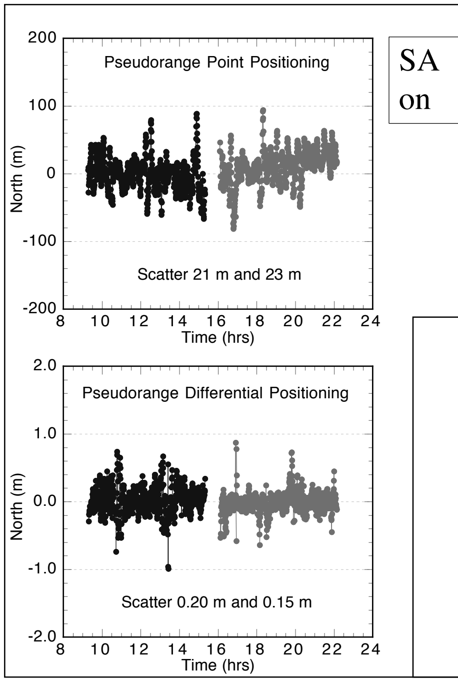
Carrier phase positioning

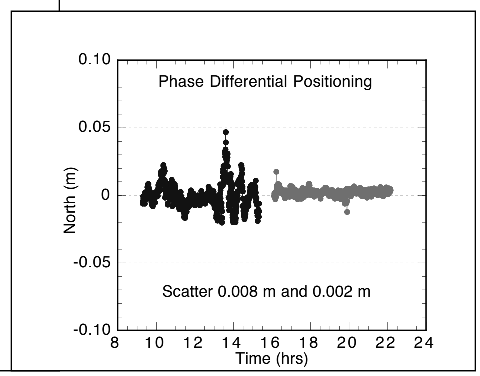
- To use carrier phase, need to make differential measurements between ground receivers.
- Simultaneous measurements allow phase errors in clocks to be removed i.e. the clock phase error is the same for two ground receivers observing a satellite at the same time (interferometric measurement).

Phase positioning

- Use of carrier phase measurements allows positioning with millimeter level accuracy and sub-millimeter if measurements are averaged for 24-hours.

Examples of positioning results

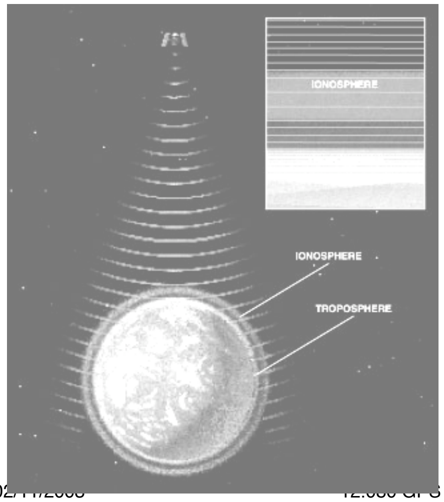




Summary

- Use of differential measurements with carrier phase allows very precise position determination (independent largely of security features).
- We use these measurements in Earth science for deformation studies and atmospheric studies

Schematic of signal propagation



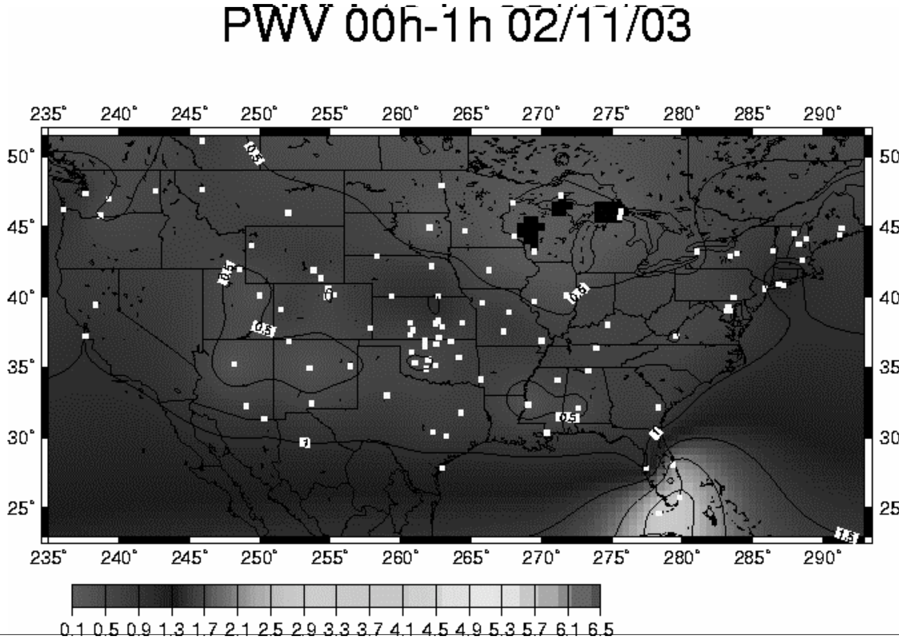
• GPS signals retarded by propagation through atmosphere

• Ionosphere (plasma) is accounted by linear combination of measurements at L1 and L2 frequencies.

Atmospheric delays

- Delay of signal due to atmosphere refraction is 2.3-30 meters, depending on elevation angle
- Elevation angle dependence can be used to estimate amount of delay due to atmosphere
- For GPS frequencies, this delay depends greatly on the amount of water vapor in atmosphere

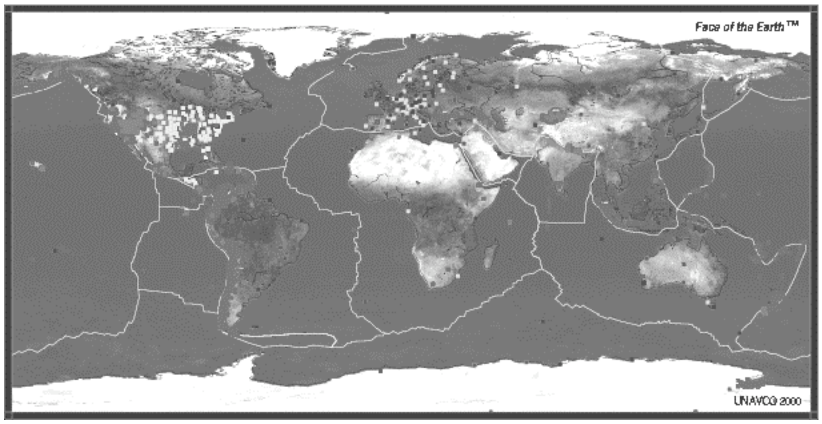
GPS Measurements of precipitable water vapor (real-time)



Tectonic Deformation Results

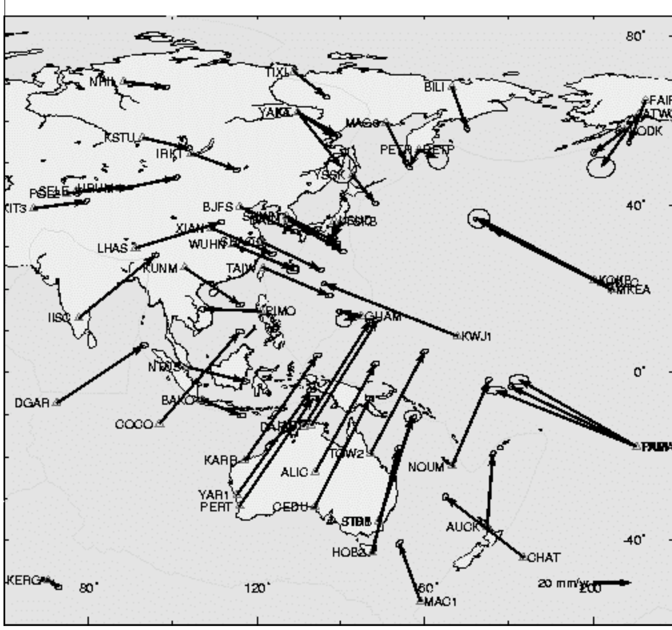
- “Fixed GPS” stations operate continuously and by determining their positions each day we can monitor their motions relative to a global coordinate system
- Temporary GPS sites can be deployed on well defined marks in the Earth and the motions of these sites can be monitored (campaign GPS)

Locations measured with GPS



- Red are campaign (~5000), other colors continuous GPS operated by different groups

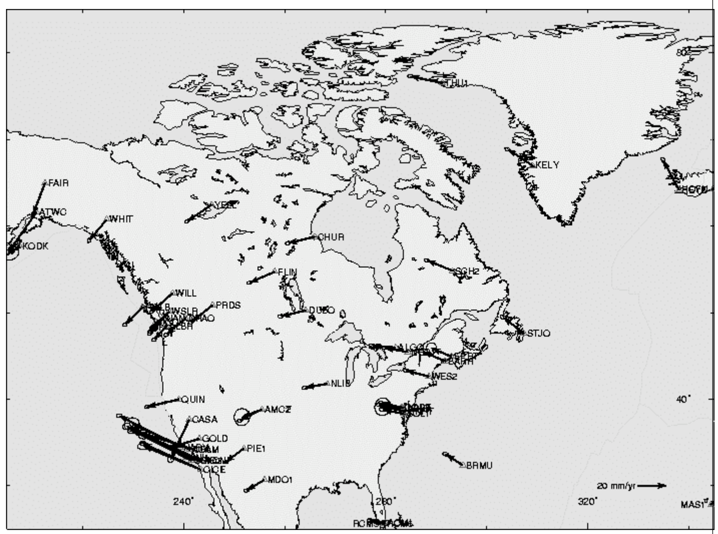
Example of motions measured in Pacific/Asia region



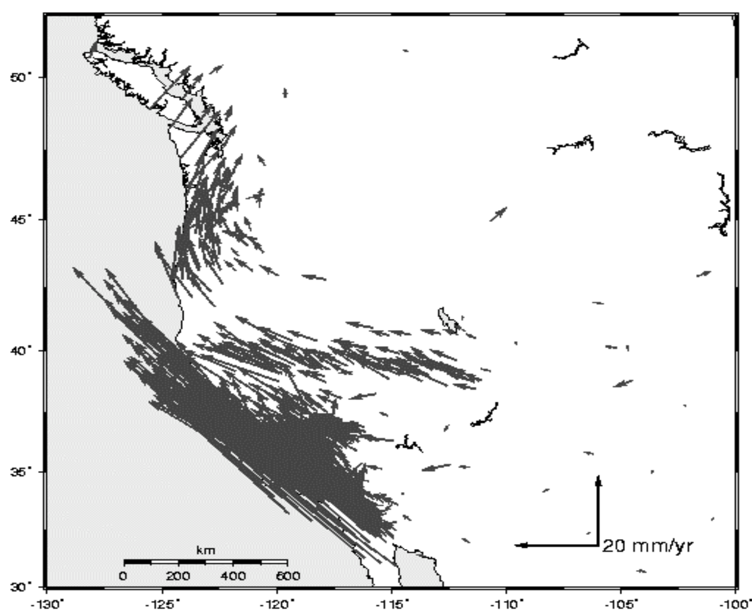
- Fastest motions are >100 mm/yr
- Note convergence near Japan

Motion in North America

- Note rapid change in California
- Remainder of field consistent with rotating NA plate



Detail in Western United States



California Detail

- Compilation of continuous and campaign GPS
- Only □<1.5 mm/yr shown
- In 100 years, fastest points move 5 m

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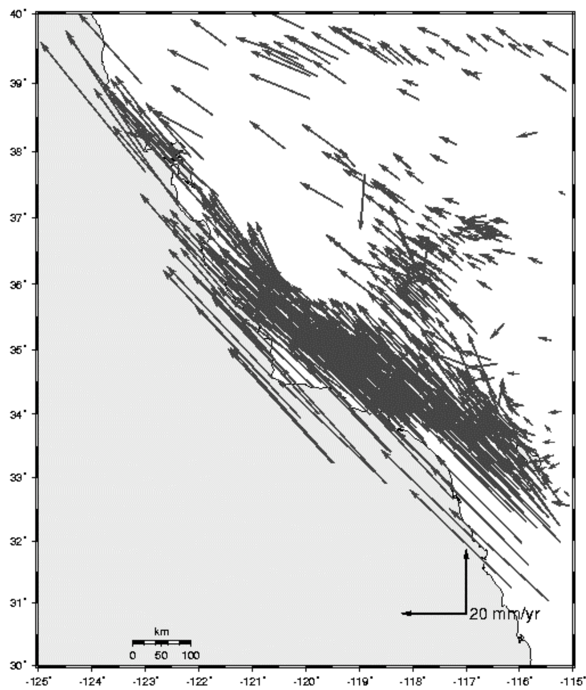

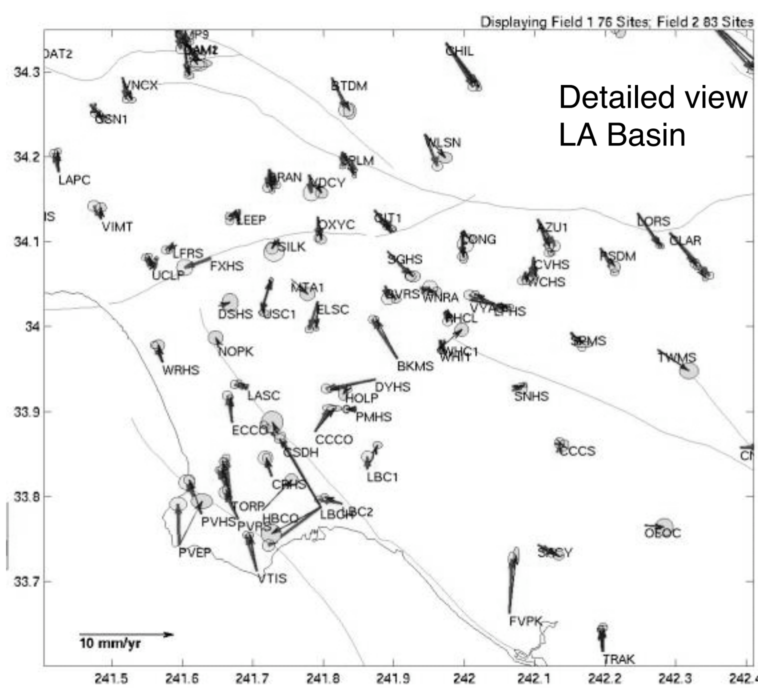

Detailed view of LA Basin

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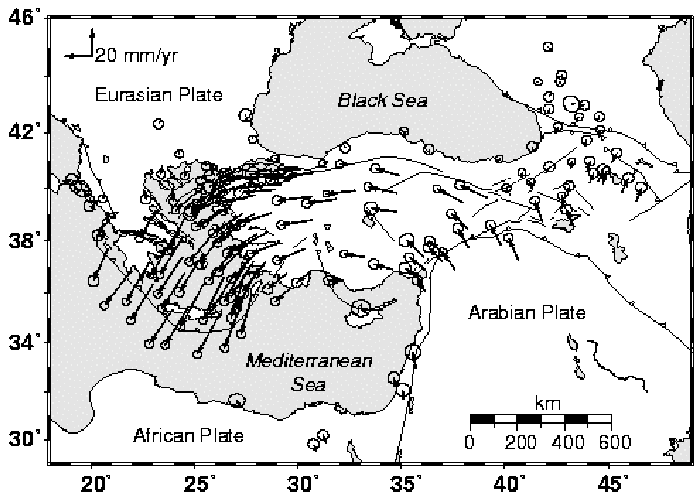
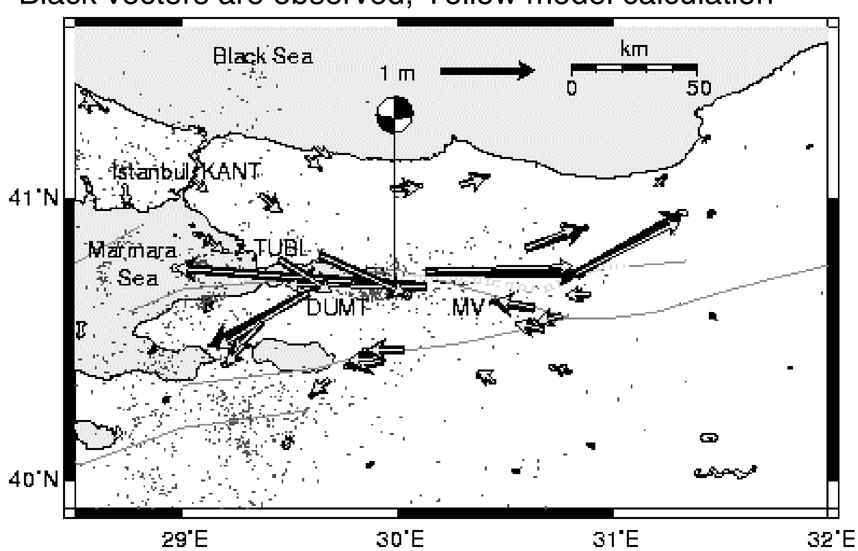
Motion in Turkey and Aegean



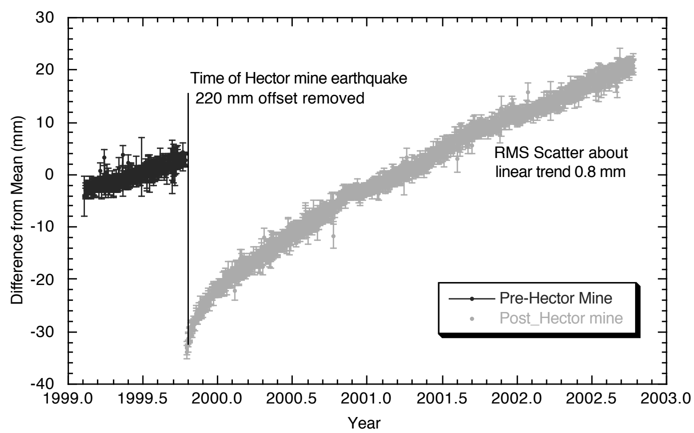
1999 Izmit Earthquake

Black vectors are observed, Yellow model calculation

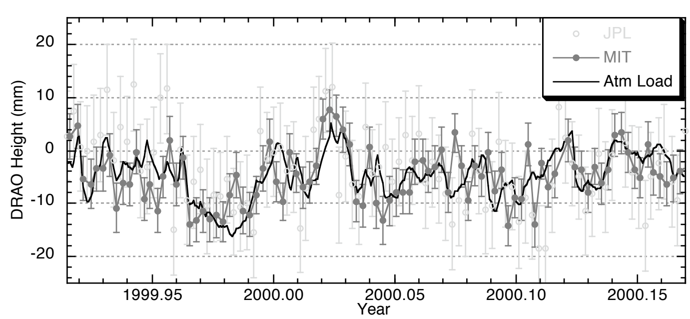


Motion after Earthquakes. Example from Hector Mine, CA

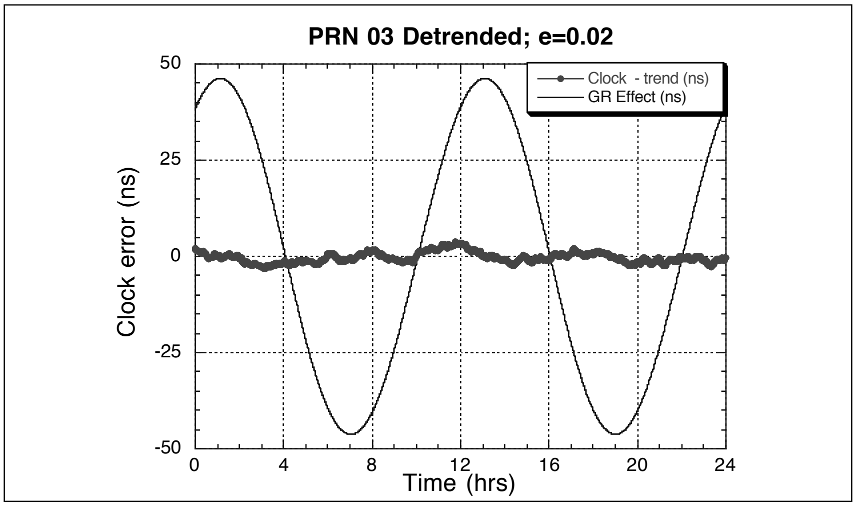
Continued motion tells us about material characteristics and how stress is re-distributed after earthquake



Atmospheric pressure loading



Relativistic Effects



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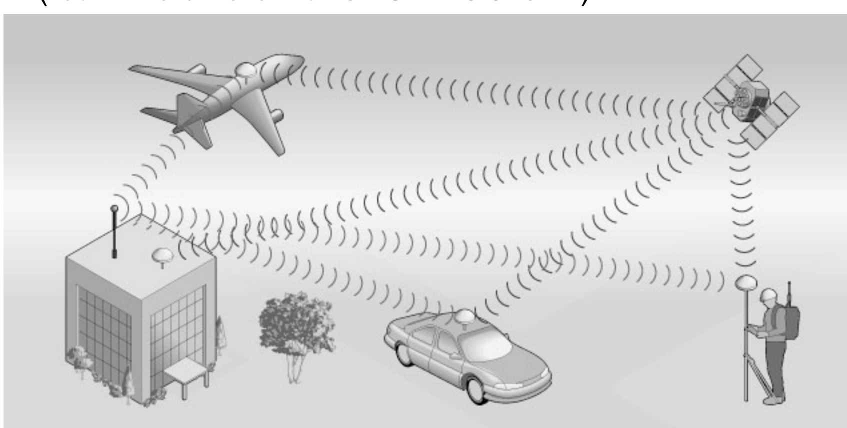
Other applications

- Aircraft positioning, vehicle navigation, engineering (real-time differential GPS links shown)



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Conclusions

- GPS dual-use technology: Applications in civilian world widespread
  - Geophysical studies (mm accuracy)
  - Engineering positioning (<cm in real-time)
  - Commercial positioning: cars, aircraft, boats (cm to m level in real-time)
- System modifications to support civilian users better underway