Geodesy is the science of the earth’s shape

Find precise positions

Monitor changes due to tectonic processes:

- Plate motion
- Plate boundary deformation
- Intraplate deformation
- Earthquake cycle
- Volcanic processes
- Land Subsidence
- Etc
TECTONIC GEODESY

Determine positions of geodetic monuments and monitor how positions change over time

Until recently, measurements made by triangulation, which measures angles between monuments using a theodolite, or trilateration, which measures distances with a laser.

Vertical motion measured by leveling, using a precise level to sight on a measuring rod.

Space geodesy measures all three components of position to sub-centimeter precision.

Space-based is cheaper, easier, faster, and does not require sites to be visible from each other.

Davidson et al, 2002
SPACE-BASED GEODESY
USE EXTRATERRESTRIAL SOURCES TO MEASURE POSITIONS ON THE EARTH

SIZE OF THE EARTH
(Eratosthenes 200 BC)

At the summer solstice the sun shone directly into a well at Syene, Egypt at noon. At the same time, in Alexandria, approximately 805 km due north of Syene (now Aswan), the angle of inclination of the sun's rays was about 7.2. With these measurements he computed the radius and circumference of the earth.

\[
\frac{7.2}{360} = \frac{805}{(2 \pi \text{ radius})}
\]

http://advancedmathyoungstudents.com/
Radio signals from quasars (astronomical radio sources which are the most distant objects in the universe) arrive at different radio telescopes at times depending on their positions and the speed of light, so the time difference gives the positions of the telescopes.

First & most precise space geodetic technique

Telescopes expensive, large, hard to move
INTERFEROMETRY: Difference in phase between waves used for very precise time and distance measurements in many branches of science.

Interferometric synthetic aperture radar (INSAR), uses radar to map the surface, so successive images show motion.

Crystal structure is found using X-ray diffraction: interference between X-rays gives the spacing between crystal planes.

http://comet.nerc.ac.uk/schoolssar_how.html
http://www.eserc.stonybrook.edu/ProjectJava/Bragg/
The Michelson–Morley experiment in 1887, one of the most famous experiments in physics, used interferometry to show that the speed of light was the same in all directions. This was not predicted by the theory that light propagated in the hypothesized “luminiferous ether.” Discarding the ether idea led to Einstein’s theory of special relativity in 1905, which postulates that all observers measure the speed of light to be the same no matter what their state of uniform linear motion.

[Diagram of Earth, Sun, and Luminiferous Ether]

[Diagram of Michelson-Morley Experiment]
SLR - SATELLITE LASER RANGING

Bounce laser beams off specially designed satellite covered with "corner reflectors" that reflect very well

- SLR accuracy and orbit determination techniques allow laser geodynamics satellite (LAGEOS) data to be routinely fit to a precision of 1-2 centimeters

- Measurements over time give the positions of the ground stations and thus determine plate motions
Class Question 27

Use Snell’s law to prove that the ray shown in red emerges from the corner reflector parallel to its direction coming in.
LUNAR LASER RANGING

https://physicsworld.com/a/how-high-the-moon/
Corner reflectors are used in boats, etc when we want to be seen

A radar reflector for sailboat masts

Corners are avoided when we want not to be seen

B-2 Stealth bomber
GPS: GLOBAL POSITIONING SYSTEM

24 Satellites
5-8 overhead most of the world

Transmit radio signals

Receivers on ground record signals and find their position from the time the signals arrive

Positions used in many applications

For tectonics, find motions from changes in position over time

Stein & Wysession, 2003
GPS receiver finds position with radio signals from different satellites

Like locating earthquake from arrivals at multiple seismometers

GPS positions 2-3 times more precise in the horizontal than vertical, because signals arrive only from above, just as earthquake locations are less precise in depth because waves arrive only from below.

Davidson et al, 2002
GPS uses very precise atomic clocks.

Synchronizing satellite clocks within nanoseconds (billionths of a second) lets a receiver find its position on earth within a few meters.

Atomic clocks use the fact that atomic transitions have characteristic frequencies (orange glow from sodium in table salt sprinkled on a flame).

Like all clocks, they make the same event happen over and over. For example, the pendulum in a grandfather clock swings back and forth at the same rate, and swings of the pendulum are counted to keep time.

In a cesium clock, transitions of the cesium atom as it moves back and forth between two energy levels are counted to keep time.
Satellites transmit code - timing signals - on two microwave carrier frequencies synchronized to very precise on-board atomic clocks.

```
L1 CARRIER 1575.42 MHz
C/A CODE 1.023 MHz
NAV/SYSTEM DATA 50 Hz
P-CODE 10.23 MHz
L2 CARRIER 1227.6 MHz
```

Carrier has much higher frequency than code
METER PRECISION GPS

GPS receiver compares code signal arriving from satellite to one it generates and finds time difference.

Time difference \( \times \) speed of light gives the distance called pseudo range.

\[ \Delta t \times c = \text{pseudo range} \]

$450$ Handheld GPS unit with MP3 player

Precision of several meters
MILLIMETER PRECISION GPS
Higher precision obtained using phase of microwave carriers

Carrier wavelengths are 19 and 24 cm. Phase measurements resolve positions to a fraction of these wavelengths. Measuring phase to 1% gives 1-2 mm precision.

Geodetic quality receivers cost about $10,000.
Combining both transmitted frequencies removes effects of passage of GPS radio signals through ionosphere.

Position errors due to signal delays from water vapor in troposphere can be reduced by estimating delays using inversion similar to solving for seismic velocity structure.

The final element for high-precision surveys is continuously operating global GPS tracking stations and data centers. These give high-precision satellite orbit and clock information, earth rotation parameters, and a global reference frame.

Using this information GPS studies can achieve positions better than 10 mm, so measurements over time yield relative velocities to precisions of a few mm/yr or better, even for sites thousands of kilometers apart.

Uncertainty of velocity estimate depends on the precision of the estimated positions and the time interval between them.
SURVEY (EPISODIC) GPS

GPS antennas are set up over monuments for short periods, and the sites are reoccupied later. Less expensive but less precise.

CONTINUOUS (PERMANENT) GPS

Continuously recording GPS receivers permanently installed. Give daily positions & can observe transient effects.

GPS = Great Places to Sleep
Precision of velocity estimates depends on precision of site position & length of time

Velocity from a weighted least squares line fit to positions

Precision increases over time

Horizontal precision is better

Sella et al., 2002

Topic 7
Depend on precision of each position and the time span of measurements

Rate $v$ of motion of a monument that started at position $x_1$ and reaches $x_2$ in time $T$

$$v = (x_1 - x_2)/T$$

If position uncertainty is given by standard deviation $\sigma$

Rate uncertainty is

$$\sigma_v = 2^{1/2} \frac{\sigma}{T}$$

Thus rate precision improves, even if the position data do not become more precise

Older geodetic data, for example those taken shortly after the 1906 San Francisco earthquake, can be of great value even if their errors are larger than those of more modern data.
Long term slip rate and earthquake recurrence on the San Andreas Fault

Wallace Creek is offset by 130 m

Offset developed over 3700 years

\[ \frac{130 \text{ m}}{3700 \text{ yr}} = 35 \text{ mm/yr} \]

Large earthquakes with \( \sim 4 \) m slip should often on average \( \sim 115 \) years apart

\[ 1906 + 115 = 2021 \]

Robert Wallace
NU Geology
BA 1938

San Andreas Fault
Over thousands of years have had 35 mm/yr motion between Pacific and North America at this site.

GPS lets us find the rate of motion *today*, which is storing strain that will be released in the next big earthquake.

Crucial parameter for estimating earthquake hazard.
Hans & Julia Weertmans’ solution:

Velocity across fault should vary as

\[ b \arctan \left( \frac{x}{D} \right) \]

where \( b \) is the plate motion speed and \( D \) is the depth to which the fault is locked.
Change Rate \((b)\), Fix Locking Depth \((D)\)

\[ V = b \arctan \left( \frac{x}{D} \right) \]

San Andreas Fault
Carizzo Plain
GPS Data
Schmalze et al. 2006
Fix Rate (b), Change Locking Depth (D)

\[ V = b \arctan \left( \frac{x}{D} \right) \]

San Andreas Fault
Carizzo Plain
GPS Data
Schmalze et al. 2006
Using the previous animations showing how various parameter choices fit the GPS data explain:

a) How the model predictions depend on the plate velocity $b$

b) Physically, why does this happen

c) What you consider the best fitting value of $b$

d) How the model predictions depend on the locking depth $D$

e) Physically, why does this happen

f) What you consider the best fitting value of $D$

Model: $V = b \arctan \left( \frac{x}{D} \right)$
Materials at distance on opposite sides of the fault move relative to each other, but friction on the fault "locks" it and prevents slip.

Eventually strain accumulated is more than the rocks on the fault can withstand, and the fault slips in an earthquake.

Earthquake reflects regional deformation.
Using materials of your choice, try to get some that will produce stick-slip behavior like that in the video.

Explain what you used, including a picture, and explain which worked, which didn’t, and why.
DIFFERENT ESTIMATES OF PACIFIC-NORTH AMERICA MOTION

Wallace Creek offset on San Andreas Fault: 36 mm/yr

Magnetics in Gulf of California: 48 mm/yr

Use space geodesy to explore possible causes of the difference
~ 50 mm/yr plate motion spread over ~ 1000 km

~ 35 mm/yr elastic strain accumulation from locked San Andreas in region ~ 100 km wide

Locked strain will be released in earthquakes

Since last earthquake in 1857 ~ 5 m slip accumulated

Gordon & Stein, 1992

**PACIFIC-NORTH AMERICA PLATE BOUNDARY ZONE: PLATE MOTION & ELASTIC STRAIN**

Gordon & Stein, 1992

**Broad PBZ**

**Elastic strain**
GPS site velocities relative to North America

Stable Sierra Nevada block

San Andreas Fault system

Central Nevada seismic belt

Eastern California shear zone

Intermountain seismic belt

Basin & Range

Colorado Plateau

Bennett et al., 1999
GPS REFERENCE FRAME

• SITE VELOCITIES GIVEN IN INTERNATIONAL TERRESTRIAL REFERENCE FRAME (ITRF)

• ITRF updated periodically, e.g. ITRF2000

• Each version (realization) derived using a global network of space geodetic sites

• Aligned so it matches NUVEL-NNR and so can be regarded as absolute motion

• For tectonic applications, usually most useful to find best fitting GPS Euler vector for a plate and remove its predictions, so site motions are wrt that plate
Most sites (e.g. Hawaii) move much as expected for absolute motion of rigid plate.

Some sites in plate boundary zones (e.g. western North America) don’t since they’re not on rigid plate.

Look for differences between GPS & NNR due to timescales.
ICELAND
GPS shows how plate motion distributed in narrow zone at the Mid-Atlantic ridge
OPENING OF THE ATLANTIC

Compare plate motions over 200 Myr with space geodesy

Measure rate from data

Calculate how much opening this would give in 200 Myr

Compare to width of Atlantic

Explore steadiness of plate motion over time

VLBI
NORTH AMERICA - EUROPE

Topic 7
GPS rates for opening of the Atlantic agree with those determined using

Seafloor magnetic anomalies

Fossil ages from deep sea drilling

Plate motions are steady!
Relative plate motions over a few years from space geodesy similar to average plate motions over the past 3 million years (NUVEL-1)

Plate motions are very steady probably because viscous asthenosphere damps out episodic motions at plate boundaries

(as cars' shock absorbers damp out road bumps)

Robbins et al., 1993
DIFFERENCES BETWEEN SPACE GEODESY & GEOLOGIC PLATE MOTION MODELS MAY REFLECT:

EITHER, APPARENT DIFFERENCES DUE TO MODEL/DATA PROBLEMS

Geologic models
- Can’t account for motion off nominal boundary
- Rely on plate circuit closure on boundaries where rate, direction or both data types aren’t available

GPS models
- Too few sites or too short time series

OR, REAL CHANGES IN PLATE MOTIONS

- May be part of long-term trends
- Can be associated with changes in plate boundary geometry: mountain building, rifting, slab detachment, etc.
GPS rate slower than NUVEL (0-3 Ma spreading rate)

Sella et al., 2002
NUBIA-
SOUTH AMERICA

GPS rate slower than NUVEL-1 (0-3 Ma spreading rate) is part of long-term slowing shown by marine magnetic data

Sella et al., 2002
Norabuena et al, 1998
NAZCA - SOUTH AMERICA: CONVERGENCE SLOWS AS ANDES RISE

Marine magnetic, NUVEL-1, and GPS data show slowing of Nazca - South America convergence

Slowing associated with rise of Andes, and accelerated shortening in thrust belt, implying complicated feedbacks

Norabuena et al., 1999

Iaffaldano & Bunge, 2008

Gregory-Wodzicki et al., 2000
ARABIA- EURASIA: CONVERGENCE SLOWS (?) AS ZAGROS RISE

REVEL slower than NUVEL (derived from closure only)

Slowing consistent with long-term trend inferred from marine magnetic data

Perhaps associated with rise of Zagros

Sella et al., 2002

McQuarrie et al., 2000
Most earthquakes occur on either narrow plate boundaries or broad plate boundary zones

Some occur within the interior of plates
1811-1812 earthquakes

Have image as almost Biblical cataclysms

Often claimed to have

- been the largest in North America (or on earth!)
  - rung bells in Boston
  - predicted by Indians
  - reversed flow of river

What actually happened?

Click for movie
Shaking intensity yields low magnitude 7 first inferred, not subsequently quoted.

Log cabin damage at New Madrid.

Minor damage in St. Louis, Nashville, Louisville, etc.

Not felt in Boston, no church bells ring.

Hough et al., 2000
NEW MADRID SEISMIC ZONE (NMSZ)

Most active in North American continental interior

Seismicity 1/30-1/100 California rate, owing to difference in motion rates

M>5 ~ every 15 yr
M>6 ~ every 150 yr
M>7 in 1811-12

Aftershocks of 1811-12

NEW MADRID SEISMICITY

1811-12 Aftershocks

NORTH AMERICAN SEISMICITY

1900-2002

PACIFIC

NORTH AMERICA
Largest in past century, 1968 (M 5.5) southern Illinois earthquake, caused no fatalities.

Damage consisted of fallen bricks from chimneys, broken windows, toppled television aerials, and cracked or fallen brick & plaster.
2 Centuries Later, Good News for Quake Area, Maybe

The New York Times Science, Tuesday, April 27, 1999, By Sandra Blakeslee

Midwesterners who worry about earthquakes got some good news last week: their risk of catastrophe may have been vastly overstated.

New measurements taken around New Madrid, MO - the epicenter of devastating earthquakes in 1811 and 1812 - show that the ground there is scarcely moving. According to many scientists, this means that it will take 2,500 to 10,000 years before another very large earthquake could occur in the region, although smaller, less damaging earthquakes are possible.

"The motions are small to zero," said Dr. Seth Stein, a professor of geological sciences at Northwestern University in Evanston, Ill., who made the new measurements. Earlier evidence showing rapid regional ground motion, a geologic sign that large quakes are probable, "was based on honest scientific errors," Dr. Stein said.
Slow Deformation and Lower Seismic Hazard at the New Madrid Seismic Zone

Andrew Newman,1 Seth Stein,1* John Weber,2 Joseph Engeln,3 Ailin Mao,4 Timothy Dixon4

Global Positioning System (GPS) measurements across the New Madrid seismic zone (NMSZ) in the central United States show little, if any, motion. These data are consistent with platewide continuous GPS data away from the NMSZ, which show no motion within uncertainties. Both these data and the frequency-magnitude relation for seismicity imply that had the largest shocks in the series of earthquakes that occurred in 1811 and 1812 been magnitude 8, their recurrence interval should well exceed 2500 years, longer than has been assumed. Alternatively, the largest 1811 and 1812 earthquakes and those in the paleoseismic record may have been much smaller than typically assumed. Hence, the hazard posed by great earthquakes in the NMSZ appears to be overestimated.

No resolvable motion
Recent cluster likely ended
Seismicity migrates
Hazard overestimated

It is also possible that 1811–1812–style earthquakes may never recur. If more accurate future surveys continue to find essentially no interseismic slip, we may be near the end of a seismic sequence. It has been suggested that because topography in the New Madrid region is quite subdued, the NMSZ is a feature no older than a few million years and perhaps as young as several thousand years (21). Therefore, New Madrid seismicity might be a transient feature, the present locus of intraplate strain release that migrates with time between fossil weak zones.

Although much remains to be learned about this intriguing example of intraplate tectonics, the present GPS data imply that 1811–1812–size earthquakes are either much smaller or far less frequent than previously assumed. In either case, it seems that the hazard from great earthquakes in the New Madrid zone has been significantly overestimated. Hence, predicted ground motions used in building design there, such as the National Seismic Hazard Maps (22) that presently show the seismic hazard there exceeding that in California, should be reduced.
As data improve, maximum possible motion keeps decreasing

< 0.2 mm/yr

No sign of large earthquake coming

Long time needed to store up slip for future large earthquake

For steady motion, M 7 at least 10,000 years away
M 8 100,000
Differences between space geodesy & geologic plate motion models are increasingly able to resolve changes in plate motions.

Inferred changes often appear to be part of long-term trends.

Can be associated with changes in plate boundary geometry: mountain building (Andes, Zagros (?)}, rifting (East Africa), slab breakoff (Adria), etc.

Better distribution of space geodetic sites and longer time series will improve ability to identify & confirm such changes.