NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

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Module 10 : Brief on Earthquake geodesy
Lecture 01: Measuring ground motion, Global Positioning System (GPS), and Synthetic Aperture Radar Interferometry (InSAR)

CONCEPTS COVERED

- Measuring ground motion
- Global Positioning System (GPS)
  - Precision and limitation
  - Data collection
- Synthetic Aperture Radar interferometry (InSAR)
  - Advantages and limitations
- Summary

Recap

- Elastic rebound theory states that strain accumulated in the rock is more than the rocks on the fault can withstand, and the fault slips, resulting in an earthquake.

- Interseismic stage consists of long periods between large earthquakes during which elastic strain accumulation occurs in the broad region.

- Preseismic stage that can be associated with small earthquakes (foreshocks).

- Earthquake itself marks the coseismic phase during which rapid motion on the fault occur and generate seismic waves.
- Postseismic phase occurs after the earthquake, and aftershocks and transient afterslip occur for a period of years.

- The two different coordinate systems, (ϕ_f, δ, λ) and ($\hat{n}$, $\hat{d}$), are useful to describe the fault geometry.

Recap

- **Unit normal vector to the fault plane is** $$\hat{n} = \begin{pmatrix} -\sin\delta \sin\phi_f \\ \sin\delta\cos\phi_f \\ \cos\delta \end{pmatrix}$$

- **Slip vector, a unit vector in the slip direction, is** $$\hat{d} = \begin{pmatrix} \cos\lambda\cos\phi_f + \sin\lambda\cos\delta\sin\phi_f \\ -\cos\lambda\sin\phi_f + \sin\lambda\cos\delta\cos\phi_f \\ \sin\lambda\sin\delta \end{pmatrix}$$

- **For pure strike-slip fault λ = 0°, the hanging wall moves to the right, and the motion is called left-lateral and for λ = 180°, right-lateral motion occurs.**

- **For pure dip-slip fault λ = 270°, the hanging wall slides downward, causing normal faulting and λ = 90°, and the hanging wall goes upward, yielding reverse, or thrust, faulting.**

Recap

- Seismograms recorded at various distances and azimuths are used to study the geometry of faulting during an earthquake, known as the focal mechanism. It uses the fact that the pattern of radiated seismic waves depends on the fault geometry.

- The first motion observed at different azimuths define four quadrants, two compressional and two dilatational. These quadrants are separated by the fault plane and auxiliary plane.

- The elastic radiation can be described as resulting from double couple of forces, these forces are known as equivalent body forces for the fault slip.

Recap

Radiation pattern for P-wave and S-wave is given by

$$u_r = \frac{1}{4\pi\rho\,\alpha^3 r}\dot{M}(t - r/\alpha)\sin 2\theta\,\cos\phi$$

$$u_\theta \hat{e}_\theta + u_\phi \hat{e}_\phi \text{ , } where$$

$$u_\theta = \frac{1}{4\pi\rho\beta^3 r}\dot{M}(t - r/\beta)\cos 2\theta\cos\phi$$

$$u_\phi = \frac{1}{4\pi\rho\beta^3 r}\dot{M}(t - r/\beta)(-\cos\theta\sin\phi)$$

Recap

- Seismic moment tensor gives additional insight into the rupture process and greatly simplifies inverting seismograms to estimate source parameters.

- We assume the equivalent body forces which produces same radiation pattern as the slip on the fault for the earthquake and other seismic sources. The seismic sources can be modeled as single forces, force couples, and double couples.

- Components of moment tensor represents the fault geometry and size of the earthquake represented by scalar moment.

- Moment tensor is symmetric in nature and there will be a set of axes which will make off-diagonal elements zero. It is similar to stress and strain tensors.

Recap

•**The Green's function:** tells us about the deformation at point and time (x,t), for a given impulse, $f(x_0,t_0)$. These are linear, for multiple sources it can be summed to find net deformation.

•**Moment Tensors:** Rotation into principle axes, gives P/T/null directions

M_{ij} i = direction of force couple
j = offset of force couple

$$M_0 = \mu DA$$

$$M_0 = \frac{1}{\sqrt{2}}\left(\sum_{ij} M_{ij}^2\right)^{1/2}$$

$$\overleftrightarrow{M} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}$$

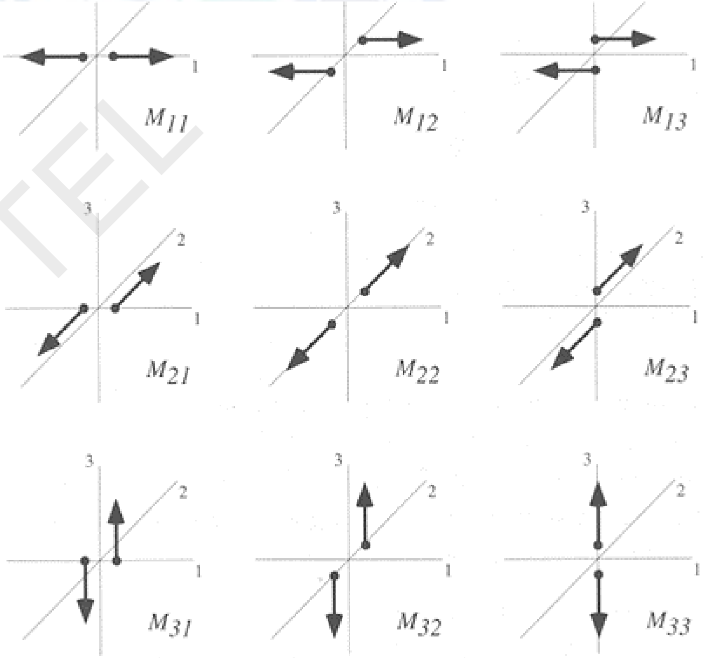


Fig. 9.2. The nine different force couples that make up the components of the moment tensor.

Recap

- Symmetric property of moment tensor shows that slip on either the fault plane or the auxiliary plane yields the same seismic radiation patterns

- The trace (sum of diagonal components) of the tensor is zero

$$\sum_i M_{ii} = M_{ii} = 2M_0 n_i d_i = 2M_0 \hat{n}.\,\hat{d} = 0$$

- The scalar moment gives the magnitude of the moment tensor, which is analogous to the magnitude of a vector.

$$M_0 = \left(\sum_{ij} M_{ij}^2\right)^{1/2} / \sqrt{2}$$

- Thus, the eigenvectors of the moment tensor are parallel to the T, P, and null axes

- The transformation changes the components, but the physical moment tensor stays the same, so these two different-looking force systems give the same radiated seismic waves

Recap

- For the isotropic moment tensor, all three diagonal terms of the moment tensor are nonzero and equal, the polarity of the first motions (focal mechanism) is the same in all directions. The moment tensor will look like:

$$\begin{pmatrix} E & 0 & 0 \\ 0 & E & 0 \\ 0 & 0 & E \end{pmatrix}$$

- A moment tensor with a nonzero isotropic component represents a volume change.

- Compensated linear vector dipoles (CLVDs) are sets of three force dipoles that are compensated, with one dipole −2 times the magnitude of the others:

$$\begin{pmatrix} -\lambda & 0 & 0 \\ 0 & \lambda/2 & 0 \\ 0 & 0 & \lambda/2 \end{pmatrix}$$

Recap

- On way to describe the CLVDs in volcanic areas is to think of an inflating magma dike, which can be modeled as a crack opening under tension.

$$\begin{pmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda + 2\mu \end{pmatrix}$$

- An alternative explanation is that CLVDs are due to near simultaneous earthquakes on nearby faults of different geometries.

- Multiple faulting events giving rise to apparent CLVDs have been reported.

- The deviatoric moment tensor can be decomposed in several ways. One is in terms of two double couples, called the major and minor double couples:

$$\begin{pmatrix} \lambda_1' & 0 & 0 \\ 0 & \lambda_2' & 0 \\ 0 & 0 & \lambda_3' \end{pmatrix} = \begin{pmatrix} \lambda_1' & 0 & 0 \\ 0 & -\lambda_1' & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\lambda_3' & 0 \\ 0 & 0 & \lambda_3' \end{pmatrix}$$

Measuring ground deformation

- The large, rapid deformation in an earthquake results from a complex deformation field which extends over a broad region and a long time.

- Hence, additional information about earthquakes and the processes causing them can be obtained by measuring slow ground deformation using techniques from geodesy, the science of the earth's shape.

- Most such techniques rely on detecting the motion of geodetic monuments, which are markers in the ground.

Measuring ground deformation

- The most familiar monuments are the metal disks attached to rocks often seen at mountain peaks, but various other designs are also used in hope of minimizing the effects of soil or near-surface motion that mask the tectonic movement.

- In soft sediment, monuments are often steel rods driven deep into the earth. The popular term for monuments is "benchmarks," although geodesists traditionally reserve this term for monuments used to study vertical motions.

- Advent of geodetic methods using signals from space permits all three components of position to be measured to sub-centimeter precision.

- As a result, geodetic data before and after earthquakes now give coseismic motion to high precision much more easily than was previously possible.

Measuring ground deformation

- **Three of these techniques are used to locate geodetic marker**

Geodetic Techniques

Very Long Baseline Interferometry (VLBI)

Uses the difference in the time when radio signals from distant quasars arrive at different points on earth.

Satellite Laser Ranging (SLR)

Uses the time required by light from ground based lasers to bounce off satellites.

Global positioning system (GPS)

The third approach relies on the travel time of radio signals between satellites and ground stations.

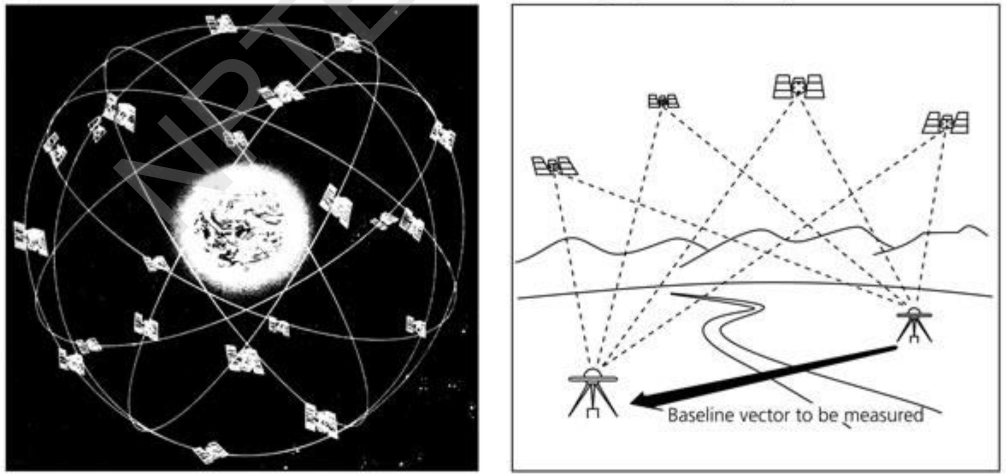
Global Positioning System (GPS)

- Global Positioning System (GPS), developed in 1970s, is popular for most tectonic applications.

- A single GPS receiver, using a minimum of four satellites, can determine position to a precision of 5 to 100 meters.

- Improvement to cm or better precision is achieved by using the phase delays of microwave carriers.

Figure 4.5-1: Cartoon of the Global Positioning System (GPS).



Constellation of GPS satellites | Relative positioning

Global Positioning System (GPS) : Precision

- Carrier frequencies are larger than modulation, so their phase provide precise positions.

- The use of differential signals from multiple satellites recorded at multiple receivers reduces clock errors.

- GPS studies can achieve positions better than 10 mm.

- There are two modes of GPS data collection: Survey mode & continuous mode

Global Positioning System (GPS)

Modes Of Data Collection

In survey mode, GPS antennas are set up for short periods, and the sites are revisited later.

Continuously recording GPS receivers are installed permanently. Continuous GPS can provide significantly more precise data, albeit at higher cost

Global Positioning System (GPS): Limitation

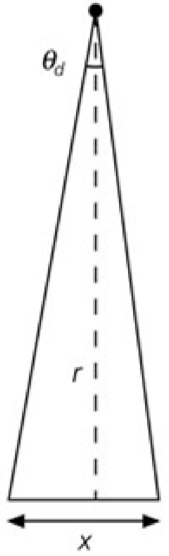
- ➔ **Position of geodetic marker is required near to the anticipated earthquake, which is not almost always possible.**
- ➔ **Thus effort and resources are required to install and survey monuments in advance, in hopes that an earthquake will occur nearby.**
- ➔ **This condition may be met in active seismic areas but this is not always true.**

Synthetic Aperture Radar interferometry (InSAR)

- A way to escape this issue is provided by Synthetic Aperture Radar Interferometry (InSAR) from satellites.

- It facilitates high-resolution radar mapping from spacecraft or aircraft.

- The single slit diffraction concept is use for estimating the resolution of a physical radar.



- For radar, d is the antenna length, so a radar at a distance r above the Earth's surface could resolve objects of size x, where

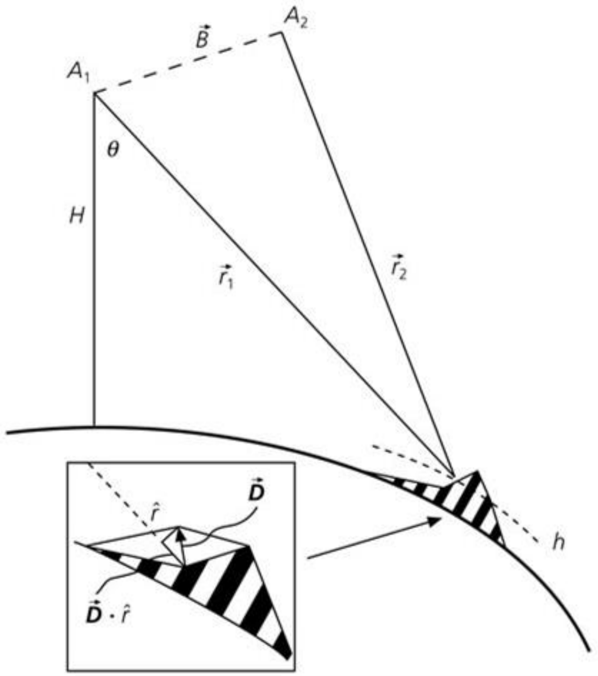
$$\theta_d = \lambda/d = x/r$$

- Because the radar wavelengths are 10s of centimeters, a radar antenna a few meters long orbiting hundreds of kilometers above the earth can normally resolve topography only on a scale of kilometers.

Synthetic Aperture Radar interferometry (InSAR)

- SAR uses a moving satellite to simulate an antenna much larger than the satellite's real antenna. For example, a real 10 m antenna can be used as a 4 km synthetic antenna.

- The synthetic antenna can thus resolve both topography and crustal deformation on a "footprint" of tens of meters.



- The phase difference between radar signals with wavelength λ reflected from the Earth's surface and recorded by antennas at position A_1 and A_2 is

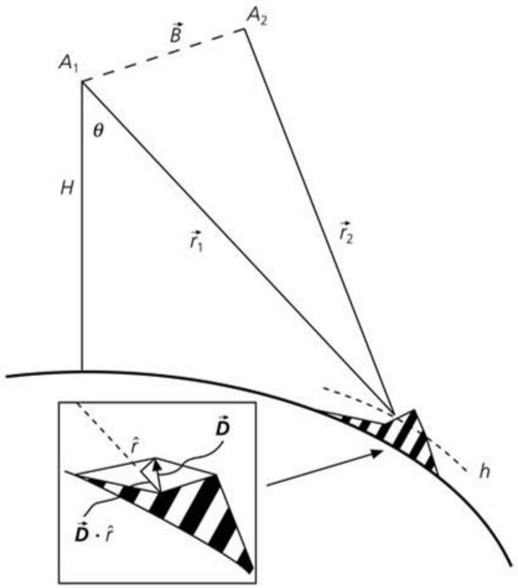
$$\phi = (4\pi/\lambda)(r_2 - r_1)$$

r_i is the range from the antenna at A_i to the reflection point.

Synthetic Aperture Radar interferometry (InSAR)

- The antenna baseline separation vector B and satellite flight height H are known from the satellite orbits.

- Because the baseline length |B| is much shorter than the ranges r_i, an analysis like that used to derive the earthquake rupture time shows that the elevation of the reflecting point is $h = H - r_1 \cos\theta$, so topography can be mapped from space.



- This method, called interferometry, is used for both earth and planetary mapping, such as the Magellan mission to Venus.

Synthetic Aperture Radar interferometry (InSAR)

- **Two such radar images can detect ground motion between successive measurements.**

- **If differences in satellite positions between the measurements are removed, a vector surface displacement D causes a phase change**

$$\phi \approx (4\pi/\lambda)\delta r, \quad \delta r = (D.\hat{r}),$$

where δr is the projection of the vector displacement along , the look direction connecting the satellite and reflection point.

- **To find the full displacement vector, observations from ascending (moving north) and descending (moving south) tracks of the satellite, or different satellites, can be combined.**

- **The results are shown as a phase difference map, called a differential interferogram.**

Synthetic Aperture Radar interferometry (InSAR)

Figure 4.5-3: SAR interferogram, data and modeling, for the 1992 Landers and Big Bear earthquakes.

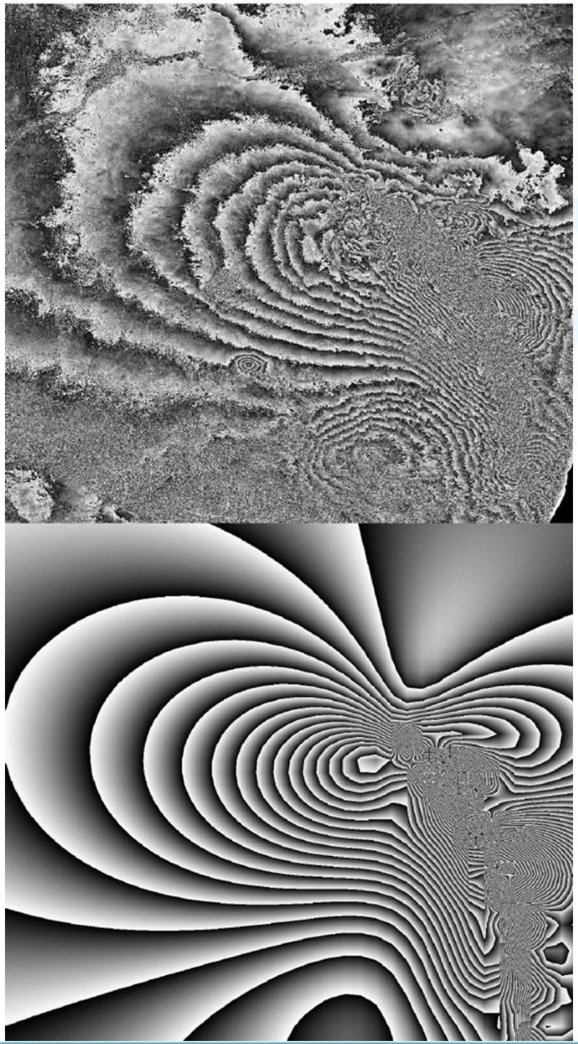


Image of the phase differences resulting from the 1992 Landers (Mw 7.3) and Big Bear (Mw 6.2) earthquakes in the Mojave desert of southern California. A range change δr of λ/2 causes a phase change of 2π that appears as one fringe (full shading change) in the map. In this case, the C-band radar has a frequency of 5.2 GHz, so a fringe corresponds to 28 mm of motion. The observed fringe pattern is coherent over large areas where deformation is resolved.

The pattern is reasonably similar to a synthetic interferogram generated for a detailed model of the Landers rupture, which involved several meters of right-lateral strike-slip on a complex set of NW-striking faults extending for about 85 km.

Synthetic Aperture Radar interferometry (InSAR): **Advantages**

- **Although radar images before an earthquake are needed, satellites can acquire them over areas far too large for geodetic monuments to have been installed everywhere.**
- **InSAR maps deformation on a spacing of tens of meters, far denser than is practical with geodetic monuments.**
- **InSAR is especially sensitive to vertical motions, the component for which the GPS is the least precise.**

Synthetic Aperture Radar interferometry (InSAR): Limitations

- It recovers motion only in the look direction. It cannot be used in some areas of steep topography, where the radar beam cannot penetrate, or where the slope facing the radar is so steep that several points have the same range to the radar.

- Another limitation is that non tectonic changes between images, such as those due to vegetation growth or weather conditions (which affect radio wave propagation in the atmosphere), can mask the effects of crustal motion.

- InSAR provides relative changes within an image that is tens to a hundred kilometers across, but does not provide absolute positions on a plate-wide or global scale.

Synthetic Aperture Radar interferometry (InSAR): Limitations

- This poses no problems for individual earthquake studies, but means that it alone cannot be used for large-scale applications like plate boundary studies.

- The advent of space-based methods like GPS and InSAR, which make collecting geodetic data faster and easier, have made earthquake geodesy and seismic wave studies common overlapping approaches to earthquake studies.

- Hence, although seismology and earthquake geodesy were long viewed as very distinct, owing to their different instrumentation, earthquake geodesy is increasingly viewed as very low-frequency seismology (or earthquake seismology as high-frequency geodesy).

Summary

- Geodetic methods using signals from space permits all three components of position to be measured to sub-centimeter precision and now give coseismic motion to high precision much more easily than was previously possible.
- Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Global positioning system (GPS) are popular geodetic technique to measure ground deformation.
- GPS uses a constellation of satellites transmit coded timing signals on a pair of microwave carrier frequencies synchronized to very precise on-board atomic clocks.
- GPS data can be obtained for continuous period of time or short period of time. The later one is cheaper.
- The biggest limitation of geodetic data for earthquake studies is that the positions of geodetic markers before the earthquake are needed.

Summary

- For radar, d is the antenna length, so a radar a distance r above the earth's surface could resolve objects of size x, where $\theta_d = \lambda/d = x/r$

- The phase difference between radar signals with wavelength λ reflected from the earth's surface and recorded by antennas at position A_1 and A_2 is $\phi = (4\pi/\lambda)(r_2 - r_1)$

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- If differences in satellite positions between the measurements are removed, a vector surface displacement D causes a phase change

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where δr is the projection of the vector displacement along , the look direction connecting the satellite and reflection point.

- The results are shown as a phase difference map, called a differential interferogram.

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THANK YOU !