Earth Crustal Deformation Observations from Space using InSAR

How can space technology help us understand our planet?

Howard Zebker
Stanford University
Disasters in the news

An earthquake in Haiti – magnitude 7.0

>100,000 killed
1,000,000 homeless
A tsunami in Indonesia

Created by a magnitude 9.2 earthquake under the Indian Ocean

– 230,000 people killed
A volcano in Iceland

Fairly small eruption, but disrupted thousands of airline flights
Earthquake and Tsunami in Japan
Continents and oceans
Plate tectonics
Historical plate motions

- Permian: 225 million years ago
- Triassic: 200 million years ago
- Jurassic: 135 million years ago
- Cretaceous: 65 million years ago

PRESENT DAY
Traditional dating of tectonic activity

- Similar arguments for isotope/chemical evidence
Earthquake basics

Earthquakes mainly occur along plate boundaries where motion is strongest and friction resists the motion.

Shown are epicenters of 358,214 events from 1963-1998.
Earthquake types

Layered Earth with a Fault

Strike-slip fault

Normal Fault

Reverse Fault
Common earthquake myths

- "Big earthquakes always happen in the early morning”
- "It's hot and dry -- earthquake weather”
- "Beachfront property in Arizona”
- "We have good building codes so we must have good buildings”
- "Head for the doorway”
- "And the earth opened...”
Volcanos

- Magma chamber
- Vent
- Lava
- Magma chamber
Lava eruptions
Lava flow forms
Mt. St. Helens before and after 1980 eruption
Mt. St. Helens eruption - 1980
Studying Earth from Space
What is a radar?

• Radar: Radio Detection and Ranging

• Measures time of flight of EM pulses
Early radars

Taylor and Young (1922)

Breit and Tuve (1925)
Distance measurements

Radar System

Target 1
7,500 m

Target 2
9,000 m

Intensity

noise level

signal level

0

50 μs
60 μs

time
Mapping multiple objects - ppi
Imaging geometry
Forming an image

Echo Time Delay (μs)

Pulse Transmission Delay (s)
Seasat – First satellite imaging radar, 1978
Interferometric Synthetic Aperture Radar (InSAR)
InSAR measures distance by measuring signal phase

1. Distances measured as signal phase

2. Mapping change in phase gives deformation

3. Radar interferogram
InSAR phase observables

Topography term
\[ \delta r = \frac{\lambda \phi}{4\pi} \]
\[ \sin(\alpha - \theta) = \frac{(r + \delta r)^2 - r^2 - B^2}{2rB} \]
\[ z(y) = h - r \cos \theta \]

Deformation term
\[ \phi = \frac{4\pi \Delta r}{\lambda} \]
Seasat also produced the first interferometric fringes

- Topographic map of Death Valley, CA
InSAR topography - SRTM

First (and only) worldwide, consistent model of elevation

World mapped at 30 m posting, 10 m elevation accuracy

90 m data available for Earth

JPL SRTM Project
InSAR topography - Examples

Mount Meru, Tanzania

Utah front range

JPL SRTM Project
Seasat deformation observations

- Local uplift and subsidence near Salton Sea, CA
ERS radar measured first earthquake from space
Geodesy – Precise measurement of Earth shape

InSAR

GPS
GPS aseismic (‘slow’) earthquakes

Cascadia subduction zone

Slow events occur in many subduction zones around the Earth

Slow earthquakes are adding stress to subduction fault

Melbourne and Webb, 2003

GPS time series
GPS views interseismic velocity field
Central California / San Andreas fault
InSAR Persistent Scatterer method

PS image of San Andreas Fault - ERS satellite

PS spacing is ~1km

PS performance

RMS error ~1 mm/yr
Integral inversion yields pressure or movement from surface subsidence.

\[ u(x, t) = \frac{\alpha(1-2\nu)}{2\mu\pi(1-\nu)} \int \Delta p(v, t) g(x, v) \, dv \]
Hector Mine earthquake and fault slip solution
Inference of stress change
Hector Mine Earthquake

Fialko et al., 2002

Static shear stress change
Static normal stress change
Volcanic deformation

Some volcanic regions, such as Galapagos islands, are extraordinarily active

How do widespread volcanoes communicate?

Amelung et al., 2000
Volcanic deformation

Multiple deformation processes occur simultaneously

Sierra Negra

Continuous inflation from an oblong sill
Trap-door faulting occurs episodically

Jonsson et al., 2005
Time series resolves temporal deformation

Long Valley Caldera
Volcanic mechanical modeling

Space measurements

Jonsson et al., 2005

Mechanical model - Sierra Negra
Energy resource management

Subsidence from petroleum extraction – Lost Hills, CA
Landsliding in Berkeley Hills, CA

Landslides appear clearly in InSAR maps.

Rates increase in years with greater precipitation.

Can be mapped by small (<1 mm) motions.
Groundwater management

Subsidence in Las Vegas Valley, 1992-97

Las Vegas, Nevada Subsidence 1992-1997

Falk Amelung
Groundwater modeling

Aquifer storage extent, Antelope Valley, 1995-98

Hoffmann et al., 2003
Sea Level Rise: a Serious Problem if Global Ice Sheets Melt

By Peter Shuger / courtesy USACE
Global View of Dynamic Ice Motion and Mass Balance
Glacial retreat marks worldwide climate change

Portage Glacier, Alaska
Mass balance

Physical processes driving mass balance

Accumulation

Snowfall

Equilibrium Line

Melting

Ablation

Outlet Glaciers

Flow

Bedrock
Climate change and the polar regions

Ice velocity mapping - Pine Island Glacier

Rignot, 2001
InSAR Observations of Ice Flow

Ice Streams in Antarctica

Blue
<10 m/yr

Red
>1000 m/yr
Natural hazards and global change

- Seismic cycle
- Volcanoes
- Climate change
  - Ocean circulation
  - Atmospheric circulation
  - Distribution of glaciation
- Sustainability