Beyond seismology: Observing earthquakes and fault motions from space

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Gareth Funning: a history

Grew up in SE England, (30 miles from London)

Transferred from physics (poorly taught) to geology (fun) in 1st year of college

Inspired by one summer holiday in France, did a middle school project on earthquakes and volcanoes, aged 9

Moved to California in 2005, because there are earthquakes here, e.g.

PhD fieldwork in Bolivia

Baja California, 2010

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Outline

Part 1: Earthquakes: the basics
Where, why and how they happen

Part 2: Imaging earthquakes from space
InSAR: how it works, and a few examples

Part 3: Imaging fault loading from space
Measuring the slow bending of the crust

The future
Monitoring movements of the surface in near-real time
Part 1: Earthquakes: the basics

Amplitude of seismic waves tells us how big the earthquake was.

Difference in arrival time between the P-wave and S-wave tells us how far away the earthquake was.
Earthquakes M 5.5 and greater, 1981–2011. Data: ISC
50 mm/yr (2 in/yr)

EQ data: ISC

GPS data: NASA

You are here!
PSA: Earthquake preparedness

- Earthquake proof your home (secure heavy furniture, objects on walls)
- Make an emergency plan – where to meet, who to contact (out of region)
- Know what to do

- 1 gallon of water per person per day for at least 3 days
- Non-perishable food, first aid kit, fire extinguisher, flashlight, radio, spare batteries (+ medications? infant supplies? pet supplies?)

earthquakecountry.org
terremotos.org
totallyunprepared.com
The most dangerous faults in California (USGS, 2008):

- Southern San Andreas (59% probability of a large $[M\geq 6.7]$ earthquake in next 30 years)
- San Jacinto (31%)
- Hayward-Rodgers Creek (31%)
Faults

Surfaces of relative weakness in the brittle upper crust

Map view

Block 1 (Pacific)  |  Block 2 (N. America)

fault (San Andreas)

3D view

fault
Rocks can bend

Most of the time, the blocks of crust are locked together by friction...

...so instead of sliding, the blocks bend when they are pulled

This may go on for 100s of years
The earthquake cycle

Block 1

Block 2

Time: 0 years
The earthquake cycle

Time: 100 years

Block 1

Block 2

1 m
The earthquake cycle

Time: 200 years

Block 1

Block 2

2 m
The earthquake cycle

Time: 200 years + 20 seconds

photos: LA Times, Examiner
The earthquake cycle

Block 1

Block 2

Time: 200 years + 20 seconds

2 m
The earthquake cycle

~200 years of slow bending

~20 seconds of rapid unbending

We can measure both processes from space!
Part 2: Imaging earthquakes from space
InSAR

Interferometric — use wave interference
Synthetic Aperture — pretend you have a big radar antenna
Radar — emit microwaves, measure echoes
SAR: how it works

1. Satellite emits radar pulse
2. Radar is backscattered
3. Amplitude and phase of echo recorded at the satellite
- SAR imaging uses amplitude of backscattered echoes
- All-weather, day/night imaging
- Maps surface roughness, slopes
- Applications: ship tracks, ice tracking, oil slicks, land-use changes, planetary
What about the phase?

Phase is a function of the distance from the satellite to the ground.

ERS-1

~6 cm

~780 km
InSAR: how it works
InSAR: how it works

Pass 1: pre-movement

Pass 2: post-movement

phase=\phi_1

phase=\phi_2

phase shift due to ground motion
InSAR: how it works

phase shift varies with distance from the fault
Interferogram = Phase A - Phase B

Remove phase from topography satellite positions earth curvature
17 August 1999, Izmit earthquake (Turkey)
17 August 1999, Izmit earthquake (Turkey)
each cycle of blue => yellow => red = 28 mm of displacement (half of the radar wavelength) away from the satellite

2008 Wells, Nevada
Strike: 172°
Dip: 38°
Rake: −95°
$M_w$: 6.06

Weston et al., 2012
Example 1:
The 2003 Bam, Iran earthquake
26th December 2003, 5.26 am local time

- M 6.6
- Official death toll 26,000
- Peak ground acceleration 0.97 g in city centre
- Earthquake initiated within 10 miles of the city
The Bam fault

The Bam fault had been identified in satellite imagery years before the earthquake occurred...

...but only minor cracking was found at the surface
Preliminary InSAR data

There is a zone of signal loss running S of Bam
Preliminary InSAR data

Surface rupture found in the field – after we told them where to go!
The Bam earthquake main fault

Main fault is 4 km west of the ‘Bam fault’

There are no surface features corresponding to this fault – we didn’t know it existed
Coseismic interferograms

The teardrop pattern on the east side indicates a second fault

Ascending interferogram  Descending interferogram
Two fault model

The ‘teardrop’ feature is reproduced in the SE

Ascending model  Descending model

Funning et al., 2005
Two fault model

Improved fit E of the fault

Ascending residual

Descending residual

Funning et al., 2005
Two fault model

Secondary fault appears to be a southward continuation of the Bam fault
Aftershock distribution

Seismogenic crust may extend ~10 km below the rupture

Jackson et al, 2006
The 1994 Northridge, CA earthquake

photos: Brant Ward, Lanny Ignelzi, Gary Avey, Gregory Davis
Example 2:
The 1994 Northridge, CA earthquake

Severson, Funning, Marshall, in prep
Southern California Earthquake Center Community Fault Model
[SCEC-CFM]
The Northridge fault has a complex shape.

Severson, Funning, Marshall, in prep
slip model shows significant slip down to \(~15\) km (9 miles)

Severson, Funning, Marshall, in prep
Model fits the data well!

Severson, Funning, Marshall, in prep
Fault moved furthest on the corner of the part of the fault that sticks out.

This may have importance for other faults in the LA basin.

Severson et al., 2013, in prep.
101 earthquakes studied with InSAR!

Funning, Weston, Ferreira, Elliott, in prep
InSAR => seismology

Seismology can mislocate earthquakes by 50 km!

Weston, Ferreira, Funning, 2011
Part 3: Imaging fault loading from space
Southern California significant earthquakes

- Fort Tejon, 1857, M 7.9
- Kern County, 1952, M 7.5
- Landers, 1992, M 7.3
- Hector Mine, 1999, M 7.1
- Imperial, 1940, M 6.9
- El Mayor-Cucapah, 2010, M 7.2
- San Fernando, 1971, M 6.6
- Northridge, 1994, M 6.7

We want to know:
- How fast the crust is bending
- When the last earthquake was
Atmospheric noise can mask the small signal from bending the crust.
‘Stacking’ interferograms

Stack = I1 + I2 + I3 + I4
(total time)

Wright et al., 2001
We can see a lot of things in such data!

- Geysers geothermal field
- Groundwater basins
- Subsidence

ERS, tracks 113, 342, 070
1992–2000
The Hayward fault creeps!

ERS, all three tracks
San Andreas: 25 mm/yr (1 in/yr)
San Jacinto: 19 mm/yr (3/4 in/yr)

Fialko, 2006
Most recent events in the area

N. San Jacinto fault
- M6.8 in 1918 (San Jacinto/Hemet)
- M6.3 in 1923 (Moreno Valley/Redlands)

S. San Andreas fault
- No historical accounts (i.e. no event since 1769)
- Geologic evidence suggests last event in ~1680
How big could the next one be?

N. San Jacinto fault
- ~100 years $\times$ 19 mm/yr = 1.9 m of potential fault movement
- Potential M6.7–7 earthquake

S. San Andreas fault
- ~330 years $\times$ 25 mm/yr = 8 m of potential fault movement
- Potential M7.5–7.6 earthquake
Part 4: The future
6 day repeat in same orbit
mean post event wait => 3 days
ascending + descending => mean wait < 3 days

SENTINEL-1A and -1B
European Space Agency
Launched April 3 2014, 2015
14 day repeat in same orbit
23 cm wavelength – less decorrelation

In final pre-launch testing
Launches May 24th
The NASA-ISRO SAR (NISAR) Mission Concept

Potential joint NASA–ISRO (India) mission, in review
What can we expect?

Rapid, routine analysis of earthquakes

Rapid damage mapping

Near real-time monitoring of fault loading, volcanoes, landslides...
Summary

Earthquakes are the sudden unbending of the crust, following decades of slow bending.

InSAR allows us to measure both processes.

We get a full picture of the complexity of each earthquake and a more accurate location.

We can measure fault loading everywhere in the world, and a lot else besides!
Thank you!

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