Remote Sensing of the Solid Earth
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• Dave Sandwell, Howard Zebker, Chuck Wicks, Yuri Fialko, Ben Brooks, Rob Mellors, Mike Poland, John Bell, Roland Burgmann, Eric Fielding, Falk Amelung, David Schmidt, and many others
Remote Sensing of the Solid Earth

InSAR

GPS
Remote Sensing of the Solid Earth

InSAR

GPS
Remote Sensing of the Solid Earth
Crustal deformation

How do the crust and mantle deform before and after an earthquake or volcanic eruption?

Short and long-term temporal fluctuations

What is the three-dimensional shape change associated with short-lived and man-made events?
InSAR - Introduction
InSAR - Introduction

• Uses two or more SAR images to generate maps of surface deformation.
• Can measure movements on the scale of about 1mm/year.
• Spatial resolution on the order of 100m, temporal resolution on the order of 15 – 30 days.
• Current satellites: Sentinel 1-A, ALOS 2
InSAR – How it works

Phase shift:
InSAR – How it works

• Subtract the phase component of two SAR images.
• Convert the phase shift you observe from phase units to meters (deformation).
InSAR – How it works
InSAR - Phase unwrapping
InSAR – Phase unwrapping

Wrapped interferogram  Uwrapped interferogram
InSAR - Challenges

• Decorrelation
InSAR - Decorrelation
InSAR - Decorrelation
X-band – 3 cm

COSMO-SkyMed interferogram using data from 19 February 2009 and 9 April 2009. Perpendicular baseline is 480 m.

Note poor correlation after less than 2 months.
C-band – 5.6 cm

Envisat interferogram interpretation.

Note decorrelation after 2 months.
On April 6, 2009 (UTC), magnitude 6.3 earthquake occurred in central Italy. The Japan Aerospace Exploration Agency (JAXA) performed an emergency observation on April 22, 2009.

Note the good correlation after more than 1 year.

L-band – 23 cm
InSAR - Challenges

- Decorrelation
- Orbital error
InSAR - Challenges

- Decorrelation
- Orbital error
- The Atmosphere
The Atmosphere
The Atmosphere
The Atmosphere

• Filtering and modeling
• Estimation using weather and climate models
• Averaging
InSAR - Applications

**ECHO**
Earth Change and Hazard Observatory

Mission Statement:
The Earth Change and Hazard Observatory is a dedicated L-band interferometric radar mission addressing two of the NASA Earth Science Enterprise strategic research priorities:

i) transformations of the Earth’s surface and their predictability, and

ii) variability of the Earth’s ice cover and its relation to sea level and climate change.

ECHO also contributes to the goals of the multi-agency EarthScope initiative.

Jean-Bernard Minster, SIO, PI
Howard A. Zebker, Stanford, Deputy PI
Paul A. Rosen, JPL, Deputy PI

Primary ECHO Science Targets

- **ICE**
- **HAZARDS**
- **VOLCANOES**
- **EARTHQUAKES**

MODELING SOLID EARTH SYSTEMS THROUGH CRUSTAL DEFORMATION

ESSP ECHO
Fact Sheet 1 of 2
InSAR – Earthquakes
May 12, 2008, M7.9 Wenchuan, China

Surface rupture mapped by: Jing Liu-Zeng, Chinese Academy of Sciences
May 12, 2008,
M7.9 Wenchuan, China

Interferogram from
ALOS PALSAR.
One fringe is 11.6 cm
LOS deformation.

Interferograms show zones
of complete decorrelation.
Additional acquisitions will
provide other components as
well as postseismic
deforation.

Xiaopeng Tong,
David Sandwell, and
Rob Mellors, SCEC, 2008
April 4, 2010
M7.2 El Mayor
(Mexico)
Earthquake.

GPS coverage
Is poor in this area.

Fialko et al.

Horizontal displacements, cm

from ENVISAT and ALOS data
Coseismic: 071016 - 080116
Postseismic: 080116 - 080302

- 9 January 2008
- M 6.4 mainshock
- M 5.9 aftershock 1 week later
- Normal fault source mechanisms
- Afterslip occurred on both fault planes and have very similar spatial deformation as coseismic period

Ryder et al. *JGR*, 2010

Huang, Burgmann, Berkeley
Line of sight velocities from stacked InSAR data

35 interferograms


Fialko, Nature 2006
Line of sight velocities from stacked InSAR data

35 interferograms


Fialko, Nature 2006
Why is this important?

• Studying fault properties.
• Evaluating earthquake hazard in a specific area.
• Making models for stress state at the plate boundary
• Gaining a general understanding of the mechanics of crustal deformation.
InSAR – Groundwater
Using InSAR to Delineate Groundwater Related Ground Deformation in the Great Basin
Impact of heavy groundwater pumping near Devil’s Hole National Monument

K. Katzenstein, PhD student
University of Nevada

Amargosa Farms
Amargosa Flat
Ash Meadows National Wildlife Refuge
NEVADA CALIFORNIA
Devil’s Hole National Monument

Amargosa Farms Profile A - A'
Amargosa Flat Profile B - B'

LOS Displacement (cm)
Using InSAR to Delineate Groundwater Related Ground Deformation in the Great Basin
Bedrock Aquifer Response to Gold Mine De-watering

K. Katzenstein, PhD student
University of Nevada

Betze Post Mine

Uplift

Gold Quarry Mine

LOS Displacement (cm)

Betze Post Profile A-A'
InSAR - Volcanoes
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Yellowstone Caldera

ENVISAT IS2

Sum of two images (~150 mm uplift and ~65 mm subsidence)

$B_\perp = 230$ m and 190 m

2004/09/22 to 2006/08/23

C. Wicks, USGS
ENVISAT interferogram of Okmok volcano, Alaska, spanning 2003-2004. Located in the central Aleutian arc, Alaska, Okmok is a dominantly basaltic complex topped with a 10-km-wide caldera that formed circa 2.05 ka. Okmok erupted several times during the 20th century, most recently in 1997; eruptions in 1945, 1958, and 1997 produced lava flows within the caldera. Previous studies utilizing InSAR images from ERS-1, ERS-2, and Radarsat-1 sensors have shown that the inflation rate after the 1997 eruption generally decreased with time during 1997-2001, but increased significantly during 2001-2003. This recent interferogram shows continued inflation during 2003-2004 at a rate of about 60% that during 2002-2003. The InSAR image also shows post-emplacement deformation of the 1997 lava flow, most likely due to thermal contraction.
Averaged InSAR image from track 229 created by stacking all unwrapped 1-year interferograms from the 1992-2005 time period. The deformation histories for several points are shown for both track 229 and 501 interferograms. We attribute this deformation to thermoelastic contraction of the 1986 pyroclastic flow deposits. The graphs on the right side of the image give the deformation history for points 11, 16 and 17, which show a small amount of LOS shortening (5-6 cm) over the east flank of the Augustine Island. The graphs at the bottom of the image show little deformation on the south and west sides of Augustine Island. Blue lines are the best second-order polynomial fits to the observed LOS displacements.

Submitted for publication in Earth, Planets, and Space as:
ENVISAT interferogram spanning November 2003 to January 2006 and showing inflation of the summits of Kilauea and Mauna Loa volcanoes, along with subsidence along both of Kilauea’s rift zones.
InSAR - Landslides
ALOS PALSAR Observation of slow moving landslides in Northern California, USA

Boulder Creek Earthflow

Other earthflows

Figure prepared by Al Handwerger

[Roering et al., GRL, 2009] From the crustal deformation group at the University of Oregon
InSAR - other

• Wetlands
• Ice
• Forests
Louisiana Wetland water level change from ALOS PALSAR

Shum et al, Ohio
Absolute water level change map from ALOS InSAR/Altimeter

(a) Open water river gage

(b) A and B areas have different scale of water level change due to levees between two areas.

Shum et al, Ohio
Helmand River Water Level: ALOS InSAR vs ENVISAT Altimetry

ALOS InSAR water level change agrees well with ENVISAT altimetry

ENVISAT Water Level (2002–2008)

Shum et al, Ohio
Image Coregistration Offsets

Frame 1550

- Arrows show offset estimates used to compute best-fit polynomial for offset between master and slave
- $\text{mean abs}(\text{range}_\text{shift}) = 0.42$
- $\text{mean abs}(\text{az}_\text{shift}) = 1.01$
- Note decorrelated regions are ignored
ALOS PALSAR HH coherence image

- Eucalypt
- Pine

Diego de Abelleira
Greenland Locations
Interferogram (HH)

Azimuth

Percolation zone site

Frame boundary

North

Range

Dry snow site

Decorrelation Artifact

Albert C. Chen

Zebker, Chen, Stanford
GPS
GPS - Introduction
GPS – How it works

- Satellites communicate with ground stations, transmit time stamp.
- Careful data processing allows for much higher resolution than hand-held GPS.
GPS – Campaign
GPS – Campaign Adventures

Digging for monuments in a Mexican graveyard
GPS – Campaign Adventures

Sampling delicious Salton Sea tilapia
GPS – InSAR comparison

**Advantages**
- Better resolution in time
- Better atmospheric correction

**Disadvantages**
- Worse spatial resolution (networks are sparse)
GPS - Applications

- Earthquakes
- Volcanoes
- Landslides
- Hydrology
- Subduction zones
2010 Mw 8.8 Chile

InSAR + GPS + seismology + tsunami

Simons, Caltech
GPS - Offshore

- GPS stations
  - Survey vessel
  - Seafloor stations (acoustic transponder)
  - Plate boundary
  - Continental Plate
  - Oceanic Plate
  - Kinematic GPS Positioning
  - Acoustic Ranging