Monitoring volcanoes with InSAR

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Act 1: What am I looking at?
What is SAR?
When does it or doesn’t it work?

Act 2: Should I believe my eyes?

Act 3: Who cares?
What have we learned about volcanoes from InSAR? Observations and models

Act 4: State of the art and future trends

Act 5: How to get a piece of the action

Magnitude 6.6 Bam, Iran earthquake in 2003
Interferogram courtesy of Yuri Fialko

Basics of Radar: (RAdio Detection And Ranging)
The Radar Concept: active transmission of microwave radiation
Works at night and sees through clouds

Object scatters energy back to radar

Ground-Bound volcano monitoring radar at Merapi
From: Matthias Hort (U. Hamburg)
- 24 GHz FMCW - Doppler radar
(Wavelength 1.25 cm: K radar band)
- Range: approx. 4.6 km
- Output: Doppler spectra

Magnitude 6.6 Bam, Iran earthquake in 2003
Interferogram courtesy of Yuri Fialko

Basics of Ground-based volcano Radar

- Transmitted frequency
- Received frequency

Measures: time, frequency and amplitude of returned radar signals
To simplify:
- Time tells us distance
- Frequency tells us velocity
- Amplitude tells us size and/or strength of radar scattering

Images courtesy of Matthias Hort (U. Hamburg)

What can we do with ground based radar?
- Radar gives a velocity distribution for up to 16 distance intervals (range gates)
- 4 range gate of 600m length are recorded at Merapi
- Velocity resolution: 0.28 m/s (radial velocity)

Images courtesy of Matthias Hort (U. Hamburg)

Basics of Imaging Radar

- Place on moving platform -- combine multiple radar bursts into an image
- Range resolution controlled by extent of pulse (short pulses = high spatial resolution = high bandwidth)
- Azimuth resolution related to antenna size

Images from: Paul Rosen

Real aperture radar resolution ~ 1 km
Synthetic aperture combines multiple views of same area (“synthetic”) ~ 10 m/pixel

Images from: Paul Rosen

Basics of Synthetic Aperture Radar

- Real aperture radar resolution ~ 1 km
- Synthetic aperture combines multiple views of same area (“synthetic”) ~ 10 m/pixel

Images from: Paul Rosen

Modified from: Matthias Hort (U. Hamburg)
More Basics of SAR: Like an image, but different

If topography is known, can correct and georeference image

Depending on the ground slope and the radar incidence angle can have layover or shadow.

Intro to InSAR: How does it work?

• Two Radar images from space: Data is complex: has amplitude and phase
• Phase change between images depends on several factors that must be removed before measuring deformation

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SAR Platforms

Satellite: Repeat pass
Fly over once, repeat days-years later
* Measures deformation and topography

Aircraft: Shown here: AIRSAR
Measures topography, ocean currents

Airframe shown here: Shuttle Radar Topography Mission (SRTM)
Measures topography, deformation with other missions

SAR Track/Frame Geometry

Modified from Rowena Lohman
Interferogram Formation

\[ \text{Amplitude} + \text{Amplitude} = \text{Interferogram} \]

\[ \text{Phase} + \text{Phase} \]

Decorrelation

- Green = good (high coherence, near 1)
- Purple = bad
- Water
- Plants/Agriculture
- High Relief
- Too much change
  - Sand Dunes
  - Landslides

Removing Topography

\[ \text{Interferogram} - \text{Topography} = \text{Deformation} \]

\[ \text{Orbital effects removed} + \text{noise} \]

Wrapped vs. Unwrapped

Hector Mine EQ

\[ \text{Color Cycle } \sim 3 \text{ cm} \]

\[ \text{Color Cycle } = 300 \text{ cm} \]

Summary: processing-modeling chain

1. Obtain 2 data takes (either raw or single-look complex)
2. Create interferogram
3. Remove orbital (a.k.a. baseline) effects
4. Use DEM to remove topographic effects
5. Convert raw phase difference to something easier to model (a.k.a. unwrapping the interferogram)
6. Convert to geographic coordinates
7. Reduce the number of data points (resample)
8. Compute the radar line-of-sight
9. Model the deformation

- Before writing the paper, Ask if the observed signal could be due to:
  - Atmospheric noise?
  - Satellite position uncertainty?
  - DEM error?
  - Unwrapping error?
**ROI_pac Two-pass Processing Flow**

1. **Condition**
   - Data
   - Form SLC
   - Resample Image #2
   - Form Interferogram
   - Estimate Correlation
   - Remove Topography
   - Filter & Look Down
   - Unwrap Phase
   - Geocode
   - Post-Process & Model

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**Orbital Errors (“Ramps”)**

- Approximately 0.1 m uncertainty in satellite positions
- Orbital fringes not always 100% removed
- In particular, not sensitive to long wavelength deformation

How to overcome?
- Simultaneously solve for position and geophysics

**Atmospheric contamination**

Two types

- **Vertical stratification**
- **Turbulence**

**Correlated vs. Random Noise**

- Atmospheric water vapor is not white noise
- Spatial length scale (turbulence)

Real noise vs White noise

Same variance
Correlated vs. Random Noise

Real noise

White noise

Mw 5

Correlated vs. Random Noise

Real noise

White noise

Inferred strike

Mw 5

Correlated vs. Random Noise

Real noise

White noise

Real fault plane

Mw 5

Can we remove the atmospheric signal from interferograms?

1) Use interferograms themselves to estimate linear or exponential phase with elevation: constant for image or spatially variable
2) Direct water vapor and "dry delay" observations:
   - From satellite (e.g., Li et al., 2005)
   - From GPS & other ground sensors (e.g., Webley et al., 2002)
3) Data stacks or APS: Assume atmosphere random in time or low-pass time domain filtering (e.g., Ferretti et al., 2001; Senus and Bibeau, 2007)
4) Global and Regional Models computed by data center (~300 km horizontal resolution by ECMWF, NCEP; North American RR ~ 32 km) (e.g., Ivanov et al., 2007; Chao et al., 2007)
5) Regional or Local Model computed by user (~3 km horizontal resolution) (e.g., Foster et al., 2006)

Based on several studies, we can't remove everything. Will likely always need to account for atmosphere via covariance matrix

Unexpected deformation can cause errors

Vertical component of deformation from Southern California GPS station (in mm)

Annual and sub-annual cycles

Not a perfect sinusoid: Amplitude varies from year to year

Presumably related to natural and human-induced groundwater changes

From Dong, JPL webpage

Should we believe GPS/InSAR?: Part 1

- How well do coincident measurements agree?

- Compare large earthquakes in South America: RMS different few cm

90 InSAR and GPS points for Mw 8.1 Antofagasta, Chile earthquake. GPS stations first occupied in 1992, as GPS was immature (Prolss et al., 2004)

10 InSAR and GPS points for Mw 8.4 Arequipa, Peru earthquake. Only 4 different GPS stations included (Prolss et al., 2007)

- For other earthquakes also agree to few cm. Landers, Northridge, Hector Mine, Juan de Fuca et al., 2001, 2004, Sturk et al., 2004, Tubbs et al., 2003, Ziemer et al., 2005
Part 2: Magma chamber inflation discovered with InSAR, confirmed with ground observations

**South Sister, Oregon**
- InSAR inflation started in 1998
- From: Wicks et al., 2001
- Confirmed by subsequent GPS ground observations
- From: Dzurisin et al., 2006

**Some volcanic deformation discovered with InSAR**

- South Sister, Oregon
  - From: Wicks et al., 2001

- Peulik, Alaska
  - From: Lu et al., 2001

- Westdahl, Alaska
  - From: Lu et al., 2001

**Comparing radar wavelengths at Hawaii**

- Correlation maps
- Interferograms
- All images from Space Shuttle (SIR-C) quan Apr-Oct
- From: Rosen et al., 1996

**Volcanoes of the southern and central Andes**

- 2500 volcanic edifices (white in central Andes)
- 100-200 “potentially active” volcanoes (red)
- 2-3 continuously monitored (Llaima & Villarrica)
- Others with some seismic data in black

**Monitoring all the volcanic arcs in the world**

- Status in 2004
- Can we survey this arc?
  - Yellow: Maybe, data is available
  - Red: Not yet, need more data

- From: Pritchard & Simons, 2004

- InSAR C-band Coherence correlates with precipitation:
  - From Montgomery et al., 2001
  - Annual Precipitation

- All images from Space Shuttle (SIR-C) span Apr-Oct
- From: Rosen et al., 1996
Volcanoes of the central Andes 1993-2007

- 600 of the 1113 volcanoes < 20 Ma
- All 53 of the 53 “potentially active”

Results:
- Tihuanaco, Bolivia - 1 month(?) inflation 2005
- Lascar, Chile - pyroclastic flow & inflation (Pritchard et al., 2006)
- Lascar, Chile - inflating since 1992 (Pritchard & Simons, 2002, 2004; Froger et al., 2007; Ruch et al., 2008)
- La Parva, Chile - inflating hydrothermal system (Ruch et al., 2008)

What range of models fit your data?
Some different model parameters to test:
- Chamber geometry: Homogeneous vs. 1D, 2D, and 3D elastic models
- Include faults and realistic topography
- Isotropic vs. Anisotropic models
- Magma compressibility: Thermally self-consistent model
- Elastic vs. Viscoelastic models

Who cares?
Impacts: Magma chamber depth, location & volume
Important for understanding relation between deformation and other parameters: seismicity, volumes erupted, gas flux, etc.

Vary shape of “magma chamber”
- Bottom line: With only one component of deformation all shapes can fit data, but have different depths

Consider:
- Spherical point source
- Prolate ellipsoid (football)
- Oblate ellipsoid (frisbee)
- Finite sphere

Effects of source geometry on inferred depth at volcanoes of the central Andes

Example data fit
- Ulluruncu stratovolcano, Bolivia
- Joint inversion for 3 independent satellite tracks
- All types of sources can fit data
- Combining ascending and descending does rule out some models but non-uniqueness remains

Lascar: Most active volcano in the central Andes
Monitor by remote sensing:
- Thermal radiation from volcanic dome

Largest eruption & collapse: April 20, 1993
Photo by: M. Vuille

Smaller eruption July 20, 2000
Photo by: Mason & Pearson

Monitor by seismology:
- Unique harmonic tremor: Probably related to shallow hydrothermal circulation

Photo by: Mason & Pearson

From: Pritchard & Simons, 2004
Three major eruptions
Largest April, 1993 (0.1 km$^3$)
Several minor eruptions
Also, no deformation during eruptions of 3 other volcanoes in central Andes, 4 volcanoes in Kamchatka, 4 in Alaska
Why no deformation?
At least 3 options:
1) Magma moves w/o deformation
2) Deep magma chamber
3) Chamber refills quickly

Deformation not visible with SRTM 90m DEM
DEM: 3 m/pixel; created by Pavez et al., 2006
Digitized aerial photographs (acquired in 1998 by SAF Chile) and ground GPS measurements
Interferogram:
Time period: 95/07/08 - 95/09/16
Pavez et al., 2006
July 20, 1995 eruption
17 mm subsidence
Source 180 m
Volume change: $2 \times 10^3$ m$^3$ deflation
(Smaller than the eruption)

Deformation not visible with SRTM 90m DEM

Interferogram spans: 19 May 1996 - 12 August 1995 (no major eruptions). See poster by Patrick Whelley

Deformation of Aleutian Volcanoes by Zhong Lu et al.

Inter-arc comparison

<table>
<thead>
<tr>
<th>Arc</th>
<th># volcanoes</th>
<th># with historic eruptions</th>
<th># with eruptions this decade</th>
<th># of volcanoes actively deforming</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. Andes</td>
<td>65</td>
<td>17</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Alaska</td>
<td>80</td>
<td>46</td>
<td>17</td>
<td>12</td>
</tr>
</tbody>
</table>

1. Although Alaska/Aleutian arc seems more active, geologic averaged magma flux about the same (Reymer and Schubert, 1984)
2. Central Andes different because of 70 km thick crust or magma composition?
3. Or amount of sediment subducted?
4. Or type of lava (basalt vs. andesite/dacite)?
5. No single global explanation for the inter-arc variation in magma flux (Shelton and Siebert, 1984)

Based on published work of Lu et al. 1997-2006

Yellowstone caldera: complex deformation in space and time

Wicks et al., 2006. Magma rises beneath the Sour Creek resurgent dome, migrates through the caldera, and exits the system near the Norris Geyser Basin.
Only use summer SAR data because of steep cover
Different Yellowstone activity starts in 2004

ENVIISAT IS2 2004-2006 interferogram with continuous GPS vectors (Chang et al., 2007)

Modified from Chuck Wicks

Sources for 2004-2006 deformation (InSAR plus GPS)
Combined with earthquakes, Coulomb stress change modeling and inferences from seismic tomography

From: Chang et al., 2007

Inferred subsurface active from deformation measurements

Activity at the Big Island, Hawai‘i

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 rift zones.

Unpublished data from Mike Poland, USGS

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Dike intrusion

Conceptual Model

Mt. Etna
From: Lundgren, et al., 2003

Kilauea

Magma inflation & sector collapse: Mt. Etna

From: F. Amelung

Magma inflation & sector collapse: Mt. Etna

From: H. Zebker

Mt. Etna

From: Lundgren and Rosen, 2003

Kilauea caldera

Pu‘u “O” o

Aloa crater

Makapuhi crater

Ocean entry

**Global Synthesis: What have we learned from InSAR?**

- Volcano life cycle:
  - Magmatic intrusions without eruption might be frequent and short-lived
  - These intrusions are mostly aseismic (caveats: Uturuncu, South Sister)
  - Implications for hazard

- Magma plumbing:
  - Image spatial complexity of deformation (or lack of complexity)

- Non-magmatic deformation:
  - Lava flow and pyroclastic flow subsidence; geothermal areas

- Eruptions with no deformation observed:
  - 4 volcanoes in Andes; 4 in Kamchatka; several in Alaska
  - Maybe chambers are deep
  - Maybe chambers quickly refill

- Different rates of activity in different arcs

**New techniques: Time series of interferograms**

Data available in southern California
From: Yuri Fialko

Possible pairs with perpendicular baseline < 200 m
From: Yuri Fialko

Actual pairs made - reduce influence of scenes with severe atmospheric noise
From: Yuri Fialko

The Basic Idea...
The Basic Idea...

A stack of interferograms provides multiple constraints on a given time interval.

Date

New techniques: Time series of interferograms

The Basic Idea...

Goal: Solve for the deformation history that, in a least-squared sense, fits the set of observations (i.e., interferograms).

Many different methods (e.g., Lundgren et al. (2001), Schmidt & Burgmann, 2003), but SBAS (Berardino et al. (2002)) is perhaps most common.

Persistent scatterers (PS or PSInSAR)

- Select pixels with stable scattering behavior over time
  - Long Valley Caldera, Hooper et al. 2004
- Only focus on "good" pixels
  - Spatial coherence @ 1 pixel
  - Need neighborhoods of good pixels
- Coherence @ 1 point
  - Need > 15-20 scenes
- Added bonus: DEM errors!

SCANSAR or Wide Swath Mode

What is it?
- During overflight, multiple subswaths acquired
- Used on SRTM, Envisat, ALOS will be part of future missions

Advantages:
- Increased area coverage of single interferogram
- Increased frequency of measurement at given ground point

Disadvantages:
- No open source software available to process this data type (yet)
- Decreased spatial resolution

Pisco, Peru earthquake:
Mw 8.1, Aug. 15, 2007

Best opportunity to constrain 3D deformation field for any earthquake in South America and in any subduction zone.

At least 12 different orbital tracks
- ALOS (Japan): 3
- Envisat (Europe): 4 + 2 wideswath (from Eric Fielding)
- ERS-2 (Europe): 4 (fringes in 11-year interferogram)

Ascending & Descending

Images from: Pritchard & Fielding, 2008

Review: Will InSAR work for you?

- What is the local rate of deformation?
  - Sensitivity of single igram ~1cm
  - How many years to get signal this big and will it be overcome by noise?
  - Can you stack several igrams together?
- What is the scale of deformation?
  - Pixel size ~30m, but generally need to average many together
  - Image size is ~100 km, but if too broad worry about precision of orbits
- What is the local noise?
  - How much vegetation/precipitation/water vapor/human cultivation?
  - Can you make igrams with data from the same seasons?
  - Can you get L-band data and find persistent scatterers?
- What data is available?
  - Is there data from multiple satellites and/or imaging geometries?
  - Is a digital elevation model available?
- Do you need rapid response for hazard assessment?
**Summary & Future directions**

InSAR and pixel tracking major advance over traditional measurements of deformation

New phenomena and sources of deformation discovered

- Geothermal and supposedly dormant volcanoes
- Spatial and temporal complex deformation at volcanoes

Complementary to ground measurements: satellite measurements provide spatial coverage, continuous ground measurements provide dense temporal sampling

**Near term developments**

- L-band InSAR opens up new areas (e.g., volcanoes with vegetation)
- New software developments (like time series and persistent scatterers) will also open new areas
- Geostationary InSAR?: Near real-time, repeat cycle (days) wavelength (cm)
- Canadian Radarsat-1: 1995-present
- European Envisat: 2003-present
- Japanese ALOS: 2006-present
- German TerraSAR-X: launched July 2007
- Italian COSMO-SkyMed 2: launched 2007
- Canadian Radarsat-2: launched Dec. 2007

**Past & Current SAR satellites**

- More advanced InSAR:
  - More advanced GPS:
    - 1 Hz GPS: Larson et al., Science, 2003
    - Persistent scatterers: Ferretti IEEE, 2001; Hooper et al., GRL, 2004; Kampes' Persistent scatterers book, 2006

**For More Information:**

- Introductions to InSAR:
  - More advanced InSAR:
    - Persistent scatterers: Ferretti IEEE, 2001; Hooper et al., GRL, 2004; Kampes' Persistent scatterers book, 2006
- More advanced GPS:
  - Reference frames: Larson et al., JGR, 1991
- Introductions to InSAR:
  - Access to software:
    - Introductions to InSAR:
      - More advanced InSAR:
        - Persistent scatterers: Ferretti IEEE, 2001; Hooper et al., GRL, 2004; Kampes' Persistent scatterers book, 2006
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**Review: How to set up InSAR capability?**

1) Establish access to data
   - Main sources: see next slide
   - How? Can be purchased commercially. Lower cost/no-cost data available with restrictions. In Europe, through ESA; In U.S., through ASF and UNAVCO. Some remote access is allowed to UNAVCO.

2) Purchase/Install software to process and visualize data
   - Open source: ROI_PAC, DORIS, RAT and IDOT (TU Berlin)
   - Commercial: Gamma, TR Europa, Velcast/Atlanta, DIAPASON, SARscape

3) Download/create DEM (SRTM is only +/- 60 degrees latitude, but ASTER G-DEM in 2009)

4) Download precise orbital information & instrument files (Only ERS & Envisat)

5) Interpret reality, create stacks, time series, persistent scatterers. May need to buy/download/create new software

6) Publish new discoveries and software tools!