Future directions in volcano remote sensing

Paul Lundgren
Jet Propulsion Laboratory
California Institute of Technology
Motivation

Volcano deformation: complex variations in space/time

Figure 1-1. Deformation of June 2007 Eruption, Kilauea volcano from L-band ALOS InSAR (processing by Z. Lu).

Figure 1-6. Yellowstone caldera InSAR observation from the sum of two interferograms spanning the 2004-2006 time period (2004-2005 and 2005-2006) showing uplift (large area within caldera) and subsidence (circular fringes on NW rim of caldera) that requires a complex set of sources and magma flow from beneath the center of the caldera [Wicks et al., in preparation, 2007].

Figure 1-3. Satellite SAR interferogram for Three Sisters (red triangles) group showing the differential interferogram spanning the 1996-2000 time interval. Each ‘fringe’ is 2.83 cm in the satellite line-of-sight (LOS). Deformation source represents an inflationary source (sill, Wicks et al., 2002) that first began to deform in 1996.
Outline

• Radar wavelength
  L-band

• Deformation resolution
  High spatial sampling, ~20m, cm-level over 30 km distance
  Need for even denser sampling → near surface, small spatial processes (dome dikes)

• Spatial coverage
  Normal 40-100km swath

• Revisit time → rapid eruption processes
  Sub-weekly repeat pass
  Atmospheric issues

• Mission duration → long-term processes
  5 year nominal
Some science objectives

- Simply characterizing deformation and other RS signals over the broad time spectrum of volcano processes
- Understanding magma migration from depth
- Understanding dynamic processes
- Differences across a broad spectrum of volcano types (chemistry) and activity
C-band InSAR volcano effectiveness

- **excellent**
- Works – better with **L-band**
- **Bad** - but good for **L-band**?
C-band vs L-band
Akutan, Aleutians

Deformation mapped by ERS (C-band, $\lambda = 5.66$ cm) InSAR

Deformation mapped by JERS (L-band, $\lambda = 23.53$ cm) InSAR

Courtesy Zhong Lu, USGS
Time and spatial scales: Etna 2001 eruption example

GPS data shows large dike went from 3 km b.s.l to 3 km summit within a few days, all within 7 days of large flank eruption.

Cont. GPS baselines, and modeled source (Bonaccorso et al., GRL 2002)

InSAR provides new discoveries, but temporal sampling inadequate

Ascending and descending data constrain source geometry, 1 month and 1 year interferograms do not constrain time evolution

InSAR observations of Etna 2001 eruption
Dense spatial sampling constrain source mechanisms

Short repeat time needed for dike propagation
Example from the Galapagos

Figure 1-2. VESPA will provide temporal resolution comparable to that of a point GPS measurement (the red line in A), but with InSAR's spatial resolution (B) to capture the pre-eruptive transient deformation. (A) Uplift history of the caldera center of Sierra Negra volcano, Galapagos, constructed by InSAR and GPS measurements [Chadwick et al., 2006]. (B) Simulated interferograms of deformation events around the onset of the 2005 eruption of the volcano, based on InSAR, GPS, seismic data, and fieldwork observations combined [Yun, 2007]. An earthquake (Mw 5.4) occurred three hours prior to the eruption, which induced lateral magma migration and dike intrusion that fed the eruption. (C) Envisat satellite InSAR data where all the intermediate stages of the transient deformation were not observed.

Courtesy Sang-Ho Yun, JPL
Adjusting InSAR using GPS

Galapagos (cont’d)
Courtesy S. Yun

\[ s = Bp \]
\[ u = Gs \]
\[ \Delta x_{t2} - \Delta x_{t1} = Du \]

\[ d_{\text{InSAR}} = G's \]
Events one interferogram contains

1. Pre-eruptive inflation

2. Faulting
   - Earthquake (Mw 5.4) 3 hrs prior to the eruption
   - Fresh fault scarp along the sinuous ridge (Chadwick & Geist, personal comm.)

3. Dike intrusion

4. Co-eruptive subsidence

5. Post-eruptive inflation

Galapagos (cont’d) courtesy S. Yun
Eruption time scales

Bezymianny lava dome
Eruption time scales

Seismicity of Bezymianny volcano from January 2000 to February 2005: map (A), vertical cross-section (B), graphs of seismic activity (C-F) for the earthquakes located within circle at map (A).

For large eruptions, seismicity shows that weekly or shorter revisit times are required to track pre-eruptive deformation.

courtesy Sergey Senyukov, Kamchatkan Branch of Geophysical Survey, Petropavlovsk-Kamchatskiy, Russia
Dynamic volcano models require high spatial temporal sampling

Steady-state periodic dome growth and eruption models

*Melnik and Sparks, Nature, 1999*

*Barmin et al., EPSL, 2002*

*Mason et al., JVGR, 2006*

Figures courtesy Oleg Melnik
3 periods of dome growth:
I - 9 pulses ~12 m$^3$s$^{-1}$, $Q_{av}=0.67$ m$^3$s$^{-1}$
II - continues, $Q_{av}=0.48$ m$^3$s$^{-1}$
III- 5 pulses <15 m$^3$s$^{-1}$, $Q_{av}=0.23$ m$^3$s$^{-1}$
Santiaguito

Cycles: 8 after 1922
- high (0.5-2.1 m³ s⁻¹): 3-6-years
- low (≤0.2 m³ s⁻¹): 3-11-years

Average discharge: ~0.44 m³ s⁻¹

Courtesy Oleg Melnik
Long-term deformation

before

Chaitén volcano, Chile

May, 2008
‘Silent’ volcano sources: Long time scales?

One of most exciting aspects of InSAR at volcanoes has been the discovery of deformation in unexpected places.
Longer term behavior

Decade time-scale deformation and magma

Caldera response times can be quite long with differing outcomes and mechanisms (Battaglia et al., 1999).

Augustine volcano 11 years of seismicity (USGS)
Recent examples

Okmok eruption 2008
Preliminary results
courtesy Z. Lu, USGS
2007-2008 Pre-eruption Deformation

2008 Co-eruption Deformation

Subsidence >50 cm

Magma loss during 2008 Eruption

Magma Accumulation from InSAR modeling 1997 - 7/10/2008
Kilauea
Complex deformation processes before and after the June 2007 Father’s Day event
Kilauea Envisat time series inversion

**ENVISAT T429_2**

TS unfiltered

June 2007 Father’s Day dike intrusion

Mean velocity 1 cm/yr fringes

E Rift

**ENVISAT T322_1**

June 2007 Father’s Day dike intrusion

Kilauea

2003 2009

June 2007 Father’s Day dike intrusion

2004.5 2009

Envisat raw data courtesy ESA and M. Poland (HVO), processing at JPL
Kilauea TSX time series analysis (2008-2009)

March 2009 increased activity

March 2009 increased activity
Kilauea TSX 1 year interferogram (2008.06.13 – 2009.07.03)

Unfiltered, 64 looks
Future trends
UAVSAR is ideally suited to making repeat pass observations of volcanic regions:

- Large swath (>20 km)
- Fully polarimetric observations
- High altitude (> 12.5 km)
- Resolution: 1.6m range; 1m azimuth.
- L-band to reduce time decorrelation.
- Repeat observations on time scales as short as 20 minutes from any desired look direction.
- Flight path control to within a 10 m tube (usually within 5 m) and adjust its look direction electronically to compensate for aircraft attitude changes.
- Has a vector deformation capability.
- Can be rapidly deployed to monitor evolving volcano hazards or routinely tasked to monitor more quiescent volcanoes.
• Fully polarimetric image of Mt St Helens collected on March 24, 2008 by the UAVSAR radar. A second acquisition was collected on March 31, 2008.
UAVSAR Alaska measured July, Sept 2009

Lundgren, Lu, & Wicks
Conclusions

- InSAR is well known for its high spatial sampling and global coverage: => imaging of complex sources and new discoveries

- Future systems should improve many of these shortcomings
  - L-band to improve temporal correlation (ALOS-PALSAR, DESDynI)
  - Denser spatial sampling
    - UAVSAR, TSX, COSMO-SkyMed
  - Short repeat observations
    - 1 day or less for UAVSAR
    - 4 days? COSMO-SkyMed (X-band)
    - 8 days (tentative) DESDynI
    - 11 days TerraSAR-X (X-band)