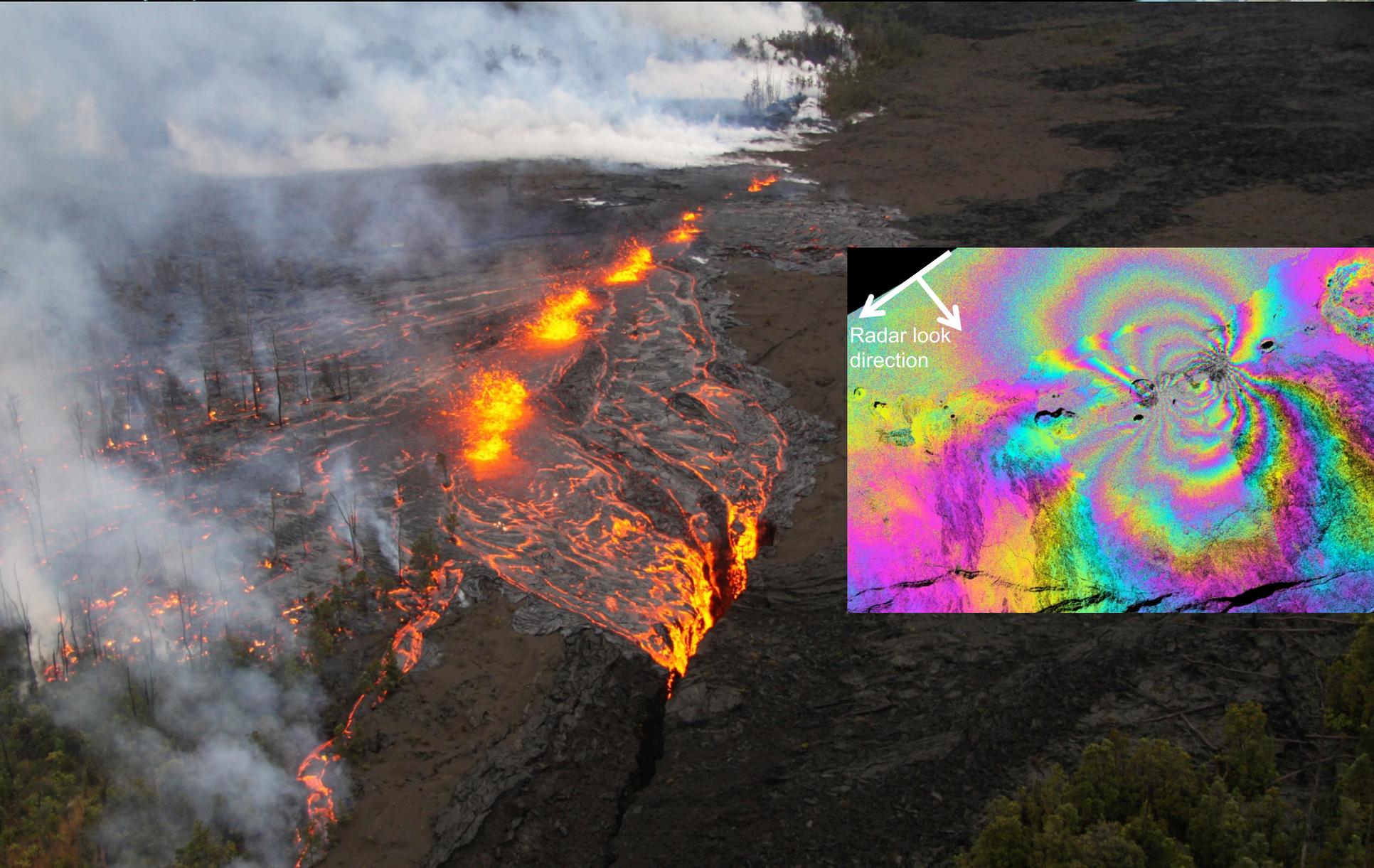
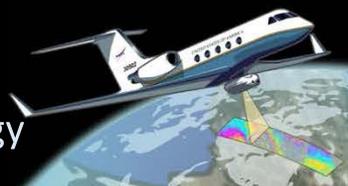




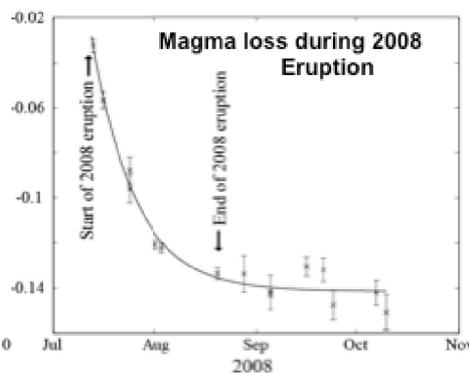
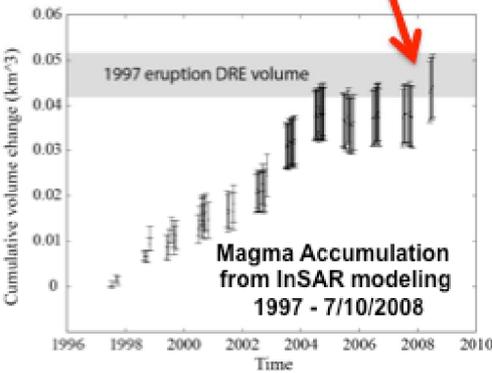
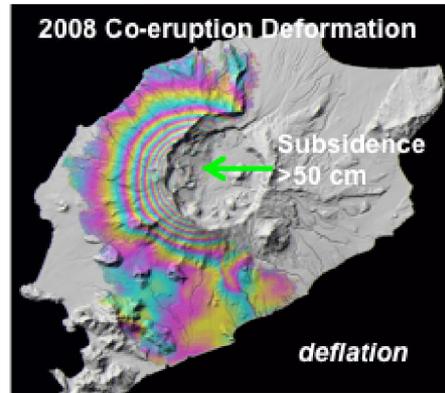
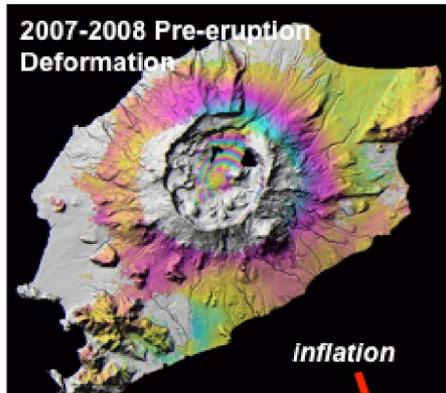
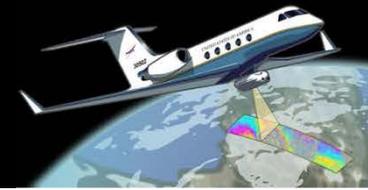
UAVSAR
Uninhabited Aerial Vehicle Synthetic Aperture Radar

UAVSAR Applied to Volcanoes

Paul Lundgren, Jet Propulsion Laboratory, California Institute of Technology



Why UAVSAR?



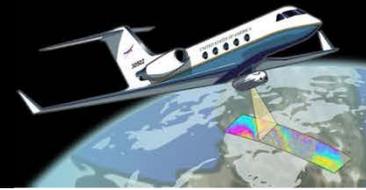
Satellite data (figure on right) can provide global coverage at fixed repeat intervals (depending on satellite).

UAVSAR is deployed annually (in current study) with the possibility to return for temporally dense observations in the event of a significant volcano eruption crisis.

Satellite InSAR data of Okmok volcano Alaska illustrating the inter-annual build-up to the 2008 eruption and the larger 2008 co-eruption deflation. *Left top*, post-1997 eruption volume change and ESA Envisat interferogram showing the 10-15 cm inflation in prior year (lower left) to the July 13, 2008 Okmok, Aleutians eruption (max VEI ~4). *Right*, InSAR data and volume change decay plot for the months following the initial eruption. [Lu *et al.*, 1998, 2005a, 2010; Lu and Dzurisin, 2010].

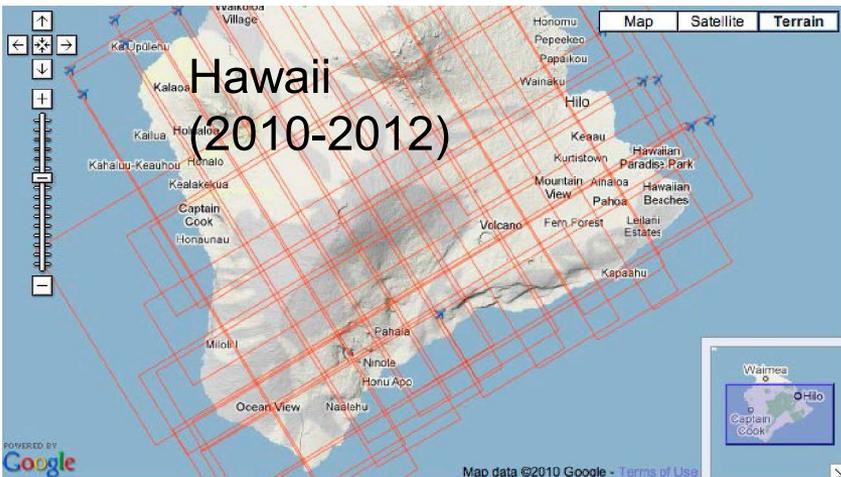
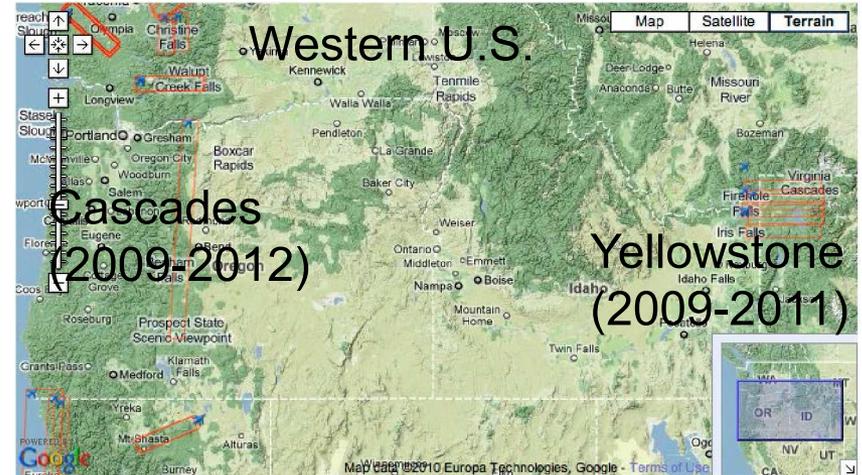


UAVSAR Volcanoes (2009-2011)

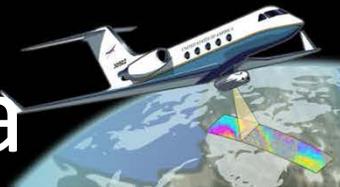


UAVSAR
Uninhabited Aerial Vehicle Synthetic Aperture Radar

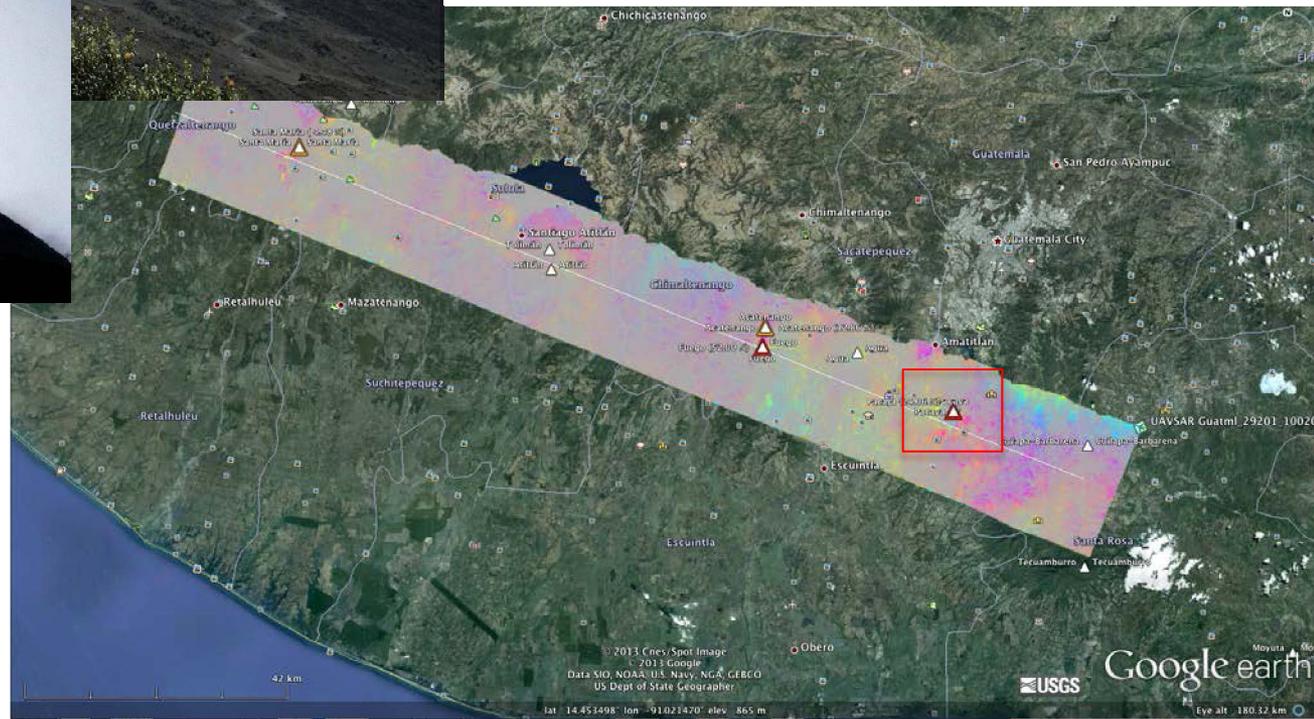
UAVSAR acquired under 1st phase of funding (2009-2011)



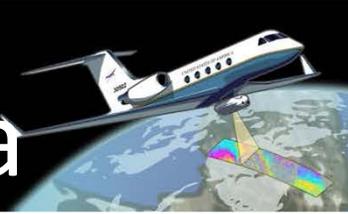
Pacaya Volcano Guatemala



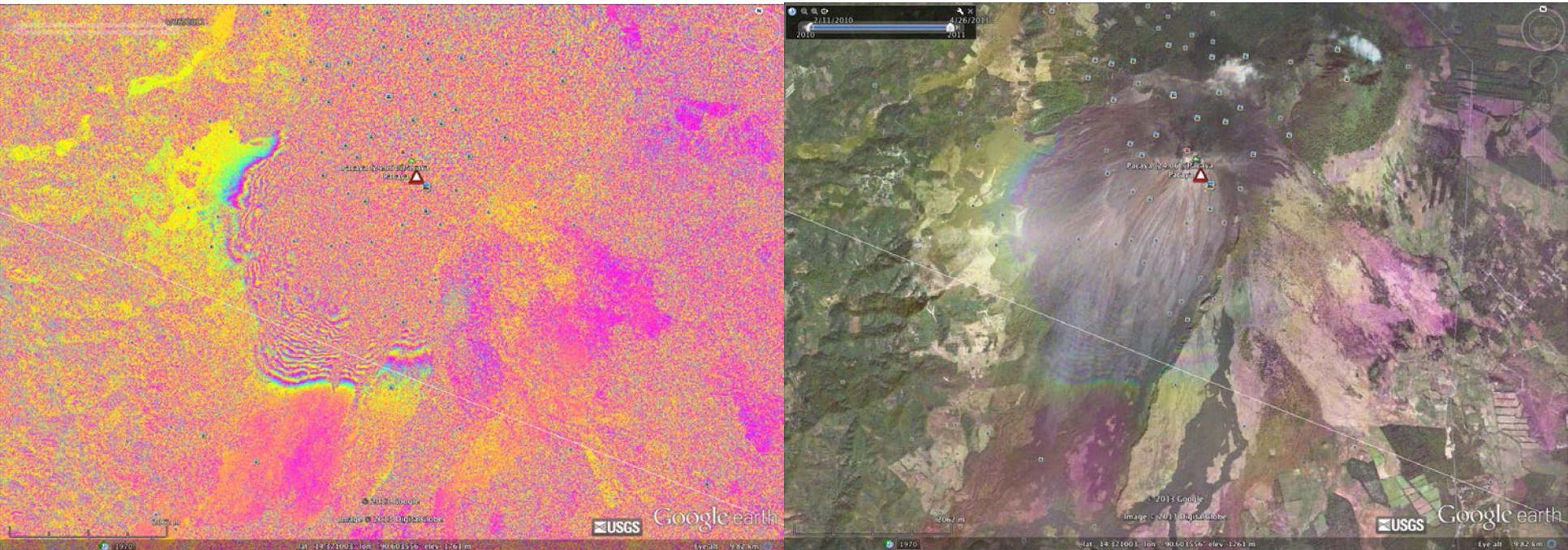
2010-2011 UAVSAR data



Pacaya Volcano Guatemala

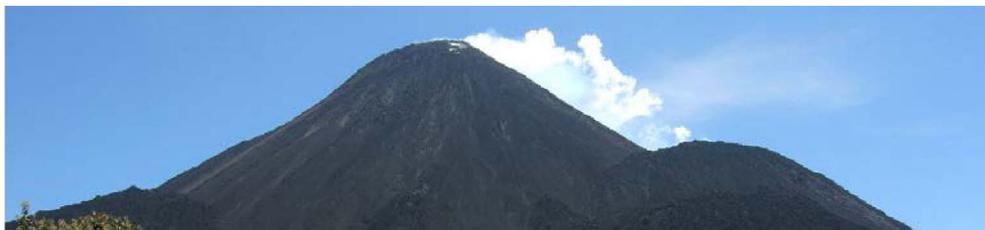
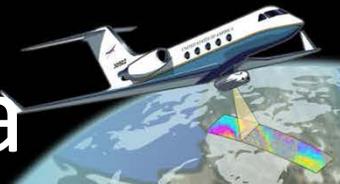


Slope instability?
(spans May 2010 eruption)

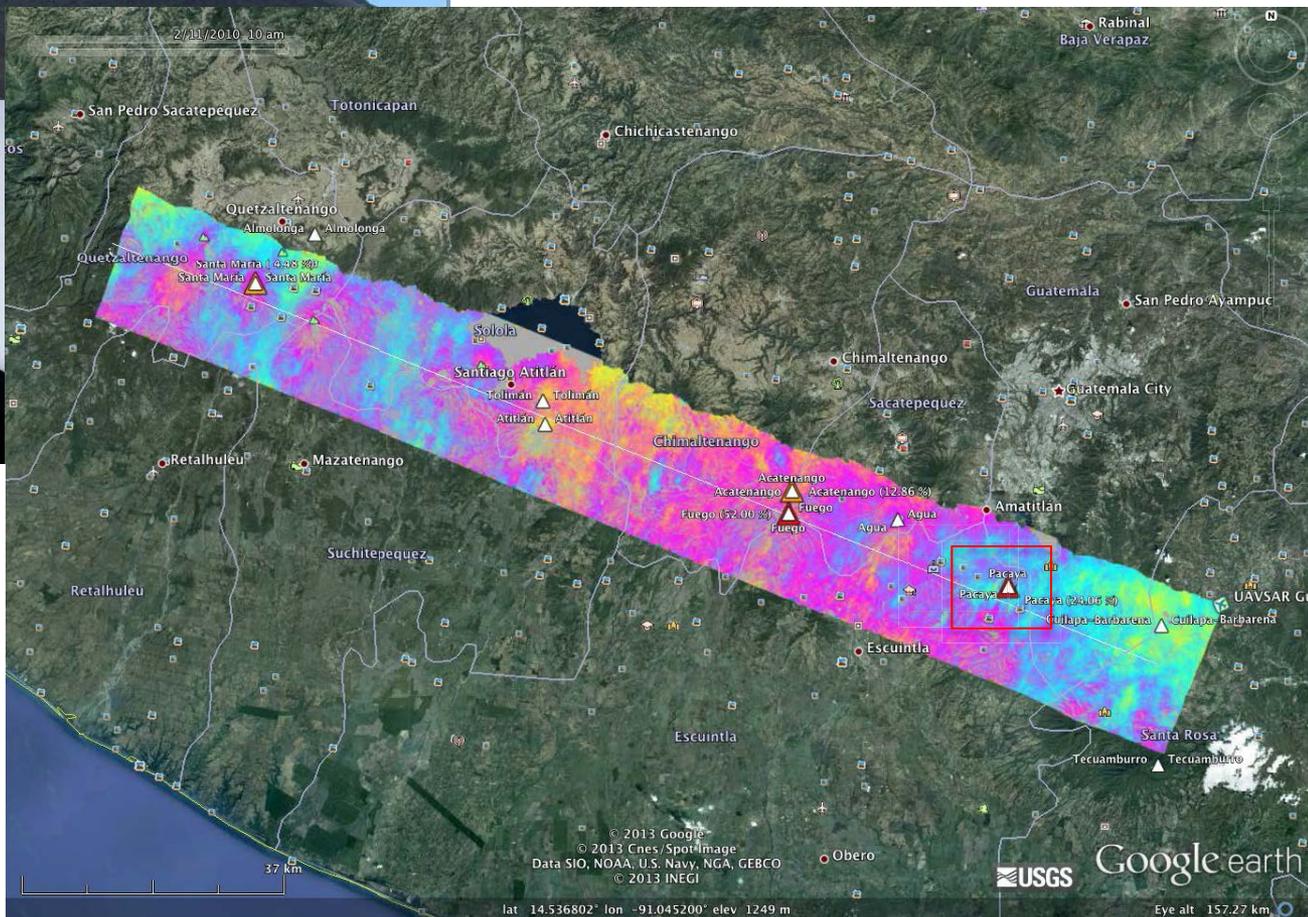


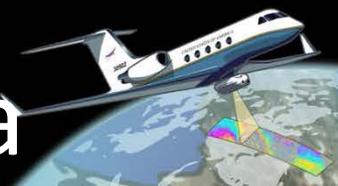
2010-2011 UAVSAR interferogram

Pacaya Volcano Guatemala



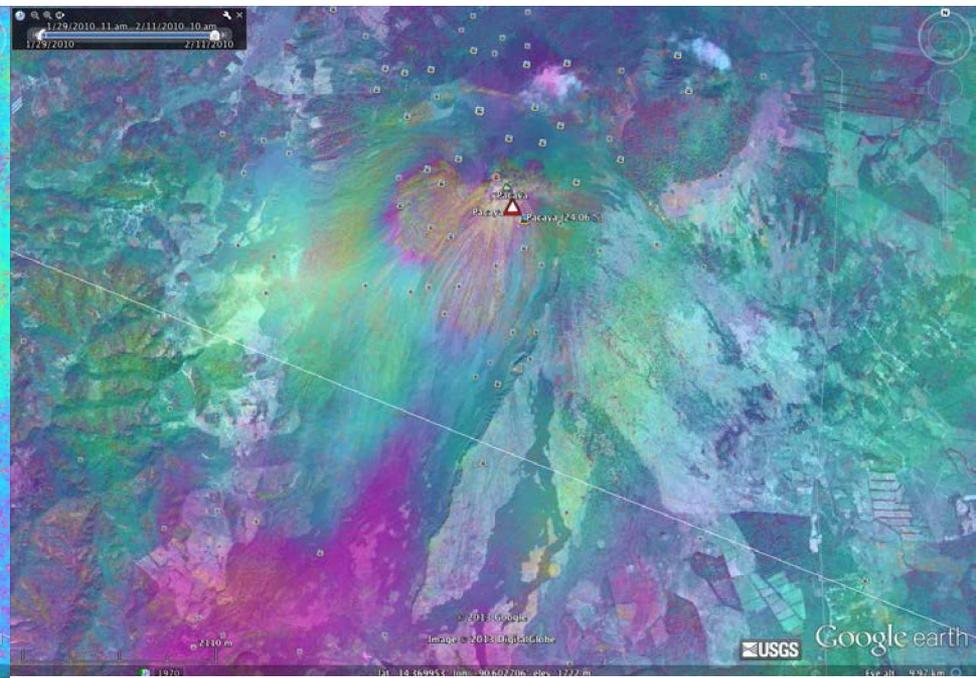
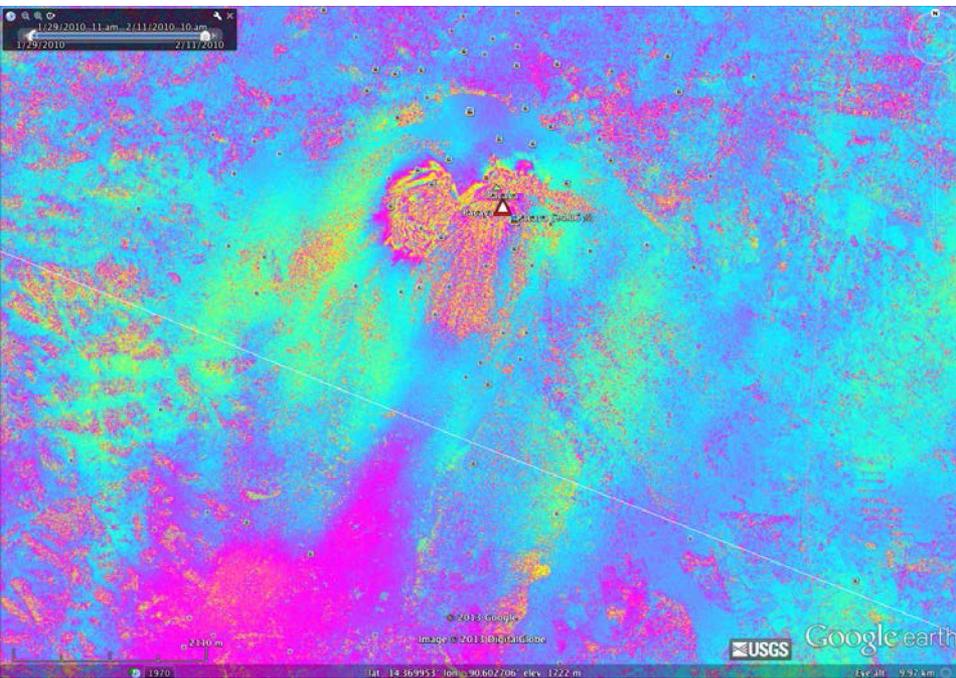
2010/01/29-2010/02/11
UAVSAR data





Pacaya Volcano Guatemala

Slope instability?
(~2 week interferogram)



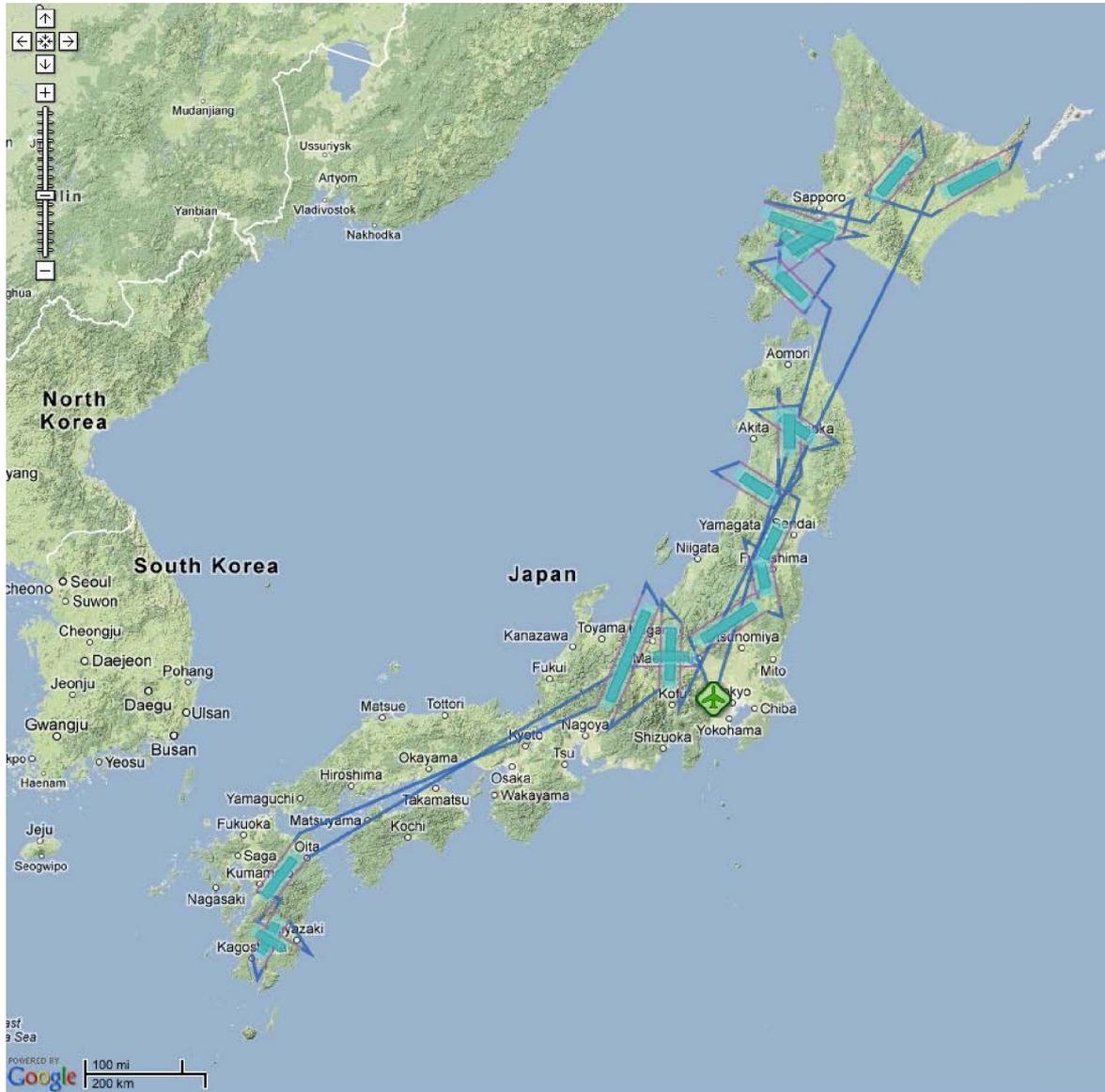
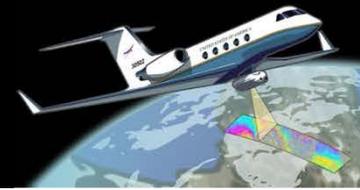
2010/01/29-2010/02/11 UAVSAR interferogram



UAVSAR

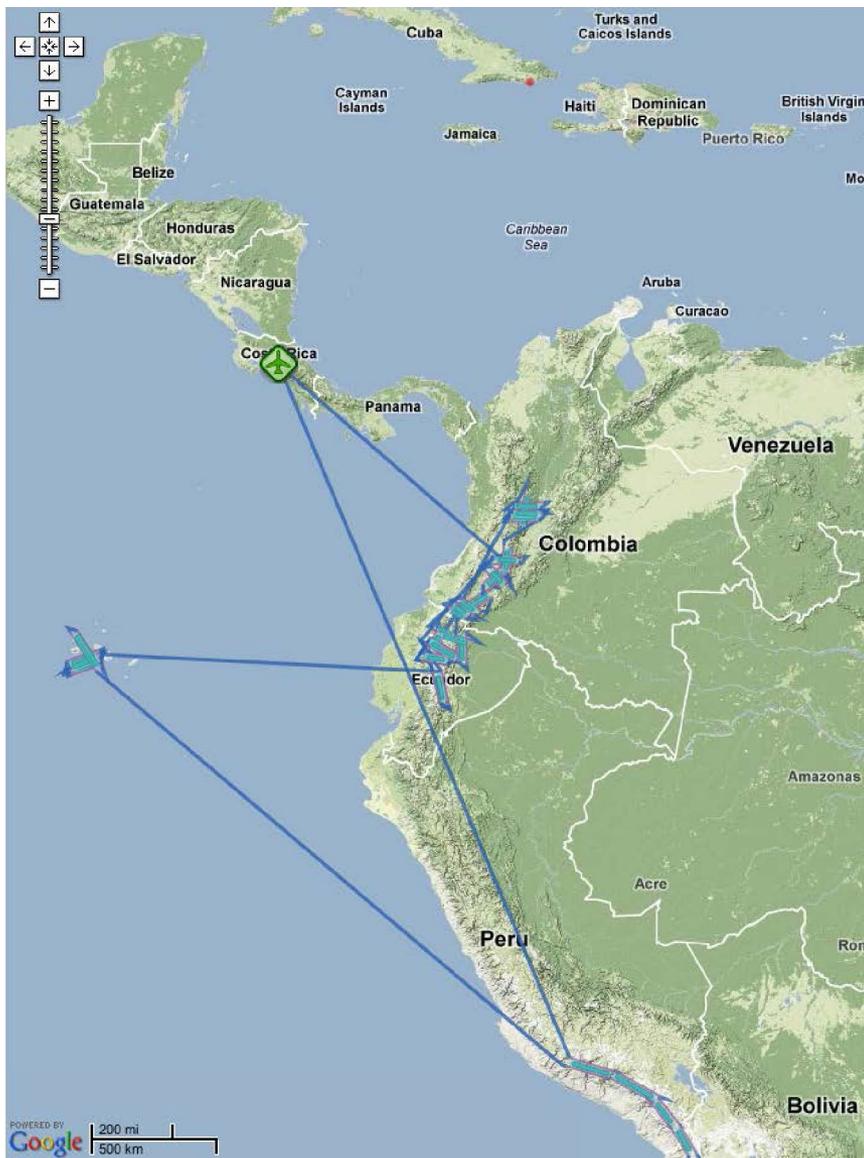
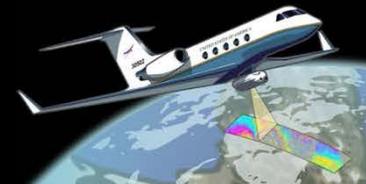
Uninhabited Aerial Vehicle Synthetic Aperture Radar

Proposed Volcano Flight Plans in Japan

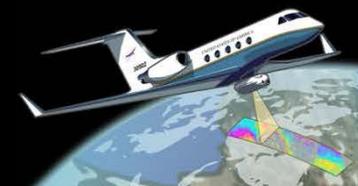


- Volcanoes will be imaged from opposite flight directions in most cases (some will also be flown at 90° for $\sim 3D$ resolution)
- Repeat interval 1 year
- Possibility to return earlier in case of significant precursory evidence for a future volcano eruption

South America 2013



Colombia



Colombia UAVSAR data from March 2013 flights already processed to polarimetry data products (map on right)

Example over Galeras Volcano

NASA Jet Propulsion Laboratory
 California Institute of Technology

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 UAVSAR Home

UAVSAR Data Search

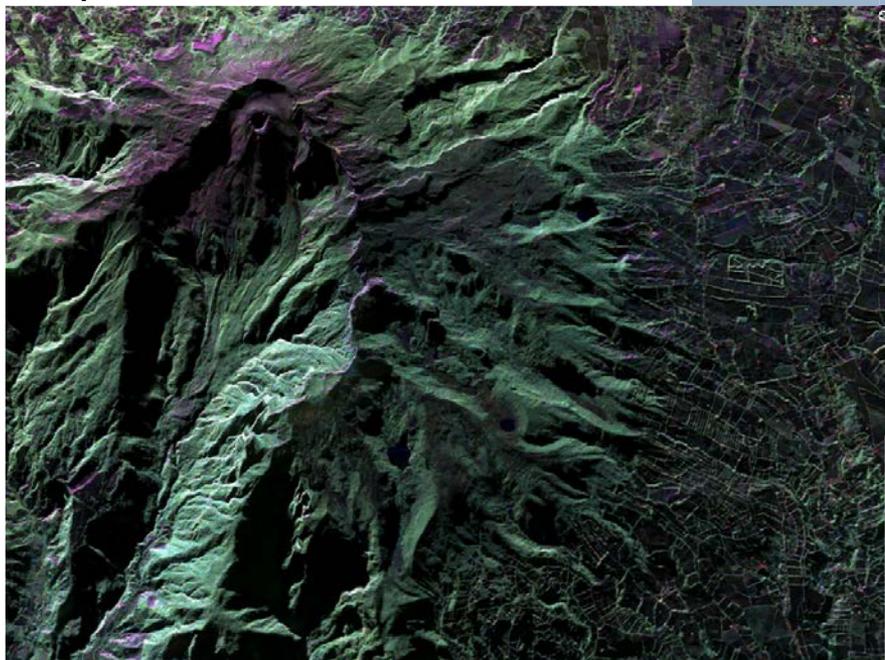
You can search by **flight ID**, **line ID**, **line sitename**, **line description**, and **date of acquisition** (in YYMMDD format). Only flight IDs can be searched as a range (e.g. "09001-09035").
 To search multiple criteria using OR, separate your search with commas (e.g. "San Andreas, 26532").
 To search multiple criteria using AND, separate your search with period (e.g. "Haiti. 11042").
 To search multiple criteria using NOT, separate your search with exclamation mark (e.g. "Haiti! 11042").

In the map, click on the **download icons** to download the data.

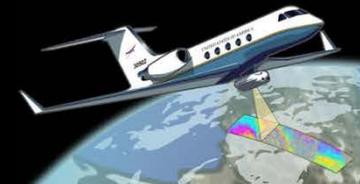
ALL Band Selections: L P Ka Search Show Show

Map Satellite Terrain

Map data ©2013 Google, MapLink



Colombia



Polarimetry UAVSAR image from Purace volcano

NASA Jet Propulsion Laboratory
California Institute of Technology

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UAVSAR Data Search

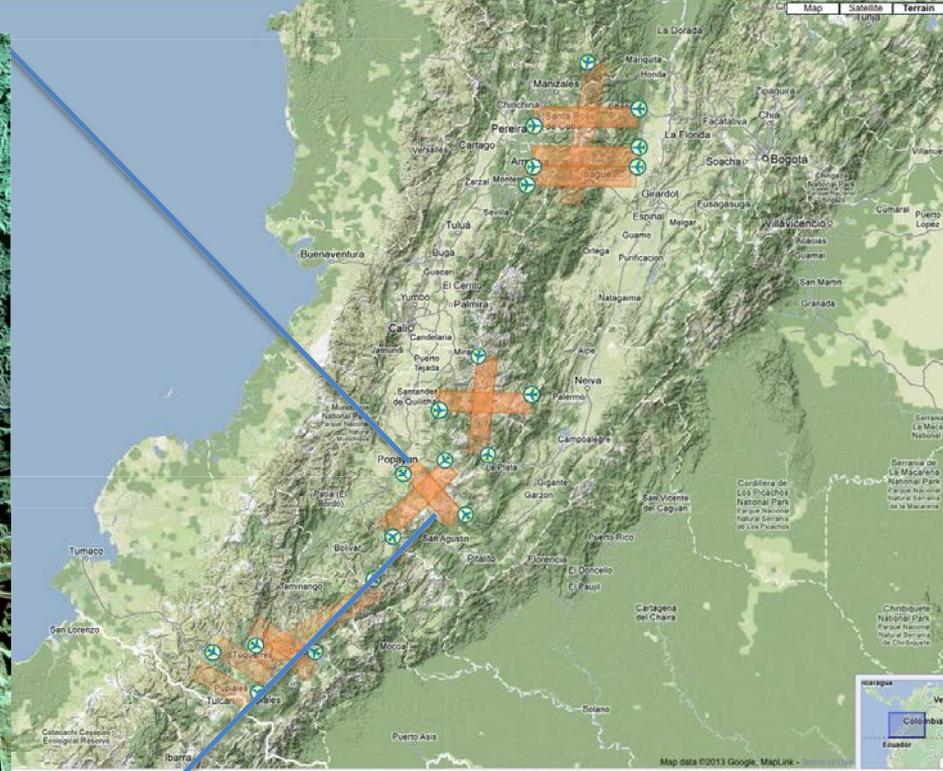
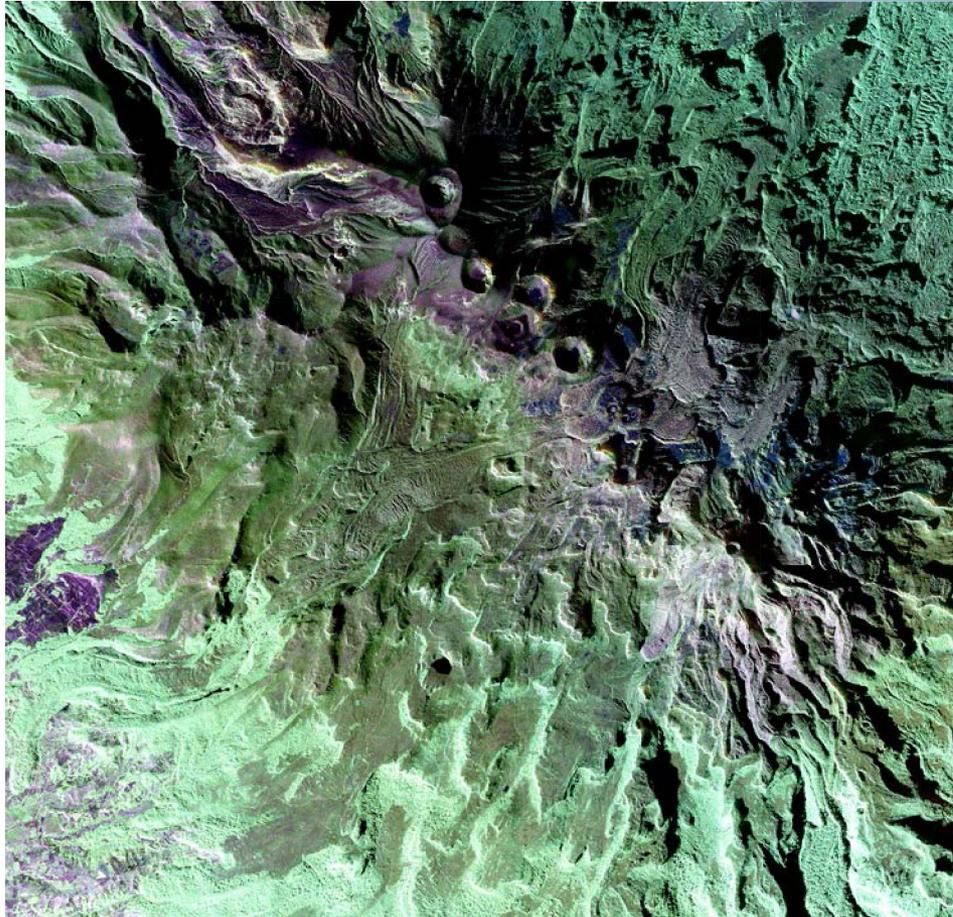
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In the map, click on the **download icons** to download the data.

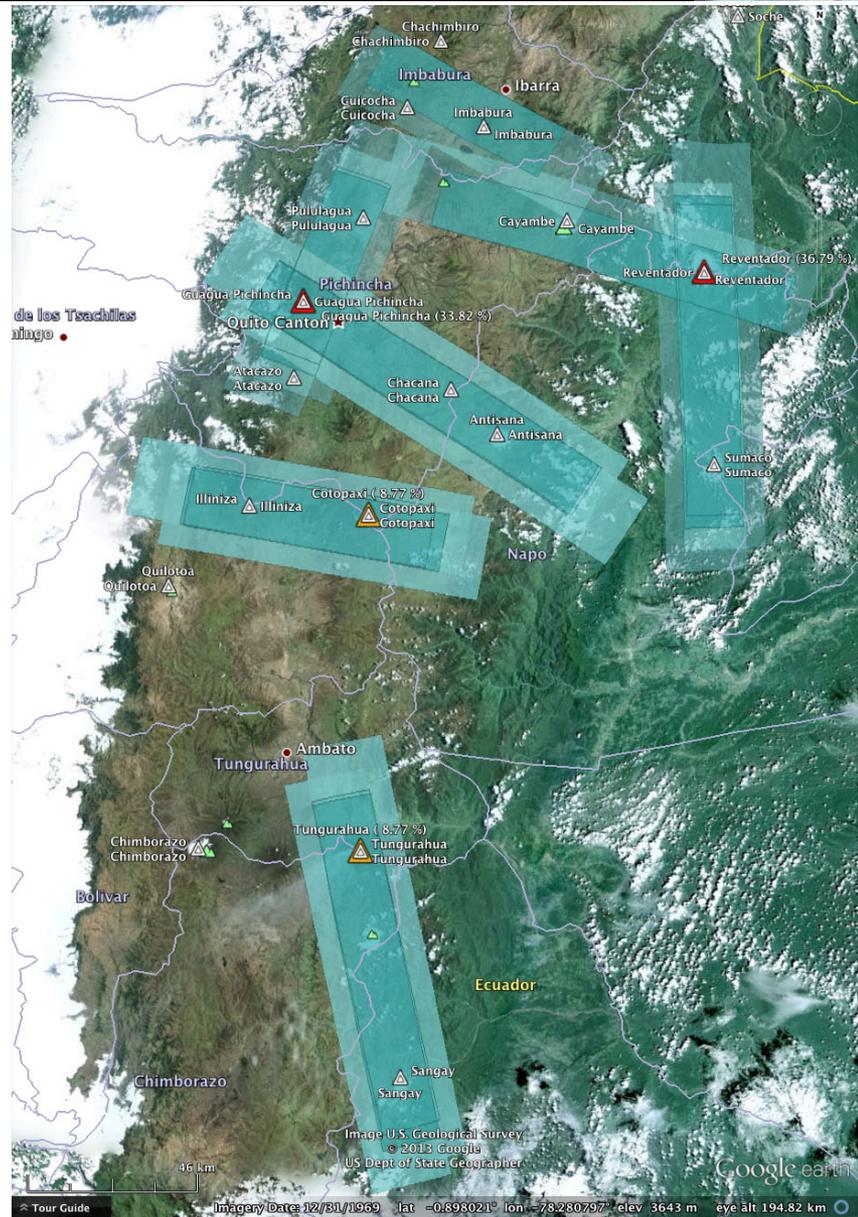
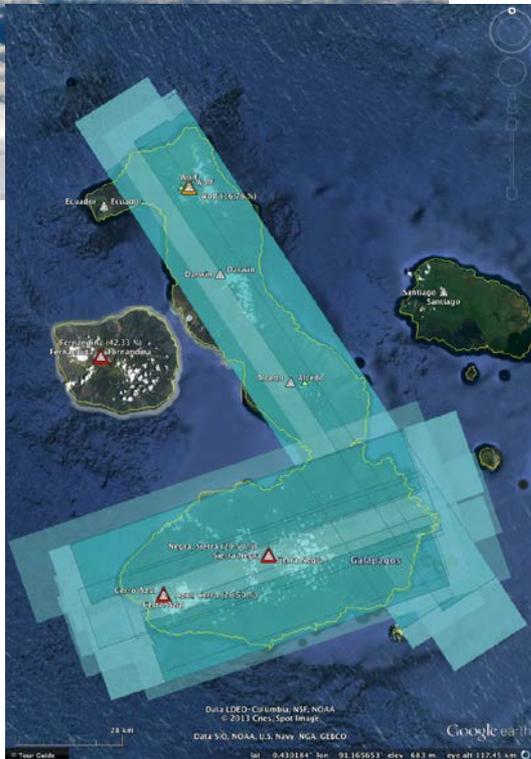
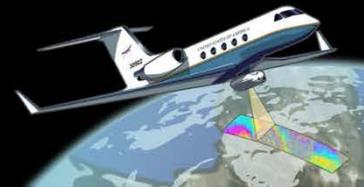
ALL Band Selections: L P Ka Search Show Show

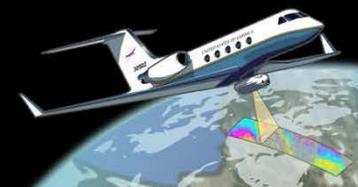
Map Search (Switch to Text search)

Map Satellite Terrain



Ecuador





Peru

UAVSAR lines flown in 2013: all volcanoes imaged from opposite flight directions





Examples from Kilauea Volcano

Collaborators: M. Poland², A. Miklius², S.-H. Yun¹, E. Fielding¹, Z. Liu¹, A. Tanaka³, W. Szeliga⁴, S. Hensley¹, and S. Owen¹

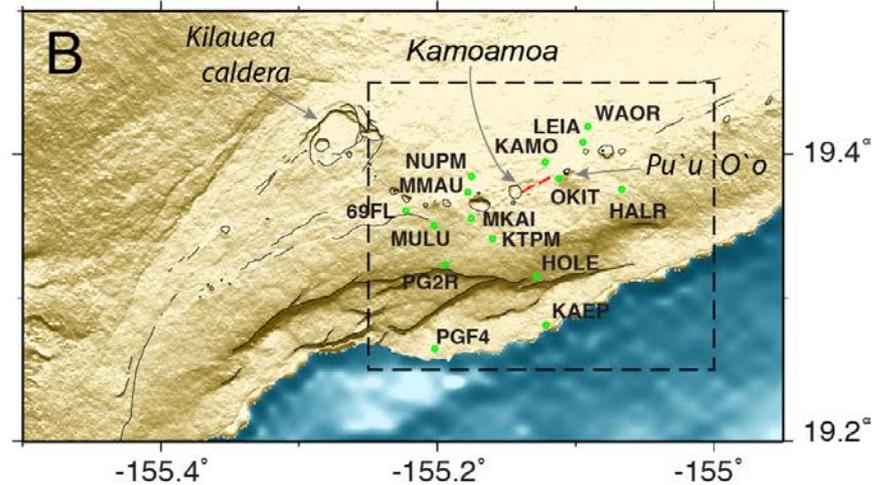
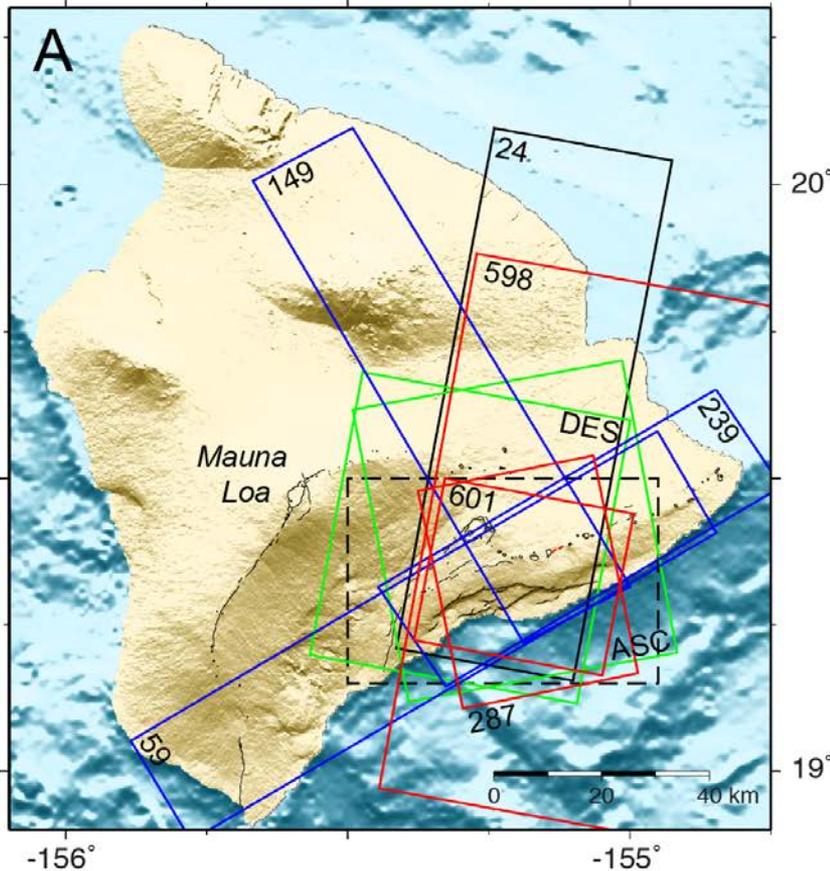
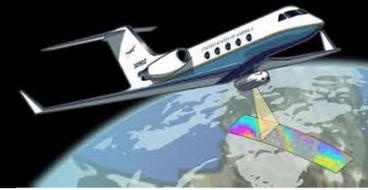
¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

²Hawaiian Volcano Observatory, U.S. Geological Survey, Hawaiian Volcanoes Nat'l Park, HI, USA

³Geological Survey of Japan, AIST, Tsukuba, Ibaraki, Japan

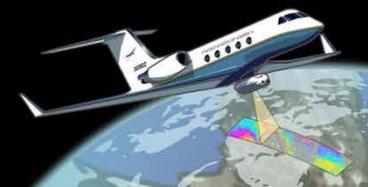
⁴Dept. of Geological Sciences, Central Washington University, Ellensburg, WA, USA

Kilauea, Hawaii

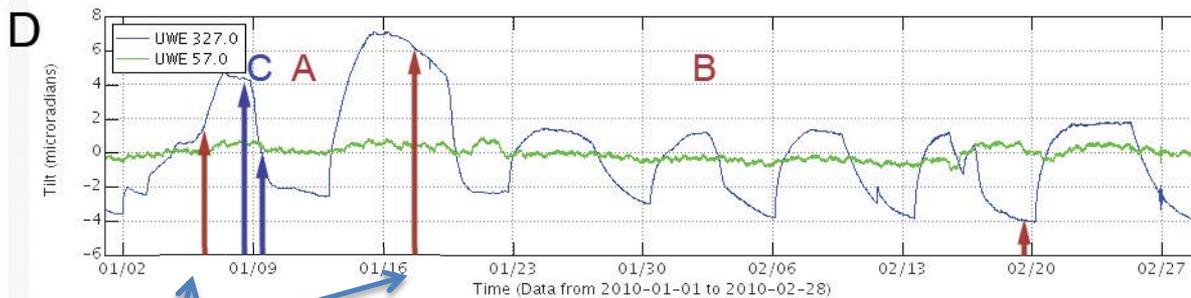
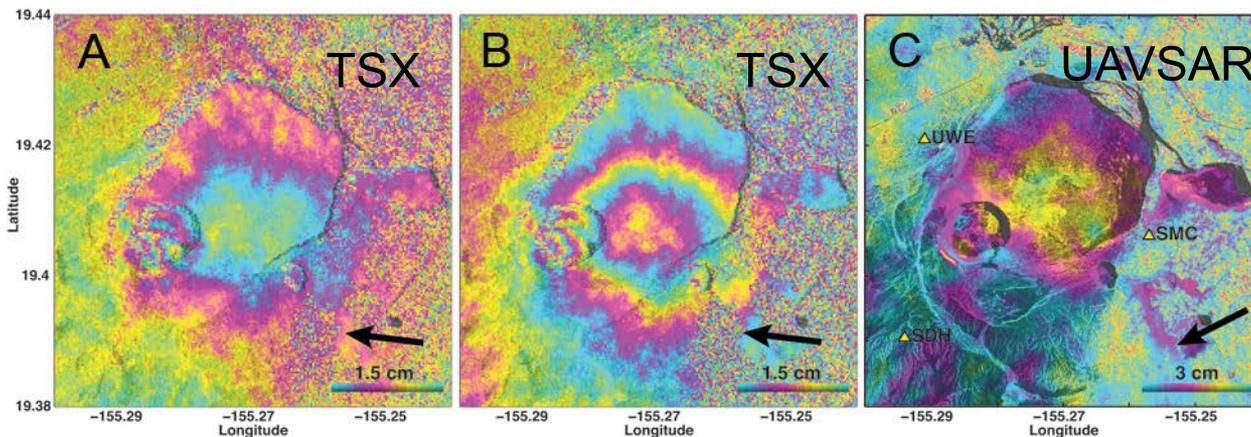


Hawaii InSAR tracks (A) and (B) Kilauea/E Rift focus area around Kamoamoa eruption (fissures in red, courtesy T. Orr, HVO, GPS sites green dots)

DI Events: January 2010

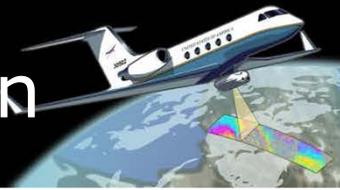


Kilauea Caldera Deflation-Inflation events

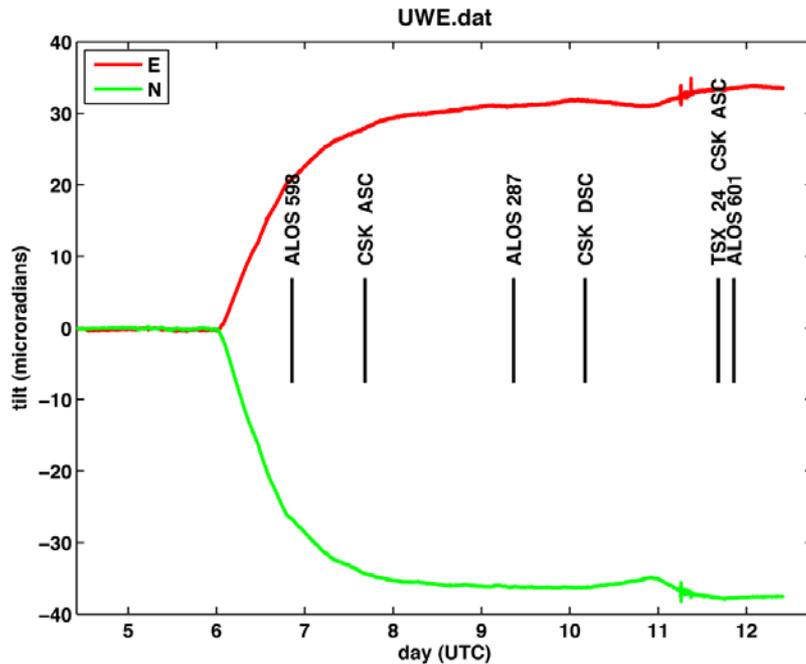


SAR acquisitions

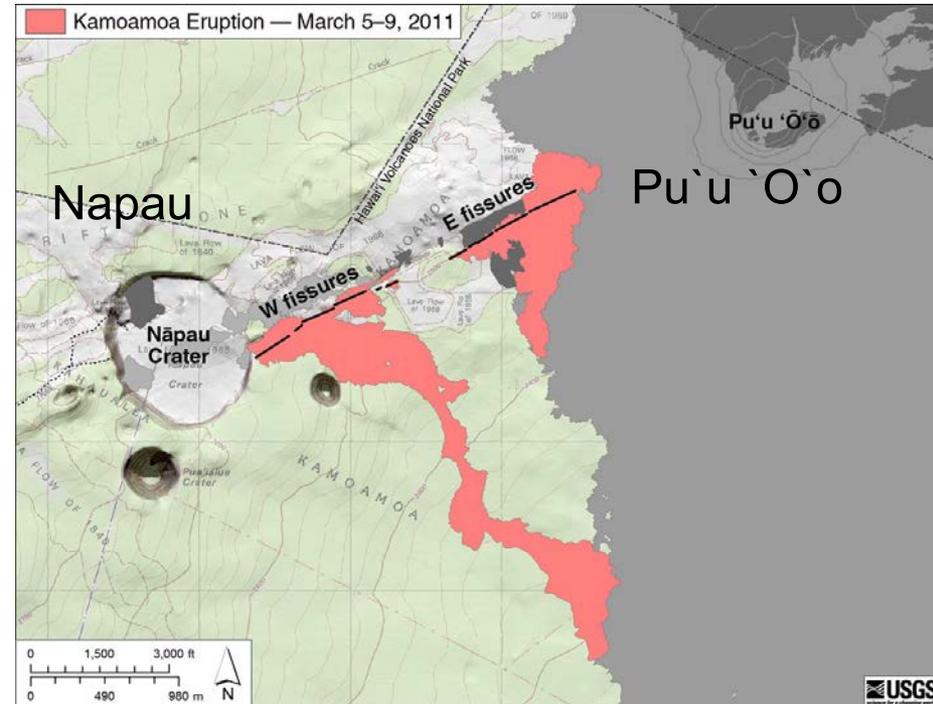
UWE electronic tilt meter



Kilauea summit tilt

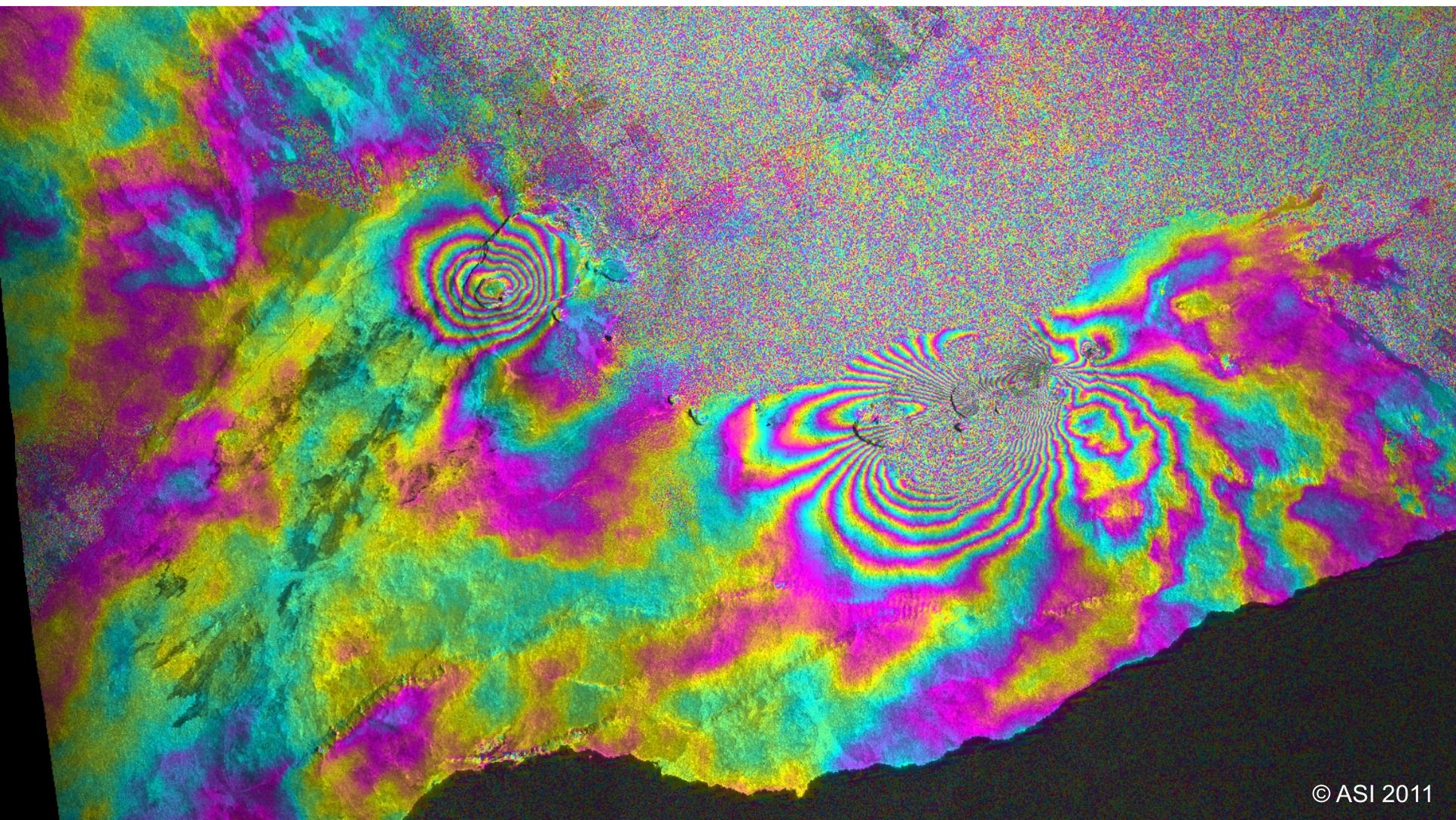
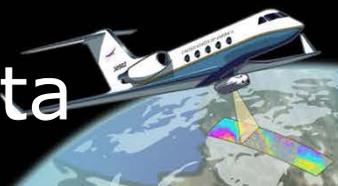


ERZ Fissure eruption



Eruption started late afternoon March 5 (HST) with Pu`u `O`o tilt (deflation) starting 30 min prior to Kilauea tilt (deflation)

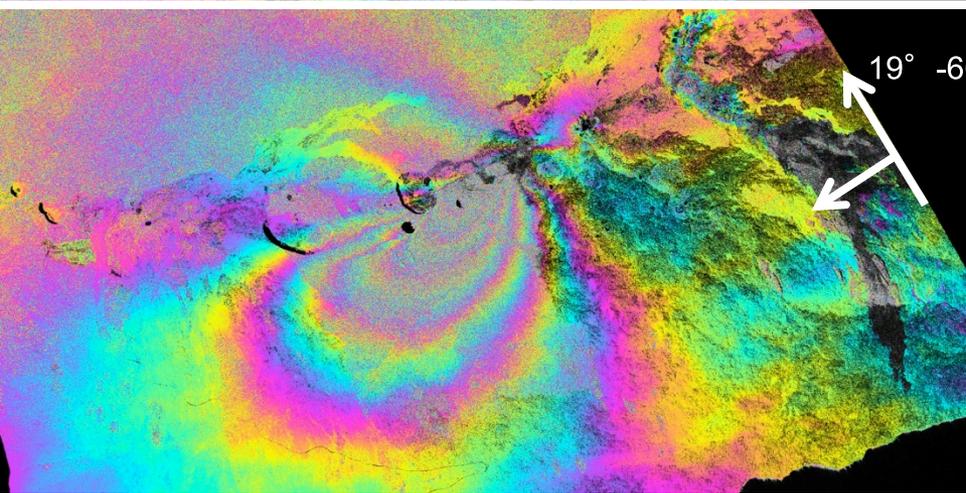
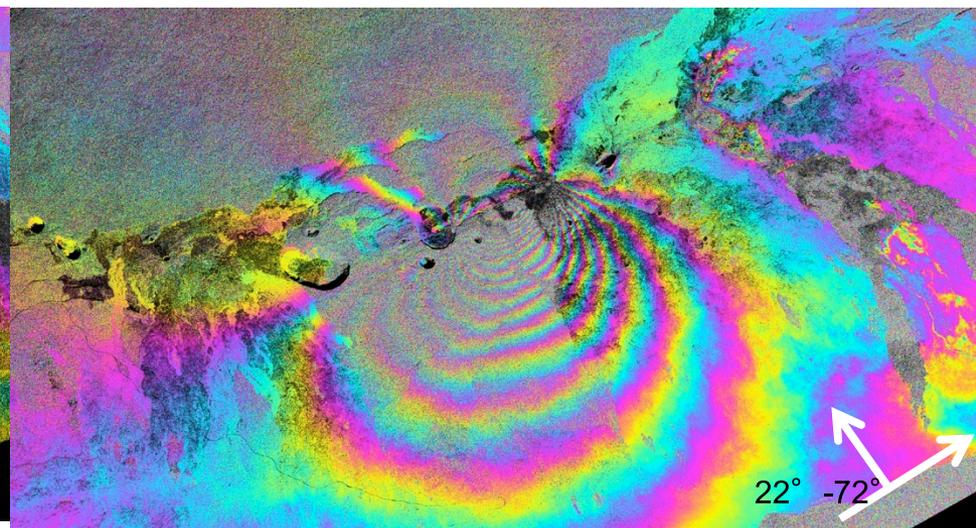
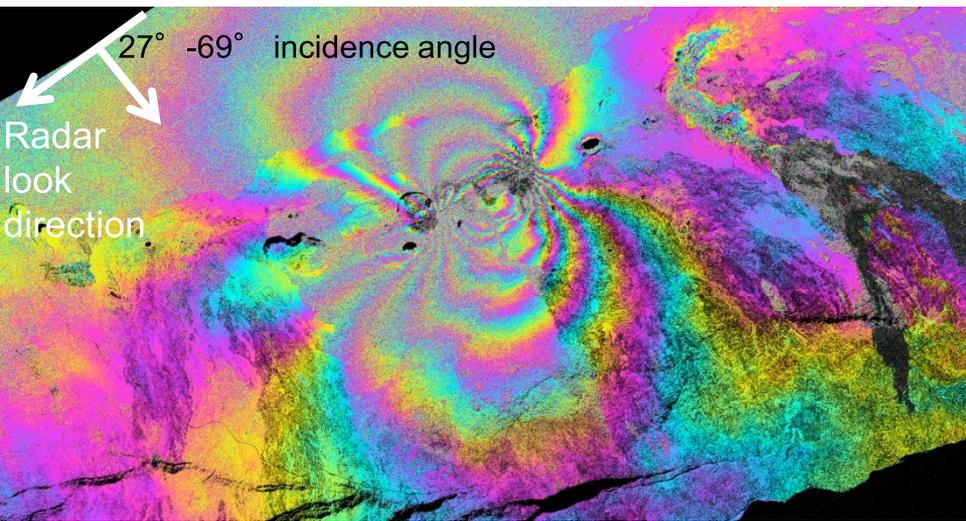
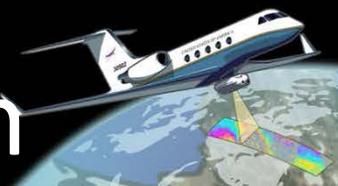
Near-real time COSMO-SkyMed data



© ASI 2011

1st interferogram on March 7, ~12 hrs after acquisition

UAVSAR spanning eruption

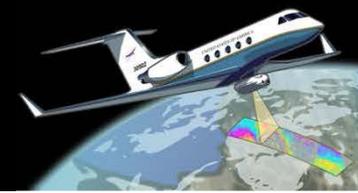


UAVSAR interferograms,
(Jan 2010 – May 2011),
1.4 years, spanning the
March 5-9, 2011 eruption

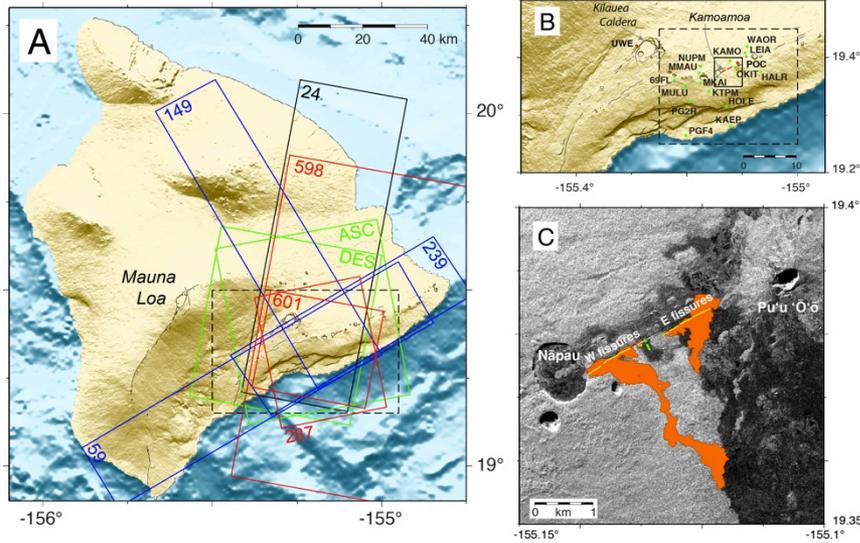
uavsar.jpl.nasa.gov for more info.



The March 2011 Kilauea Fissure Eruption



UAVSAR
Uninhabited Aerial Vehicle Synthetic Aperture Radar



UAVSAR plus satellite InSAR and GPS data were used to constrain the detailed dike opening models and dike volume history shown in the next slide.

Figure 1. Maps of Hawaii, Kilauea Volcano, and the Kamoamoia eruption area. (A) Satellite and airborne SAR processed scenes: in red, ALOS tracks, green, COSMO-SkyMed, black, TerraSAR-X, and blue, UAVSAR. (B) Close-up view of Kilauea, showing GPS sites (green dots), tilt meter sites (red dots), and the Kamoamoia fissures (red lines). Dashed box shows the interferogram area and the smaller solid box is the area shown in (C). (C) Close-up view of the fissures and lava flows.

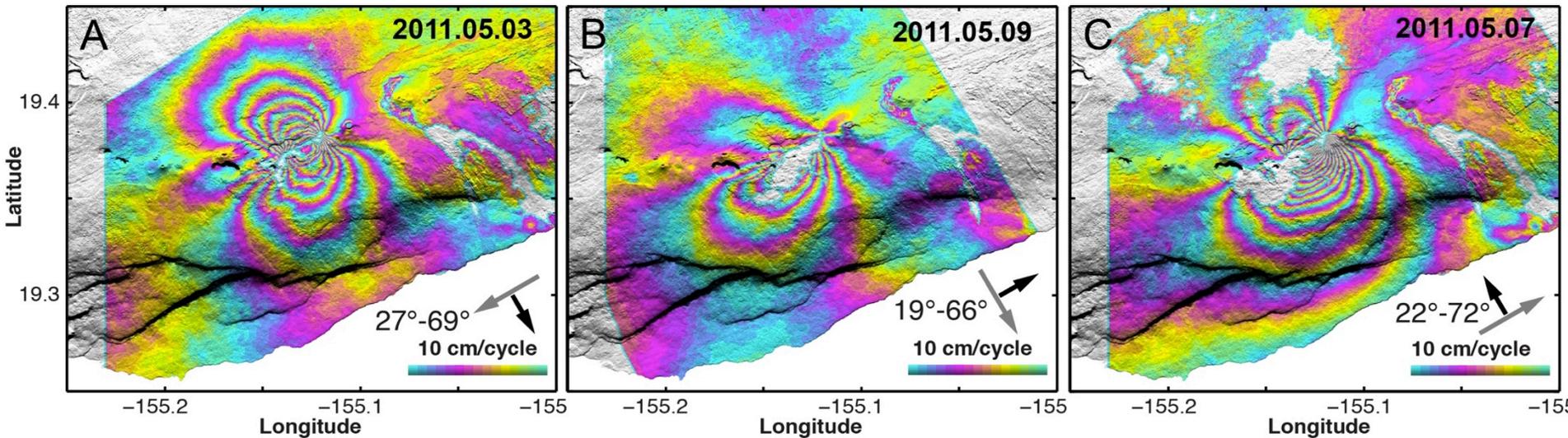
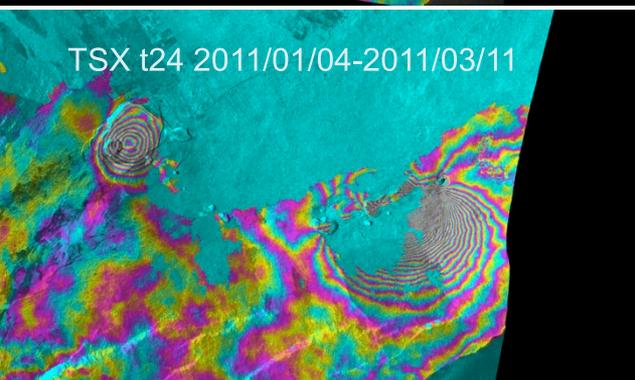
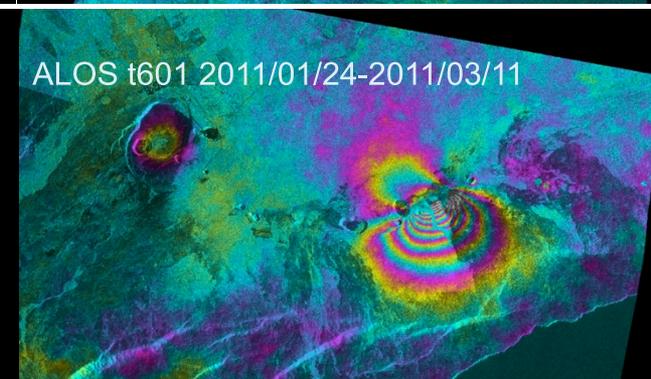
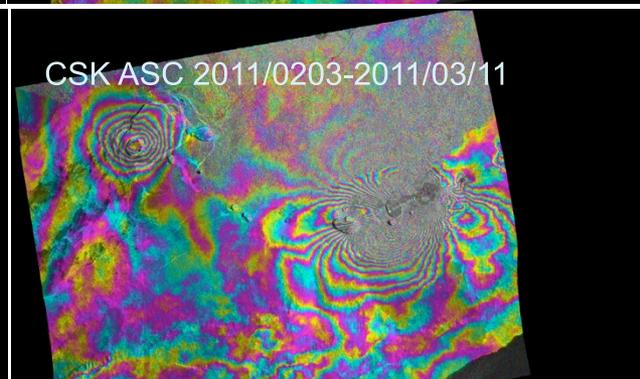
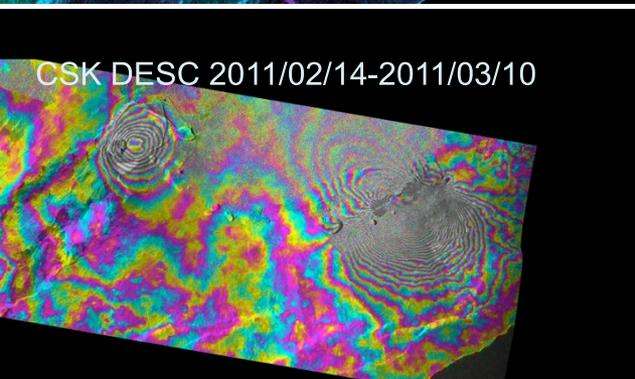
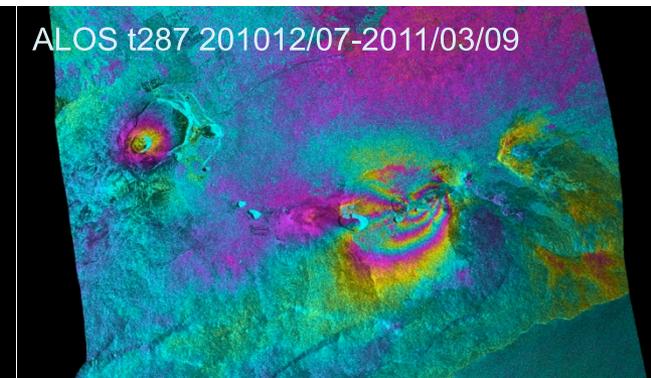
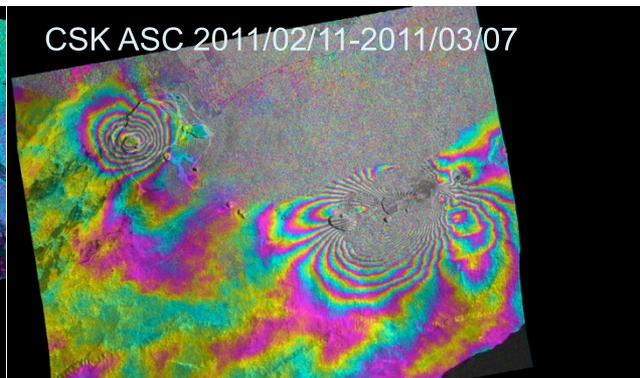
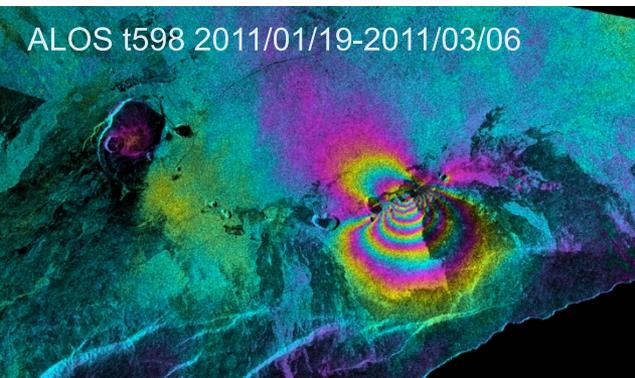
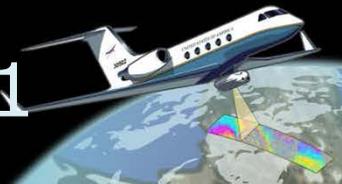


Figure 2. UAVSAR interferograms for the dashed box area in Fig. 1B. Each interferogram is from a different viewing directions as indicated by the aircraft heading (gray) and look direction (black) arrows and their near to far range ground incidence angles.

Interferograms ending March 6-11



L-band (ALOS) better coherence vs X-band
(but higher noise over bare rock)

Unwrapped interferograms: 12 cm/cycle ALOS; 1.5 cm/cycle TSX and CSK



UAVSAR
Uninhabited Aerial Vehicle Synthetic Aperture Radar

The March 2011 Kilauea Fissure Eruption

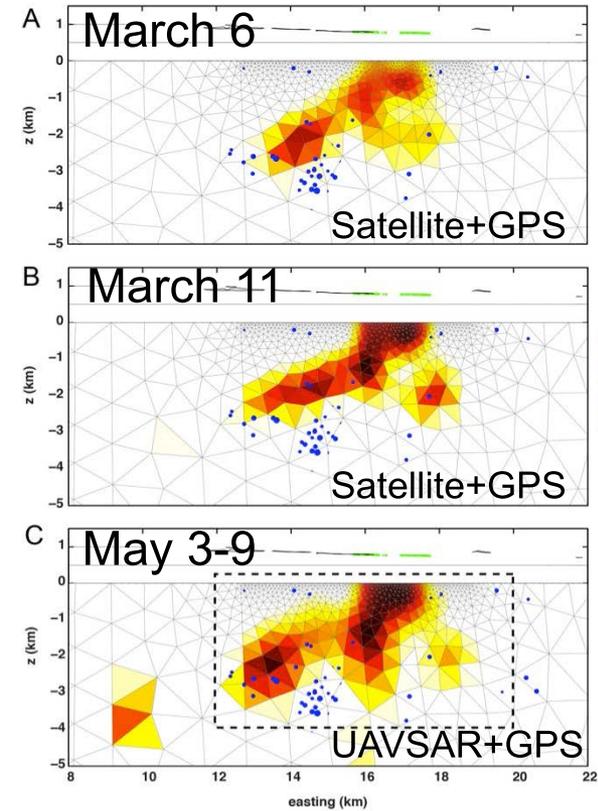
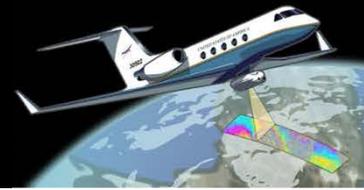


Figure 3. InSAR + GPS constrained model side views of dike opening for three dates: March 6, within 24 hours of the eruption start (ALOS); March 11, after the end of the eruption (ALOS, CSK, TSX); and early May (UAVSAR). The models show growth in amount of opening and area and suggest the dike was fed from its deeper limb plunging to the left and a shallower limb to the right.

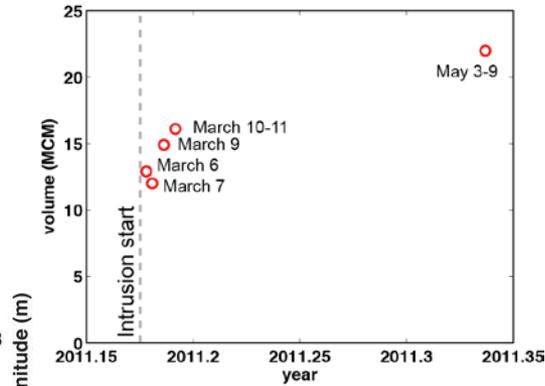


Figure 4. Dike volume increase as a function of time for the dates with InSAR data and models. Following the end of the eruption (March 9) there was continued dike volume increase as shown by the March 10-11 model and the UAVSAR constrained May models.

Dike models give a detailed view of the dike complexity and details that help explain the simultaneous feeding of the dike from sources beneath both Kīlauea Caldera and Pu‘u ‘Ō‘ō.

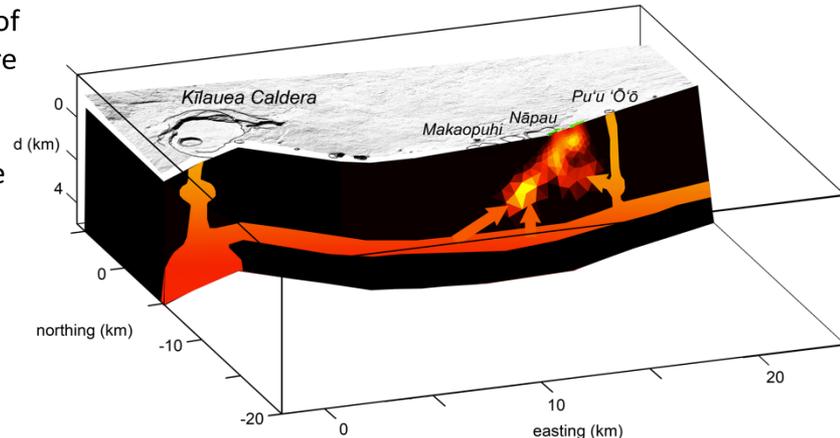
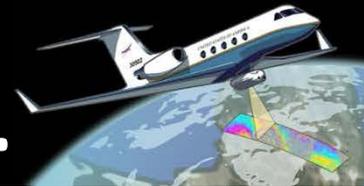
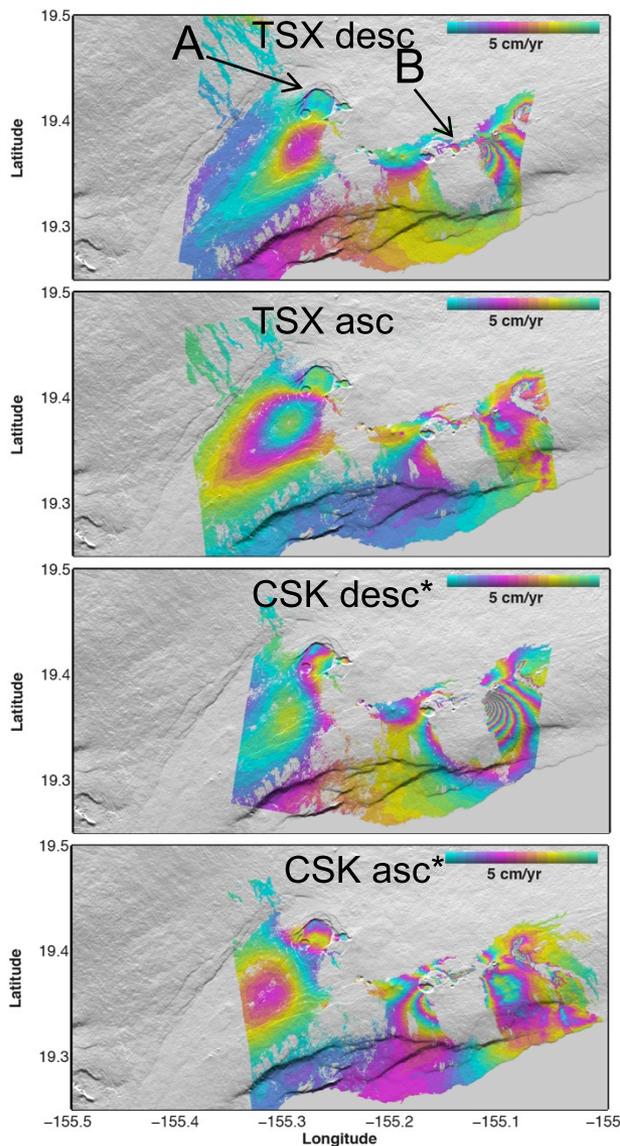
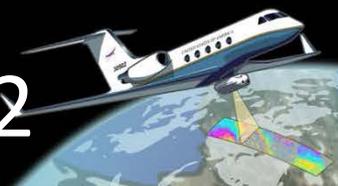


Figure 5. Conceptual model for the Kīlauea magmatic system related to the summit caldera source, the Pu‘u ‘Ō‘ō conduit, and the ERZ conduit thought to exist below 3 km depth. Model for March 6 is shown, red arrows show our interpretation of magma feeding the dike intrusion from the ERZ conduit from the up-rift limb of the dike and from the Pu‘u ‘Ō‘ō conduit in the down-rift direction.

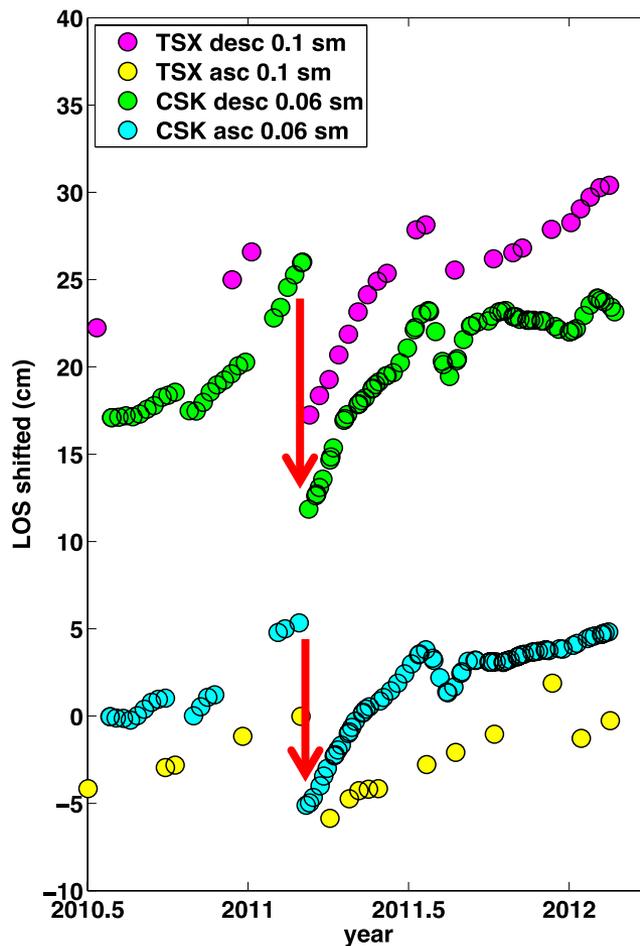
Post-diking deformation...



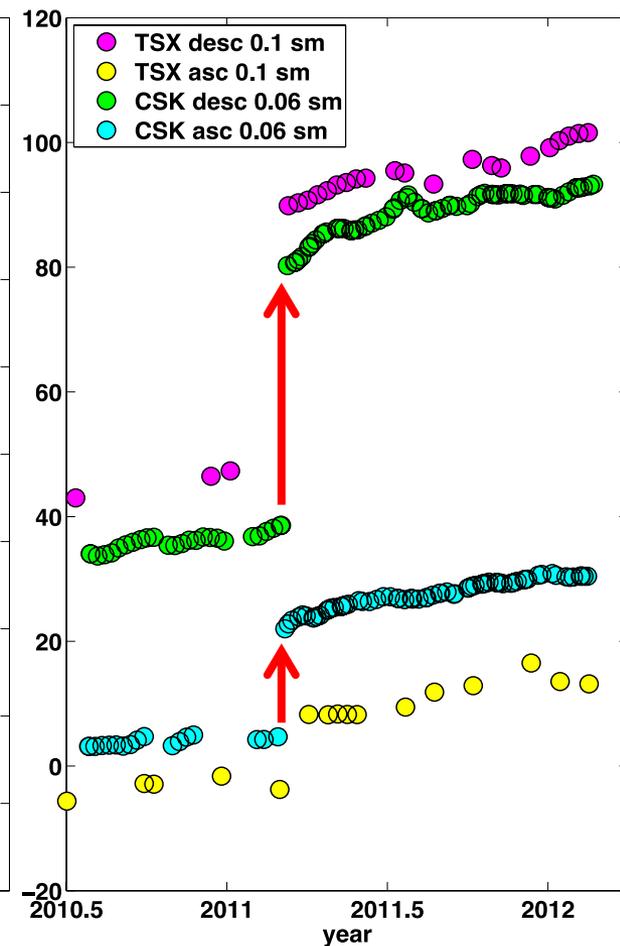
InSAR time series 2010.5 – 2012.2



Kilauea summit (A)

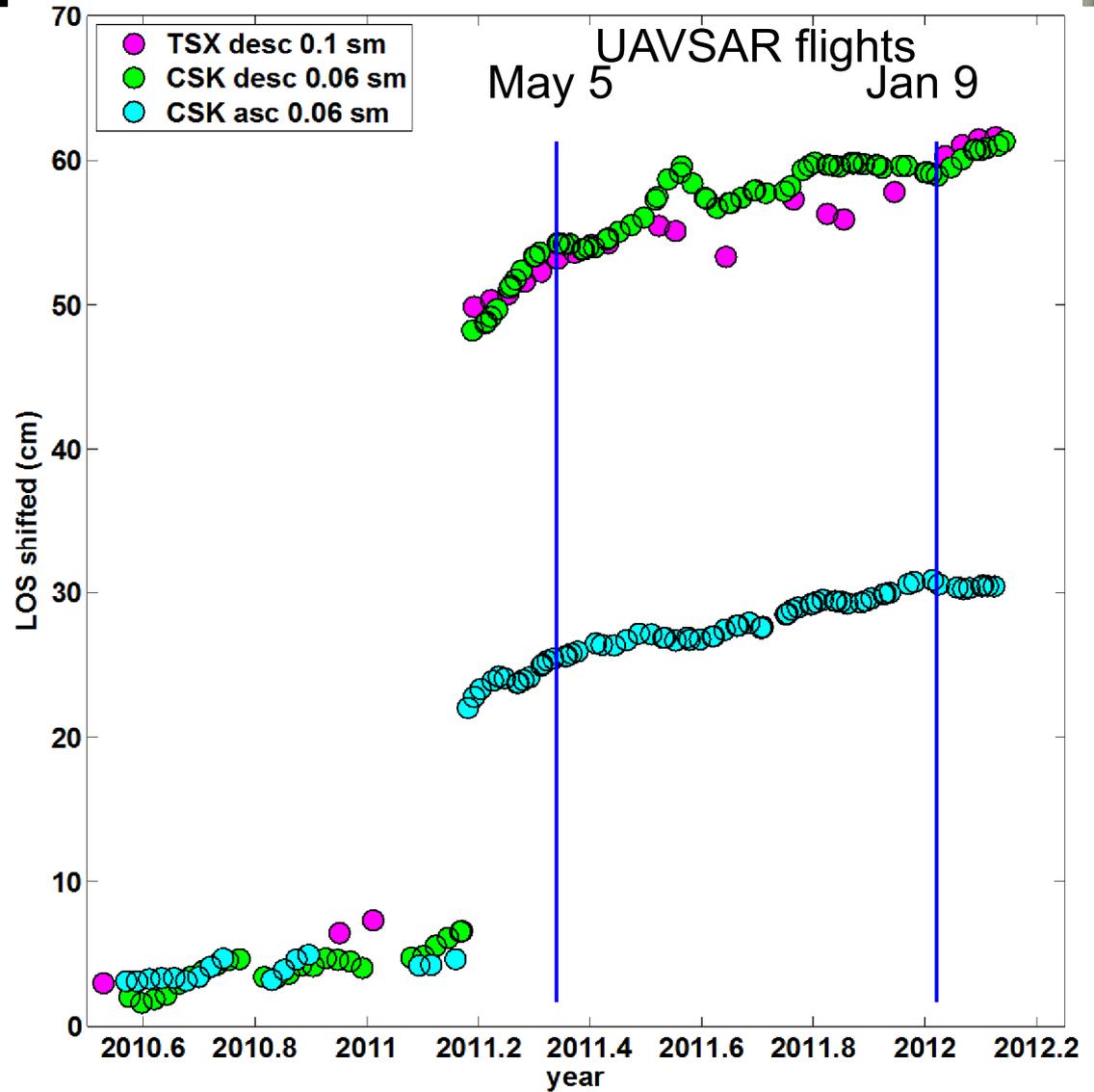
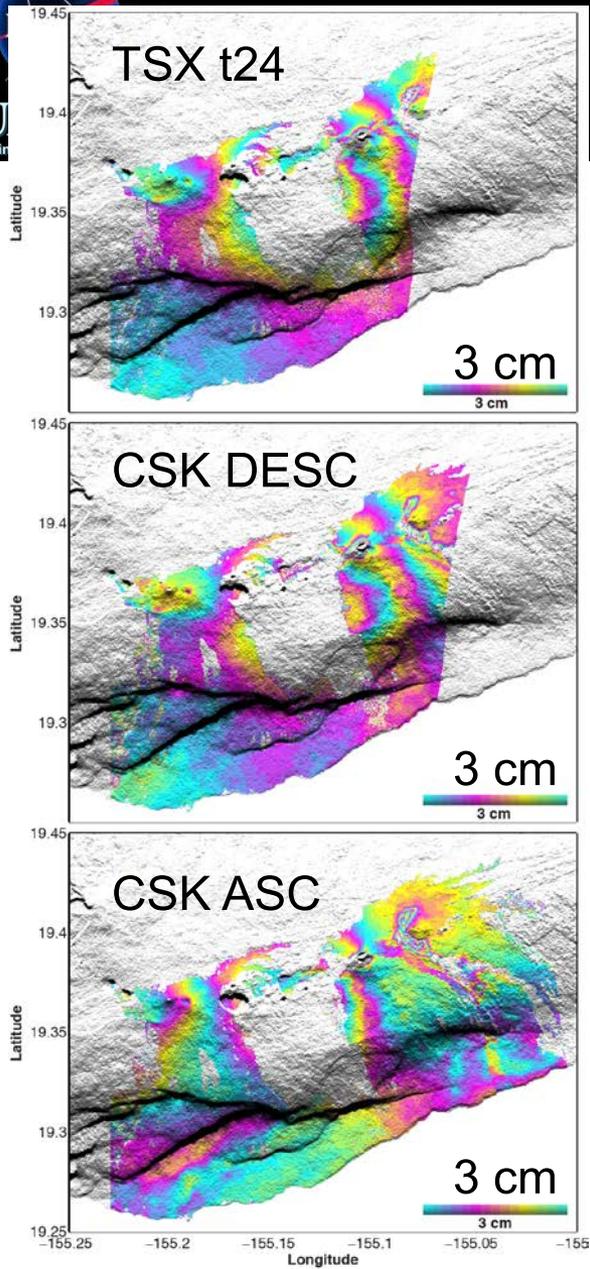


Kamoamoia (B)



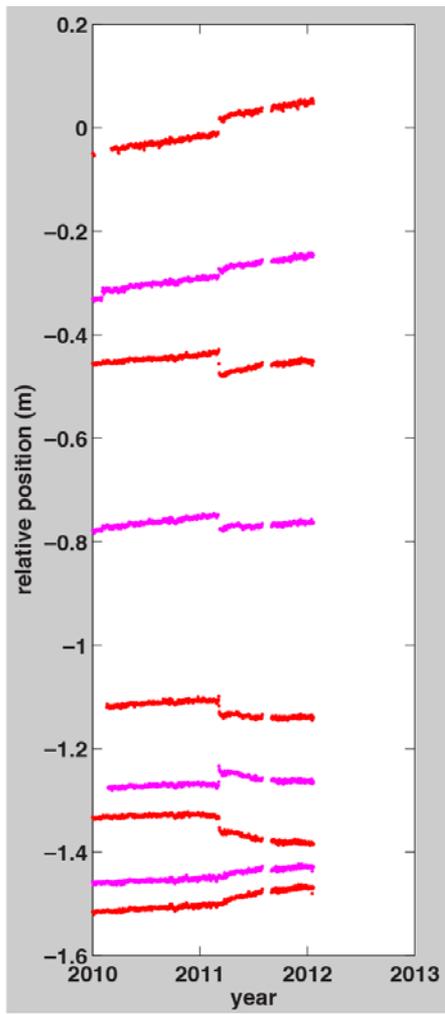
*CSK swaths cut from original width

Post-diking deformation from InSAR time series

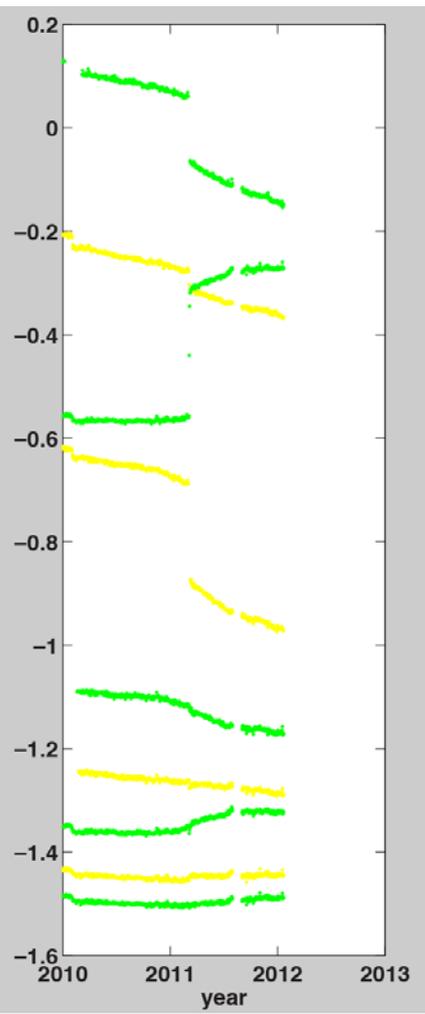




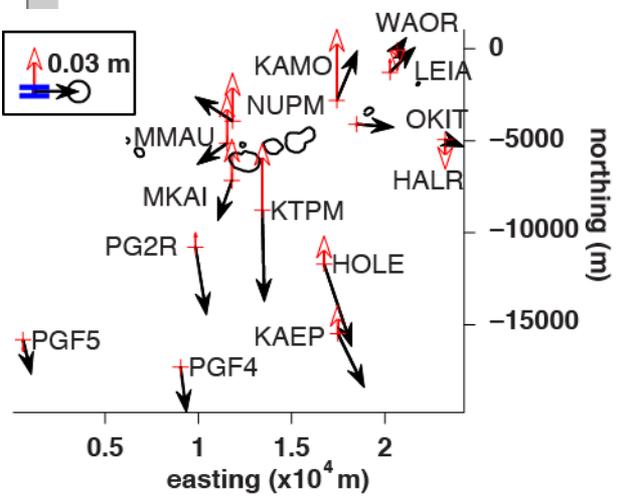
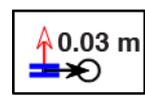
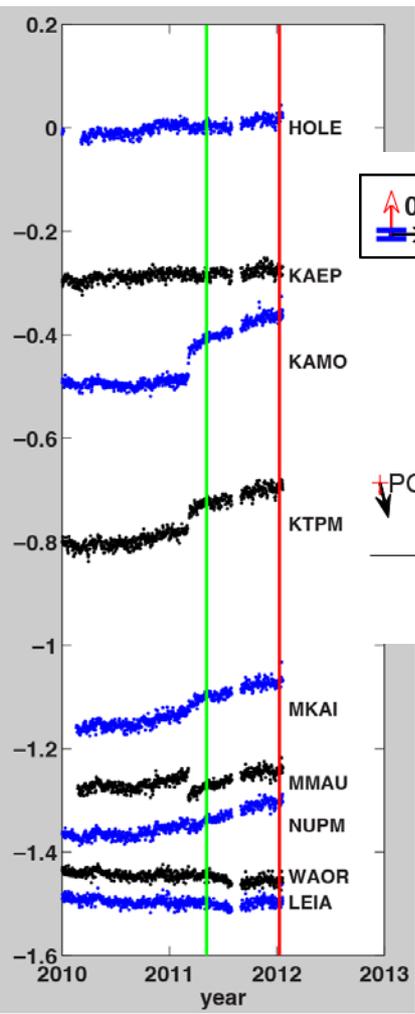
East



North

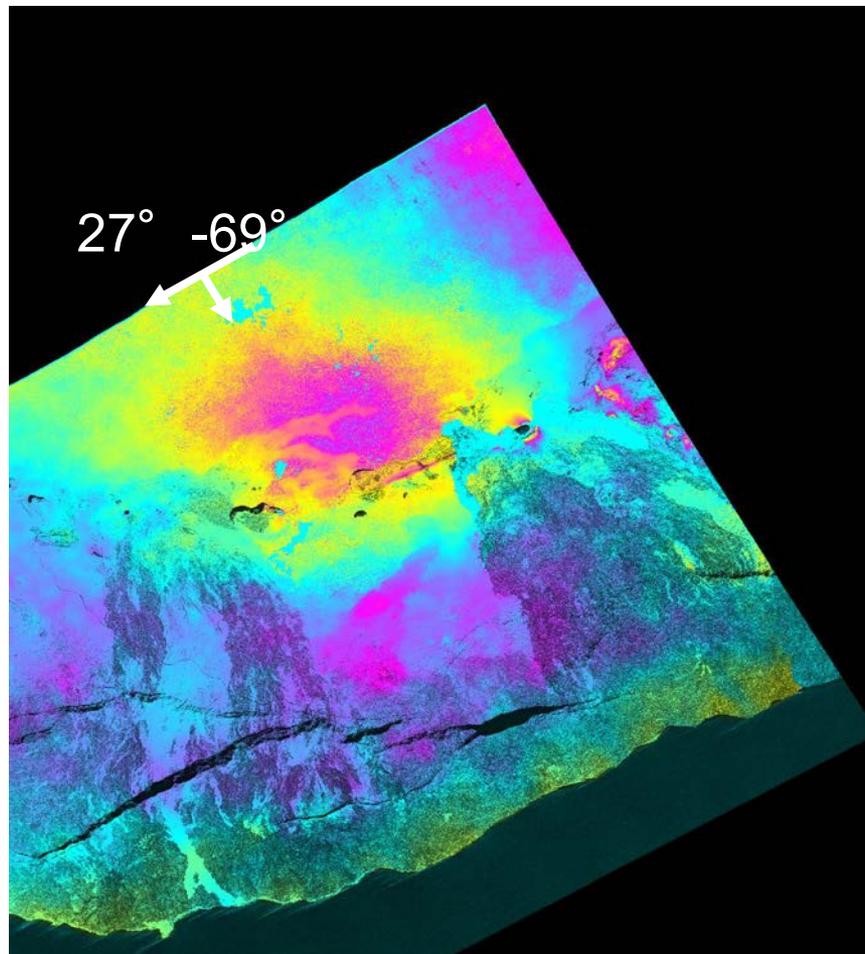
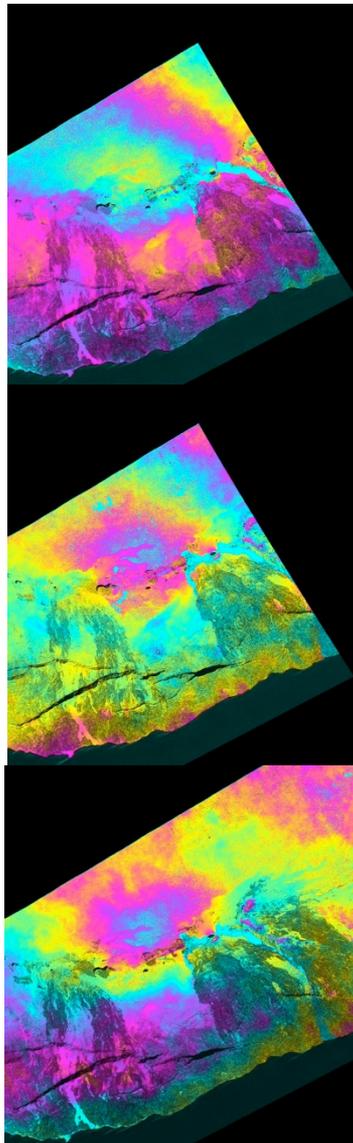
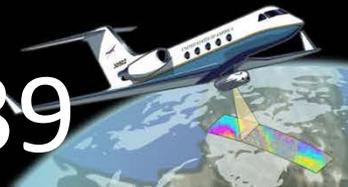


Up



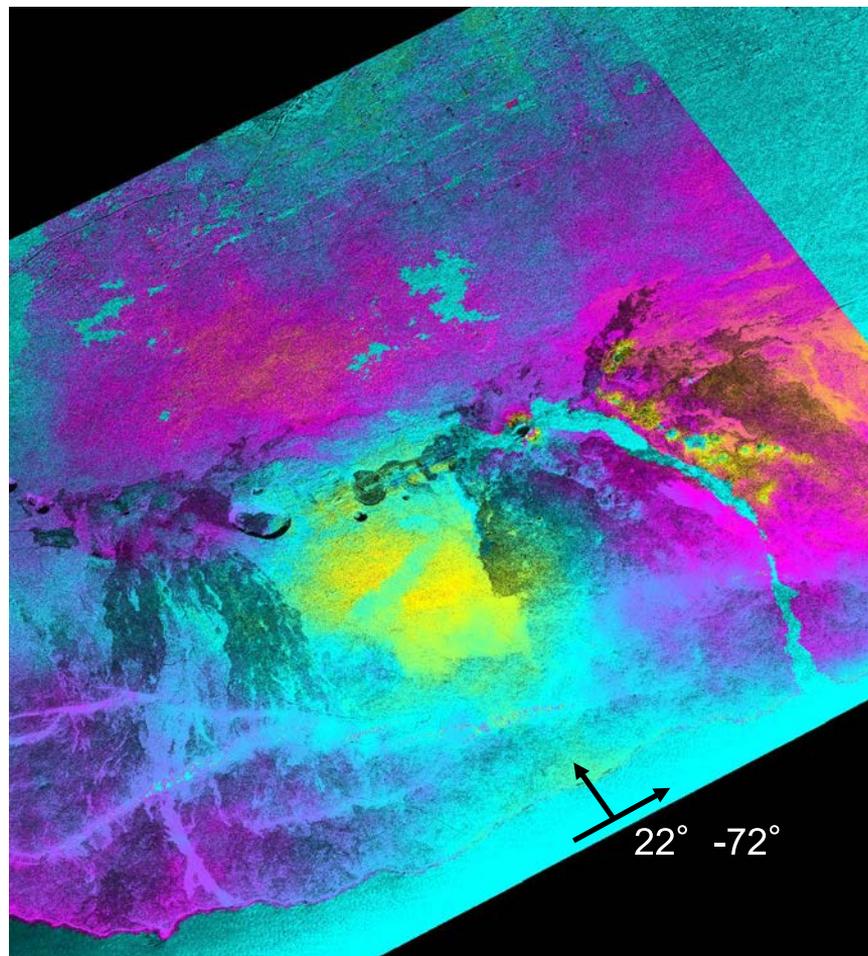
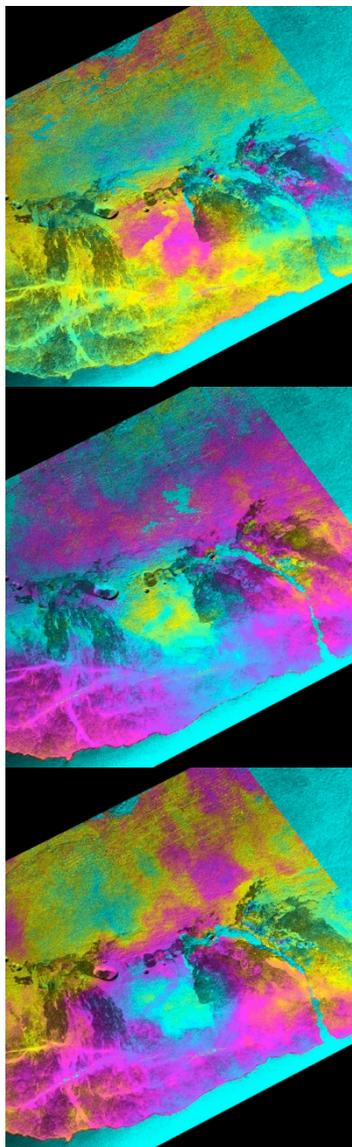
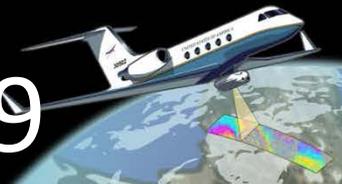
UAVSAR flight dates shown by green/red lines through U time series. TS shown for only a subset of GPS sites on map.

UAVSAR post-diking: line 239



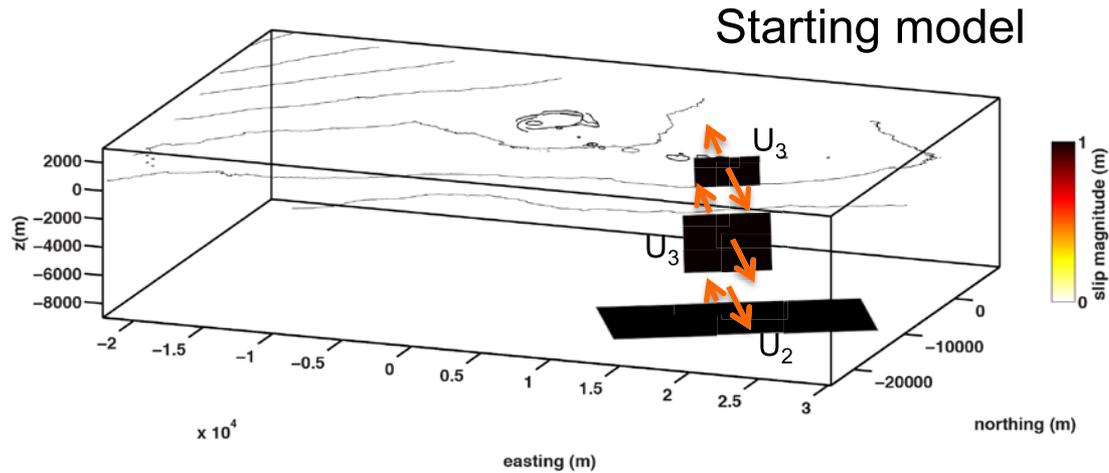
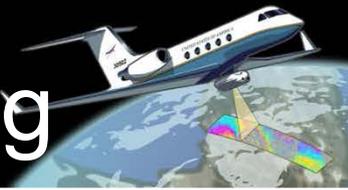
(right) Three independent interferograms.
(left) stack of the three interferograms

UAVSAR post-diking: line 59



(right) Three independent interferograms.
(left) stack of the three interferograms

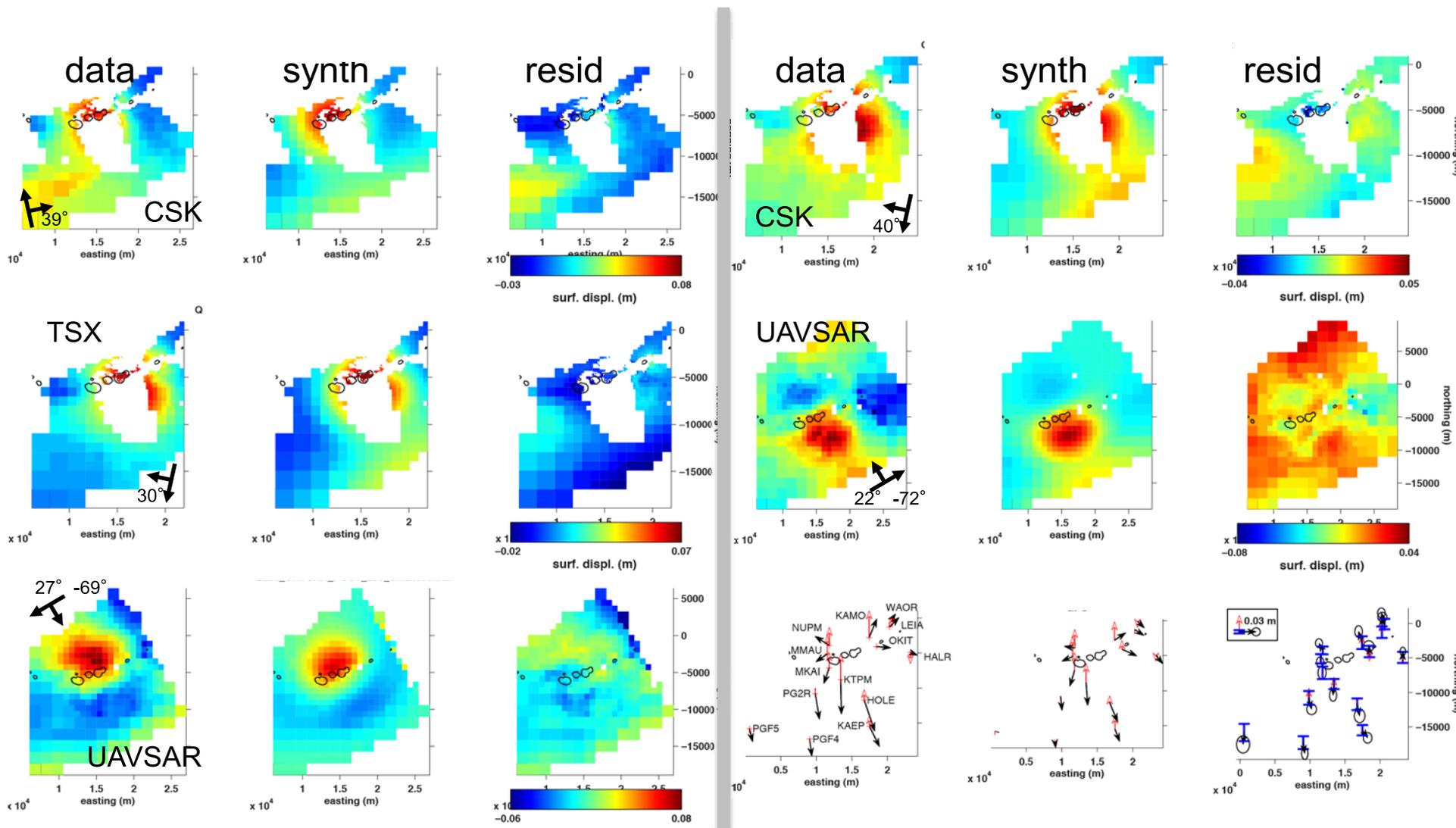
Post-diking MCMC modeling



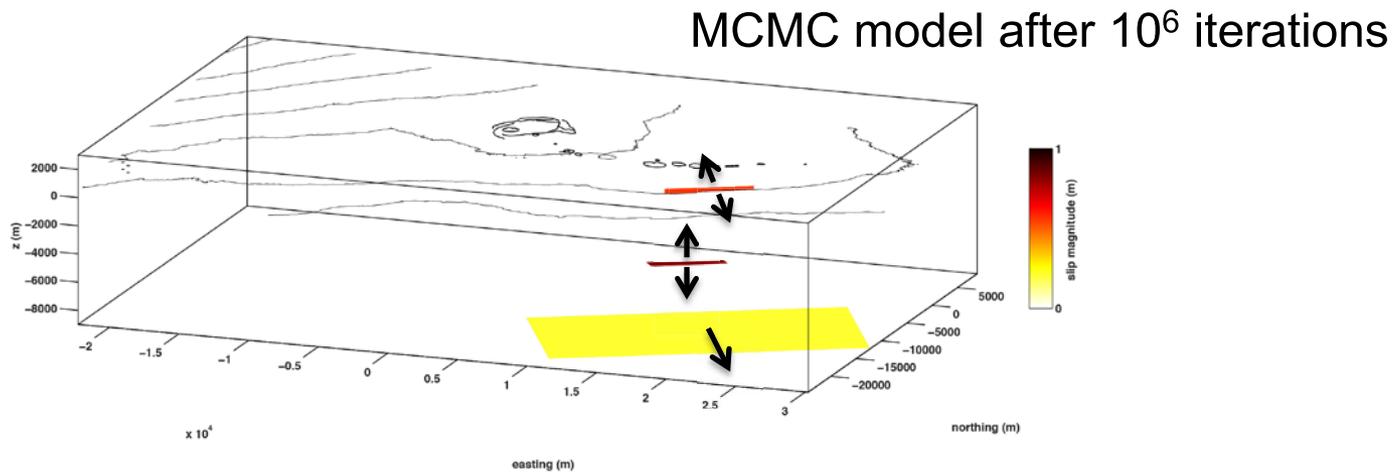
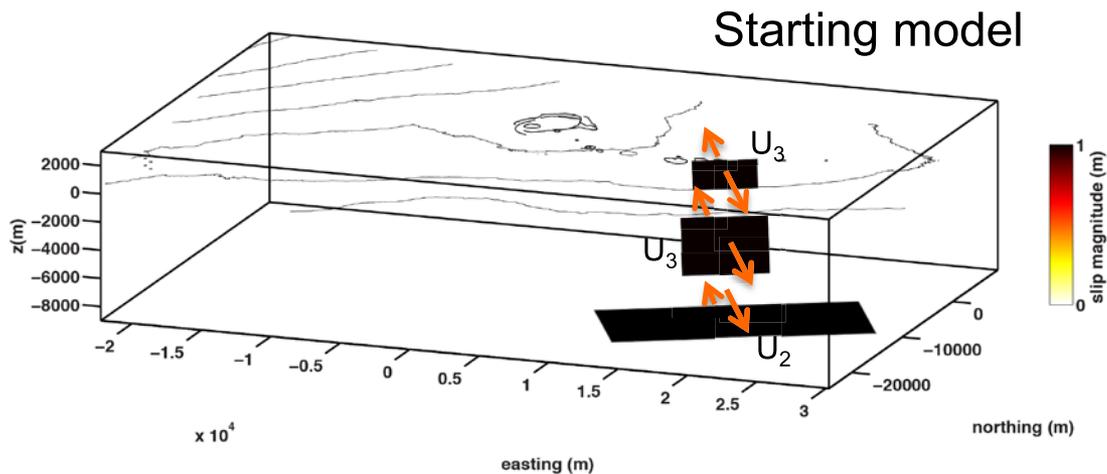
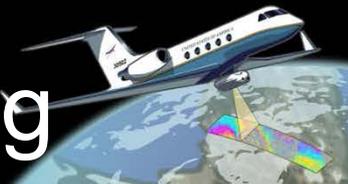
Model set-up was designed to address the type of process observed by Desmarais and Segall (2007):

- near vertical dikes in starting model
- horizontal detachment fault

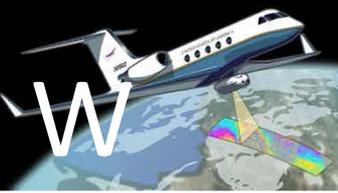
Post-diking TSX, CSK, UAVSAR, GPS



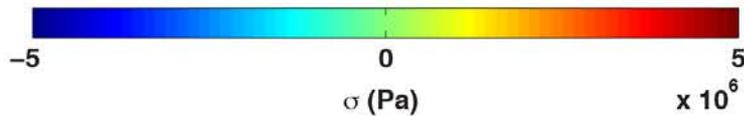
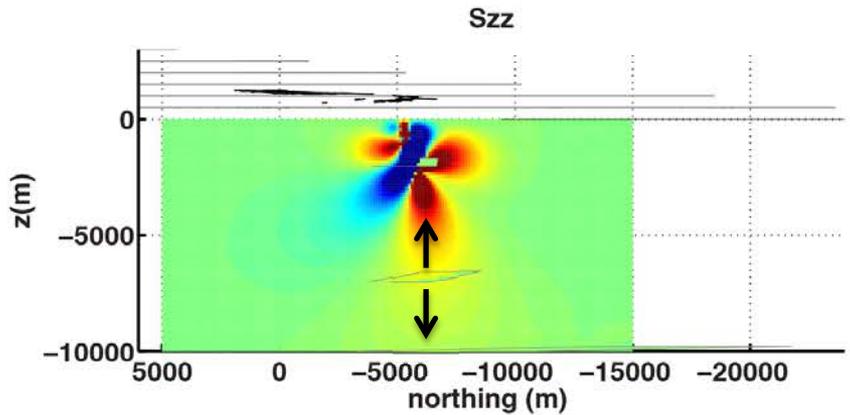
Post-diking MCMC modeling



Co-eruption $\Delta\sigma$ viewed from W

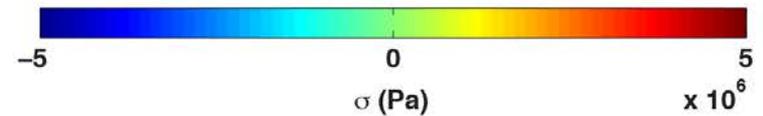
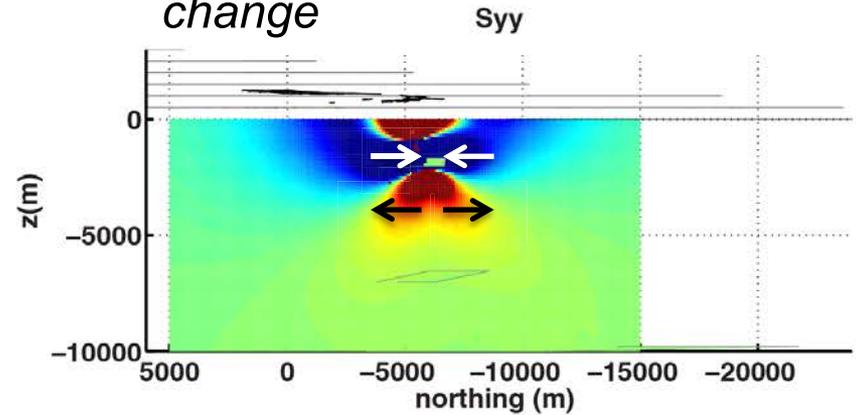


Sill opening promoted



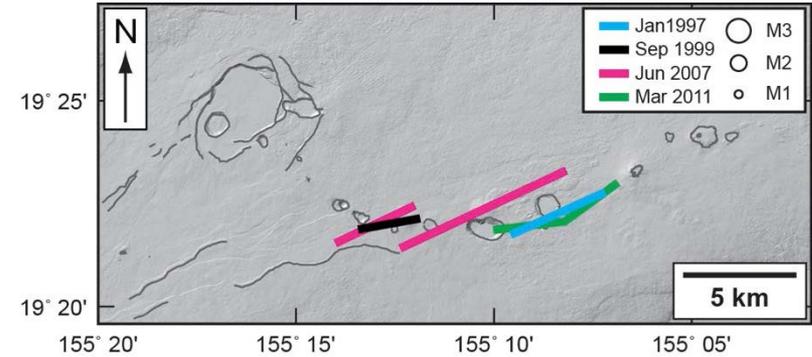
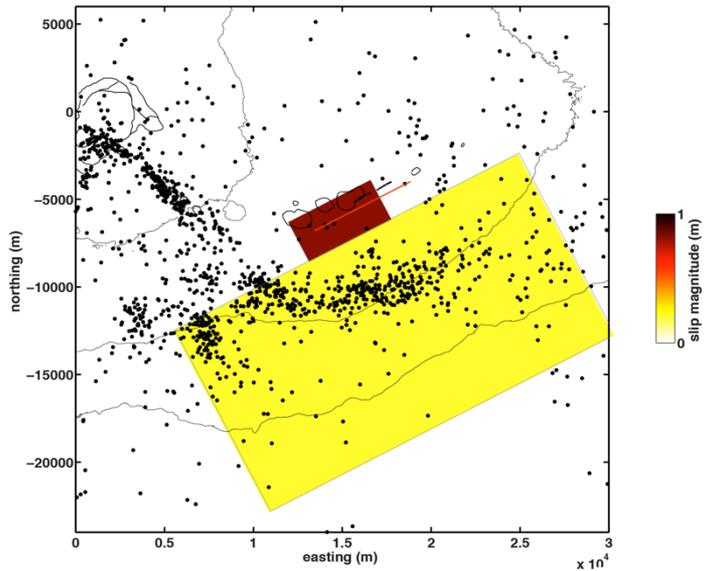
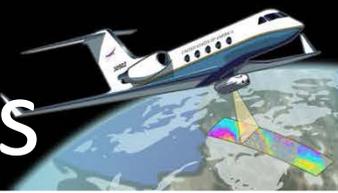
Positive S_{zz} promotes opening of horizontal sills

Shallow dike opening inhibited, but in area of complex stress change



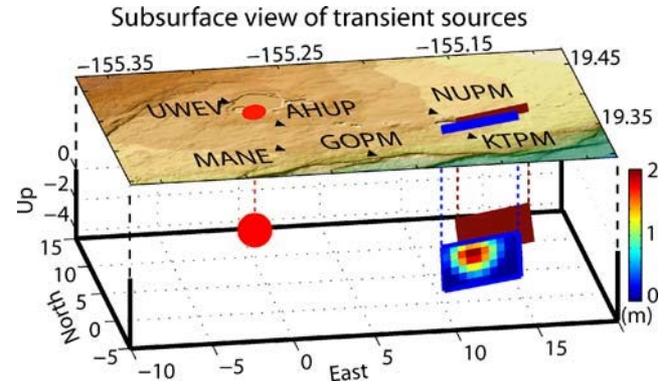
Positive S_{yy} promotes opening of vertical dikes

Comparison with past dikes



Surface traces of recent dikes (from M. Poland)

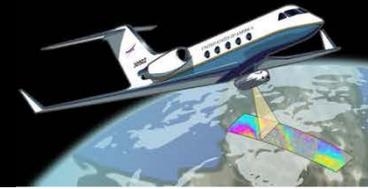
Models of 2011 and 1997 post-diking (Desmarais and Segall, 2007) are quite different, with the latter finding deeper (2-4 km) opening compared to both shallow dike opening and deep sill opening



ed slip modeled in this study

Desmarais and Segall, 2007

Future directions

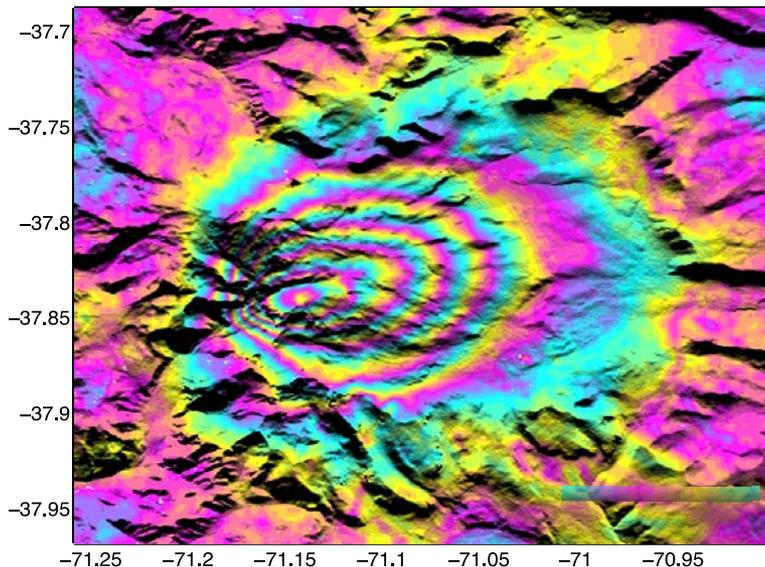


UAVSAR needed for volcano rapid response:

- Need dense temporal sampling when system is most dynamic
- Need for low-latency data
- Need to characterize signals to drive models that will improve forecasts

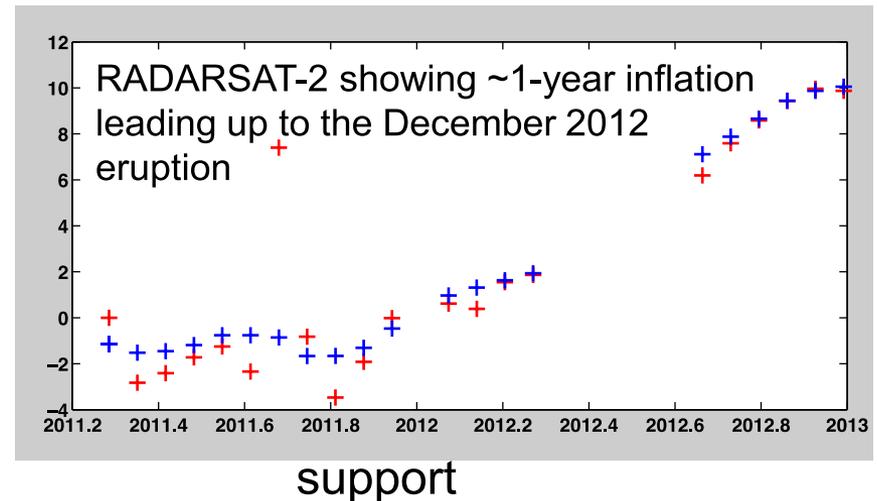
Current efforts in the Pacific “Ring of Fire” are designed to lay the foundation for future volcano eruption response.

Need topographic change for effusive eruptions, including lava domes



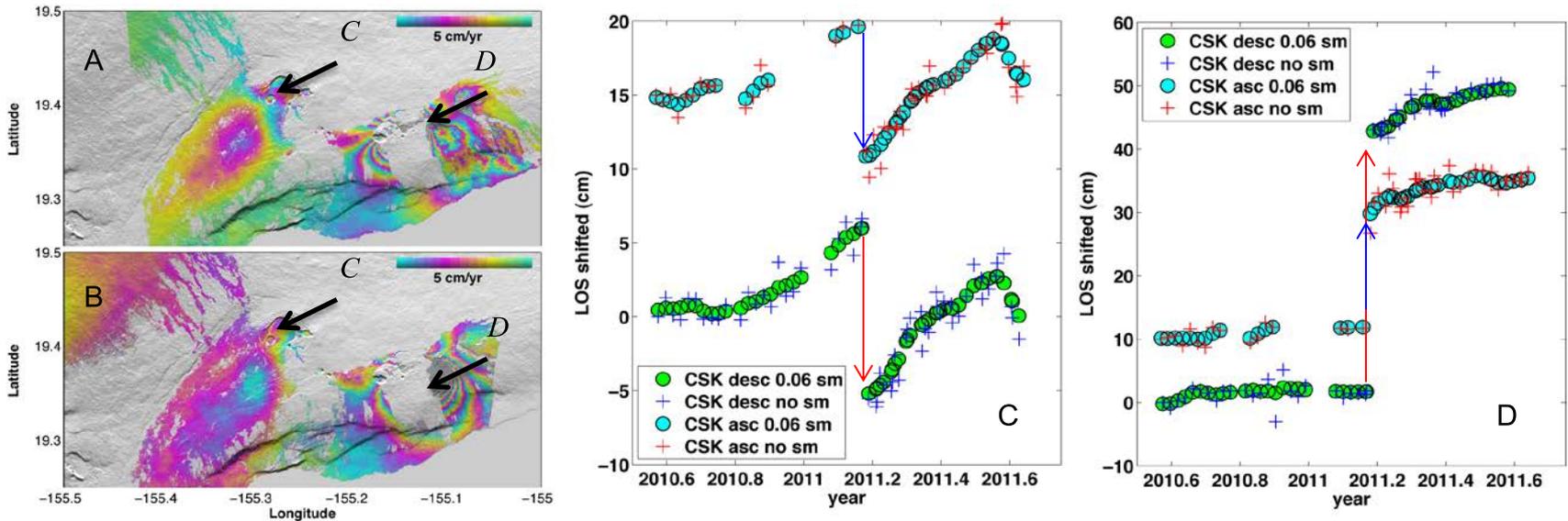
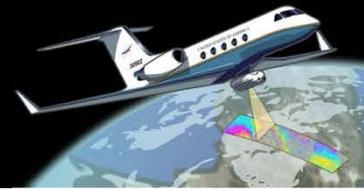
Mean velocity map for smoothed solution. Fringe rate is 2 cm/yr.

Copahue Volcano, Southern Andes



Red + raw InSAR TS for area of peak deformation; blue + smoothed TS.

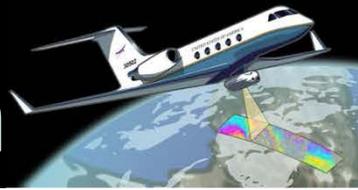
Kilauea: CSK time series



InSAR time series for one year (late July 2010 – August 2011) of COSMO-SkyMed data. (A) Ascending track mean velocity (5 cm/yr color cycle). Arrows indicate approximate locations of time series shown in (C) and (D). (B) Descending track mean velocity. (C) Point time series for Kilauea caldera and (D) for points near the Kamoamo dike eruption. The March 2011 fissure eruption shows sharp deflation at Kilauea until mid-2011, whereas (D) shows post-dike transient. Plus (+) signs are unsmoothed time series, circles are time series with a temporal triangular filter width of 3 weeks. Ascending data time series are shifted relative to the descending data. *A* and *B* in (C) and (D) refer to series from (A) and (B).

Arrows show Kilauea summit deflation and ERZ opening due to March 2011 fissure eruption.

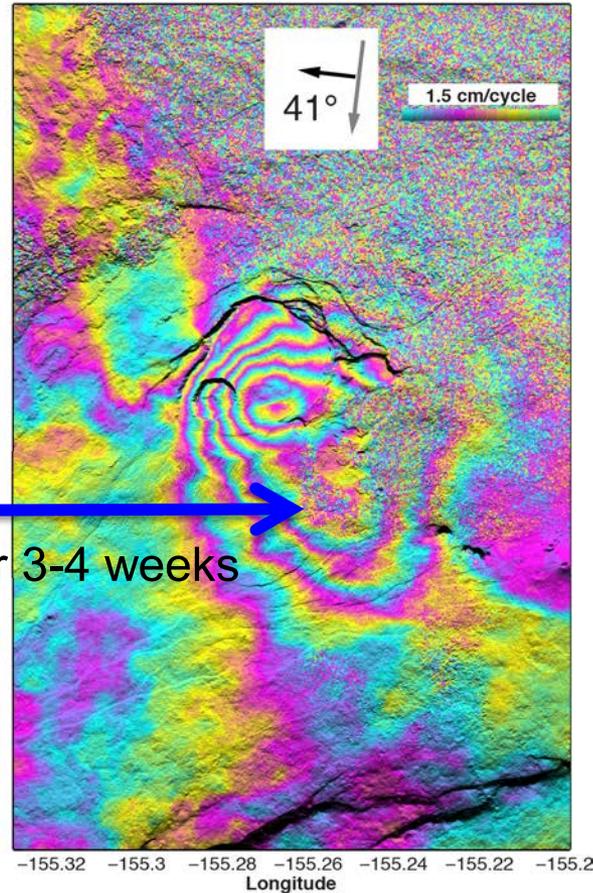
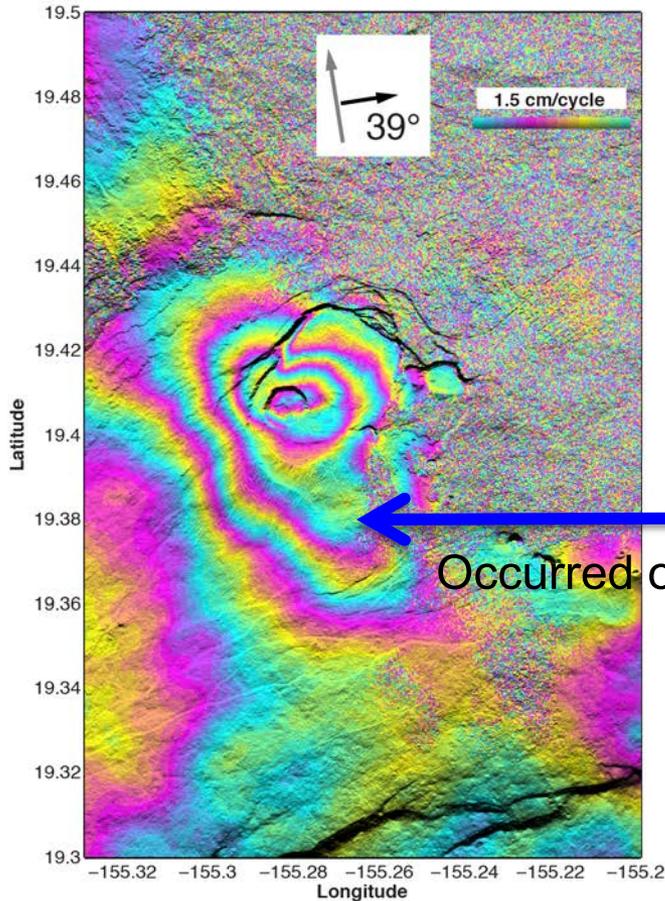
Pre-eruption deformation



COSMO-SkyMed 4-months pre-Kamoamoao eruption

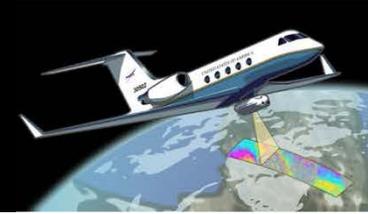
ascending 30/10/2010-27/02/2011

descending 10/11/2010-03/03/2011



Occurred over 3-4 weeks

Precursory deformation south of Kilauea caldera in the 3 weeks prior the Kamoamoao eruption are several fringes at X-band and would only be about half a fringe at L-band.



Summary

- UAVSAR applied to active volcanoes has been successful in constraining dike opening of the 2011 Kamoamoao eruption, Kilauea volcano, Hawaii.
- Post-diking deformation from multiple look directions from UAVSAR are important for constraining deep dike accommodation.
- Local deformation at volcanoes such as Pacaya Volcano, Guatemala, provide important insight into edifice deformation and slope hazard.
- Future repeat observations in Japan and South America expand background observations that will provide the basis for responding to future large eruptions in the Pacific Rim.

Acknowledgement:

Copyright 2013 California Institute of Technology. Government sponsorship acknowledged.