Status Report on the Volcano Pilot

Mike Poland (USGS)
Simona Zoffoli (ASI)

WG Disasters #4
Frascati, Italy
8 -10 September, 2015

Overview

- Overview by Objective
- Pilot Partners
- CEOS Data Commitments and Data Usage 2015
- Achievements to date
- Milestones 2015-2017
- Issues

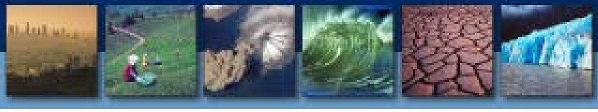
Volcano Pilot

Merapi, Indonesia, erupting in 2010. From Pallister and others, 2013

WHY?

- **Over 300,000 people have been killed by volcanoes since the 1600s.**
- **Hundreds of millions live within 20 km of an active volcano today.**
- **In 2010, the Eyjafjallajökull eruption brought losses of $200m/day, and 100,000 cancelled flights.**

Volcano Pilot

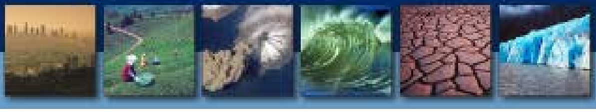


Bardarbunga, Iceland, erupting in 2014.
Photo credit: M Parks

WHAT IS MISSING?

- **Only ~10% of the ~1500 active volcanoes in the world are being monitored in some way**
- **Current EO data collection is not coordinated for volcano monitoring**
- **Need systematic observations before, during, and after volcanic events**

Objectives of the Pilot



Objective A – Regional Demonstration

Demonstrate the feasibility of global volcano monitoring of Holocene volcanoes by undertaking regional monitoring of volcanic arcs in Latin America, stretching from Mexico to southern Chile, and including the Lesser Antilles, using satellite EO data to track deformation as well as gas, ash, and thermal emissions.

Objective B – Geohazard Supersites and Natural Laboratories

Multi-disciplinary, multi-platform monitoring of a few volcanoes that represent a diverse cross section of eruptive activity and unrest.

Objective C – Significant Global Event

Specific studies in case of a major eruption with significant regional or global impact, providing data for a comprehensive analysis of all aspects of the eruption cycle, including local (e.g., mass flows on the volcanic slopes), regional (e.g., ash emissions that may be hazardous to aircrafts), and global (e.g., volatile and aerosol emissions that may influence climate) impacts.

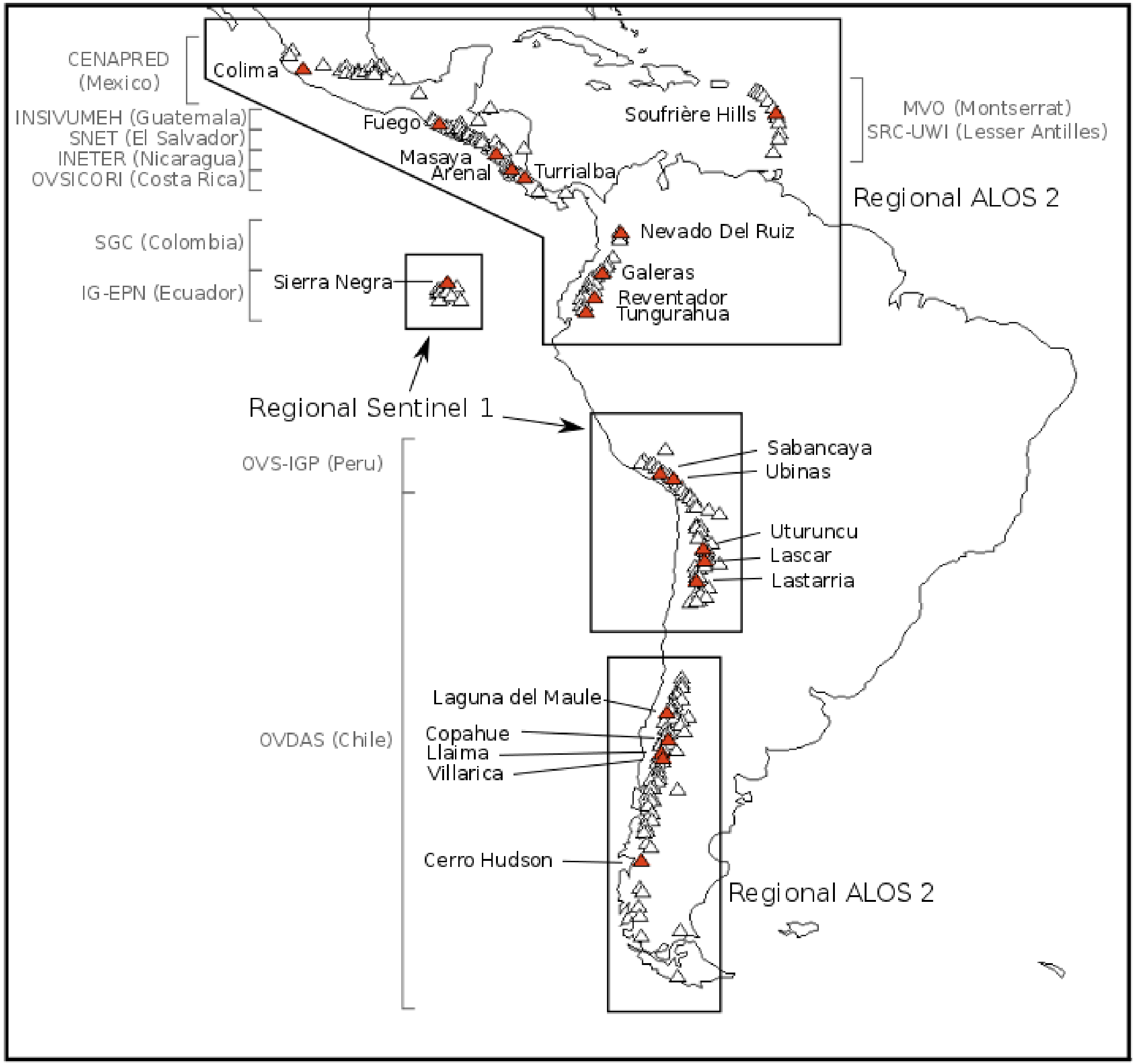
CEOS
WG Disasters #4
Frascati, Italy
8-10 September, 2015

Objective A: Regional demo

- demonstrate how EO data can be used to cost-effectively monitor all 315 volcanoes in the region that erupted in the last 10,000 years
- identify volcano that may became active
- track eruptive activity

Why Latin America?

- Diversity of environments
- Abundant volcanic activity
- Benefits to local users



Participants in the Pilot

CEOS partners:

USGS, ASI, CNES, CSA, DLR, ESA, NASA, NOAA, JAXA

Other partners:

University of Bristol (UK), Cornell University (US), University of Miami, Pennsylvania State University, British Geological Survey, Italian National Research Council (IREA –CNR), Open University (UK), University of Iceland, INGV, Volcano Observatories (several with confirmed interest in Latin America), VAACs (Buenos Aires and Washington), VDAP, Civil Protection Agencies.

Research Consortia:

IAVCEI, STREVA (University of Bristol), Global Volcano Model (BGS), WOVO, VHUB, COMET+(University of Leeds), ALVO

Pilot Outcomes by Partner

Objective	Outcome	Value Added Partner
A	Identification of volcanoes that are in a state of unrest in Northern Andes and Lesser Antilles	University of Bristol
A	Identification of volcanoes that are in a state of unrest in Southern and Austral Andes	Cornell University
A	Identification of volcanoes that are in a state of unrest in the Galapagos	IREA/CNR
A	Identification of volcanoes that are in a state of unrest in Mexico	University of Miami
A	Identification of volcanoes that are in a state of unrest in Central America	Pennsylvania State University
A	Validation of EO-based methodology for improved monitoring of surface deformation	All
A	Capacity-building and training activities in countries that do not currently have access to abundant EO data and/or the ability to process and interpret such data	Bristol
A	Collect feedbacks form users	All

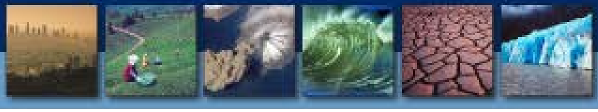
Pilot Outcomes by Partner

Objective	Outcome	Value Added Partner
B	Interferograms and models of earthquake and magmatic deformation on Supersites	USGS/University of Iceland/INGV
C	Thermal monitoring of November-December 2014 eruption of Pico do Fogo, Cape Verde	Open University
C	Response to major eruptive event	All
ALL	Global observation EO strategy for volcanoes	All

User Communities:

- SERNAGEOMIN, Observatorio Volcanológico de Los Andes del Sur (OVDAS) Chile;
- Observatorio San Calixto, Bolivia;
- Instituto Geofísico del Perú;
- Instituto Geofísico de la Universidad Nacional de San Agustín, Peru;
- Instituto Geofísico, Escuela Politécnica Nacional, Ecuador;
- Servicio Geológico Colombiano, Colombia
- Buenos Aires Volcanic Ash Advisory Center, Argentina
- Instituto nacional de sismología, vulcanologia, meteorología e hidrologia, (NSIVUMEH), Guatemala
- Instituto Nicaraguense de Estudios Territoriales (INETER), Nicaragua

Interface Users



- Products provided by the Pilot are being used by various government agencies to discover whether unrest at a volcano is related to magma ascent (which may inform installation of ground-based equipment and monitoring levels) and how eruptive activity is impacting the region (including location and hazard of ash plumes).
- The pilot has received numerous informal expressions of thanks and confirmation of the importance of these datasets from local volcano observatories, VAACS, and other government agencies, but during times of crisis there is little time to formulate a formal endorsement and provide feedback.
- Face to face meeting with users in Peru (September) and in Chile (October)
- Questionnaire

User feedbacks

1.Name of your organization and brief statement of mandate.
2.What satellite data were provided to you as part of the CEOS volcano pilot project? How was the data used? (For example, images used in staff meetings, discussions of volcano alert levels, strategies for deploying ground sensors used in making figures for internal or external distribution, etc.)?
3. Were the data useful? If so, please describe in a few lines what level of products was most useful:
(For example, raw data, interferograms, google earth files, a written summary of the significance of the data, etc.).
If not, how could we improve on the use of satellite data for your needs? For example, by sending data in a more timely manner or in a different format.
4. Looking to the future, would your organization like increase the use satellite of observations and what do you think is needed to make that happen?

Data Commitments and Usage

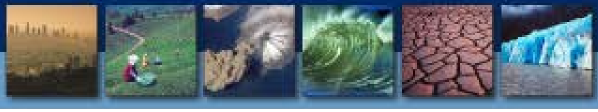
Obj	Mission	Data Ordered/Allocated	Products developed
A	RADARSAT-2	**139/270** SOAR-Geohazard project 5297 Data on :Reventador (Ecuador), Cordón Caulle (Chile), Popo, Santiguito, Turrialba, Pacaya, Llaima A quota extension approved by CSA	Interferograms and models
A	COSMO-SkyMed	**313/900** Data on: Masaya (Nicaragua), Cordon Caulle (Chile), Soufriere Hills (Montserrat), Chiles-Cerro Negro (Ecuador/Colombia), Llaima (Chile), Villarica (Chile), Hudson (Chile), Fuego (Guatemala), Turrialba, (Costa Rica) Cerro Blanco (Argentina), Calbuco (Chile)	Interferograms and models
A	TSX	**26/400**	Interferograms and models
A	ALOS-2	**5/100** Data on Chile and Ecuador	Interferograms and models

*Sentinel-1A data have not been included since those data are distributed at no cost and with no restrictions.

Data Commitments and Usage

Obj	Mission	Data Ordered/Allocated	Products developed
C	**Pleiades**	**3/50** Data on Fogo, Cape Verde	
C	**EO-1 ALI**	**5**	Effusion rate estimates
C	**Landsat -8 OLI**	**2**	Effusion rate estimates

2015 Activities



- We tested the utility of ALOS2 data for regional monitoring. Making interferograms using the wide-swath mode was mostly successful, but requires tweaking before we can order on a large scale
- We completed a data proposal to CEOS for Objective C of the project – monitoring a major eruptive event in a populated area. When we identify such an event, we should be prepared to order data immediately to track not just eruptive activity, but also pre- and post-eruptive changes.
- We completed a data proposal for CSA that was approved and we got RADARSAT-2 data extension
- We increased the team with new participants
- We started using Geohazard Exploitation Platform for data access and sharing between the partners

2015 Activities

- We responded to eruptive activity in Latin America, including at Calbuco (Chile) and Cotopaxi (Ecuador). Products have been distributed to local end users, where they have aided in constraining such variables as erupted volumes and ash emissions.
- We have tracked unrest at several volcanoes in Latin America, including
  - Chiles-Cerro Negro (on the Columbia-Ecuador border), where thousands of earthquakes suggest a reawakening of the system and may have triggered a nearby tectonic earthquak
  - Cordon Caulle (Chile), which is inflating following it's 2011–2012 eruption.

These insights have been provided to local scientists and managers, who have used them to inform their decisions about what is likely to occur at the volcanoes and how they should respond.

2015 Activities

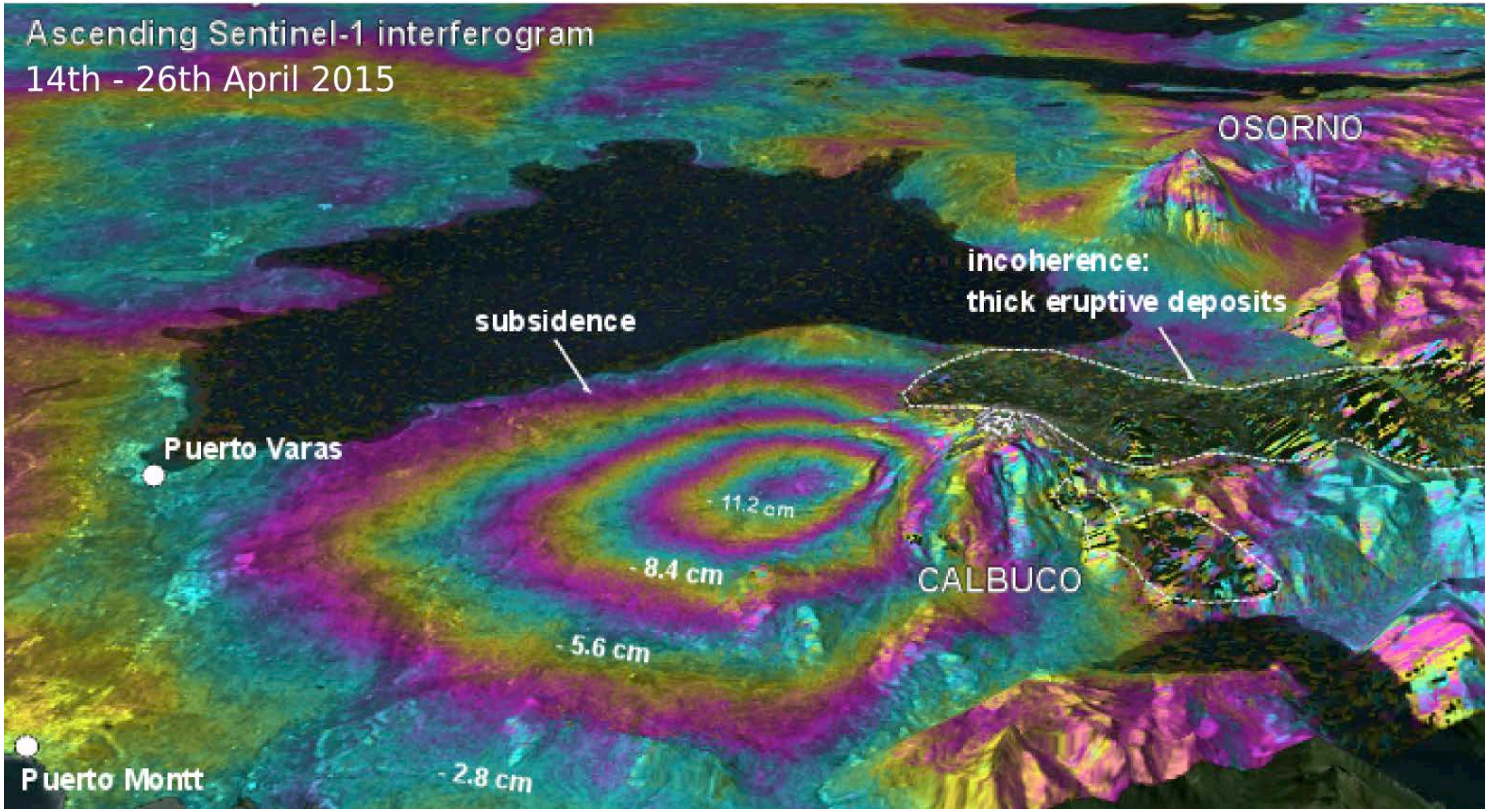
- We continue to support the volcano Supersites.
  - In Hawai‘i, these data were instrumental in mapping deformation associated with a small intrusion at Kīlauea’s summit – the first such event in that area in over 30 years.
  - Following the formation of the Ecuador supersite (for Cotopaxi and Tungurahua volcanoes), we are working with the space agencies to arrange data acquisition and distribution.
- No eruption meeting our criteria has occurred for ObjectiveC, however the potential application of this objective was demonstrated in the remote sensing response to the 2014-2015 eruption of Pico do Fogo, Cape Verde.

Calbuco, Chile

- After 43 years of quiescence, Calbuco, Chile, began erupting on **22 April 2015**, with very little warning.
- The large amount of ash (more than 0.1 km3) had significant impact on air traffic on Chile and Argentina. Several thousand people were evacuated from villages closest to Calbuco .
- Ash was tracked using data from the pilot and was communicated to VAAC in Buenos Aires.
- SAR data from the pilot project were used to characterize co-eruption surface deformation, which helps to constrain the location of the magma body that fed the eruption.
- Other interferograms constrain the deformation to have started no later than 1.5 days before the eruption, and to have lasted no more than 1 day.
- A preliminary model of the deflation indicates that the **source** is located about 5 km SW of the volcano's summit at a depth of 9.3 km beneath the surface, with a volume changes of ~0.045 km^3. This source geometry and strength is consistent with recordings from a tiltmeter located 4 km W of the volcano.

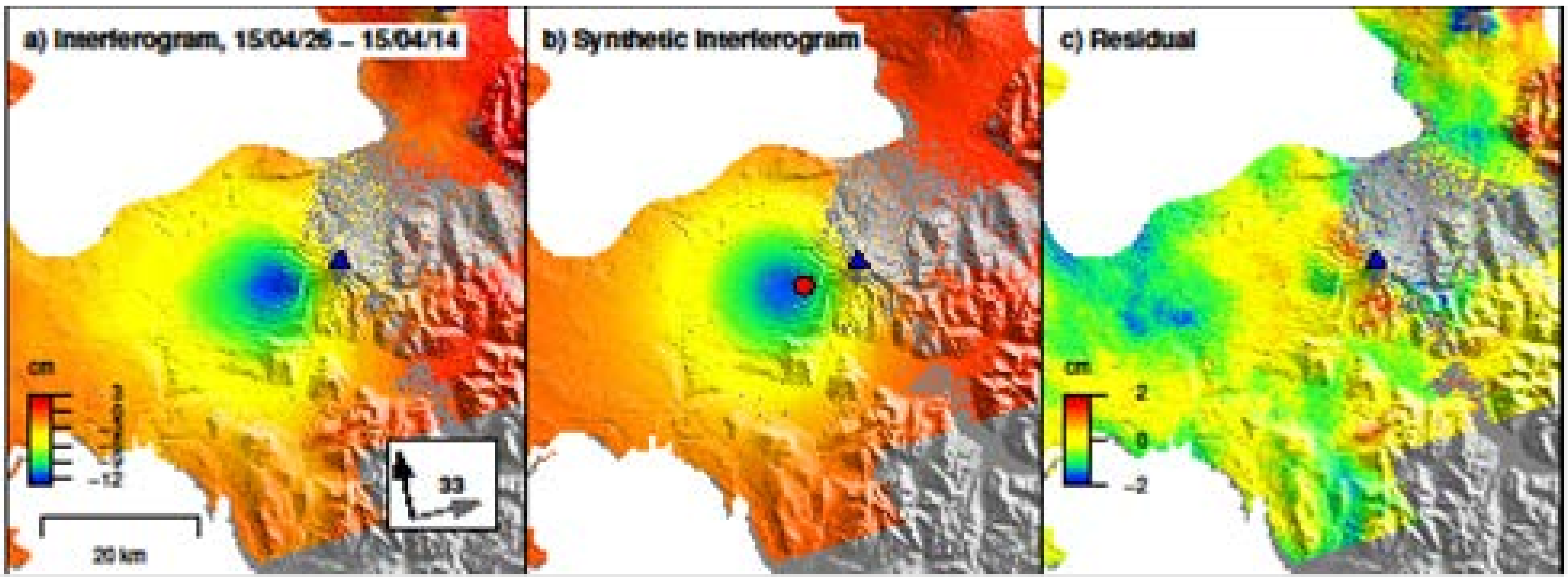
Partner agencies: SERNAGEOMIN, Chile; Buenos Aires Volcano Ash Advisory Center, Argentina; University of Bristol, UK; Cornell University, USA; National Oceanic and Atmospheric Administration, USA

Calbuco, Chile



Perspective view of deformation at Calbuco as determined from a Sentinel-1a interferogram
Coeruptive ascending Sentinel-1 interferograms show deflation with a maximum line of sight change of 12 cm located on the west flank of the volcano.

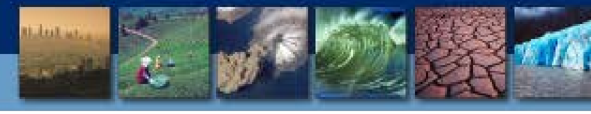
Calbuco, Chile



Observed (left), modeled (center), and residual (right) deformation at Calbuco from a Sentinel-1a interferogram spanning April 14–26, 2015. Deformation can be approximated by a source at ~9 km depth beneath the volcano's west flank.

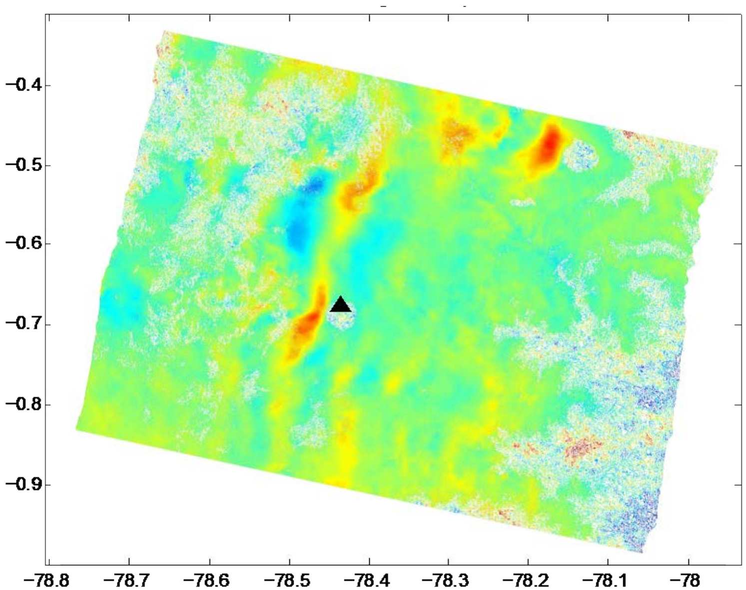
OVDAS used this source model to validate their tilt meter records

Cotopaxi, Ecuador

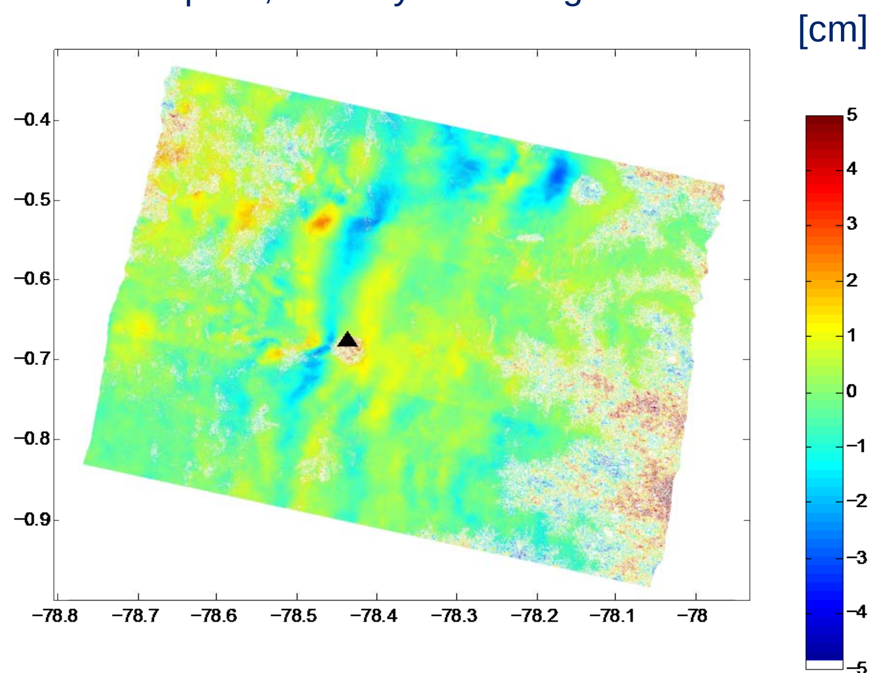


- Small eruption on August 14, 2015
- No measureable pre-eruptive or co-eruptive deformation (sentinel-1 data)
- Agrees with ground observations that record deformation of < 1cm

Pre-eruptive, 6th July - 30th July



Co-eruptive,30th July - 23rd August

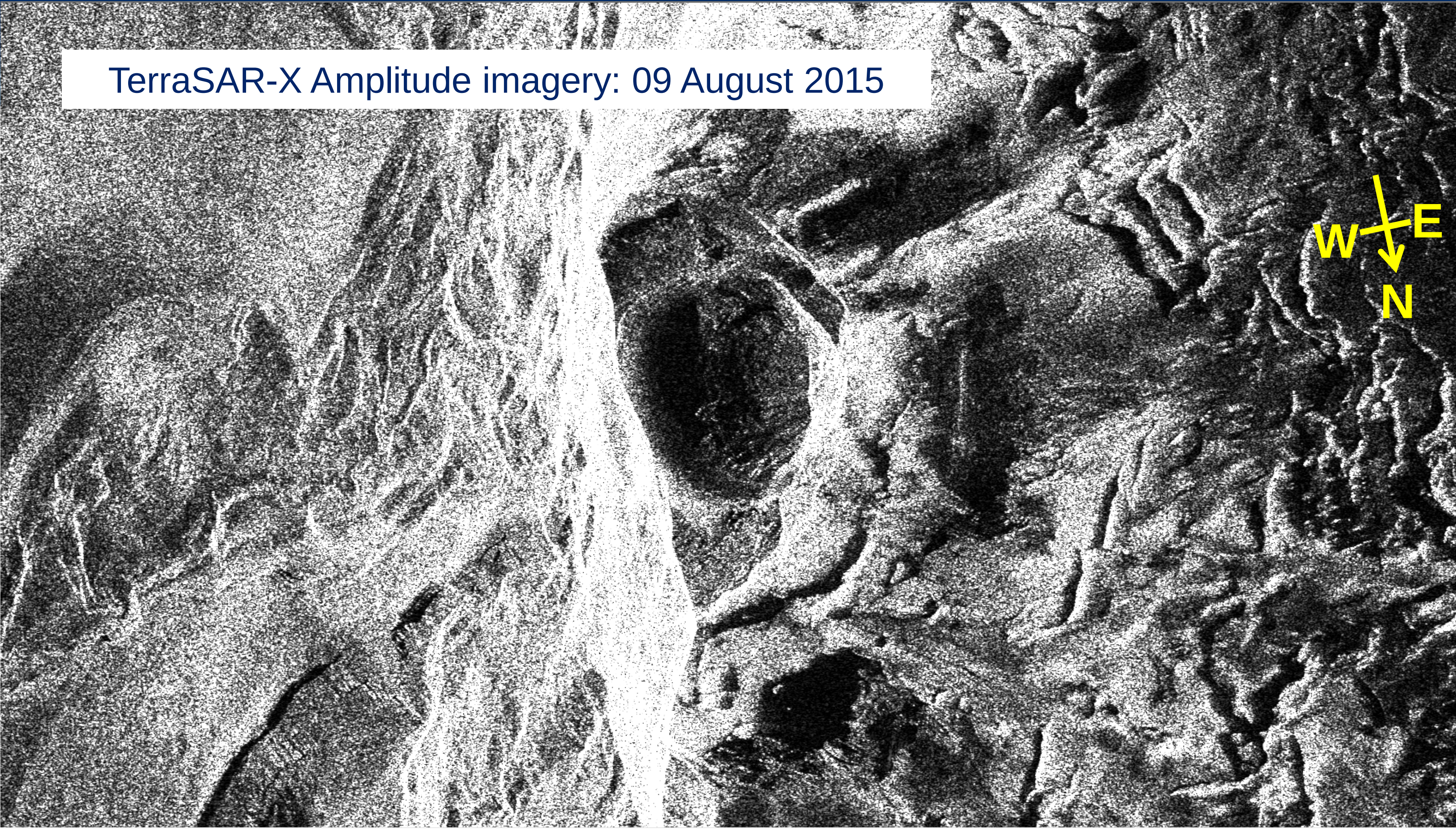


A. Parker, University of Bristol

WG Disasters #4

Cotopaxi, Ecuador

TerraSAR-X Amplitude imagery: 09 August 2015



D. Arnold
University of Bristol

WG Disasters #4

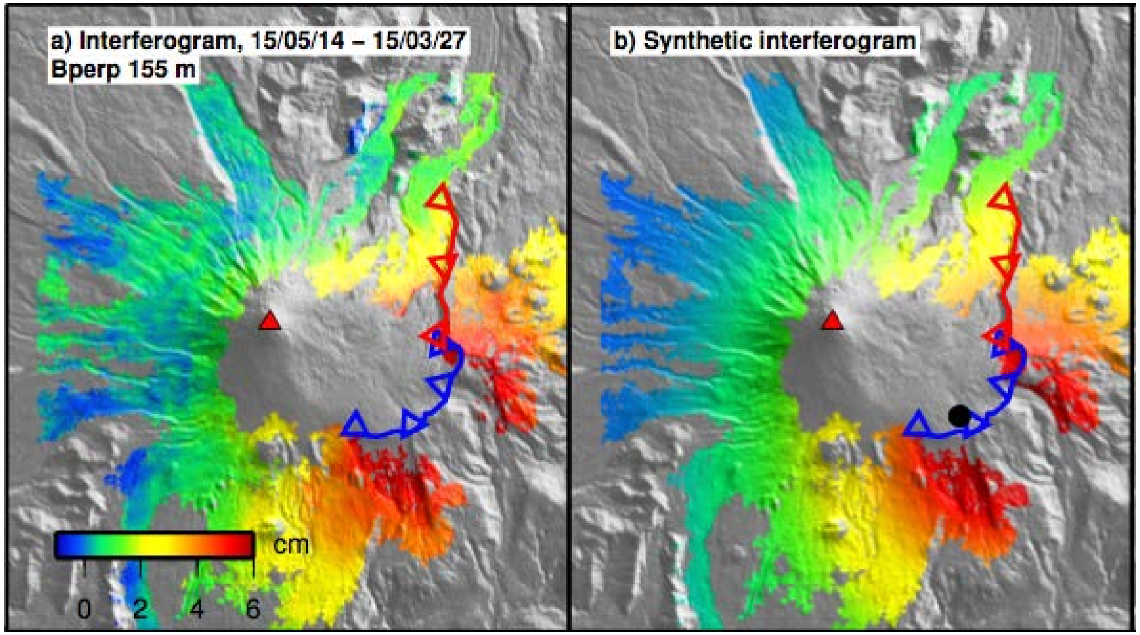
Cotopaxi, Ecuador

- Deepening of summit crater
- Ashfall
- Widening of crevices?

D. Arnold
University of Bristol

Villarrica, Chile

- Eruption March 3rd 2015, no coeruptive deflation
- No pre eruptive uplift observed with InSAR between January 2003 and March 2 2015.
- Inflation episode in the SW part of the volcano observed with InSAR and a single GPS during mid April – mid May 2015.
- OVDAS requested InSAR results of the volcano to confirm their GPS records and to raise the alert level due to geodetic unrest.



Chiles-Cerro Negro de Mayasquer

Chiles and Cerro Negro are stratovolcanoes on the Ecuador-Colombian border that, until recently, had no historical activity

photos: Instituto Geofisico, Ecuador

Since 2013 unrest has persisted at the volcanoes, culminating in a swarm of several thousand volcano-tectonic earthquakes per day in October 2014. At the height of this unrest there was a M5.6 earthquake just south of Volcano Chiles. As there have been no historical eruptions, ground based monitoring is limited:

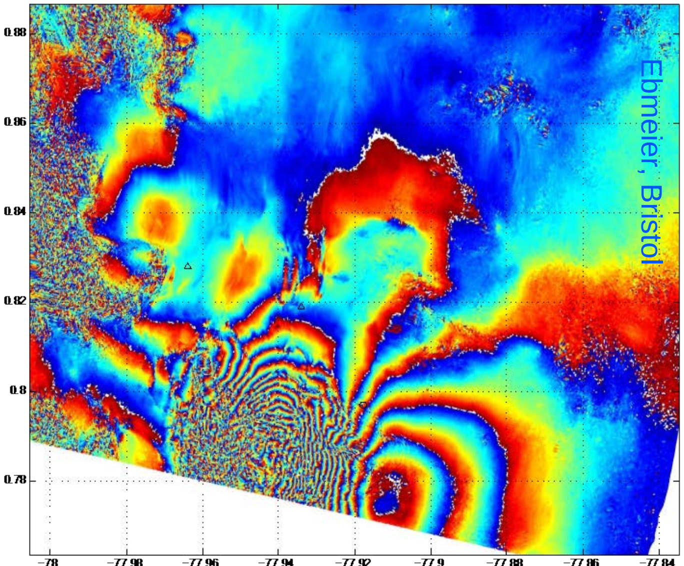
-> satellite data are critical

CEOS

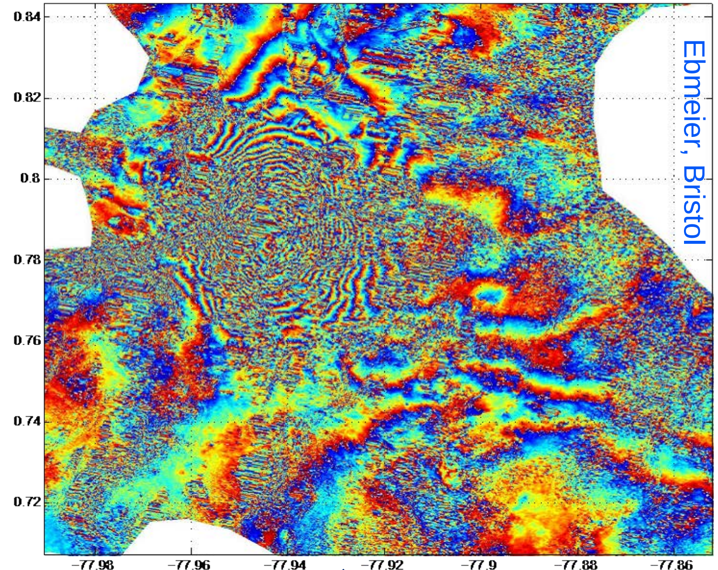
WG Disasters #4
Frascati, Italy
8-10 September, 2015

Chiles-Cerro Negro de Mayasquer

Scientists at the University of Bristol have processed and analyzed CosmoSkyMed and TerraSAR imagery provided by the CEOS Volcano DRM Pilot and shared with Volcano Observatories Instituto Geofisico (Ecuador) and Servicio (Colombia)



CEOS data



University of BRISTOL

CEOS data have been used to find fault geometries and constrain location of magmatic intrusion

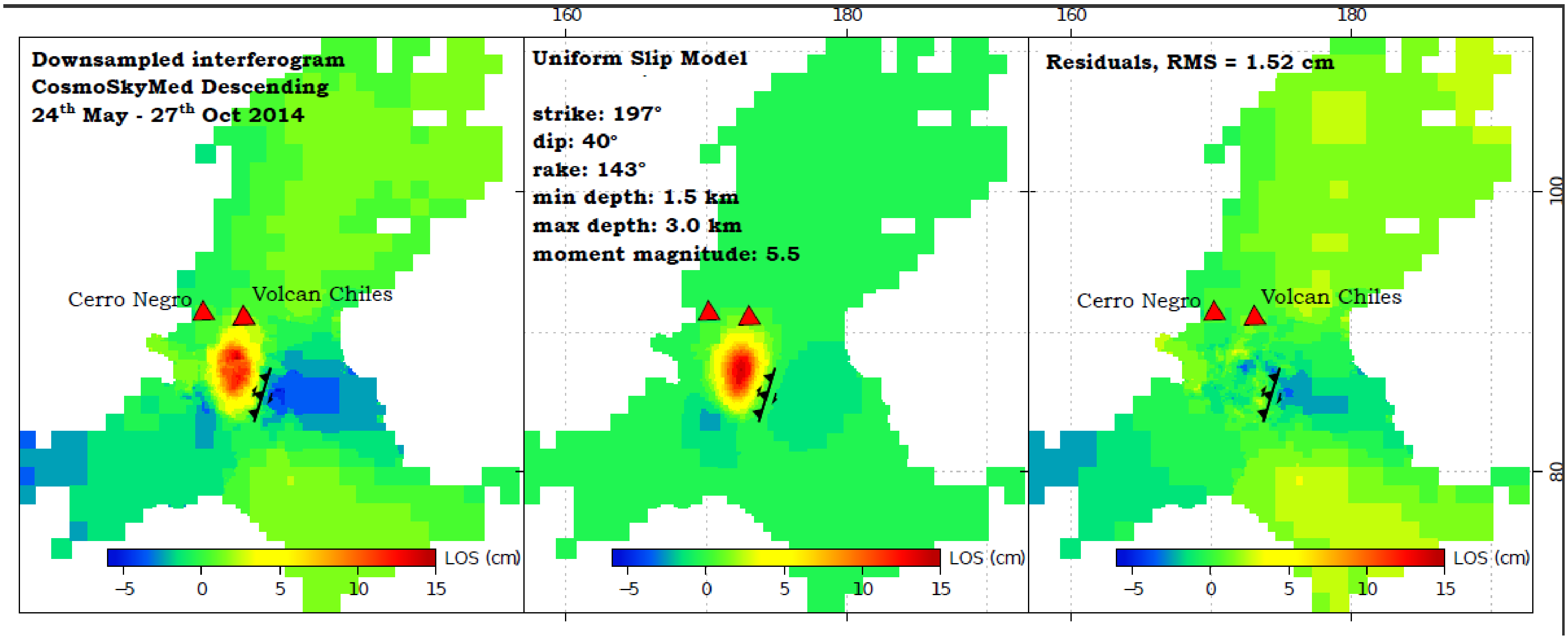
IG Instituto Geofísico

Escuela Politécnica Nacional

Servicio Geológico Colombiano

regular processing of CSK and TSX data since October 2014 to help volcano observatories

Chiles-Cerro Negro de Mayasquer



Deformation **Best-fit fault plane solution** **Residuals**

The deformation detected using InSAR has so far been primarily associated with a larger (M5.6w) earthquake on the 22nd October 2014. This earthquake result in maximum displacements of 15 cm towards the satellite in a region SW of Chiles volcano.

The majority of deformation can be explained by oblique slip on a fault at depths ~1.5-3 km dipping WNW. The orientation of this fault aligns well with faults mapped from regional topographic structures.

Chiles-Cerro Negro de Mayasquer

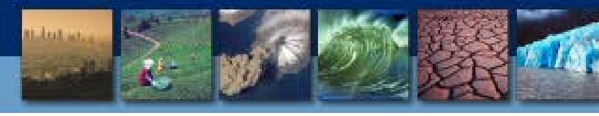
- Pilot team have been talking about the Chiles unrest with **P. Mothes** (IG-EPN – Ecuador) and **Lourdes Medina** (SRC-Colombia) since 2013.
- At their request, we ordered TerraSAR-X acquisitions in 2013 and May 2014. Acquisitions were restarted in October 2014
- All interferograms and model results have been sent to users
- SE (Bristol) spent a month in Ecuador last November working with scientists at Instituto Geofisico. CEOS data were presented at their weekly meeting to discuss hazard at Chiles and incorporated into hazard assessments where considered useful.
- We are now processing both CSK and TSX imagery in Bristol, acquired through CEOS Volcano Pilot / Supersite

Partner agencies: SERNAGEOMIN, Chile; Observatorio San Calixto, Bolivia; Instituto Geofísico del Perú, Instituto Geofísico de la Universidad Nacional de San Agustín, Peru; Instituto Geofísico, Escuela Politécnica Nacional, Ecuador; Servicio Geológico Colmbiano; University of Bristol, UK; Cornell University, USA; National Research Council of Italy, Istituto Per Il Rilevamento Elettromagnetico Dell'Ambiente, University of Miami, USA; Pennsylvania State University, USA

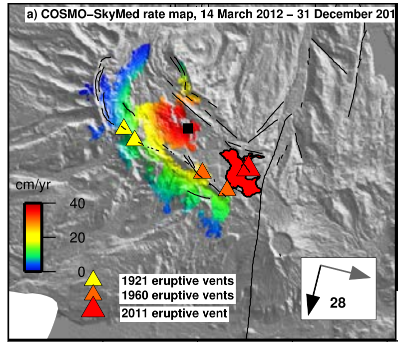
Cordon Caulle, Chile

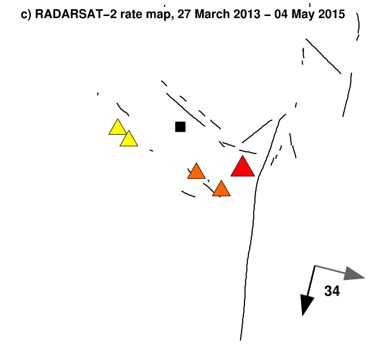
- Volcano with three rhyo-dacite eruptions in the last century (total volume erupted ~2 km^3)
- Large plinian eruption in 2011-2012 produced widespread damage and disrupted air travel.
- Limited ground-based monitoring.

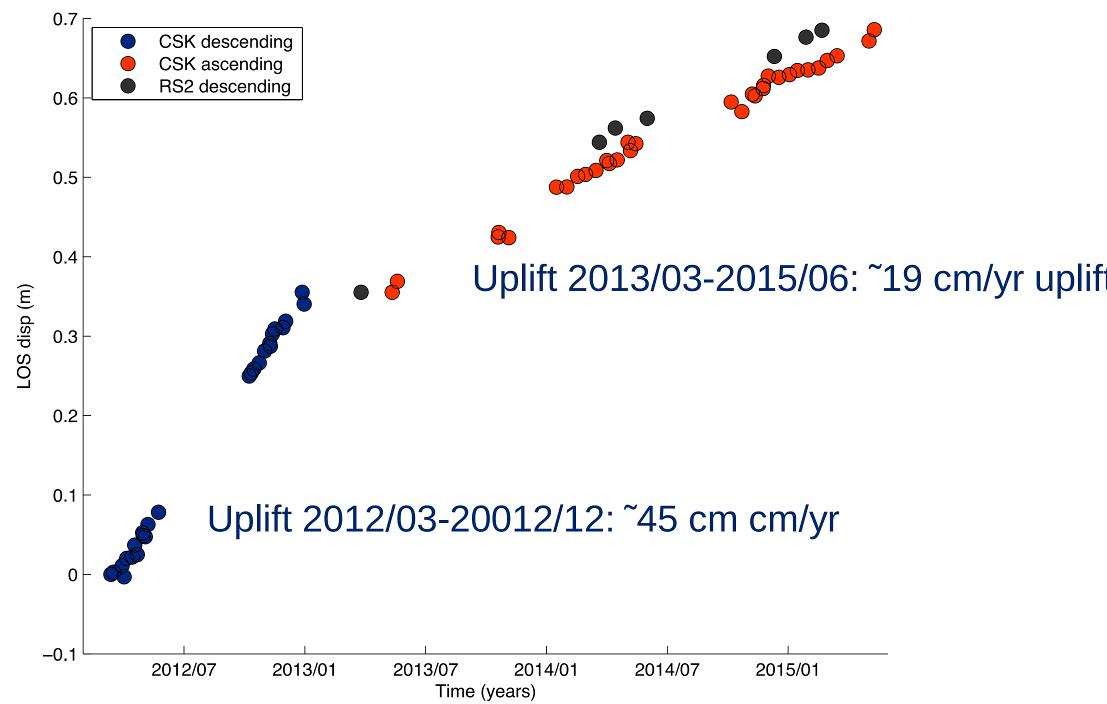
Cordon Caulle, Chile



- CEOS RADARSAT-2 and COSMO-SkyMed SAR data processed by Cornell University has discovered widespread volcano inflation
- The uplift has been mostly aseismic.
- OVDAS does not have geodetic instrumentation and were not aware of the unrest.
- OVDAS decided to deploy a GPS based, but had to be postponed due to the Villarrica and Calbuco eruptions.



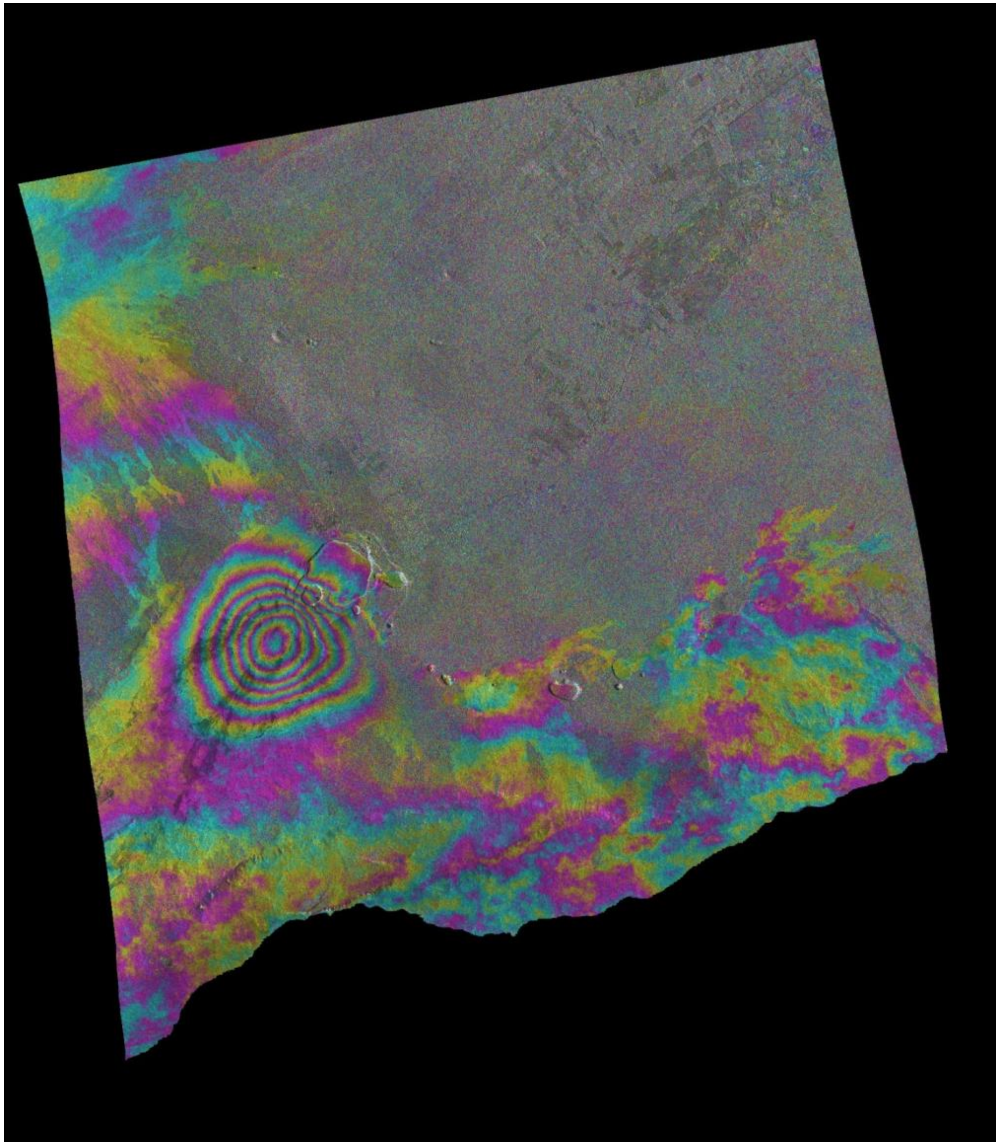




Kilauea, Hawaii

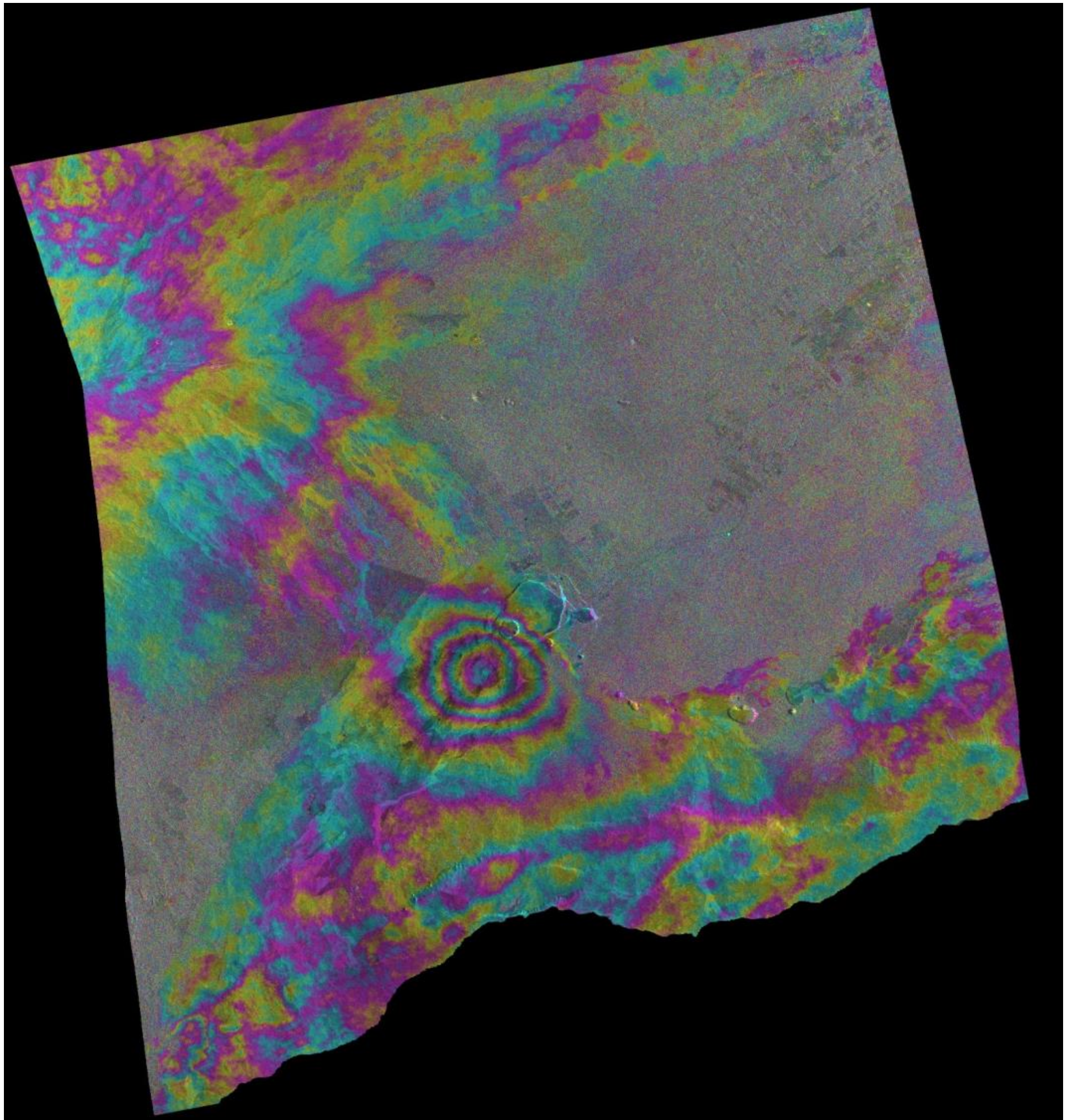
May 2015, intrusion

COSMO-SkyMed
Ascending
April 11 (6AM)– May 22 (6AM)



Kilauea, Hawaii

RSAT2
Ascending
April 1 (6PM)– June 12 (6PM)



Activities 2015

Objective C – Significant Global Event

- No eruption meeting our criteria has occurred, so we continue to wait for a suitable event.
- However, the potential application of this objective was demonstrated in the remote sensing response to the 2014-2015 eruption of Pico do Fogo, Cape Verde.
  - During that eruption, a large quantity of thermal satellite data were analyzed and used to construct a time series of lava effusion rate, one of the most critical volcano monitoring parameters in terms of potential hazard (Open University)
  - Thanks to the CEOS Volcano pilot coordination, NASA (S. Frye) arranged 9 EO-1 acquisitions and CNES (S. Hosford) provided 3 Pleiades data acquired in two dates.
  - Results were communicated to on-site monitoring agencies for use in hazards assessment and mitigation activities.

Publications / obj A

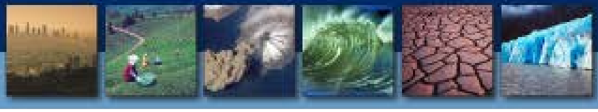
Work related to Objective A has appeared in multiple on-line stories and newsletters:
http://comet.nerc.ac.uk/latest-earthquakes-and-eruptions/satellite-observations-of-the-ongoing-april-2015-eruption-of-volcan-calbuco-chile/
http://www.nerc.ac.uk/research/funded/programmes/resilience/bulletin-mar2015/

In addition, two articles were recently published that are relevant to Objective A, although they were initiated prior to the availability of pilot data:

Muller, C., del Potro, R., Biggs, J., Gottsmann, J., Ebmeier, S. K., Guillaume, S., Cattin, P.-H., and Van der Laat, R. (2015). Integrated velocity field from ground and satellite geodetic techniques: application to Arenal volcano. Geophysical Journal International, 200(2), 863–879, doi:10.1093/gji/ggu444.
Jay, J. A., Delgado, F. J., Torres, J. L., Pritchard, M. E., Macedo, O., and Aguilar, V. (2015). Deformation and seismicity near Sabancaya volcano, southern Peru, from 2002 to 2015. Geophysical Research Letters, 42(8), 2780–2788, doi:10.1002/2015GL063589.

Several presentations that make use of Pilot data will be made at the Fall American Geophysical Union meeting in December 2015, and a manuscript for the Journal of Applied Volcanology is in preparation (submission planned for 2016).

Publications / obj B



A large number of publications and conference presentations have utilized GSNL-provided data; a comprehensive list is available in the status reports for individual Supersites. Highlights include:

- *Pinel, V., Poland, M.P. and Hooper, A*., 2014, Volcanology: **Lessons learned from synthetic aperture radar imagery**. Journal of Volcanology and Geothermal Research, 289, 81-113, doi:10.1016/j.jvolgeores.2014.10.010.
- *Sigmundsson, F., et al*., 2014, **Segmented lateral dyke growth in a rifting event at Bardarbunga volcanic system, Iceland**. Nature, 517(7533), 191-195, doi:10.1038/nature14111.
- *Chen, J., Zebker, H.A., Segall, P. and Miklius, A.,* 2014. **The 2010 slow slip event and secular motion at Kilauea, Hawai`I inferred from TerraSAR-X InSAR data**. Journal of Geophysical Research, 119(8): 6667–6683, doi:10.1002/2014JB011156.
- *Lundgren, P., Poland, M., Miklius, A., Orr, T., Yun, S.-H., Fielding, E., Liu, Z., Tanaka, A., Szeliga, W., Hensley, S. and Owen, S.,* 2013. **Evolution of dike opening during the March 2011 Kamoamoa fissure eruption, Kīlauea Volcano, Hawai‘i**. Journal of Geophysical Research, 118(3): 897-914, doi:10.1002/jgrb.50108.

Publications / obj C

- *Ferrucci, F., Day, S., Hirn, B., Faria, B., and Zoffoli, S.*, 2015, **Multi-payload multi-platform tactical monitoring and evaluation of the 2014 eruption of Fogo, Cabo Verde**, European Geosciences Union General Assembly, Vienna, Austria, 12–17 April.

- *Ferrucci, F., Hirn, B., Faria, B., and Zoffoli, S.*, 2015, **Multi-payload multi-platform simultaneous tactical monitoring of major effusive eruptions in 2014**, International Geosciences and Remote Sensing Symposium, Milan, Italy, 26–31 July.

The Open University

UCL

IES Consulting s.r.l.

Milestones 2015-2017

Objective A – Regional Demonstration

2015: Provide derived products to appropriate users in Latin America (e.g., VAACs, Observatories) and agencies working on site-specific volcanoes. Collect feedback from users about the data and derived products, and use the feedback to refine monitoring strategies. Provide initial evaluation of pilot results to the World Conference on Disaster Risk Reduction. (80% -- derived products given to end-users in Latin America and some initial feedback received)

2016: Achieve overall monitoring of all Latin America volcanoes . Continue to provide products and collect feedbacks form users. Receive reports from Latin American users on derived products and adjust as needed. Evaluate results from site-specific studies. Write a Journal of Applied Volcanology article describing the results of our work, and especially the value to end users, to be submitted in 2016 (0%)

2017: Develop broader space-based EO strategy using insights from pilot in a formal report. (0%)

Milestones 2015-2017

Objective C – Significant Global Event

- submit proposal in advance of any suitable Objective C eruptive event (100%)
- identify an eruptive event, hopefully in southeast Asia, that threatens a significant population and in which results from remote sensing data would not otherwise be available to local emergency management officials (0%)
- process SAR and thermal/visual data and provide derived products (effusion rates, deformation, deposit maps, etc.) to local scientists and emergency management agencies (20%)

Issues

- **Data integration** – mostly INSAR, although some attempts to integrate InSAR and thermal dataset, and SAR amplitude imagery have been used to map changes at some erupting volcanoes. Still more effort needs to be target towards data integration
- **User feedbacks** – we know that EO data have been useful to observatories (i.e. plan installations of future sensors in new area of unrest found by EO data, validate the limited ground-based deformation networks), but need to obtain detailed feedbacks in a formal way. Plan to distribute a questionnaire.
- **Coordination with other groups** – not yet formally reached out to other groups working in the region. Need to establish ties to those groups so that our and their results are more complimentary and provide a complete picture of volcanic activity form Mexico to Patagonia

Issues

- **Need of regular satellite acquisition** – some satellites change frequently mode and resolution over a given area. Develop an acquisition strategy for different satellites type that might be considered by space agencies to provide the most useful data for volcano disaster risk reduction
- **Limited data quotas** – for volcanoes (especially in vegetated areas) dozen of images are needed to glean a useful deformation results to mitigate against atmospheric artifacts and poor coherence. Quite easy to consume hundred of images for few volcanoes..
- **Sustainability** of the pilot beyond 2017

Thank you