

Volcano Pilot
Final Report
 (April 2014 – November 2017)
Draft as of March 2017 (to be update for Plenary in October 2017)

Summary: please provide a short statement (about ten lines) indicating what the pilot has achieved, using the pilot objectives as a starting point, using non-technical language, for public release

The volcano pilot project was designed to be a stepping-stone towards the long-term goals of the Santorini Report on satellite EO and geohazards with respect to volcanic activity, namely: 1) global background observations at all Holocene volcanoes; 2) weekly observations at restless volcanoes; 3) daily observations at erupting volcanoes; 4) development of novel measurements; 5) 20-year sustainability; and 6) capacity-building. Specifically, the pilot aimed to:

- A. Demonstrate the feasibility of integrated, systematic and sustained monitoring of Holocene volcanoes using space-based EO
- B. Demonstrate applicability and superior timeliness of space-based EO products to the operational community (such as volcano observatories and Volcanic Ash Advisory Centers) for better understanding volcanic activity and reducing impact and risk from eruptions
- C. Build the capacity for use of EO data in volcanic observatories in Latin America as a showcase for global capacity development opportunities.

Much of the pilot work focused on demonstrating the feasibility of global volcano monitoring of Holocene volcanoes through a regional monitoring of volcanoes in Latin America. That region was chosen because: 1) the volcanoes are situated in a diversity of environments (from rain forest to high-altitude desert), providing a good test of the capabilities of different types of satellite data in different settings, 2) volcanic activity is abundant, including persistent eruptive activity, discrete eruptions, and unrest without eruption, 3) explosive eruptions that disrupt air travel were likely to occur over the course of the three-year pilot, and 4) volcano observatories and monitoring agencies in Latin American countries would directly benefit from the additional resources made available by the pilot.

The results of the pilot demonstrated that EO data are critical for identifying volcanoes that may become active in the future, as well as tracking eruptive activity that may impact populations and infrastructure on the ground and in the air. For example, rapid inflation of Cordón Caulle, Chile, starting in 2012 occurred in the absence of seismicity and was not tracked by any ground-based means, but the discovery prompted the responsible volcano observatory to install GPS sensors to track the activity. In contrast, EO data from Chiles-Cerro Negro, on the Colombia-Ecuador Border, revealed that anomalous seismicity was not accompanied by significant volcano-related deformation, which aided volcanologists on the ground in interpreting the activity. At Masaya, Nicaragua, inflation and increases in thermal emissions, which were not detected from the ground, accompanied an increase in eruptive activity at the volcano. And EO data were critical for tracking ash associated with several eruptions, like that of Calbuco, Chile, in 2015, allowing Volcanic Ash Advisory Centers to issue warnings about air travel in the region.

Pilot leads:	Collaborating organizations
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<p>Michael Poland, USGS mpoland@usgs.gov</p> <p>Simona Zoffoli, ASI simona.zoffoli@asi.it</p> <p>Contributing projects: Geohazards Supersites and Natural Laboratories, CSA Volcano Watch, NOAA Volcanic Cloud Monitoring</p> <p>Other relevant projects: EVOSS, STREVA, Global Volcano Model, VUELCO</p>	<p>CEOS partners: USGS, ASI, CSA, ESA, NOAA, JAXA, NASA, DLR, CNES</p> <p>Other partners: University of Bristol (UK), Cornell University (US), University of Miami (US), Pennsylvania State University (USA), University of Iceland, British Geological Survey, Italian National Research Council / Istituto per il Rilevamento Elettromagnetico dell'Ambiente (IREA –CNR), Italian Civil Protection Department, the Open University (UK), Buenos Aires and Washington, D.C Volcanic Ash Advisory Center volcano observatories (mostly in Latin America), USGS Volcano Disaster Assistance Program</p> <p>Research Consortia: IAVCEI, WOVO, COMET+, ALVO</p>
<p>Initial Objectives:</p> <p>The Volcano Pilot proposed three objectives over the 2014–2017 life of the project:</p> <ol style="list-style-type: none"> 1) a regional study of volcanic unrest and eruption in Latin America using SAR and visible/IR satellite data; 2) support of Geohazard Supersites and Natural Laboratories volcano targets, especially in Hawaii, Iceland, and Italy; 3) comprehensive remote sensing coverage of a significant eruptive event that threatens population, preferably located in Southeast Asia (where Pilot activities are currently limited) <p>Pilot work has dominantly been on Objective 1. Objective 2 is self-sustaining and needed no direct input from pilot members. There was no major eruption meeting the criteria of Objective 3 during the lifetime of the pilot, so that aspect of the work was never implemented. A demonstration of the potential for Objective 3, however, was provided by the team’s response to the 2014–2015 eruption of Fogo, Cape Verde islands.</p>	
<p>Achievements (linked to objectives and also to CEOS objectives in the proposal):</p> <p>Objective 1 achievements:</p> <ul style="list-style-type: none"> • <i>Evaluation of the cause of unrest at Chiles-Cerro-Negro volcanoes, Colombia/Ecuador</i> • <i>Mapping of lava flows at Reventador volcano, Ecuador</i> • <i>Monitoring unrest and minor eruptive activity at Cotopaxi, Ecuador</i> • <i>Monitoring deformation and thermal emissions before and during eruptive activity at Sabancaya volcano, Peru</i> • <i>Tracking ash associated with the 2015 eruption of Calbuco volcano, Chile; also monitoring of co- and post-eruptive deformation</i> • <i>Detection of uplift at Cordón Caulle volcano, Chile</i> • <i>Recognition of a source of uplift at Villarica volcano, Chile, that was off-center with respect to the volcano’s summit and not well-covered by ground-based monitoring</i> 	

- *Recognition that Guallatiri volcano, Chile, was not deforming, and that a ground-based sensor indicating otherwise was malfunctioning*
- *Modeling deformation associated with the 2015 eruption of Wolf volcano, Galápagos Islands, to assess magma chamber location and shape*
- *Assessing the size and shape of the magmatic system of Fernandina volcano, Galápagos Islands, from satellite deformation data*
- *Assessment of thermal emissions and surface deformation associated with elevated levels of volcanic activity at Masaya, Nicaragua, in late 2015 and early 2016*
- *Assessment of ground deformation and thermal and ash emissions associated with the 2015 eruption of Momotombo volcano, Nicaragua*
- *Exploration of the magmatic system of Pacaya volcano, Guatemala, based on deformation data from SAR sensors*
- *Mapping of topographic change associated with volcanic activity at Soufrière Hills Volcano, Montserrat*
- *High-spatial-resolution mapping of flank motion at Arenal volcano, Costa Rica*

Objective 2 achievements:

- *Characterization of surface deformation associated with the May 2015 intrusion beneath the summit area of Kīlauea Volcano, Hawai‘i*
- *Determination of the timing of pit crater formation near the summit access road on Mauna Kea volcano, Hawai‘i, and recognition of pre-collapse subsidence*
- *Tracking of lava flows associated with ongoing eruptive activity at Kīlauea Volcano, Hawai‘i*

Objective 3 achievements:

- *High-temporal-resolution tracking of lava effusion from Fogo volcano, Cape Verde islands, to assess changes in eruptive activity in near-real time*

Data accessed (list satellites and make statement)

The pilot accessed a wide variety of data from space agencies around the world. Many of the datasets are a result of public-private partnerships and are not freely available, namely:

ALOS-2 (moderate- to high-spatial-resolution L-band SAR)
 RADARSAT-2 (moderate- to high-spatial-resolution C-band SAR)
 COSMO-SkyMed (high-resolution X-band SAR constellation)
 TerraSAR-X (high-resolution X-band SAR)
 TanDEM-X (high-resolution X-band SAR with emphasis on topographic mapping)
 Pleiades (very-high-resolution tri-stereo-optical visual data for topographic mapping)

In addition, the pilot made use of a large number of freely available satellite resources, with some of the more frequently accessed datasets including:

Sentinel-1a/b (moderate-spatial-resolution C-band SAR)
 LANDSAT-8 (moderate-spatial-resolution visible and thermal capability)
 MODIS (low-spatial-resolution multispectral sensor with infrared capability)
 ASTER (moderate-spatial-resolution visible and thermal capability)

Products:

- *Interferograms constructed from Synthetic Aperture Radar data and showing displacements of the ground surface between image acquisitions (provided to volcano observatories throughout Latin America)*
- *Maps of topography and topographic change from radar and optical satellite data to assess the emplacement of volcanic deposits (provided to Montserrat Volcano Observatory, the Instituto Geofísico in Ecuador, and scientists and civil defense officials in Fogo in the Cape Verde islands)*
- *Time series of surface displacements based on data from number acquisitions and multiple Synthetic Aperture Radar satellites (provided to volcano observatories throughout Latin America, particularly the Instituto Geofísico in Ecuador and OVDAS in Chile)*
- *Detection of thermal and ash emissions associated with volcanic unrest and eruption (provided to the Washington, D.C., and Buenos Aires Volcanic Ash Advisory Centers)*

Dissemination:

Numerous conference presentations highlighting pilot results have been made, especially at American Geophysical Union, European Geosciences Union, and Cities on Volcanoes conferences.

A number of site visits were made by pilot team members to volcano observatories in Latin America to initiate and continue capacity building exercises. At the Cities on Volcanoes 9 meeting, held in Chile during November 2015, staff from volcano observatories throughout Latin America participated in a workshop, led by pilot team members, about the use of satellite data in volcano monitoring and eruption response. A similar workshop will be held at the August 2015 International Association of Volcanology and Chemistry of the Earth's Interior Scientific Assembly.

Several scientific publications have resulted from pilot work, including:

Jay, J. A., F. J. Delgado, J. L. Torres, M. E. Pritchard, O. Macedo, and V. Aguilar (2015). Deformation and seismicity near Sabancaya volcano, southern Peru, from 2002 to 2015. *Geophysical Research Letters*, 42(8), 2780–2788, doi:10.1002/2015GL063589.

Muller, C., R. del Potro, J. Biggs, J. Gottsman, S. K. Ebmeier, S. Guillaume, P-H. Cattin and R. van der Laat (2015). Integrated velocity field from ground and satellite geodetic monitoring: Insights from Arenal volcano. *Geophysical Journal International*, 200(2), 863–879, doi:10.1093/gji/ggu444.

Delgado, F., M. Pritchard, D. Basualto, J. Lazo, L. Cordova, and L. Lara (2016). Rapid re-inflation following the 2011–2012 rhyodacite eruption at Cordón Caulle volcano (Southern Andes) imaged by InSAR: Evidence for magma reservoir refill. *Geophysical Research Letters*, 43(18), 9552–9562, doi:10.1002/2016GL070066.

Naranjo, M. F., S. K. Ebmeier, S. Vallejo, P. Ramón, P. Mothes, J. Biggs, F. Herrera. Monitoring lava flow hazards: effusion from 2002-2009 at El Reventador Volcano, Ecuador, from field measurements and satellite remote sensing. *Journal of Applied Volcanology*, 4, 8, doi:10.1186/s13617-016-0048-z October 2015.

Ebmeier, S. K., J. R. Elliott, J. M. Nocquet, J. Biggs, P. Mothes, P. Jarrín, M. Yépez, S. Aguaiza,

P. Lundgren, and S. V. Samsonov (2016). Shallow earthquake inhibits unrest near Chiles–Cerro Negro volcanoes, Ecuador–Colombian border. *Earth and Planetary Science Letters*, 450, 283–291, doi:10.1016/j.epsl.2016.06.046.

Arnold, D. W. D., J. Biggs, G. Wadge, S. K. Ebmeier, H. M. Odbert, and M. P. Poland (2016). Dome growth, collapse, and valley fill at Soufrière Hills Volcano, Montserrat, from 1995 to 2013: Contributions from satellite radar measurements of topographic change. *Geosphere*, 12(4), 1300–1315, doi:10.1130/GES01291.1.

Morales Rivera, A. M., F. Amelung, and P. Mothes (2016). Volcano deformation survey over the Northern and Central Andes with ALOS InSAR time series. *Geochemistry, Geophysics, Geosystems*, 17(7), 2869–2883, doi:10.1002/2016GC006393.

Wnuk, K., and C. Wauthier (in review). Temporal evolution of surface deformation and magma sources at Pacaya Volcano, Guatemala revealed by InSAR. *Journal of Volcanology and Geothermal Research*.

Delgado F., M. E. Pritchard, S. Ebmeier, P. Gonzalez, and L. Lara (in review). Recent unrest (2003–2015) imaged by space geodesy at the highest risk Chilean volcanoes: Llaima, Villarrica and Calbuco (Southern Andes). *Journal of Volcanology and Geothermal Research*.

The entire pilot team is also working on a manuscript for *Journal of Applied Volcanology* entitled: *Towards coordinated regional multi-satellite InSAR volcano observations: Results from the Latin America pilot project*. We expect to submit the manuscript for publication in mid-2017.

Evaluation Against Predefined Criteria

- 1) Identification of new areas of unrest through regional InSAR monitoring.

The pilot used a large amount of InSAR data to identify several previously-unknown deformation sources at active volcanoes. For example, Cordón Caulle volcano, Chile, was found to be inflating after its 2011–2012 eruption, but this was unknown because there was not accompanying seismicity and no ground-based deformation monitoring. This discovery motivated the responsible volcano monitoring agency, OVDAS, to install ground-based GPS sensors to track the deformation. In other cases, InSAR monitoring confirmed that no deformation was occurring despite the initiation of eruptive activity—at Momotombo (Nicaragua) and Sabancaya (Perú), for instance. Finally, volcanoes that were known to be deforming, like Pacaya (Guatemala) and Fernandina (Galápagos Islands), were the focus of intensive study, which allowed for detailed mapping of the magmatic systems that feed eruptions.

- 2) Uptake by Latin American volcano monitoring agencies of EO-based methodologies for tracking deformation, as well as gas, thermal, and ash emissions.

A series of capacity-building efforts by pilot team members, including in-person visits to volcano observatories as well as workshops associated with conferences, has increased the awareness of, and ability to interpret, volcano remote sensing data. The volcano observatories frequently ask for InSAR results, and Volcanic Ash Advisory Centers make frequent use of the NOAA/NESIDS VOLcanic Cloud Analysis Toolkit (VOLCAT). A significant challenge in increasing uptake of SAR data is the need for long-term, in-depth long-term training. This is perhaps best done by having students from Latin America obtain advanced degrees from universities in the US, Europe,

and Japan that have research programs focusing on SAR. Already, such efforts are underway, and students who are receiving training are likely to return to their home countries with the ability to spread their knowledge and launch their own research and monitoring programs.

- 3) Utilization of EO data for operational monitoring by volcano observatories at Supersite targets.

This result is demonstrated well by the Hawaiian Volcano Observatory, which uses SAR data on a routine basis to track surface deformation and surface change (for example, due to lava flow emplacement). Data can be processed soon after acquisition, which ensures that SAR data and derived products are used in making decisions related to assessment of volcanic activity and associated hazards. Thermal data are also used in an operational manner and are particularly useful for tracking lava flow activity when field observations are not possible.

- 4) Interest expressed by volcano community to broaden approaches adopted in pilot (especially regional monitoring and new methodologies for EO-based monitoring) through representative bodies such as IAVCEI, WOVO or GVM.

The volcano pilot has garnered excellent reviews from the volcanological community. A follow-on effort, sponsored by the US Geological Survey Powell Center, was funded largely on the basis of pilot results, which demonstrate the feasibility of regional, and perhaps global, volcano monitoring from space. In addition, the US Geological Survey's Volcano Disaster Assistance Program, which assists developing countries with assessment of volcanic hazards and responses to volcanic unrest/eruptions, is interested in aiding with future coordination of EO volcano monitoring at volcanoes in Latin America and elsewhere.

Lessons Learned

- *A diversity of SAR data is important for any regional or global volcano monitoring strategy. Different bands offer different advantages and should be used in a coordinated fashion. L-band sensors, like ALOS-2, are critical, given the numbers of volcanoes threatening population centers in densely forested tropical areas.*
- *Background SAR missions that are dedicated to volcano observation are critical, as examination of data from before unrest at any given volcano is critical for understanding the context for that unrest and forecasting its possible outcome. CSA's Volcano Watch Program and the CSK background volcano observations are excellent examples in this regard. In lieu of dedicated volcano acquisitions, global observation strategies, like that of Sentinel-1, provide assurance that every active volcano on Earth will be imaged on a regular basis with at least one band.*
- *Tight orbital control is extremely advantageous for mapping deformation and topographic change over time. This allows consecutive overpasses to be used consistently to make maps of deformation and topography. TerraSAR-X and TanDEM-X offer exceptional value in this regard.*
- *Freely available datasets, especially with high temporal resolution (and hopefully high spatial resolution), are a foundation for near-real-time detections of thermal anomalies and ash detection. Such warning signs of an impending or ongoing eruption cannot be missed, given the extreme hazard to local and regional air traffic.*

Sustainability

The coordination between researchers, space agencies, and end users was a highlight of the volcano pilot. Data flowed from space agencies to researchers, who developed derived products (ranging from interferograms and ash detections to models of magmatic plumbing systems) and provided insights to the end users that are responsible for assessing and mitigating volcanic hazards. This model can serve as a basis for future efforts, but should involve a dedicated employee or agency who has the specific job of coordinating EO observations of volcanoes. To this point, these efforts have been done on a volunteer basis.

We envision two potential models for building on the pilot activities.

1) Status quo. No new funds are needed, but space agencies should continue to provide data at no cost and with quotas similar to those provided thus far for regional volcano monitoring activities. Teams of academic researchers, who will write proposals for data, summarize results in regular reports, and manage data quotas, will work with volcano observatories to identify needs, build capacity, and respond on a best-effort basis to volcanic crises. This could be scaled from regional to global depending on the level of interest and commitment shown by academic teams, space agencies, and end users.

2) Dedicated effort. One or more full-time employees will serve as bridges between teams of academics, space agencies, and volcano observatories and other end users to ensure that user needs are met, and that space agencies receive the proposals and reports that are needed to justify their continued support. Large quotas of satellite data, especially from SAR sensors, should be made available. Data processing will be routine and occur with low latency, and crisis response will be immediate. Data processing and interpretation will be subject to continuous scientific input to ensure the development and exploitation of best practices. This could be scaled from regional to global depending on the level of interest and commitment shown by academic teams, space agencies, and end users.

Option (1) represents the current situation, which is difficult to sustain given that researchers are working largely on a volunteer basis, and space agencies may not be able to continue to justify data quotas for work on volcanic activity. Nevertheless, if data quotas continue to be made available, the option is viable at least for regional volcano monitoring in Latin America.

Option (2) is possible only if funding is made available to support dedicated employees and space agencies commit to providing sufficient amounts of data for a sustainable program of volcano monitoring. The viability of this model is not yet clear, although a number of agencies could serve as a “home base” for coordinating such an effort.

Next Steps

- 1. Develop a strategy for providing EO data (especially SAR) for use in volcano hazards mitigation—effectively a continuation of pilot activities for Latin America, and possibly beyond. This might require proposals, data quotas, reports, etc.*
- 2. Identify an agency (or agencies) that can coordinate volcano observation efforts. Such an agency should have good connections with local volcano observatories, academic researchers who make use of volcano remote sensing data, and space agencies that collect and provide those data. In the USA, the US Geological Survey’s Volcano Disaster Assistance Program is a logical coordinating organization. Ideally, the agency (or agencies) would have the resources to hire a full-time employee who can serve as a point of contact to link space agencies, scientists, and end users to ensure efficient use of*

data and transfer of knowledge. Such efforts should not continue to be done on an ad-hoc basis, as has been the case to this point.

- 3. Support capacity-building efforts, which should include site visits by experts to volcano observatories and agencies that are looking to increase their use of EO data, workshops at scientific conferences, and, most importantly, training of students.*
- 4. Emphasize the continuing need for automated near-real-time detection of volcanic ash clouds and thermal anomalies. As one example, NOAA/NESDIS has been providing this service through their VOLCAT toolkit, but that effort is not sustainable without continued investment.*

User Feedback/Endorsements

1. "The interferograms that no longer showed significant displacements, as well as the descending GPS data values, along with a lowering of the energy levels of the overall seismic events, were fundamental in helping us arrive to the decision to lower the alert level from orange to yellow."

*- Patricia Mothes, Geophysicist, Instituto Geofísico (Ecuador)
(Referring to Chiles-Cerro Negro unrest)*

2. "These [InSAR] results surprised OVDAS, as the volcano does not have geodetic instrumentation, and will lead to the deployment of the first c[ontinuous] GPS stations over the volcano."

*- Luis Lara, Director, Observatorio Volcanológico de los Andes del Sur (OVDAS, Chile)
(Referring to Cordon Caulle inflation results)*

3. "We, in Colombia, are very interested in using InSAR but we need more InSAR training and help to interpret the InSAR data so those types of workshops and trainings are very useful for us"

*- Carlos Andrés Laverde, Geohazards Direction team, Colombian Geological Survey (Colombia)
(Referring to a November 2016 workshop about processing and interpreting InSAR data)*

4. "We appreciate your help in volcanic monitoring in Guatemala, unfortunately we lack a lot of equipment and [InSAR] is going to strengthen [our monitoring ability]."

*- Gustavo A. Chigna, volcanologist, INSIVUMEH (Guatemala)
(Referring to the use of InSAR to track deformation of Pacaya volcano)*

5. "The satellite data we have received from CEOS has been very useful, and we thank the space agencies for making it available to us. The data helped us to pinpoint the exact location of the deformation, which we could not do with only a few ground-based points. This helped the emergency managers to know which zone was affected, which is very important. Both the observatory and the local communities have benefitted from the CEOS Pilot project and we hope that it continues in the future."

- Lourdes Narvaes Medina, volcanologist, Observatorio Vulcanológico y Seismológico de Pasto (Colombia)
(Referring to the crisis at Chiles-Cerro Negro, on the Ecuador-Colombia Border)

6. *“The USGS Volcano Disaster Assistance Program works with volcano observatories throughout Latin America and has seen firsthand the impact of the CEOS volcano pilot project. The rapid availability of a variety of data types, coupled with outreach done by pilot participants, has aided local volcanologists in assessing volcanic unrest, like that at Chiles-Cerro Negro (Colombia-Ecuador) in 2014, and also in responding to eruptions, including the unheralded explosion of Calbuco, Chile, in 2015. We and our Latin American counterparts are grateful for the commitment of the CEOS member agencies and the volcano pilot team to provide data, products, and expertise, and we hope that these efforts can be expanded in the future.”*

- John Pallister, Chief, Volcano Disaster Assistance Program, U.S. Geological Survey (USA)

7. *“We use InSAR satellite observations when available along with our ground observations to understand the threat of ongoing eruptions in Sabancaya and determine the level of alertness. As it is known at the moment the volcano is in full eruption, and we need this information of satellite InSAR [to help] us to forecast.”*

- Ing. Victor Aguilar Puruhuaya, Jefe de Sismología, Instituto Geofísico, Universidad Nacional San Agustín de Arequipa (Perú)
(Referring to the ongoing eruptive activity at Sabancaya volcano)

8. *“SAR data provided to the US Geological Survey's Hawaiian Volcano Observatory via CEOS agencies are an invaluable resource for both scientific research and volcanic hazards assessment. We have been able to incorporate the data into our operational monitoring of Kilauea and Mauna Loa volcanoes, which helps us maintain situational awareness of lava flows and surface deformation that may herald a change in the locus or style of hazardous activity. The data have also helped us better understand the magmatic and tectonic systems of Hawaiian volcanoes, a critical basis for forecasting future volcanic activity.”*

- Christina Neal, Scientist-in-Charge, Hawaiian Volcano Observatory, U.S. Geological Survey (USA)