Volcano Pilot

Final Report
(April 2014 – November 2017)
Draft as of September 2017

Summary:

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.

Although the ideal volcano monitoring system involves the integration of both ground- and

space-based observations, the great expense and limited deployment of ground-based monitoring requires increased satellite observations to promote volcanic disaster risk reduction worldwide.	
Pilot leads: Michael Poland, USGS mpoland@usgs.gov Simona Zoffoli, ASI simona.zoffoli@asi.it **Contributing projects:** Geohazards Supersites and Natural Laboratories, CSA Volcano Watch, NOAA Volcanic Cloud Monitoring **Other relevant projects:** EVOSS, STREVA, Global Volcano Model, VUELCO	**Collaborating organizations** **CEOS partners:** USGS, ASI, CSA, ESA, NOAA, JAXA, NASA, DLR, CNES **Other partners:** University of Bristol (UK), Cornell University (US), University of Miami (US), Pennsylvania State University (US), University of Iceland, British Geological Survey, Italian National Research Council / Istituto per il Rilevamento Elettromagnetico dell'Ambiente (IREA–CNR, Italy), Italian Civil Protection Department (Italy), 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 (US) **Research Consortia:** IAVCEI, WOVO, COMET+, ALVO

Initial Objectives:

The Volcano Pilot proposed three objectives over the 2014–2017 life of the project:

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)

Pilot work has dominantly been on Objective 1. Objective 2 is self-sustaining and needed no direct input from pilot members, but lessons learned from the work under Objective 2 were incorporated into pilot activities under Objective 1. 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. In the event of a future major event, theses lessons may serve as a starting point for integrated, intensive observations over a volcano.

Achievements (linked to objectives and also to CEOS objectives in the proposal):

Objective 1 achievements:

- *Evaluation of the cause of unrest at Chiles-Cerro-Negro volcanoes, Colombia/Ecuador, which helped the volcano observatory determine the appropriate state of alert.*

- *Mapping of lava flows and eruption flux at the ongoing eruption of Reventador volcano, Ecuador (2002-present), which shows a pseudo-continuous but decaying rate of effusion.*
- *Monitoring unrest and minor eruptive activity at Cotopaxi, Ecuador, which helped the Instituto Geofísico set monitoring priorities.*
- *Monitoring deformation and thermal emissions before and during eruptive activity at Sabancaya volcano, Peru, which was important for establishing that there was no deformation associated with activity in 2013-14, but deformation occurred in 2015-17.*
- *Tracking ash associated with the 2015 eruption of Calbuco volcano, Chile, for aviation safety and awareness; also monitoring of co- and post-eruptive deformation that might indicate magma recharge and the potential for future activity.*
- *Detection of uplift at Cordón Caulle volcano, Chile, which made OVDAS aware of the aseismic deformation and motivated installation of a continuous GNSS station.*
- *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, which provides a blueprint for future monitoring.*
- *Recognition that Guallatiri volcano, Chile, was not deforming, and that a ground-based sensor indicating otherwise was malfunctioning, which aided in the assessment of activity by local volcanologists.*
- *Modeling deformation associated with the 2015 eruption of Wolf volcano, Galápagos Islands, to assess magma chamber location and shape—information that could not be determined from ground-based sensors.*
- *Assessing the size and shape of the magmatic system of Fernandina volcano, Galápagos Islands, from satellite deformation data (no ground-based observations were available).*
- *Assessment of thermal emissions and surface deformation associated with elevated levels of volcanic activity at Masaya, Nicaragua, in late 2015 and early 2016, which helped INETER understand the nature of the unrest.*
- *Assessment of ground deformation and thermal and ash emissions associated with the 2015 eruption of Momotombo volcano, Nicaragua, which helped INETER understand the nature of the unrest (InSAR showed a lack of major shallow magma storage).*
- *Exploration of the magmatic system of Pacaya volcano, Guatemala (including during the 2014 eruptions), based on deformation data from SAR sensors (no ground-based observations were available).*
- *Mapping of topographic change associated with volcanic activity at Soufrière Hills Volcano, Montserrat, demonstrating the use of InSAR for studying eruption volumes at long-lived andesitic eruptions.*
- *High-spatial-resolution mapping of flank motion at Arenal volcano, Costa Rica, which showed that landslides near the volcano summit are restricted to the steepest part of the edifice, but increase following ground shaking from large earthquakes (e.g. the 2012 Nicoya earthquake).*
- *Demonstrated the ability of high-resolution, high-repeat InSAR from the ComsoSkyMed to detect deformation related to conduit processes at basaltic volcanoes, using an explosive eruption at Masaya Lava Lake as an example. This analysis was retrospective, but demonstrated the ability of satellite observations to monitor rapid as well as long-term changes in volcanic systems.*
- *Measured topographic change associated with lava flows, lava dome growth, and other processes at numerous other volcanoes (Pacaya, Fuego and Santiaguito, Guatemala, Nevado del Ruiz, Colombia, Chaitén, Llaima, Villarrica, Copahue, Cordón Caulle, and Hudson volcanoes, Chile). Updating topographic maps is vital for*

hazards assessment and mitigation.

Objective 2 achievements:

- *Characterization of surface deformation associated with the May 2015 intrusion beneath the summit area of Kīlauea Volcano, Hawai'i, which provided the Hawaiian Volcano Observatory with an estimate of the volume and location of the magma body.*
- *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, and communication of that information to the Hawaiian Volcano Observatory, which combined the remote and ground-based data and released maps to the public.*

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)—200 scenes
RADARSAT-2 (moderate- to high-spatial-resolution C-band SAR)—270 scenes
COSMO-SkyMed (high-resolution X-band SAR constellation)—900 scenes
TerraSAR-X (high-resolution X-band SAR)—450 scenes
TanDEM-X (high-resolution X-band SAR with emphasis on topographic mapping)—150 scenes
Pleiades (very-high-resolution tri-stereo-optical visual data for topographic mapping)—no limit

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-7 and 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, European Space Agency FRINGE, International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), Chilean Geological Congress, DLR's International Symposium on the Remote Sensing of the Environment, 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, including training courses at the IG-EPN (Ecuador), OVSICORI (Costa Rica), SGC (Colombia), and during the Workshop on Volcanoes, in Quetzaltenango, Guatemala. In fact, one of the papers below—that of Naranjo et al., 2016—resulted directly from a 6-week visit by Susi Ebmeier to Ecuador in 2014. At the Cities on Volcanoes 9 meeting, held in Chile during November 2015, staff from volcano observatories throughout Latin America participated in a 3-day workshop, led by pilot team members, about the use of satellite data in volcano monitoring and eruption response. A similar 2-day workshop was held before the August 2017 International Association of Volcanology and Chemistry of the Earth's Interior Scientific Assembly.

Several scientific publications have resulted from pilot work, including:

Ebmeier, S. K., J. Biggs, C. Muller and G. Avard (2014). Thin-skinned mass-wasting responsible for edifice-wide deformation at Arenal Volcano, Frontiers in Earth Science, 2, 35, doi:10.3389/feart.2014.00035.

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.

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.

Naranjo, M. F., S. K. Ebmeier, S. Vallejo, P. Ramón, P. Mothes, J. Biggs and F Herrera (2016). Mapping and measuring lava volumes from 2002-2009 at El Reventador Volcano, Ecuador, from field measurements and satellite remote sensing. Journal of Applied Volcanology, 5, 8, doi:10.1186/s13617-016-0048-z.

Stephens, K. J., S. K. Ebmeier, N. K. Young, and J. Biggs (2017). Transient deformation associated with explosive eruption measured at Masaya volcano (Nicaragua) using Interferometric Synthetic Aperture Radar. Journal of Volcanology and Geothermal Research, doi:10.1016/j.jvolgeores.2017.05.014.

Wnuk, K., and C. Wauthier (2017). Surface deformation induced by magmatic processes at Pacaya Volcano, Guatemala revealed by InSAR. Journal of Volcanology and Geothermal Research, doi:10.1016/j.jvolgeores.2017.06.024.

Delgado F., M. E. Pritchard, S. Ebmeier, P. Gonzalez, and L. Lara (2017). Recent unrest (2002–2015) imaged by space geodesy at the highest risk Chilean volcanoes: Villarrica, Llaima, and Calbuco (Southern Andes). Journal of Volcanology and Geothermal Research, doi:10.1016/j.jvolgeores.2017.05.020.

Arnold, D.W.D., J. Biggs, K. Anderson, S. Vallejo Vargas, G. Wadge, S. K. Ebmeier, M. F. Naranjo, and P. Mothes (in review). Decaying lava extrusion rate at El Reventador Volcano, Ecuador measured using high-resolution satellite radar. Journal of Geophysicla Research.

Pritchard, M.E., J. Biggs, C. Wauthier, E. Sansosti, D.W.D Arnold, F. Delgado, S.K. Ebmeier, S.T. Henderson, K. Stephens, C. Cooper, K. Wnuk, F. Amelung, V. Aguilar, P. Mothes, O. Macedo, L.E. Lara, M.P. Poland, and S. Zoffoli (in review). Towards coordinated regional multi-satellite InSAR volcano observations: Results from the Latin America pilot project. Journal of Applied Volcanology.

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 it's 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 significant broad-scale deformation was occurring despite the initiation of eruptive activity—at Momotombo (Nicaragua) and Sabancaya (Perú), for instance. Volcanoes that were known *to be deforming, like Pacaya (Guatemala), Fernandina (Galápagos Islands), and Masaya (Nicaragua) were the focus of intensive study, which allowed for detailed mapping of the magmatic systems that feed eruptions. The same is true of volcanoes experiencing long-lived eruptions, like Soufrière Hills (Montserrat), Tungarahua (Ecuador), and Reventador (Ecuador).*

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). In some examples, InSAR data have been used to help set the volcano alert level, which in turn determines the response from Civil Protection Authorities. A significant challenge in increasing uptake of SAR data is the need for long-term, in-depth 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. Another challenge is to get processed data to the volcano observatories as quickly as possible.

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 and the* *limits to monitoring these heavily vegetated volcanoes with the commonly used 12 or 24 day repeat of Sentinel-1a/b (C-band). X-band satellites, particularly the Cosmo-SkyMed constellation, offer rapid repeat observations at high resolution, which is vital in providing timely information to volcano observatories and in detecting shallow processes preceding eruptions.*

- *Background SAR missions that are dedicated to volcano observation are essential, as examination of data from before unrest at any given volcano is important 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 (albeit not always with the optimal resolution or temporal repeat).*
- *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. Obtaining perpendicular baseline information before ordering SAR data from the CSK constellation would be extremely valuable, so as to know in advance which data pairs are best suited for InSAR processing.*
- *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.*
- *Close collaboration between research scientists, space agency representatives, and end users—especially scientists based at volcano observatories—is critical for transferring the insights from volcano remote sensing data to actions for mitigating volcanic hazards and risk. This collaboration may involve capacity building efforts to ensure that end users are able to best interpret and exploit the supplied data and derived products.*

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 with the specific job of coordinating EO observations of volcanoes. In the context of the pilot, these efforts were on a volunteer basis, undertaken by academic faculty and their graduate students.

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

1) <u>Pilot extension</u>. 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. The ultimate goal would be to expand beyond Latin America, but this vision is subject to the limitations of the academic scientists who are volunteering their time and energy for the project.*

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. If data quotas continue to be made available, however, the option can be made more viable by recruiting additional partners to help with data processing, interpretation, and outreach to volcano observatories (especially in developing nations). Engaging numerous partners would be critical for spreading the workload and ensuring that lapses in funding to individual researchers would not result in an interruption in the project.

Option (2) is possible only if funding is made available to support dedicated employees, and if 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. The potential availability of researchers from ASI is a positive step towards this possibility, as is interest expressed by the U.S. Geological Survey's Volcano Disaster Assistance Program (VDAP).

Next Steps

The major lesson of the volcano pilot is that with sufficient access to data and effort provided by partners to process and interpret those data, volcanic activity can be detected and sometimes forecast. This information, when made available to the local volcano observatories tasked with hazards assessment and mitigation, provides critical input to decisions related to alert levels, deployment of ground-based sensors, and protection of people, property, and resources. The volcano pilot demonstrated that the remote sensing data had value and caused the end-users at volcano observatories to do some things differently than they would have without satellite data. Further, the pilot demonstrated that there is useful data being collected by satellites that is not being exploited by observatories.

The obvious next step for the CEOS volcano pilot is to shed the "pilot" status and expand beyond Latin America to operational global monitoring of volcanic activity from space. Such an evolution can only happen in stages, as the current team and its practices were established over years to maintain an effort in Latin America, and because there is little funding or dedicated staff available. We therefore propose to scale the Latin America Pilot Project to Global over a period of several years, adding additional partners as necessary to ensure success of the project. Our proposal is as follows:

1) *During the first year, we will continue working with volcano observatories in Latin*

America on data analysis and, especially, capacity building, so that the observatories may ultimately process and interpret remote sensing data themselves. We will also continue to develop partnerships with research institutions around the world who are interested in contributing to a global monitoring effort, perhaps through the auspices of the new International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Commission on Volcano Geodesy. Leveraging the existing efforts of these institutions can help to fill gaps in global volcano monitoring.

2) *The second year will see expansion of operational monitoring efforts to volcanoes in Africa. A number of volcanoes in this region are deforming, and eruptions with attendant thermal and gas emissions are common. Local scientists and volcano monitoring agencies in Africa have little ability to use remote sensing data (and in some countries like Tanzania, there are no volcano observatories), so providing this information, and training local users in the derivation and interpretation of Earth observation imagery, is of critical importance to volcano monitoring efforts.*
3) *The third and fourth years of the project will see expansion to Indonesia and the Philippines—both countries with abundant volcanic activity but little ability for the update of remote sensing. Training can be done in coordination with the U.S. Geological Survey's Volcano Disaster Assistance Program, which has established contacts in both locations, and by recruiting partners at institutions with active research programs in southeast Asia.*
4) *By the fifth year, we expect to have demonstrated that global volcano monitoring from space is possible, and we hope to have engaged agencies with a volcano monitoring mandate in establishing a permanent and funded program to sustain global volcano monitoring from space.*

Additional factors to consider in this strategy for ramping the pilot effort from regional to global include:

- *We will not focus attention on developed countries, including the United States, Japan, and those in Europe, which already have sufficient resources and expertise in remote sensing of volcanic activity. Instead, our focus will be on the highest-risk volcanoes in developing nations.*
- *The quotas of SAR data needed for successful implementation of this vision will not simply be scaled, based on the Latin American pilot project, by the numbers of volcanoes in the countries to which monitoring will be expanded, but rather the hazard potential, activity history, and environment of those volcanoes. This analysis will be an ongoing effort.*
- *The primary need in this expansion will be for SAR and very-high-resolution optical data, which are not freely available in most cases. We will continue to make use of thermal and visible data, however, especially through existing global monitoring programs, like MODVOLC, VOLCAT, and the ASTER Volcano Archive. In so doing, we hope to demonstrate the continued need for these tools, emphasizing that continued support from the responsible agencies is vital.*
- *A particular focus will be topographic data, which is of use not only for detecting changes due to emplacement of volcanic deposits, but also for assessing hazards due to mass flows (like lava, lahars, and pyroclastic density currents).*
- *We will better integrate our efforts with the Geohazards Supersites and Natural Laboratories (GSNL) initiative. For example, the GSNL Ecuadorian Volcanoes Supersite already provides data for several high-risk volcanoes in Ecuador, and GSNL Supersite proposals have been submitted for studying volcanoes in the southern Andes*

and the Kivu Basin of east Africa. In these cases, a framework between data providers, experts, and end users may already exist.

- *Capacity building will continue to be a priority, with the goal of making volcano observatories and/or research institutions (in the absence of dedicated observatories) in developing countries self-sufficient with respect to obtaining, processing, and interpreting remote sensing data. This will be accomplished through a variety of efforts, ranging from workshops and site visits to training of students.*

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 Vulcanologio y Seismologico 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 Agustin de Arequipa (Perú)
(Referring to the ongoing eruptive activity at Sabancaya volcano)

8. "We use these [InSAR] data sets for different purposes. The main ones are: to inform our executive authorities about the findings of the activity at Masaya volcano related to the most recent unrest and that we are not capable to produce by ourselves; to learn ourselves about the behavior of our volcanoes during particular volcanic activities; to help us to better locate our ground monitoring instruments so that we can better capture the volcano activity signal; and to correlate with data sets from other sensors"

- Armando Saballos, Dirección Gral. de Geología y Geofísica, INETER (Nicaragua)
(Referring to the use of InSAR data for monitoring Masaya volcano)

9. "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)