GROUP ON EARTH OBSERVATIONS

GEO Disaster Resilience SBA

GSNL - Geohazard Supersites and Natural Laboratories

Biennial report for Candidate/Permanent Supersite

Hawai'i Supersite

Status	*Permanent*
Proposal documents	*http://www.earthobservations.org/documents/gsnl/proposals/Hawaii_proposal.pdf*
Acceptance letter(s)	*http://www.earthobservations.org/documents/gsnl/proposals/Hawaii_notification_letter.pdf*
Previous reviews	*http://www.earthobservations.org/documents/gsnl/proposals/Hawaii_biennial_review_report_2012_2014.pdf*
Point of Contact	*Michael Poland (mpoland@usgs.gov)* *USGS – Cascades Volcano Observatory* *1300 SE Cardinal Ct,, Suite 100* *Vancouver, WA 98683 USA*

Science teams

Falk Amelung	Department of Marine Geosciences, Rosenstiel School Of Marine And Atmospheric Sciences, University of Miami, 4600 Rickenbacker Causeway, Miami, Fl, 33149, USA, famelung@rsmas.miami.edu, http://www.rsmas.miami.edu/personal/famelung/Home.html
Simone Atzori	Istituto Nazionale di Geofisica e Vulcanologia, via di Vigna Murata 605, Roma, 00143, ITALY, simone.atzori@ingv.it
Scott Baker	UNAVCO, 6350 Nautilus Drive, Boulder, CO 80301, USA, baker@unavco.org
Yunmeng Cao	Central South University, Changsha, Hunan, 410083, CHINA, ymcch93@gmail.com
Gilda Currenti	Istituto Nazionale di Geofisica e Vulcanologia, Piazza Roma 2, Catania, 95125, ITALY, gilda.currenti@ct.ingv.it, http://www.ct.ingv.it/en/component/content/article/97-curriculumpersonale/600-currenti-gilda.html
Kurt Feigl	Department of Geoscience, University of Wisconsin – Madison, 1215 W Dayton St, Madison, WI, 53706, USA, feigl@wisc.edu, http://geoscience.wisc.edu/geoscience/people/faculty/feigl
Liu Guang	Institute of Remote sensing and Digital Earth, Chinese Academy of Sciences, No.9 Dengzhuang South Road, Haidian District, Beijing, 100094, CHINA, liuguang@radi.ac.cn
Hyung-Sup Jung	Department of Geoinformatics, The University of Seoul, 90 Jeonnong-dong, Dongdaemun-gu, Seoul 130-743, REPUBLIC OF KOREA, e-mail: hsjung@uos.ac.kr
Paul Lundgren	Jet Propulsion Laboratory, M/S 300-233, 4800 Oak Grove Drive, Pasadena, CA 91109, USA, paul.r.lundgren@jpl.nasa.gov, https://science.jpl.nasa.gov/people/Lundgren/
Michael Poland	USGS – Cascades Volcano Observatory, 1300 SE Cardinal Ct., Suite 100, Vancouver, WA 98683, USA, mpoland@usgs.gov, https://profile.usgs.gov/mpoland/
Sergey Samsonov	Canada Centre for Mapping and Earth Observation, Natural Resources Canada, 560 Rochester Street, Ottawa, ON K1A 0E4, CANADA, sergey.samsonov@nrcan-rncan.gc.ca,

	http://www.insar.ca/
Eugenio Sansosti	National Research Council (CNR), Istituto per il Rilevamento Elettromagnetico dell'Ambiente, IREA – CNR, via Diocleziano, 328, Napoli, 80124, ITALY, sansosti.e@irea.cnr.it, http://www.irea.cnr.it/en/index.php?option=com_comprofiler&task=userprofile&user=119&Itemid=100
Manoochehr Shirzaei	School of Earth and Space Exploration, Arizona State University, PO Box 876004 , Tempe, AZ 85287-6004, USA, shirzaei@asu.edu, http://ratlab.asu.edu/
Antonio Valentino	Advanced REmote-sensing SYStems, Via Bistolfi 49, Milano, 20134, ITALY, antonio.valentino@aresys.it
Thomas Walter	Deutsches GeoForschungsZentrum GFZ, Telegrafenberg, 14473 Potsdam, GERMANY, thomas.walter@gfz-potsdam.de, http://www.gfz-potsdam.de/en/section/physics-of-earthquakes-and-volcanoes/staff/profil/thomas-walter/
Bing Xu	School of Geoscience and Info-physics, Central South University, Changsha, Hunan, 410083, CHINA, xubing@csu.edu.cn
Howard Zebker	Stanford University, 397 Panama Mall, Mitchell Building 101, Stanford, CA 94305-2210, USA, zebker@stanford.edu, https://profiles.stanford.edu/howard-zebker

Science team issues

- The science team has remained static since the last biennial report. A goal for the next reporting period is to refresh the roster of science teams working on the project by identifying those groups that continue to actively research Hawaiian volcanism and attracting new teams to the Supersite. There is also a need to improve communication between the PoC and the science teams, perhaps through a listserv or some regular group email (for example, to share results or recent relevant publications). There has been little anomalous volcanic activity in Hawaii during the past 2 years (not including the lava flow crisis in Pahoa during 2014-2015, which, with a few exceptions, was more germane to geological and sociological studies than geophysical research), and work on Hawaiian volcanism will increase significantly during the next eruption of Mauna Loa, or during the next intrusion or change in the current eruption at Kīlauea. Such activity is likely during 2017–2018, given the high levels of inflation and seismicity at both volcanoes.

- The science teams behave independently, and there is no mechanism in place to facilitate communication between teams. A potential solution to this issue would be to hold a workshop or coordination meeting, or to propose a formal project along the lines of the Icelandic and Italian volcano supersites (Futurevolc and MED_SUV, respectively). There is little funding available for such a project, so it may be that electronic communications or side meetings during other events (for example, the Fall AGU meeting) are the best ways to ensure improved collaboration between science teams. Any new volcanic activity in Hawai'i will also certainly stimulate a desire for data (both space- and ground-based) and bring the community together to better understand the change in volcanism.

In situ data

Type of data	Data provider	How to access	Type of access

GPS	*USGS – HVO*	*UNAVCO*	*Unregistered public*
Seismic	*USGS – HVO*	*IRIS*	*Unregistered public*
Gas emissions	*USGS – HVO*	*Published USGS Open-File Reports**	*Unregistered public*
Gravity	*USGS – HVO*	*Published manuscripts**	*Unregistered public*
Tilt	*USGS – HVO*	*Contact USGS – HVO***	*GSNL scientists*
Camera	*USGS – HVO*	*Contact USGS – HVO***	*GSNL scientists*
Strain	*USGS – HVO*	*Contact USGS – HVO***	*GSNL scientists*

** Denotes data that are only released when published because significant data processing is necessary to achieve useable results. Peer review is necessary to assure the quality of the processed data.*
*** Denotes data that are not made publically available due to lack of a suitable archive, but that can be obtained through collaboration with scientists at the USGS Hawaiian Volcano Observatory*

In situ data issues

A few datasets, like gas emissions and gravity, require significant post-processing. Because of the need for stringent quality control, such data are not made publically available until they have been through the peer review process and published (either in academic journals or USGS Open-File Reports). Other datasets, including tilt, visual/thermal camera, and strain, are only available by contacting the data provider, since there are no established archives or agreed-upon formats for storing such data. The data may also be difficult to understand, requiring the provider to offer guidance on processing and interpretation to ensure that the user can meet their objectives.

Satellite data

Type of data	Data provider	How to access	Type of access
ENVISAT	*ESA*	*http://eo-virtual-archive4.esa.int/?q=Hawaii*	*Registered public*
RADARSAT-1	*CSA*	*Supersites web page**	*Registered public*
ALOS-1	*JAXA*	*Supersites web page**	*Registered public*
TerraSAR-X	*DLR*	*Available after acceptance of PI proposal by DLR*	*GSNL scientists*
Cosmo-SKyMed	*ASI*	*POC requests access from ASI for individual users, data then accessible via UNAVCO*	*GSNL scientists*
RADARSAT-2	*CSA*	*POC requests access from CSA for individual users, data then accessible via UNAVCO*	*GSNL scientists*
ALOS-2	*JAXA*	*https://auig2.jaxa.jp/ips/home*	*GSNL scientists*
Sentinel-1 a/b	*ESA*	*https://scihub.copernicus.eu/*	*Registered public*

NOTE: This list only includes SAR data, which typically require payment or approval of a research proposal. Freely available data (e.g., MODIS, Landsat) are not listed.
** Interface for downloading Radarsat-1 and ALOS-1 data does list available scenes, but clicking the link for a given image results in an error.*

Satellite data issues

The same issues that existed during the previous reporting period (2012–2014) still exist during the current reporting period (2014–2016), namely:

- Links to RADARSAT-1 and ALOS-1 data on the Supersite website do not work. That there have been no complaints about this, however, suggests that the page is not being used to download data.

- There is no streamlined method for requesting user access to SAR data; each space agency has a different access policy, some of which require PoC approval (e.g., ASI and CSA), others of which do not (e.g., DLR). A single method for "joining" a Supersite and accessing restricted data (mostly SAR imagery) would be preferable, but would obviously be difficult to implement.

- There is no Supersite-specific archive for non-SAR satellite data, like EO-1, Landsat, MODIS, ASTER, and other usually free datasets (although the USGS Hazards Data Distribution System has been stockpiling some imagery of Kīlauea since 2014). This imagery constitutes an important source of information for synergistic studies using SAR and ground-based data. Developing an archive for visual and thermal remote sensing data, as well as other relevant resources (e.g., DEMs), would be an important next step in growing the Hawai'i Supersite to a new level of capability and utility.

Research results

The Hawai'i Supersite proposal emphasized the complementary nature of space-based, airborne, and ground-based data as a tool for investigating large-scale research questions related to Hawaiian volcanism—namely, the nature of magma supply to Hawaiian volcanoes; the best indicators of an impending change in eruptive activity; improving predictions of the timing, magnitude, and location of eruptions; and the relation between volcanic and tectonic activity. After four years as a permanent Supersite, all of these questions have received considerable attention. For example, magma supply to Kīlauea has been found to fluctuate on timescales of just a few years, and changes in supply have a direct impact on eruptive activity. Inflation of Kīlauea was found to promote failure of nearby faults, triggering M4+ earthquakes. Deformation and seismicity have been used to construct a map of magma storage and transport at both Kīlauea and Mauna Loa volcanoes, providing a basis upon which to interpret past, present, and future monitoring data. Many of these insights may not have been achievable without the support of the numerous space agencies and research institutions that have contributed data to the Hawai'i Supersite.

In addition to these "big picture" questions, the wealth of available data opened a number of additional, smaller-scale processes for scrutiny, and also promoted the development of non-traditional uses of SAR data. For example, in September 2015, a small (~30-m-diameter) pit crater opened without warning within ~1 km of the summit access road on the south flank of Mauna Kea volcano (which has not erupted in over 4000 years). RADARSAT-2 was the only SAR satellite acquiring data over the region at sufficiently high resolution to image the new crater, and examining RADARSAT-2 SAR amplitude imagery helped to narrow the formation time of the feature. Further, interferometry using RADARSAT-2 data revealed a small amount of subsidence at the site of the pit crater in the months prior to its formation. This result suggests that it may be possible to detect the impending formation of pit craters by looking for small-scale subsidence features in high-resolution SAR data.

RADARSAT-2 data also helped to develop a means of mapping lava flows over time. In 2014, when a lava flow from Kīlauea invaded a forested area on its way towards the village of Pāhoa, the usual means of identifying lava flow activity using InSAR—incoherence—was no longer useful because the forest was also incoherent. Co-polarized amplitude imagery was also not helpful, since lava and vegetation had the same backscatter characteristics. The two surfaces were easily distinguishable in cross-polarized images, however. By combining the cross-polarized amplitude data from acquisitions on two different dates with the interferometric coherence between those dates in a three-band image (band1=date1_HV_amplitude; band2=date2_HV_amplitude; band3=date1-date2_coherence), it is possible to identify areas of lava flow activity regardless of where that activity occurs (in both vegetated and unvegetated areas). After being proven using RADARSAT-2 imagery, this procedure has been put into operational practice using regularly acquired Sentinel-1a/b data, thereby providing a new means of mapping lava flow activity at any time of day and during any type of weather. This is especially important in an era of shrinking budgets, when helicopter visits for observing remote lava flow activity are not always possible. Tracking lava flows can also be accomplished using data form the TanDEM-X mission, which is capable of mapping topographic changes over time. By summing these topographic changes, it is possible to derive the lava discharge rate—one of the most fundamental parameters of interest for forecasting lava flow hazards.

More "traditional" use of SAR data also yielded insights into the dynamics of Hawaiian volcanism. For example, in May 2015, a small intrusion of magma occurred beneath the south part of Kīlauea Caldera. The intrusion was preceded by several weeks of surface inflation and rising lava level within the summit eruptive vent. Inflation was tracked by tilt, GPS, and InSAR, and was associated with abundant seismicity, changes in gas emissions, and increases in gravity, while visual and thermal cameras monitored the rising lava lake, which eventually overtopped the vent rim and began spreading lava onto the floor of Halemaʻumaʻu Crater. Cosmo-SkyMed and Sentinel-1a data proved especially valuable in tracking the activity, as images were acquired during the transition from inflation to intrusion. These data were available very soon after they were acquired, which aided with hazards assessments by the Hawaiian Volcano Observatory during the intrusion. Subsequent modeling of the deformation has helped to elucidate aspects of Kīlauea's magma plumbing system.

Despite these success stories, synergistic exploitation of Supersite data is still in a nascent stage. For example, SAR and other thermal/visual data acquired from space are rarely combined to better

understand volcanic processes. In addition, the large SAR dataset—probably the largest for any volcanic area in the world—has only begun to be used for development of new techniques (a noteworthy success in this regard is mapping 3D displacements via multiple-aperture interferometry). Continued operation of the Hawaiʻi Supersite, however, should lead to more work in these areas by providing the means for aiding technological developments and stimulating innovative usage of the vast catalog of available data.

MORE INFORMATION ON RESEARCH RESULTS IS AVAILABLE IN THE ANNEX TO THIS REPORT

Publications

Peer reviewed journal articles

Wauthier, C., Roman, D.C., and Poland, M.P., 2016, Joint analysis of geodetic and earthquake fault-plane solution data to constrain magmatic sources: A case study from Kīlauea Volcano: Earth and Planetary Science Letters, v. 455, p. 38–48, doi:10.1016/j.epsl.2016.09.011.

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Lin, G., Amelung, F., Shearer, P.M., and Okubo, P.G., 2015, Location and size of the shallow magma reservoir beneath Kīlauea caldera, constraints from near-source Vp/Vs ratios: Geophysical Research Letters, v. 42, no. 20, p. 8349–8357, doi:10.1002/2015GL065802.

Jo, M.-J., Jung, H.-S., Won, J.-S., and Lundgren, P., 2015, Measurement of three-dimensional surface deformation by Cosmo-SkyMed X-band radar interferometry; Application to the March 2011 Kamoamoa fissure eruption, Kīlauea Volcano, Hawai'i: Remote Sensing of Environment, v. 169, p. 176–191, doi:10.1016/j.rse.2015.08.003.

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González, P.J., Samsonov, S.V., and Palano, M., 2014, The 2012 Kilauea volcano, Hawaiʻi, slow-slip event captured by cGPS and satellite radar interferometry: Mathematics of Planet Earth (Lecture Notes in Earth System Sciences), p. 373–376, doi:10.1007/978-3-642-32408-6_83.

Conference presentations/proceedings
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…
…

NOTE: It would be impossible to list all presentations that make use of Hawaiʻi Supersite data (there would be several dozen), especially without direct input from science team members; therefore, the table has been left blank. The most important research results are contained within the publication list.

Research products

In a strict sense, the Hawaiʻi Supersite has yet to directly produce any formal community research products. The data have been used by individual investigators to develop products, however, which are having an impact on the overall field. Chief among these are:

- new methods for extracting three-dimensional displacement data from SAR imagery

- deformation maps and time series generated by numerous investigators, but particularly by the Jet Propulsion Laboratory's ARIA (Advanced Rapid Imaging and Analysis) project

- schemes for mapping change due to active volcanism, particularly associated with the emplacement of lava flows (via coherence, amplitude, and topographic data)

- strategies for modeling atmospheric delay based on GPS and UAVSAR data collected in October 2016

Because these products are either in development for release as part of InSAR processing software (for example, Multiple Aperture Interferometry methods) or are primary research results or operational tools with specific applications (for example, interferometry time series, topographic change due to lava flow emplacement, and atmospheric modeling strategies), they should not yet be considered research products, and the table below has been left blank.

Type of product	Product provider	How to access	Type of access
e.g. ground deformation time series, source model, etc.	*Name of scientist(s)*	*Link to publication, research product repository or description of procedure for access*	*E.g. public, registered, limited to GSNL scientists, etc.*
…	…	…	…
…	…	…	…

Research product issues

There are currently few publically available research products for the Hawai'i Supersite. Deformation maps and time series generated by the JPL ARIA project are still in development, and so are only open to JPL scientists and their collaborators. The WInSAR consortium of UNAVCO provides a portal for users to upload and assign DOI numbers to products, like interferograms and time series (https://winsar.unavco.org/portal/insar/), but users have yet to take widespread advantage of this resource. Several investigators have provided links to time series and deformation maps on their personal websites. Most Supersite researchers, however, have yet to make products available beyond their own publications (although published data are, in most respects, considered open source, and so should be available in manuscript supplements or by contacting the authors). Funding, staff, and other assistance are needed to assist with the dissemination of research products. Few organizations have the funding to develop a resource to its full potential, especially once the research has been published (the "end game" for many scientists). The only exceptions include projects that have been created to specifically develop a resource—for example, the GMTSAR software from the Scripps Oceanographic Institution (the code was tested using data from the Hawai'i Supersite) and the JPL ARIA project (which will eventually provide research products to the scientific community; this happens regularly for events, like earthquakes, but not yet for ongoing processes, like eruptions and unrest episodes at Hawaiian volcanoes)—but these are few in number.

Dissemination and outreach

The primary means of informing the public of the existence and benefits of the Hawai'i Supersite are outreach efforts, including newspaper articles and lectures. For example, public presentations on the Island of Hawai'i as part of "Volcano Awareness Month" (every January) and weekly "Volcano Watch" newspaper articles have highlighted the benefit of the Supersite for the assessment and mitigation of volcanic hazards in Hawai'i, and also the greater understanding of Hawaiian volcanoes that the

Supersite makes possible (through better access to data and by attracting scientific innovators to work on those data). Outreach to the scientific community has done via conference presentations (highlighting the available datasets and encouraging their exploitation) and personal visits to research institutions and universities around the world, where Supersite researchers share their results and encourage new users to participate in the work. These efforts have yielded fruit. For example, researchers at the GFZ German Research Center for Geosciences are interested in examining localized deformation of actively erupting volcanic vents using GPS and high-resolution X-band SAR data, and researchers at the University of Leeds (U.K.) have advertised for a Ph.D. student to study SAR amplitude imagery as a tool for better understanding volcanism in Hawai'i (and elsewhere by extension).

Funding

There is no dedicated nor specific funding for the Hawai'i Supersite. The Volcano Hazards Program of the U.S. Geological Survey, however, supports the Supersite by directing the PoC (who is a USGS employee) to manage the effort and cultivate a user community. This includes the use of funds from the Volcano Hazards Program's InSAR project to archive and manage SAR data from Hawai'i and to build computing resources for SAR data processing and analysis. Individual project scientists have obtained research funding from various organizations—like the U.S. National Science Foundation—and have leveraged the availability of Supersite data in their proposals, but no proposals that were specifically targeted to exploit the Hawai'i Supersite have been submitted.

Societal benefits

The most direct beneficiary of the Hawai'i Supersite is the U.S. Geological Survey's Hawaiian Volcano Observatory (HVO). Founded, in 1912, HVO maintains a dense network of geophysical stations around the island (which have been made available to the Supersite) and also collects geochemical and geological data on volcanic and seismic activity. These measurements fulfill a US Congressional mandate (the Stafford Act) to provide volcano and earthquake hazard warnings, supported by research, to local populations, emergency managers, and land-use planners. SAR data constitute a critical resource for this monitoring and research, but would be cost-prohibitive if not for the Supersite.

HVO communicates hazards information, much of which is aided by Supersite data, to a number of other organizations—primarily the National Park Service and Hawai'i County Civil Defense. These agencies are tasked with managing responses to volcanic and earthquake crises in the lands they oversee, while HVO is responsible for providing the information needed by responders to make decisions. This level of cooperative interaction was on display in 2014–2015 during the Pāhoa lava flow crisis, when lava nearly inundated a community on the Island of Hawai'i. Supersite data helped to assess the changing state of summit deformation, which was directly tied to lava effusion rate (and therefore lava flow advance rate), and also to map lava flow activity during periods of inclement *weather, when direct observations were not possible. When a new phase of lava flow activity began in mid-2016, Supersite data (specifically, TanDEM-X results) were used to build a new topographic map of the lava flow field (accounting for recent lava flows that modified the landscape since the last whole-island Digital Elevation Model was acquired in 2005). This new map was used to chart the likely path of the new lava flow and was communicated to Hawai'i Volcanoes National Park, Hawai'i County Civil Defense, and the general public (via HVO's website) to keep all land managers and Park visitors aware of lava flow hazards.*

Supersite data also contribute to the development of interpretations that are communicated to the public as part of daily volcanic activity updates, weekly newspaper articles, online content, and community outreach events (presentations, open houses, exhibits, etc.).

Conclusive remarks and suggestions for improvement

As demonstrated by the publications list, the Hawai'i Supersite continues to generate high-quality scientific products that have had a profound impact on understanding of Hawaiian volcanism and have also contributed critical input to hazards assessments and mitigation efforts in Hawai'i. Chief among the success stories are:

- *understanding of magma supply variations to Kīlauea Volcano and the impact of these variations on eruptive activity*

- *elucidation of the magma plumbing systems at Kīlauea and Mauna Loa volcanoes, which provide an essential framework for interpreting past, present, and future unrest*

- *investigations into interactions between magmatism and tectonism at Hawaiian volcanoes*

- *tracking of geophysical changes—especially deformation and seismicity—at Kīlauea and Mauna Loa, which provides situational awareness of potential future eruptions or changes to ongoing eruptions*

- *development of new tools for tracking lava flow emplacement, including both areal coverage and effusion rate, and implementation of these tools in an operational framework to aid volcano monitoring efforts*

- *testing of new algorithms for determining 3D displacements from InSAR data*

- *high-resolution views of small-scale processes, including the formation and evolution of pit craters (at both Kīlauea and Mauna Kea)*

Despite these successes, a few issues continue to prevent the full realization of the Hawai'i Supersite:

- The scientific teams operate independently, and so there is no organized effort to promote any specific scientific goals. Improved coordination between investigators could generate better exploitation of research opportunities and collaboration between scientists.

- There is no specific funding for the Hawai'i Supersite, outside of that provided in-kind by the U.S. Geological Survey to support the efforts of the PoC. If funding were available, it could be used to better organize the user community and support collaborations and better dissemination of results.

- The website for the Hawai'i Supersite is static and has not been updated in some time (in addition, a number of links are broken, including those pointing to RADARSAT-1 and ALOS-1 data). A more dynamic web presence would allow for posting of research results and products, and it could also be used for dissemination and outreach efforts aimed at not only scientific users and agencies, but also stakeholders and the general public.

A few operational challenges also exist:

- The quota of RADARSAT-2 data for the Hawai'i Supersite has been exhausted.

- The relationship between the PoC's TanDEM-X PI proposal and the Supersite is not clear—are TanDEM-X data obtained by the PoC available for distribution to registered Supersite users, or should interested scientists order the data using separate PI accounts, as is the case with TerraSAR-X requests?

- Non-SAR satellite data from Hawai'i are not archived anywhere. Such an archive would facilitate data fusion efforts that would merge SAR, visual, and thermal remote sensing imagery to gain new insights into Hawaiian volcanism.

- There is no archive for supporting data, like DEMs, which could be useful to Hawai'i Supersite investigators, as well as the general public and stakeholders.

These challenges should not dissuade support for the continued operation of the Hawai'i Supersite, however, given the great weight of the successes and the certainty that future efforts will build on the extensive record of work completed thus far. Insights from Supersite data have become invaluable to stakeholders on the Island of Hawai'i, and results provide exceptional fodder for scientific research into how volcanoes work. Future exploitation of the Supersite will open new avenues for investigating Hawaiian volcanism, as well as how the synergy between space-, air-, and ground-based datasets can be optimized to provide insights into assessing, forecasting, and mitigating volcanic hazards.

DATA REQUESTS FOR FUTURE OPERATIONS

Based on the record of success presented above, the Hawai'i Supersite requests continued allocation of SAR data from international space agencies for research into volcanic processes and hazards. This would include:

- <u>TerraSAR-X</u> acquisitions every 11 days on 2 tracks (one ascending and one descending) covering the summit of Kīlauea Volcano.

- <u>Cosmo-SkyMed</u> acquisitions as frequently as possible on two tracks (one ascending and one descending), with Mauna Loa imaged every 16 days on each track and Kīlauea's summit imaged 2–3 times per 16 days on each track.

- A new allocation of <u>RADARSAT-2</u> scenes, which will be used to investigate past (since 2015) and future deformation of both Kīlauea and Mauna Loa. An additional 200 scenes would bring the Supersite "up to date" on several key viewing angles, providing a continuous set of C-band observations since 2008 (a unique dataset, and one capable of providing a long-term perspective of several important episodes of activity, including the onset of inflation at Mauna Loa in 2014, and the transition from deflation to inflation of Kilauea in the early 2010s.

- <u>Sentinel-1a/b</u> data are freely available, and a limited number of <u>ALOS-2</u> scenes is available to the PoC and selected members of the scientific team via "Research Announcement" projects, so no specific requests for those data are necessary.