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PERSPECTIVES

Volcano geodesy using InSAR in 2020: the past and next decades

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Abstract
The study of volcano deformation has grown significantly through they year 2020 since the development of interferometric synthetic aperture radar (InSAR) in the 1990s. This relatively new data source, which provides evidence of changes in subsurface magma storage and pressure without the need for ground-based equipment, has matured during the past decade. It now provides a means to address previously inaccessible questions and offers input to increasingly complex models of magmatic processes. Here, we review how technological advances in InSAR during 2010-2020 have facilitated our ability to monitor and interpret volcanic processes, primarily through rapid and accurate observations of the changing surfaces at active volcanoes worldwide. Specifically, we examine how current systems achieve excellent resolution in time and space, provide global coverage, and generate products that are easy to use by non-specialists—factors that have often limited the practical study of volcanoes using radar measurements. We also look to the future, offering our perspective about how advancements in technology and data management in the decade to come will increase the value and accessibility of InSAR applied to the geodetic study of volcanoes and monitoring of hazardous volcanic processes. New developments will include the launch of additional satellites by both public space agencies and private companies, as well as implementation of algorithms for exploiting the growing volumes of data. To meet their full potential, these efforts will require coordination between data users and data providers so that the relevant imagery is acquired, made available to volcanologists in a timely fashion, and utilized to assess and mitigate volcanic hazards.

Keywords Volcano geodesy · Deformation · InSAR · Interferometric synthetic aperture radar

Introduction

Within a year of the introduction of interferometric synthetic aperture radar (InSAR) as a tool for mapping earthquake displacements in 1994 (Massonnet et al. 1994), the first interferograms of volcanic deformation were published—of apparent deflation at Mount Etna, Italy (Massonnet et al. 1995). Although subsequent analysis found that a significant component of the apparent deflation signal was due to atmospheric path delay (Delacourt et al. 1998; Massonnet and Feigl 1998; Beauducel et al. 2000), the implications were clear: InSAR offered a means of assessing volcano deformation on a previously unimagined scale. It was suddenly possible to map deformation at volcanoes globally, regardless of the status of ground-based monitoring. There were still complications, of course; results are poor in heavily vegetated areas unless a long radar wavelength (especially L-band, versus the shorter C- and X-bands) is used. In addition, snow and ice cover confound the method, sensitivity to along-track (~ north–south) displacements is low, and data are not collected consistently over all volcanoes of interest. Nevertheless, InSAR was a game changer in volcanology, and application of the technique grew rapidly (Pinel et al. 2014). The discovery of many deforming volcanoes demonstrated how the measurements could be used to identify sources of potential future eruptions and has focused research and monitoring efforts on sites that otherwise may have been overlooked (e.g., Wicks et al. 2002; Dzurisin 2003; Pritchard and Simons 2004; Pritchard

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Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

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et al. 2018). An early and striking example was the recognition of widespread and rapid deformation of volcanoes in the Galápagos archipelago (Amelung et al. 2000), which prompted the installation of ground-based monitoring and fueled research into the dynamics of magma accumulation, dike emplacement, and eruption by generations of volcanologists (e.g., Jónsson et al. 1999; Chadwick et al. 2006; Geist et al. 2006; Jónsson 2009; Bagnardi et al. 2013; Davis et al. 2021). Importantly, these discoveries were not limited to remote unmonitored volcanoes. The recognition of uplift near South Sister volcano, Oregon, demonstrated the presence of an active magma body in an area previously thought to be dormant, despite a record of past ground-based monitoring (Wicks et al. 2002; Dzurisin et al. 2006, 2009; Lisowski et al. 2021).

Further SAR sensor development and the availability of large volumes of SAR data led to new insights into volcanic processes, especially when InSAR was combined with other datasets, like seismology, gas geochemistry, and physical volcanology (Kilbride et al. 2016). Used in response to volcanic crises, SAR-derived products including deformation, amplitude, interferometric coherence, and topography have contributed to successful forecasts of volcanic eruptions and are credited with saving thousands of lives (Pallister et al. 2013). We build on previous reviews (e.g., Massonnet and Sigmundsson 2000; Zebker et al. 2000; Pinel et al. 2014) and explore the evolution of satellite SAR and InSAR as applied to volcanology during the 2010s and explore the potential of the field in the 2020s. Future advances in SAR instruments and processing methods are inevitable, but exploiting these improvements will require commensurate investments in data handling and availability; otherwise, we risk underutilizing a vital resource for assessing and mitigating volcanic hazards around the world.

2010–2020: the decade that was

During the 2010s, use of InSAR in volcanology experienced an important transition, evolving from a tool used for research to one that could also be applied for timely monitoring of volcanic unrest and eruption. This evolution was fueled by developments in satellite capabilities as well as data availability and analysis methods. The most significant advance was the free availability of frequent and regular SAR data to the community—for the first time, monitoring agencies and research groups alike could rely on a steady flow of observations supporting both scientific research and hazards assessment and mitigation.

Sensor developments

The beginning of the 2010s saw a changing of the guard in terms of satellite SAR. The 2000s were dominated by the C-band ASAR instrument on the ENVISAT satellite and the L-band PALSAR instrument on the ALOS-1 satellite. Both satellites failed in 2011, leaving the C-band RADARSAT-2, which was launched in 2007, as the remaining source of long-term satellite SAR data. In the late 2000s, two X-band systems, TerraSAR-X and COSMO-SkyMed, were launched, and throughout the 2010s, they provided SAR imagery with spatial resolutions of a few meters (and in some cases less than a meter!). These data were used to highlight very localized deformation that would not otherwise have been detected by ground instruments or moderate-resolution SAR (Richter et al. 2013; Salzer et al. 2014), but they are only available at a limited number of volcanoes. By the middle of the decade, the L-band ALOS-2 satellite and C-band Sentinel-1 satellites had been launched. The major volcanological innovations offered by Sentinel-1 were frequent and consistent repeat observations of nearly all volcanoes on Earth, albeit at moderate (~ 15 m) spatial resolution. ALOS-2 provided a new source of L-band imagery, which had been absent since the failure of ALOS-1, at a range of spatial scales but with inconsistent and infrequent repeat intervals. Nevertheless, the combination of targeted high-resolution X-band data, broad systematic C-band coverage, and sporadic L-band acquisitions provided a suite of information that facilitated new applications in volcanology. It was during this decade that InSAR transitioned from a research application to a tool that could be applied to timely monitoring of volcanic hazards. For example, InSAR data acquired during dike emplacement events in Iceland (2014) and Hawai‘i (2018) provided deformation data that revealed the staggering scope of magmatic intrusions before they erupted, triggering the months-long Holuhraun (Sigmundsson et al. 2015) and Kīlauea lower East Rift Zone (Neal et al. 2019; Fig. 1) eruptions, respectively.

Data availability and analysis

Two community efforts opened access to satellite SAR for volcanology in the 2010s. First, the Geohazard Supersites and Natural Laboratory (GSNL) initiative established a network of volcano "supersites" (listed at https://geo-gsnl.org/), where SAR images were freely available and could be used in combination with other volcanological data (Dumont et al. 2018; Dzurisin et al. 2019). Second, the Committee on Earth Observing Satellites (CEOS) Volcano Pilot and Demonstrator projects made available satellite SAR data first from Latin America, and then also from southwest Asia and Africa, allowing for detailed examination of volcanoes

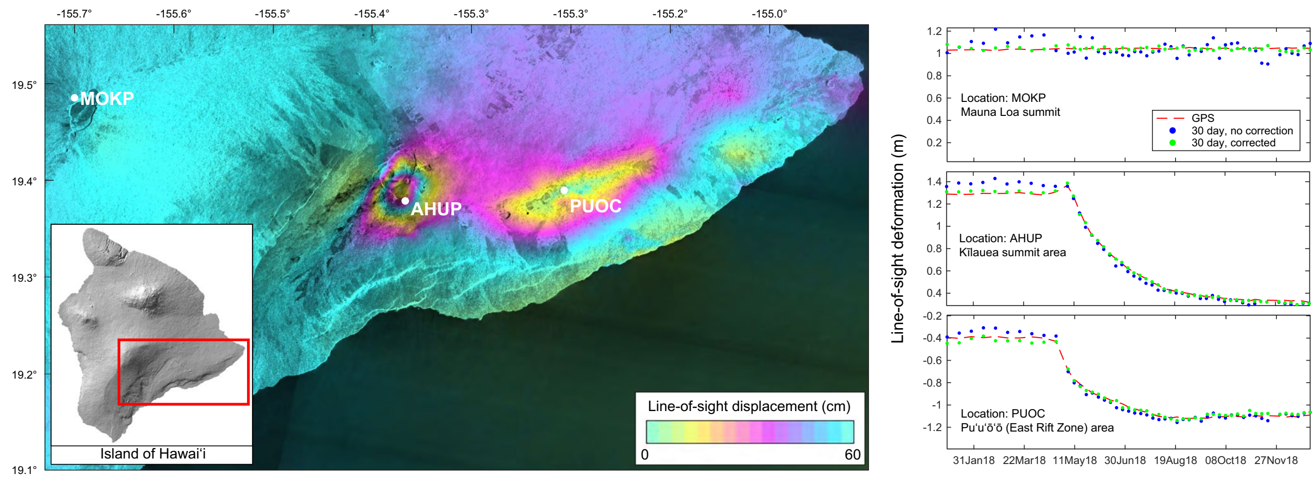

Fig. 1 Cumulative deformation over 2018 at Hawai'i's Kīlauea Volcano, at its summit and along its East Rift Zone, as observed by Sentinel-1 InSAR (left). Labeled white dots give locations of GPS stations used for reference to time series. Comparison of GPS (red dashed lines) and InSAR time series (green and blue dots based on maximum 30-day temporal separation) show centimeter-level accuracy of InSAR time series when a tropospheric propagation correction (green dots) is applied (right). Figure and method adapted from Zebker (2021)

throughout that region and laying the groundwork for a better understanding of how satellite data in general might be used to monitor volcanoes (Pritchard et al. 2018; Reath et al. 2019). Although these initiatives cover only a small proportion of active volcanoes worldwide, they illustrate the potential of SAR data in volcano monitoring and research when utilized more fully than is possible via projects driven by single investigators or in response to isolated episodes of unrest or eruptive activity. The growing availability of InSAR results from volcanoes also led to an explosion (pun intended) in knowledge of the widespread nature of volcano deformation. In the 20 years between 1997 and 2017, the number of volcanoes known to have experienced some sort of surface deformation expanded from 44 to over 220 (Biggs and Pritchard 2017). Analyses of this growing database provided evidence of the strong connection between deformation and eruption (Biggs et al. 2014), the varied styles of magmatic and non-magmatic volcano deformation (Ebmeier et al. 2018), and the recognition that deformation served as a pre-eruptive phenomenon far more often and for a longer period than any other satellite dataset (Furtney et al. 2018).

The sheer volume of satellite SAR data created a new challenge: how could these data best be utilized? Several parallel developments emerged to aid data management. Multi-temporal analyses capitalized on growing computational power to generate spatially and temporally dense time series of ground deformation using persistent scattering (Hooper et al. 2012; Spaans and Hooper 2016) and small baseline subset analysis (Berardino et al. 2002). Implementation of automated processing engines (Lazecký et al. 2020) and artificial intelligence approaches enabled users to automatically scan many thousands interferograms for indications of anomalous surface displacements (e.g., Anantrasirichai et al. 2018, 2019; Gaddes et al. 2018, 2019), increasing the likelihood that deformation of a volcano is detected. Corrections for atmospheric conditions also became widely available, aiding interpretation of InSAR results that might otherwise be ambiguous, especially on tall and steep volcanic edifices (Yu et al. 2018; Yip et al. 2019). In addition, the advent of user-friendly InSAR products yielded measurements in common coordinates rather than the radar-specific slant range and Doppler system, allowing non-specialists to take advantage of the powerful observing capabilities without requiring deep training in the details of radar technology (Zebker 2017).

2020–2030: the decade to be

The 2020s will see new satellite missions that provide additional capacity for InSAR monitoring of active volcanism, and missions developed by fully private enterprises will materially contribute to SAR data and capabilities. Exploiting the growing trove of SAR data for volcano monitoring and research will require coordination and cooperation among data providers and users, as well as continued development of resources that take advantage of all aspects of SAR and InSAR.

Sensor developments

The most anticipated technological advance in satellite SAR in the 2020s will undoubtedly be offered by NISAR (NASA-ISRO Synthetic Aperture Radar), an L- and

S-band satellite mission currently hoped for launch in 2023 but more likely to fly in 2024. NISAR will acquire repeat L-band (24-cm wavelength) data every 12 days over nearly all subaerial volcanoes on Earth, offering a swath width of 240 km, resolution of 3–10 m, single/dual/quad polarimetry, and open data access (Rosen et al. 2017). Additional S-band (12-cm wavelength) data will be available on a select group of potentially active volcanoes. Both of these longer wavelengths are less sensitive to surface decorrelation and will reveal deformation unseen by shorter-wavelength radars. Although the acquisition of L-band satellite SAR is not new—SeaSat, JERS, ALOS-1, ALOS-2, and SAOCOM all did or do carry L-band SAR sensors—the reliable worldwide coverage and free availability set NISAR apart. In fact, the massive quantity of data itself will pose a challenge, since the mission will generate more data than any other NASA mission by far (Jasper and Xaypraseuth 2017).

Sentinel-1 continuity through follow-on missions from the European Space Agency (ESA) will extend the current capability of consistent, global, freely accessible C-band SAR for 30 years, far outpacing NISAR's planned 3 years. It is highly likely that NISAR will last much longer than 3 years, however, and NASA is already planning NISAR's successor through a Surface Deformation and Change study. ESA will undoubtedly improve the capabilities of each new generation of Sentinel satellites, providing an ever-increasing ability to observe volcanoes through all stages of the eruption cycle. For example, ESA's proposed Earth Explorer 10 Harmony mission would combine with Sentinel-1 to provide repeat topography and better resolution of along-track displacements—both critical datasets for volcano surveillance (Kubanek et al. 2021; López-Dekker et al. 2021).

We also expect private development of SAR capabilities to flourish during 2020–2030, following the precedent of entrepreneurial space launches. As of 2021, two commercial companies, ICEYE and Capella, are acquiring X-band SAR data of selected targets through constellations of smallsats that will eventually number in the tens of spacecraft. Both companies have offered data in support of volcanic crises, specifically for the 2021 eruptions of Soufrière, St. Vincent, and Nyiragongo, Democratic Republic of Congo. These and similar private companies will eventually achieve daily or better SAR coverage of any location on Earth. Such dense spatiotemporal coverage will represent a new era in satellite SAR monitoring of volcanic activity, provided that data are acquired and available to the volcanology community in advance of a crisis and on a consistent, instead of ad hoc, basis. The rapid response by international space agencies to unrest and eruption at Merapi volcano, Indonesia, in 2020–2021, provides an example of the value of such a response. High-resolution SAR data that would not otherwise have been available were freely provided and used to identify localized but high-rate displacements on the flanks of the volcano (Fig. 2). This information was communicated to local volcanologists monitoring the eruption and aided their response to the crisis, offering important constraints on potential hazards, especially given the lack of monitoring instruments located on the upper flanks of the volcano and the danger in accessing those areas during the crisis.

With these developments in satellites and sensors, volcanologists must not become overly reliant on any single dataset but rather continue to take advantage of all satellite SAR data. The mix of available wavelengths, repeat intervals, and spatial resolutions that is currently and will become available through the 2020s offers the best opportunity for detecting the variety of potential surface changes that might precede, accompany, and follow volcanic eruptions.

Data availability and analysis

Three capabilities are needed from satellite SAR systems to aid with responses to volcanic unrest and eruptions: (1) flexible and responsive acquisition planning, including regular background observations that are appropriate for each volcano, (2) low-latency data delivery, and (3) free access. Current methods for tasking and accessing SAR data are heterogeneous, and no system is completely optimized for providing the "right" data at the "right" time of the "right" place and for the "right" price. Near-global and consistent dense temporal repeatability from Sentinel-like systems greatly reduces the need to specifically target volcanoes in advance of an eruption, but these broad views are not appropriate in all situations. Small island volcanoes, for example, require higher-resolution views than are available from current satellite missions with global background coverage. Targeting flexibility is therefore critical for fine-resolution, limited-coverage satellite systems that can best image small volcanic systems with localized activity.

Especially during a volcanic crisis, rapid delivery of satellite data is vital. Real- and near-real-time satellite monitoring of thermal and ash emissions are a cornerstone of detecting eruptions, especially at remote volcanoes (Poland et al. 2020), but all SAR data have a latency. As of the early 2020s, only Sentinel-1 and COSMO-SkyMed offer delivery of the full complex dataset within a few hours of acquisition, at least in ideal situations. Many other satellite SAR systems can provide at least amplitude data within hours in cases where the International Charter: Space and Major Disasters is invoked. In addition, only Sentinel-1 data are 100% openly accessible. Other satellite SAR datasets must be accessed via special initiatives, like the GSNL or CEOS projects (Pritchard et al. 2018), or via research agreements, although such proposals do not typically allow for open-ended response-style data usage. For satellite SAR to be

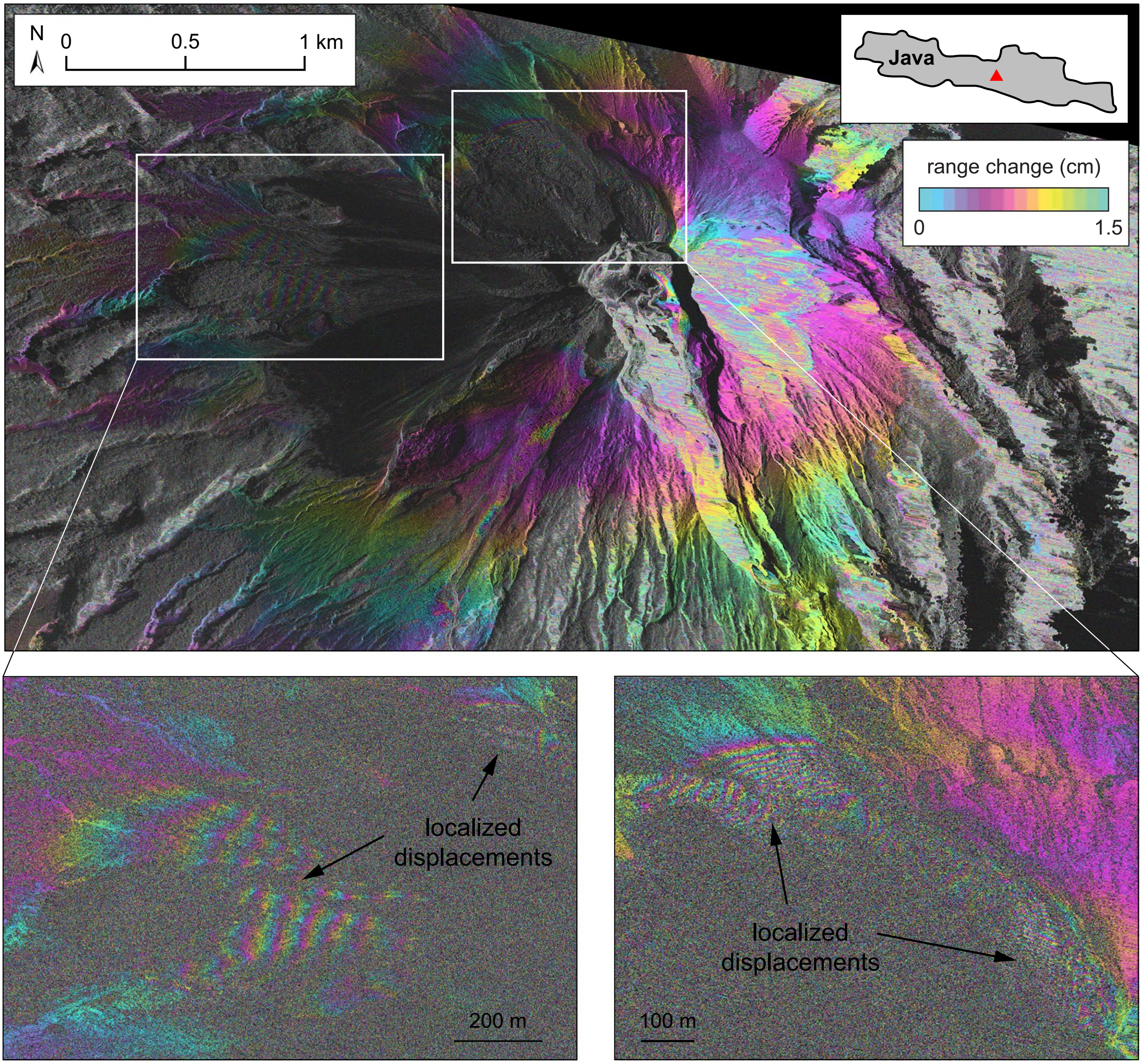

Fig. 2 TerraSAR-X staring-spotlight interferogram of Merapi volcano, Indonesia, spanning November 16–27, 2020. Upper image shows phase change overlain on amplitude. Zoomed frames show only phase change and highlight multiple areas of localized high-rate deformation on the volcano's west flank that could not be easily detected by limited ground-based datasets

fully integrated into volcano monitoring, they must be freely available to monitoring agencies.

The capabilities outlined above require coordination among the volcanology community and collaboration with space agencies and private companies. Thus far, international work on volcano monitoring with satellite SAR has been done by individual investigators, or on a "best effort" basis without specific funding through the GSNL and CEOS Volcano Pilot/Demonstrator projects—efforts that are neither sustainable nor robust and that do not meet the needs of the global volcanology community and of populations at risk from volcanic eruptions. A formal coordination office, akin to that organized by the polar science community, for managing satellite SAR datasets could serve as a liaison between space agencies (private and public) and the scientists/institutions tasked with volcano monitoring and crisis response. This point-of-contact approach, ideally with some redundancy spread around the world to ensure rapid responses across time zones, would facilitate communication, ensure that conflicting acquisitions are not scheduled, provide a mechanism for managing datasets and user licenses that respects investments of the contributing space agencies and private companies, and ensure feedback and accountability between data providers and users. A coordination office could also encourage capacity building at volcano observatories and monitoring agencies that might not be able to independently process, analyze, or interpret satellite SAR data.

Of course, commensurate developments will continue in analysis methods. Automated processing and anomaly detection are already a reality, thanks to advances in computing power and artificial intelligence approaches, but these methods are not yet implemented at the scale of global volcano monitoring. We expect that within the decade of the 2020s, operational use of such techniques will be implemented.

Satellite SAR volcano monitoring must also extend beyond interferometry. It has long been known that SAR data from volcanoes offer more information than merely phase changes caused by surface deformation—for example, providing insights into surface characteristics and volcanic activity from coherence (Zebker et al. 1996; Dietterich et al. 2012), backscatter (Pallister et al. 2013; Arnold et al. 2018), and topographic change (Kubanek et al. 2021; López-Dekker et al. 2021). Capitalizing on all aspects of the richness of SAR data is the only way to fully exploit their utility for monitoring volcanic unrest and eruptions and to best serve societal needs for volcanic hazards assessment and mitigation.

Conclusions

The 2010-2020 decade has seen great strides in our ability to measure, monitor, and understand volcanoes. Space-based InSAR permits worldwide observation of entire volcanic systems at fine resolution and offers direct measurements of how a surface deforms under stresses due to migration of magma or subsurface pressure changes. InSAR has matured from a limited research tool to a capability that is applied to monitoring and mitigating volcanic hazards.

The availability of free and comprehensive crustal deformation observations, most notably from Sentinel-1, has led to an explosion in new analysis methods that characterize change at the centimeter level, promising a chance at timely forecasts and the development of hazard warning tools. New SAR systems on the drawing board for the next decade and in today's production facilities will provide long-term continuous coverage at several wavelengths, with commercial and specialized SAR systems providing a range of imaging options that will facilitate flexible responses to threatening volcanic activity. For these data to be useful in volcanology, however, they must be accessible to scientists in a timely fashion—a task that will require robust communication, coordination, and collaboration between monitoring agencies, research institutes, space agencies, and private companies.

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Declarations

Competing interests The authors declare no competing interests.

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