Applications of Bistatic Radar to Volcano Topography—A Review of Ten Years of TanDEM-X

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Abstract—The TanDEM-X satellite mission has revolutionized DEM generation from spaceborne synthetic aperture radar. In addition to the primary objective of generating a consistent digital elevation model with global coverage and unprecedented accuracy, the mission has acquired time series of topographic data over several volcanoes, providing an excellent opportunity to test the use of this innovative dataset for volcano monitoring and research. In this article, we review the utilization of the single-pass TanDEM-X data for studying various kinds of volcanic activity, such as basaltic lava flows, the formation and destruction of lava domes and related pyroclastic density currents, and subsurface magma withdrawal and intrusion. We then consider the uses of these data for hazard assessment and forecasting. Our goal is to highlight the importance of timely and repeated topographic information in volcanology, and to suggest the development of future spaceborne bistatic synthetic aperture radar satellite missions, such as ESA's Earth Explorer 10 candidate mission, “Harmony.”

Index Terms—Bistatic synthetic aperture radar (SAR) interferometry, Earth Explorer 10 Harmony, future missions, TanDEM-X, topographic change, volcano research.

NOMENCLATURE

ASI Agenzia Spaziale Italiana.
ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer.
CEOS Committee on Earth Observation Satellites.
CoSSC Coregistered Single look Slant range Complex.
CSA Canadian Space Agency.
CSK COSMO-SkyMed.
DEM Digital Elevation Model.
DIAPASON Differential Interferometric Automated Process Applied to Survey Of Nature.

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I. INTRODUCTION

TOPOGRAHY is among the most fundamental datasets in volcanology, with applications to mapping deposits and assessing hazards. Measurements of changes in topography are comparatively rare, however, meaning that accurately estimating eruption volumes and effusion rates remains a major challenge in volcanology. Prior to the Shuttle Radar Topography Mission (SRTM) in 2000 [1], topographic data at volcanoes varied widely in quality and availability, and for some volcanoes no useful data were available. Even now, repeat topographic measurements at...
erupting volcanoes remain rare, even though differencing of derived digital elevation models (DEMs) can provide quantifica-
tion of topographic changes over time—information that offers
valuable insight into eruption dynamics and related volcanic
hazards that might not otherwise be available.

A well-known example of the use of repeat topographic
surveys is the 2004–2008 eruption of Mount St. Helens, in
Washington, USA [2]. Vertical aerial photogrammetry was used
to generate a total of 17 DEMs during the first 1.5 years of
crisis. A comparison with pre-eruption DEMs enabled the as-
sessment of volume changes associated with lava dome growth
and destruction. The DEMs and derived information, also
generated from oblique terrestrial and aerial imagery, were
one of the most widely used datasets during the eruption [3]–[7],
demonstrating the importance of topographic information for
hazard assessment and risk reduction. In fact, these data were
vital to creation of physicochemical models of the Mount St.
Helens magma system that helped to constrain magma reservoir
volume, recharge status, and volatile content [8], [9]. This dataset
is, to the best of authors’ knowledge, the best to date in terms of
periodic sampling of time-series topographic change at an active volcano.

The generation of such an important dataset was only possible
because baseline data and the photogrammetric infrastructure
were already in place before the onset of the eruption [2]. This
is only feasible for a limited number of well-instrumented
and accessible volcanoes worldwide. Furthermore, meteorological
clouds, as well as plumes of ash and gas emitted during an
eruption, often prevent photogrammetric approaches that are
based on optical imagery, whether acquired from the ground,
air, or space.

Satellite-based synthetic-aperture radar (SAR) provides an
other source for measuring topographic changes, either through
analysing variations in the amplitude of the complex SAR
data [10]–[12], or using interferometry (InSAR) to generate
DEMs. From the phase difference between two radar images
of the same target area, it is possible to generate a DEM with
meter-level accuracy [13]. The cloud-penetrating characteristics
and potential global coverage make satellite radar an ideal
method for deriving topography and topographic change over
active volcanoes.

An increasing number of SAR satellite missions, such as
Sentinel-1 A and B from the European Space Agency (ESA),
the German Aerospace Center’s (DLR’s) TerraSAR-X, ALOS-2
Palsar-2 from the Japan Aerospace Exploration Agency
(JAXA), COSMO-SkyMed (CSK) from the Agenzia Spaziale
Italiana (ASI), and the Radarsat Constellation Mission (RCM)
from the Canadian Space Agency (CSA) acquire SAR data with
different wavelengths and temporal repeat intervals that range
from 1 to several days. The data are typically used to map defor-
mation between two or more acquisitions separated in time [14],
[15], but are also sensitive to changes in topography that have
occurred since a reference DEM was collected, provided that the
two acquisitions were made from slightly different positions in
space. Unfortunately, most missions are designed for monitoring
surface deformation, such as the Sentinel-1 mission, where spa-
tial baselines are kept intentionally short, meaning that the data
are not very sensitive to topography and, thus, not optimal for
DEM generation. As long as the backscattering conditions on the
ground and atmospheric conditions remain stable, and the spatial
baseline is long enough, repeat-pass InSAR provides useful
results for measuring topographic change at volcanoes [16]–
[19]. The surface around erupting volcanoes, however, often
changes rapidly due to ashfall, lava flows, dome collapse,
and explosions, reducing the coherence between acquisitions made
at different times and hindering (or even preventing)
interferogram generation [19]–[22]. Two SAR images acquired during
a single pass (simultaneously acquired, or bistatic, data) are,
therefore, necessary to reliably derive topographic information
for fast-changing environments, like volcanoes [19], [23].

The first spaceborne attempt to generate short-temporal
baseline interferograms took place in 1994 with the SIR-C/X-
SAR mission (Shuttle Imaging Radar with Payload C/X-SAR).
Another attempt was made a few years later during the ERS-1/2
(European Remote Sensing Satellite 1/2) tandem phase. These
data, however, still were incoherent in places due to vegetation,
volcanic activity, etc., highlighting once again the need for
bistatic acquisitions (i.e., [19]). The first comprehensive satellite
bistatic SAR data were acquired in 2000 by SRTM, which pro-
vided near-global topography at 1 arc second resolution between
latitudes of 60° N and 56° S [1]. Unfortunately, SRTM was not
designed for long-term repeat topography measurements, as the
mission flew on the Space Shuttle only once. Another major
step forward in the quantification of global topography occurred
with the launch of the German Earth observation TanDEM-X
(TerraSAR-X add-on for Digital Elevation Measurements) satel-
life mission in June 2010 [24]. As a long-term mission,
TanDEM-X not only provided global topography at 12 m reso-
lution, it also offered the opportunity to map topographic change
over time, including at numerous volcanoes worldwide.

This article gives an overview of the volcanology applica-
tions of ten years of repeat TanDEM-X acquisitions. Following
an introduction to topographic data generation with bistatic
TanDEM-X imagery, we present applications to active vol-
canism. We also summarize studies where TanDEM-X data
were combined with other data, such as DEMs generated from
structure from motion (SfM), repeat-pass InSAR, or the Pléiades
satellite mission, to estimate topographic change. We also give
an overview of the challenges in using TanDEM-X data to
study active volcanoes. We close by advocating for the devel-
ropment of future SAR satellite missions capable of acquiring
time-series topographic data, such as ESA’s Earth Explorer 10
mission proposal “Harmony,” which was submitted as Stereo
Thermo-Optically Enhanced Radar for Earth, Ocean, Ice, and
land Dynamics (STEREOID) by the scientific community [25],
[26].

II. TOPOGRAPHIC CHANGE FROM SPACE

TanDEM-X is the first radar system to enable the consist-
tent and repeated generation of topographic information from
space. Two almost identical satellites, TerraSAR-X (TSX) and
TanDEM-X (TDX), fly in a close helical formation. In bistatic
mode, one satellite, i.e., the active satellite, emits the electro-
magnetic signal while both satellites serve as receivers [24]
Fig. 1. Bistatic TanDEM-X data for repeated DEM generation. The two satellites TerraSAR-X (TSX) and TanDEM-X (TDX) fly in formation and acquire two SAR images simultaneously during every overflight. The phase information of both radar images is used to calculate the interferometric phase, from which a DEM is generated for each acquisition time. Differencing the DEMs calculated over time enables the assessment of topographic changes.

TABLE I

| Volcano          | Mean Coherence of TanDEM-X Scenes | Number of Scenes |
|------------------|-----------------------------------|-----------------|
| Merapi           | 0.76                              | 3               |
| Volcán de Colima | 0.70                              | 28              |
| Tolbachik        | 0.87                              | 18              |
| Shiveluch        | 0.81                              | 45              |

A. General Data Processing Considerations

The mean coherence for selected scenes around several volcanoes is given in Table I. A coherence of 0.6 is generally acceptable for interferometric analysis and sufficient for good phase unwrapping quality [27]. Differences in coherence are mainly caused by land cover types. Soil and rock show generally higher values than rain forests. The common error sources that influence the interferometric performance of single-pass SAR systems, such as (thermal) noise, volume decorrelation, quantization errors, and baseline decorrelation errors are investigated in detail in [27].

The general principles for processing bistatic TanDEM-X data are displayed in Fig. 1. Two radar images are acquired simultaneously during each fly over of the satellite pair. The phase information from both acquisitions is used to calculate the interferometric phase $\phi$. In the repeat-pass (monostatic) acquisition geometry, $\phi$ is calculated as

$$\phi = -\frac{4\pi}{\lambda} \Delta R$$

(1)

where $\Delta R = R_1 - R_2$ is the difference in the path length of the signal. $R_1$ and $R_2$ are the slant-range distances for both satellites, i.e., the distance between each satellite and the target in the line-of-sight (LOS). $\lambda$ is the wavelength, which is 3.1 cm for X-band (used by the TerraSAR-X and TanDEM-X satellites). The factor $4\pi$ results from the range distance for the transmitted and received signal, while the satellite transmits and receives during both fly-overs.

In the single-pass (bistatic) case, this numerator reduces to 2, leading to

$$\phi = -\frac{2\pi}{\lambda} \Delta R.$$  

(2)

The changing numerator from (1) to (2) results from the fact that in monostatic mode, one satellite emits and receives the signal during two fly overs and serves each time as receiver. In contrast, in bistatic mode, only one satellite emits and both satellites receive the signal.

The difference between bistatic and monostatic acquisition mode can be approximated using half the length of the perpendicular baseline $B_{\perp}$, which is also referred to as the effective baseline $B_{\text{eff}}$ for bistatic TanDEM-X products. The perpendicular baseline $B_{\perp}$ is defined as the theoretical distance between the satellites at the time of recording perpendicular to the look direction, whereas the baseline $B$ is the real distance between the satellite positions (see also Fig. 1). As the height of ambiguity $h_{\text{amb}}$, i.e., the height difference between two adjacent discontinuities, is inversely proportional to the perpendicular baseline, $h_{\text{amb}}$ is increased with smaller $B_{\perp}$, reflecting the decreased sensitivity of the bistatic compared to monostatic case.
Fig. 2. Example images showing intermediate products that are generated when processing a bistatic TanDEM-X CoSSC data pair. The example here shows Merapi on Java, Indonesia. (a) Backscatter image, (b) ambiguous wrapped phase $\phi$, (c) interferometric phase after unwrapping $\phi_{\text{unw}}$ and phase to height conversion, and (d) coherence. All images are still in slant range (radar) geometry.

From the unwrapped interferometric phase $\phi_{\text{unw}}$, i.e., the absolute, measured phase wrapped to the $[-\pi, \pi]$-interval, the terrain height $h$ is derived according to

$$h = -\frac{\lambda R \sin \theta}{4\pi B_{\perp}} \phi_{\text{unw}}$$

with the slant range distance $R$ and the incidence angle $\theta$. This is an approximation based on the parallel ray approximation and is only valid for planar 2-D orbits [30].

The differential phase $\phi_{\text{mon}}$ in the repeat-pass interferometric phase is composed of [31]

$$\phi_{\text{mon}} = \phi_{\text{ref}} + \phi_{\text{topo}} + \phi_{\text{disp}} + \phi_{\text{atmo}} + \phi_{\text{scat}} + \phi_{\text{orb}} + \phi_{\text{noise}}$$

with the reference phase $\phi_{\text{ref}}$, i.e., the phase caused by the reference surface [World Geodetic System 1984 (WGS84)], the topographic phase change $\phi_{\text{topo}}$, the phase change due to the displacement of the ground scatterer in the LOS of the satellite $\phi_{\text{disp}}$, the phase change contribution due to atmospheric delays $\phi_{\text{atmo}}$, a phase change due to the changing backscattering properties on the ground $\phi_{\text{scat}}$, a phase change due to orbit errors $\phi_{\text{orb}}$, and finally phase noise $\phi_{\text{noise}}$. This noise term is thermal and can generally lead to phase measurement errors, but the effects can easily be evaluated and removed [32].

For single-pass interferometry, the temporal baseline between two acquisitions, $B_{\text{temp}} = 0$, meaning $\phi_{\text{disp}} = \phi_{\text{atmo}} = \phi_{\text{scat}} = 0$. Consequently, the interferometric phase $\phi_{\text{bi}}$ only consists of the reference phase $\phi_{\text{ref}}$, the topographic phase change $\phi_{\text{topo}}$, the phase noise $\phi_{\text{noise}}$, and $\phi_{\text{orb}}$, and (4) reduces to

$$\phi_{\text{bi}} = \phi_{\text{ref}} + \phi_{\text{topo}} + \phi_{\text{noise}} + \phi_{\text{orb}}.$$  

The term $\phi_{\text{orb}}$ depends on the effective baseline between acquisitions, which for bistatic mode is half the length of the perpendicular baseline. The satellite orbits of current SAR missions, such as of the TerraSAR-X and TanDEM-X satellites, are estimated with an orbit accuracy of better than 10 cm for precise science orbits [33]. Errors in $\phi_{\text{orb}}$ are, therefore, considered to be insignificant.

Altogether, this improves the signal to noise ratio and enables the derivation of a DEM from every fly-over of the satellite pair (see Fig. 1). Fig. 2 displays example images of the intermediate products that are generated when processing a bistatic TanDEM-X data pair, including backscatter, wrapped phase, height, and coherence. The complex raw data of the TanDEM-X mission are provided as coregistered single look slant range complex (CoSSC) files [34]. The data can be processed using different SAR software, for instance, GAMMA [35], [36], the Differential Interferometric Automated Process Applied to Survey Of Nature (DIAPASON) [37], [38], SARScape [39], [40], or the Delft
Object-oriented Radar Interferometric Software (DORIS) [41], [42].

For TanDEM-X, the orbital repeat interval is 11 days, which in theory means that a DEM could be produced over a specific site using the same acquisition geometry every 11 days. As volcano monitoring was not a driver of the TanDEM-X satellite mission, only selected volcanoes were observed repeatedly, resulting in a time-series of DEMs for these sites. Data over other selected volcanoes were also acquired when a dedicated proposal was submitted or during phases of increased activity.

The choice of acquisition geometry (i.e., ascending or descending track) depends both on the satellite configuration and the volcanic system. Steep-sided edifices cause foreshortening and layover in radar images, meaning ascending geometries produce better results on the eastern side of volcanic edifices and descending geometries perform better on the western flanks. This was, for instance, seen while using TanDEM-X data to study Volcán de Colima [43], [44], and is also described in [45]. Furthermore, the orbits of the satellites cross at the poles, which can lead to short effective baselines $B_{\text{eff}}$ at high latitudes and results in low height sensitivity [24]. Ascending and descending acquisition geometries are always suitable for mapping equatorial regions (including, for instance, Merapi in Indonesia and Volcán de Colima in Mexico), but only one acquisition geometry is suitable for mapping high latitudes at any given time. At the start of the TanDEM-X satellite mission in 2010, the ascending orbit was favorable for the northern hemisphere, but the satellite formation was swapped between August 2013 and April 2014 to enable utilization of the opposite acquisition geometry for generating the WorldDEM [29]. This was particularly useful to fill gaps in difficult terrain, such as valleys, mountains, and areas characterized by dense vegetation [46], [47]. The swap was realized by a 180° shift of the libration phase in the Helix formation [24]. This swap made the descending orbit the favorable geometry for high-northern latitudes and the ascending orbit for high southern latitudes. After acquisitions for the global DEM were finalized, a dedicated science phase to test different acquisition geometries, such as very long across-track baselines, followed (see, e.g., [48], [49] for reference).

III. APPLICATIONS TO VOLCANO TOPOGRAPHY

Differencing DEMs over time enables study of topographic changes associated with volcanic eruptions, from which volumes of erupted products can be estimated and other parameters, like magmatic ascent rates, derived (see Fig. 3). Here, we give an overview of the variety of volcanic phenomena that were studied with TanDEM-X DEMs over the past ten years. We have chosen to organize the review by eruptive phenomenon, rather than by the problem that we might be addressing, so that interested users may more easily identify specific situations of interest. We conclude the section with a description of the uncertainties of the TanDEM-X data and derived products to highlight the suitability of the data for volcano topography applications.

A. Lava Domes

Lava domes are one of the most hazardous phenomena in volcanology owing to their tendency to collapse unexpectedly, generating dangerous pyroclastic density currents (PDCs). Dome-building eruptions are episodic and can be cyclic and range in duration from weeks to decades, during which phases of long-term effusive dome growth are interrupted by dome collapses [50]. Although quantitative knowledge of the mass transport through the volcanic system is essential to assess the eruption dynamics of dome-building volcanoes, data are often very difficult and expensive to retrieve with ground-based or airborne methods (see, e.g., [2], [50]–[53].

TanDEM-X has great potential to give better insight into lava-dome eruptions, including both the growth of lava domes and their effusion rates as well as collapses and related PDCs. Studies of dome growth and destruction at Shiveluch, Merapi, and Volcán de Colima provide instructive examples of the importance of repeat topographic data for monitoring and research of lava domes.

1) Growth of Volcanic Domes: The Shiveluch massif (56.653° N, 161.36° E) in Kamchatka, Russia, is a stratovolcano and is one of the largest and most active volcanoes of the peninsula [see Fig. 4(a)]. It is located in the northern part of the Central Kamchatka Depression at the junction of the Aleutian and Kamchatka volcanic arcs [54]. Since 1964, volcanic activity has been characterized by periods of lava dome growth, fumarolic activity, and explosive eruptions.

The most recent eruptive phase began in 1999 and is ongoing. A new lava dome started to form in May 2001. The research by [54] highlights that studies of this latest dome-forming period are rare. The authors analyzed this most recent phase of dome growth and provided morphometric measurements derived from photogrammetric processing of stereo photographs.

The study by [55] is, to the best of authors’ knowledge, the first that used TanDEM-X data to monitor a growing lava dome. The authors used TanDEM-X data to generate a time-series of DEMs to study dome growth, destruction, and related lava flows and PDCs at Shiveluch between June 2011 and September 2014 (see also [56]). During this time, a total of 85 bistatic scenes were acquired along the ascending track and 77 along the descending orbit. Due to geometric constraints from the side-looking acquisition geometry, the lava dome area was studied using data acquired from the descending orbit, and the lava flows and PDCs were analyzed using data acquired along the ascending orbit. Fig. 4(b) shows the topographic change mapped from data
acquired on July 26, 2011 and August 21, 2014. The maximum dome growth was measured to be over 200 m and the calculated volume increase of the lava dome was $94.4 \pm 4 \times 10^6$ m$^3$. Fig. 4(c) shows cross sections of the growing lava dome for selected DEMs and includes SRTM data (2000) as reference. The time series highlights changes in dome growth patterns—for example, the time period spanned was initially characterized by lava dome growth to the south, but this switched to growth in the dome’s northern part after 2013. Based on these data, the dome effusion rate reached a maximum of $2.4 \pm 2.4 \times 10^6$ m$^3$/day.

2) Lava Dome Destruction: Merapi (7.542°S, 110.442°E, Fig. 5), in Central Java, is one of Indonesia’s most dangerous volcanoes and one of the most hazardous worldwide due to the high population density combined with the type of volcanic activity. Merapi’s 2010 eruption was initiated with a major explosion, leading to a topographic change of about $-200$ m in the summit area. The eruption was one of the first eruptions in which satellite data, including SAR, were rapidly analyzed to monitor morphological and topographic changes in support of volcanic hazards assessment [10]. The amplitude of the complex SAR data from TerraSAR-X and RADARSAT-1 was used to monitor the lava dome and support warnings that probably saved thousands of lives. A description about how this information was used in near-real time to support evacuation plans during the eruption is given by [10]. The summit area of Merapi changed drastically during the 2010 eruption [see Fig. 5(d) and (e)]. Before the activity, Merapi’s morphology was that of a classic conical stratovolcano with a small lava dome on top. In contrast, the post-eruption topography of the summit was characterized by a crater rim with two peaks to the east (higher) and west (lower) with an intervening crater about 200 m deep [see Fig. 5(a)].

TanDEM-X data acquired before and after the 2010 eruption were used to quantify the large accompanying topographic changes [57].
(pre-eruption), October 24, 2011, and November 4, 2011 (both post-eruption), were processed and clearly showed the topographic changes in backscatter images. Fig. 5(b) and (c), respectively, shows the topographic change map and cross-sections across the summit from DEMs derived from these data. The volume change in the summit area due to the eruption was $-18.9 \times 10^6 \text{m}^3 \pm 0.4 \times 10^6 \text{m}^3$. The calculated volume changes caused by the eruption are consistent with the analyses carried out by [10].

Another example where TanDEM-X data were successfully used to analyze topographic changes due to lava dome destruction is given in [58] and [44]. Volcán de Colima ($19.513^\circ \text{N}, 103.587^\circ \text{W}$) is located approximately 30 km north of the city of Colima in western Mexico. The volcano is an andesitic stratovolcano—one of the most active volcanoes in North America—and poses a high risk to the local population because its PDCs have reached distances of up to 15 km from the summit [59].

TanDEM-X data were used to study the end of the 2007–2011 eruptive period. After four phases of lava dome growth, a small explosion occurred on June 26, 2011, on the western crater rim [60]. The explosion led to a topographic decrease of up to 20 m. Fig. 6(a) shows Volcán de Colima’s summit area with the dome nested in the crater. The photograph was taken during a fly-over with a light airplane in November 2012 and shows the dome topography and crater after the June 2011 explosion studied by [58] and [44]. Photographs of Colima’s lava dome before and after the eruption can be found in [60].

Two pre-eruption DEMs from data acquired on June 8 and 19, 2011, were used to generate the pre-explosion topography and compared to seven DEMs generated after the explosion between June 30 and September 26, 2011 [see Fig. 6(b)]. The cross-sections through the DEM time series are shown in Fig. 6(c). The topographic decrease of up to 20 m becomes clear in the summit area, as well as the fact that no measurable topographic change occurred after the explosion until the end of the time series on September 26, 2011. The topographic change was too small to be visible in the amplitude and coherence images, highlighting the necessity to utilize the phase information from TanDEM-X for DEM generation and topographic change detection [44].

The average volume change at the dome due to the June 2011 explosion was estimated from TanDEM-X data to be $-0.184 \times 10^6 \text{m}^3 \pm 0.027 \times 10^6 \text{m}^3$. This is corroborated by the study of [60], who used aerophotogrammetric observations to study the lava-dome changes in the same time interval as analyzed with TanDEM-X and suggested a volume change of $-0.190 \times 10^6 \text{m}^3$.

### B. Lava Flows

DEM differencing using data from TanDEM-X is especially well suited for mapping topographic changes due to lava flows, providing a measure of erupted volume (e.g., [36], [38], [42]). When multiple acquisitions are available during flow emplacement, the data can be used to assess lava discharge rates. The effusion rate of lava is among the most important eruption parameters to measure, given its control on flow length and the long-term development of mafic systems (e.g., [61], [62]) and the potential for collapse in silicic systems (e.g., [63]). Effusion rates are typically characterized by a combination of methods, including measurements of flux through lava tubes and channels (e.g., [64]), thermal radiance detected by satellite (e.g., [65]), and the emission rate of SO$_2$ (e.g., [66]). Unfortunately, these methods are often complicated by eruptive and environmental conditions—clouds can obscure thermal satellite imagery, pre-eruptive degassing stymies the use of gas measurements, and some flux measurements require the presence of specific volcanic features (e.g., lava tubes or channels). The capability of TanDEM-X to assess lava discharge has been demonstrated across the entire spectrum of magmatic compositions, from basaltic to rhyolitic. Basaltic and andesitic lava flows are described in the following sections, while rhyolitic flows are addressed in Section III-D.

#### 1) Basaltic Lava Flows: Kilauea provides an exceptional example of the use of TanDEM-X to determine the discharge rates of basaltic lava. The volcano experienced near-continuous activity during 1983–2018, erupting about 4.4 km$^3$ of lava from vents on the volcano’s East Rift Zone during that time [67]. During 2011–2013, lava flows were mostly confined to barren areas and did not enter the ocean, so TanDEM-X DEM differences
Fig. 7. TanDEM-X-derived thickness of lava flows erupted from the Pu‘u ‘Ō‘ō vent on Kilauea Volcano, Hawaii, between June 30, 2011 and June 14, 2013. Modified from [36].

could capture the entire volume of erupted lava (see Fig. 7). Comparison of successive TanDEM-X DEMs indicated that the dense-rock equivalent (DRE) time-averaged discharge rate of lava was mostly less than 2 m$^3$/s, well below the long-term average for the eruption of 3–4 m$^3$/s and, when considered along with magma storage rates derived from deformation measurements, indicating a decrease in magma supply to the volcano relative to previous time periods [36]. A subsequent analysis of lava flow activity in 2016, when lava also was active in barren areas and mostly on land, indicated increased lava discharge rates relative to 2011–2013, implying a return to average effusion and magma supply rates. These insights into Kilauea’s behavior would not have been possible without TanDEM-X data.

Remote sensing is also of special importance in Africa, because political instabilities often hinder or even prevent ground-based measurements of volcanic products. TanDEM-X has been used to estimate eruption volumes at one of Africa’s most active volcanoes, Nyamulagira [68]. A time-series of DEMs with a resolution of 5 m was generated from TanDEM-X data, and differential analysis of the DEMs enabled estimation of the erupted volumes, revealing that $305.3 \pm 36.0 \times 10^6$ m$^3$ of lava was emplaced during eruptive episodes in 2011–2012 at Nyamulagira. Furthermore, TanDEM-X DEMs were differenced with the SRTM DEM (2000) to reveal estimates of eruptive volumes for five other eruptions that occurred since then.

TanDEM-X has also been used to derive lava flow estimates in remote regions, such as Kamchatka. The Tolbachik (Fig. 8(a), 55.832° N, 160.326° E) 2012–2013 fissure eruption lasted for about nine months, during which very fluid lava fountained and effused from two eruptive centers, the Menyailov and Naboko Vents [profiles A-A’ and B-B’ in Fig. 8(d)–(f)], about 20 km apart [69], [70]. TanDEM-X data were used to generate a total of 18 DEMs to map the changing lava flow fields and to estimate flow volumes and lava discharge rates [see Fig. 8(b) and (c)] [42], [70]. The total lava flow volume was calculated from TanDEM-X to be $0.53 \pm 0.01$ km$^3$, and the final area covered by lava 36 km$^2$. Fig. 8(b) shows the increasing lava volume over time. The lava extrusion rate was very high in the beginning of the eruption (248 m$^3$/s) but decreased rapidly after the first few weeks [see Fig. 8(c)]. These values are consistent with those calculated using aerophotogrammetric observations [69], [71] and ArcticDEMs [72].

2) Andesitic Lava Flows: The abovementioned examples were all from basaltic volcanoes, but TanDEM-X data have also proven their value with systems erupting more silicic lava flows, like El Reventador volcano—one of the most active in Ecuador. Despite the proximity to the capital city of Quito (<100 km west), the volcano is largely inaccessible due to the high relief and dense vegetation of the Amazon basin and is mostly cloud-covered, making cloud-free optical imagery difficult to acquire [73]. A series of 9 TanDEM-X pairs acquired between September 2011 and July 2014 were used to measure the topographic change associated with around 40 individual flows [74], [75]. Height changes of up to 80 m were documented, and the total volume of lava flows was estimated to be $26.7 \times 10^6 \pm 1.2 \times 10^6$ m$^3$ DRE, giving an effusion rate similar to that of other long-lived, dome-forming andesitic eruptions (0.3–0.4 m$^3$/s) [74]. These data were combined with 32
Fig. 8. (a) Photograph showing Ostry Tolbachik and Plosky Tolbachik. A lava field originating from the 2013 fissure eruption is seen in the foreground. Image courtesy: https://flickr.com/photos/31176607@N05/20689483279. (b) and (c) Lava flow volume calculations and lava extrusion rates derived from TanDEM-X and compared to aerophotogrammetric results from [71], respectively. (d) Elevation difference between a pre-eruption DEM and a post-eruption DEM. The lava flow extent is outlined in black, lava thickness is indicated by color. (e) and (f) Cross sections of the Menyailov and Naboko vents indicated in (d), respectively. Figure modified from [70] and [42].

SAR images from the Canadian RADARSAT-2 satellite collected from September 2011 to August 2016 and that were used to measure flow height using the radar shadow method (with typical height errors of 2–3 m) to produce a time-series of volume change. The decreasing rate of effusion is consistent with either a closed depressurising magma reservoir without magma recharge or an open depressurising magma reservoir being resupplied at a rate less than 0.35 m³/s DRE [74].

Individual flows at El Reventador range in length from a few hundred metres to almost two kilometres, with average thicknesses between 8 and 28 m and volumes between 0.5 and $5 \times 10^6$ m³ [75]. The flow lengths decrease with time, and the decrease in flow volume is correlated with a long-term decrease in effusion rate, suggesting that temporary magma storage in the conduit acts as “capacitor” between the magma reservoir and the surface. Although the flows were mostly emplaced over time-periods shorter than the time between acquisitions, the TanDEM-X image on May 19, 2012 was acquired during the emplacement of flow 19 and allowed for the study of the behavior of an individual flow [75]. Comparing profiles of topography captured during and after the emplacement of flow 19 shows a decrease in elevation of up to 10 m in the channel balanced by an increase in height of the levees of ~6 m and accumulation of $0.98 \pm 0.10 \times 10^6$ m³ at the tip of the flow, consistent with a model of channel drainage [75].

C. Pyroclastic Density Currents

PDCs can reach distances of tens of kilometres in large explosive events, and they are one of the largest cause of fatalities during volcanic eruptions because they move too quickly for people to escape [76]. The estimation of the volume of PDCs is crucial for improving risk assessment and for forecasting future events, but is challenging during an ongoing eruption due to terrain access and poor visibility. The deposits are typically much thinner than those associated with lava flows and are, therefore, more challenging to study with TanDEM-X. Here, we describe recent applications of TanDEM-X to study PDC emplacement at Shiveluch and Fuego volcanoes.

The lava dome growth of Shiveluch volcano described in Section III-A was accompanied by several PDCs. According to the Global Volcanism Program, PDCs, and lava flows were generated between 2013 and 2014, with the PDCs reaching distances between 5 and 12 km in several different directions. Heck et al. [55] calculated the volume of PDCs using TanDEM-X data to be $75.0 \times 10^6$ m³.

Fuego volcano [see Fig. 9(a)] (Guatemala) erupted on June 3, 2018, producing a series of destructive PDCs that traveled more than 12 km from the summit down the Barranca Las Lajas [main channel visible in Fig. 9(a)] to the towns of San Miguel Los Lotes and El Rodeo, 10 km SE of the summit at the base of
Las Lajas ravine, prompting the evacuation of 12,000 people and causing the destruction of infrastructure and the deaths of hundreds of inhabitants [77]. Albino et al. [40] derive pre- and post-eruptive TanDEM-X DEMs [see Fig. 9(b)] and detect positive topographic change of >25 m in Barranca Las Lajas [see Fig. 9(c)] and collapse of >68 m near the summit (not shown in Fig. 9), with an estimated total deposit volume of $1.5 \pm 0.4 \times 10^6$ m$^3$. Analysis of the volume budget between units indicates that a large proportion of the material deposited in the main channel originated from the collapse located close to the summit, indicating that the addition of nonjuvenile material (bulking) had a major influence on the run-out distance of the PDCs. Some negative topographic changes along the PDC pathway were also detected, possibly due to the stripping of leaves from the trees, creating the appearance of topographic decreases because the radar waves bounced off the ground instead of the forest canopy.

D. Subsurface Magma Intrusion and Withdrawal

The examples mentioned above focus on the emplacement of volcanic deposits at the surface. TanDEM-X data, however, are also exceptionally useful for characterizing near-surface magma accumulation and withdrawal, both of which can cause dramatic topographic changes.

Puyehue–Cordón Caulle (40.59° S, 72.117° W) belongs to a cluster of Pleistocene to recent volcanic vents in the Chilean Andes [78]. The magmas erupted from surrounding volcanoes are mainly basaltic to andesitic, but Puyehue–Cordón Caulle is characterized by rhyolitic lavas. During the first month of the volcano’s 2011–2012 eruption, a shallow laccolith with a volume of 0.8 km$^3$ was emplaced at depths of 0.2–0.4 km [79]. The subsequent effusive phase, which lasted until March 2012, involved the eruption of 0.5 km$^3$ of rhyolitic lava.

Delgado et al. [80] used both InSAR ground deformation and DEM data from TanDEM-X to study the dynamics of the effusive phase of the 2011–2012 Puyehue–Cordón Caulle eruption. The eruption is particularly important as it is, to date, the best instrumentally recorded rhyolitic eruption [79]–[84]. In addition, it is one of the few events in which both co-eruptive satellite data and topographic time-lapse information from satellite data are available.

A total of 16 ENVISAT interferograms and five TerraSAR-X and RADARSAT-2 interferograms were used to study co-eruptive subsidence with variable amplitudes of 5–20 cm. A set of six TanDEM-X data pairs were used to generate six DEMs spanning the eruption. In addition, a pre-eruptive DEM was generated from SRTM data and a post-eruption DEM from tristereo optical Pléiades photogrammetry [85]. DEM differencing revealed the topographic changes produced during the eruption. The topographic change caused by lava flow extrusion reached magnitudes of 150 m. East of the eruptive vent, the laccolith caused topographic changes of up to 250 m. TanDEM-X data were exceptionally helpful to study this unique eruption and provided vital constraints for a physicochemical eruption model that offered insights into the temporal evolution of the eruption and the volatile budget of the extruded rhyolitic flow. This was the first time that these sets of complementary data were available during a rhyolitic eruption. It is also the first time that such a model was developed utilizing only satellite data [80].

An example of TanDEM-X observations of magma withdrawal is Bárðarbunga in Iceland. Bárðarbunga is a subglacial basaltic volcano with a caldera of 70 km$^2$ and is completely covered by the Vatnajökull ice cap [86]. The Holuhraun eruptive fissure was reactivated in August 2014, preceded by a seismic swarm that started beneath Bárðarbunga and migrated to the northeast, signaling subsurface magma movement [86], [87]. The seismic signal indicated the emplacement of a large dyke along a northeast oriented fissure swarm, leading to an effusive eruption 40 km away from the Bárðarbunga caldera [87]. The eruption lasted for about 6 months until February 2015, and the caldera gradually deflated in response to the magma transport through the dike. This slow collapse of a caldera is a rare event in Iceland—the most recent previous caldera collapse happened in 1875 and was explosive in nature [87], [88].

Rossi et al. [88] used TanDEM-X data to investigate topographic changes caused by the eruption. Five acquisitions were used to monitor caldera subsidence, which averaged 16 m and
reached a maximum of 50 m as a result of the activity. The volume loss was estimated to be about 1 km³. It should be noted that the caldera subsidence does not directly refer to the ground volume loss. At subglacial volcanoes, such as Bárðarbunga, the activity can also result in melting of the snow/ice cap, which can lead to jökulhaups, i.e., glacial/subglacial outburst floods. These were, however, not observed at Bárðarbunga, and it was unclear to where the water drained. This means that the volume loss due to the caldera collapse is not directly comparable with the extruded lava flow volume.

Dirscherl and Rossi [89] continued the study of [88] by using a time-series of DEMs to study the caldera collapse and the effusion of lava in the Holuhraun plain in more detail. A total of 13 pre-, co-, and posteruptive TanDEM-X DEMs were used to study the caldera and 9 co- and posteruptive TanDEM-X DEMs to study the Holuhraun lava field. A mosaicked preprocessed TanDEM-X DEM provided pre-eruptive topography. DEM differencing resulted in a maximum vertical displacement of the Bárðarbunga caldera of approximately −65 m and a total subsidence volume of −1.4 ± 0.13 km³. The highest point of the lava field was measured to be +43 m, and the DRE lava volume was estimated as 1.36 ± 0.07 km³. The ratio between caldera subsidence and estimated lava volume indicated a coupling between collapse and magma drainage.

E. Combination With Other Sensors

1) Long-Lived Eruptions: For several long-lived eruptions, TanDEM-X data have been utilized alongside DEMs from other sources to produce a long-term view of topographic change at erupting volcanoes spanning longer time periods than the duration of any one data source.

Pritchard et al. [90] used bistatic CoSSC data in combination with SRTM data to generate maps of topographic change for several volcanoes in Latin America. The main topographic changes that occurred between the acquisition of the SRTM data in 2000 and the respective TanDEM-X data pair (i.e., 2012 and 2017, depending on the volcano) were ascribed to extruding lava domes and flows, in addition to glacial retreat.

At Soufrière Hills Volcano, Montserrat, Arnold et al. [16] combined a TanDEM-X DEM from November 2013 with DEMs generated using 9 mono-static ALOS-1 radar acquisitions, light detection and ranging (LiDAR) data from 2005, and digitized maps from before the eruption began to investigate the topographic changes that occurred during the 15 years of eruptive activity (1995–2010). Over the course of five eruptive phases and numerous cycles of dome growth and collapse, they estimated a net DRE volume increase of 108 ± 15 × 10⁶ m³ of the lava dome and 300 ± 220 × 10⁶ m³ of talus and subaerial PDC deposits.

Another example is Bagana volcano, Papua New Guinea, where Wadge et al. [91] combined DEMs from TanDEM-X and SRTM with earlier topographic maps to study the topographic changes of the volcanic edifice over 70 years, from 1945 to 2014. During this time, the edifice grew from a height of 1742 m to 1897 m above sea level, with a total volume change of 2.2 ± 0.9 km³, giving an average extrusion rate of 1.0 ± 0.5 m³/s. This extrusion rate is steady over timescales of years to decades, and if the last 70 years are representative, this suggests that the edifice could have been built in only 300 years.

2) No Pre-Eruption TanDEM-X Acquisitions: As TanDEM-X is not systematically acquiring data globally, for several recent eruptions no pre-event TanDEM-X acquisitions are available. Nonetheless, by combining other pre-eruptive DEMs with posteruptive TanDEM-X data, it is still possible to estimate topographic change.

Jebel et Tair island, a stratovolcano located in the south-central Red Sea between Yemen and Eritrea, covers an area of about 11.4 km². On September 30, 2007, a fissure eruption started, which lasted for a total of 107 days [92]. Jebel at Tair is—apart from a small military outpost—uninhabited; therefore, neither seismic nor geodetic instruments were installed to monitor volcanic activity.

Xu and Jónsson [92] used high-resolution optical images and InSAR to study the 2007–2008 eruption. Optical images from different satellites (Quickbird, WorldView-1 and 2) from before and after the eruption were used to study detailed surface changes on the island. In addition, 17 ALOS-1 images acquired between December 2006 and April 2010 were used to map the evolution of the lava flows while analyzing the coherence of the interferometric pairs. Multiple ALOS-1 interferograms were also used to derive a pre-eruptive DEM, while TanDEM-X data were used to map post-eruptive topography. DEM differencing revealed lava flow thicknesses of 20–40 m and also identified a 60 m high scoria cone that was built during the eruption. The average subaerial thickness of volcanic products was estimated to be 3.8 m, and the bulk flow volume to be 22 ± 11 × 10⁶ m³ (only including lava that appears above sea level). Considering that the majority of flows were ‘a’ā and, thus, assuming a vesicularity of 25%, the DRE was estimated with ~17 ± 8 × 10⁶ m³.

The Zubair archipelago is located approximately 50 km to the southeast of Jebel at Tair and is composed of 10 volcanic islands [93]. Eruptions occurred occasionally in the eighteenth and nineteenth centuries, after which a long phase of quiescence followed. In 2011–2012 and in 2013, however, two submarine eruptions, the Sholan and Jadid eruptions, took place in the archipelago, resulting in the birth of two volcanic islands. Xu et al. [93] used TanDEM-X data to generate topographic maps of the newly built islands. The subaerial height and volume of Sholan Island was measured to be 94 m and 0.0057 km³, respectively, and for Jadid Island were approximately 186 m and 0.047 km³.

TanDEM-X data were also used to study basaltic lava flows at Piton de la Fournaise. The volcano is located on La Réunion Island in the Indian Ocean about 800 km east of Madagascar. It is one of the most active basaltic shield volcanoes in the world with an average eruption frequency of 1 eruption per 8 months, but with occasional eruptive pauses of up to six years [38], [94].

Bato et al. [38] used bistatic TanDEM-X data, together with monostatic CSK images, to estimate the volume of a lava flow at Piton de la Fournaise that erupted in October 2010. By differencing a post-eruption TanDEM-X DEM with a pre-eruption LiDAR DEM, Bato et al. [38] generated a lava thickness map showing an average thickness of 6 m. The total bulk and DRE volumes were calculated to be 4.10 ± 0.21 × 10⁶ m³ and 1.83 ± 0.65 × 10⁶ m³,
respectively. The results were compared to volume estimates derived by using a series of monostatic CSK data (3.97 ± 0.48 × 10^6 m^3 bulk volume and 1.77 ± 0.75 × 10^6 m^3 DRE volume). Total DRE volume estimated using the Moderate-resolution Imaging Spectroradiometer (MODIS) data was between 2.44 and 4.40 × 10^6 m^3, indicating that analysis of thermal remote sensing data might have overestimated the eruptive volume in this case. The need to use many interferograms generated from monostatic CSK data was identified as a major bottleneck in terms of near-real-time monitoring, highlighting the benefit of bistatic TanDEM-X data for lava flow volume and effusion-rate estimation. Hrysiewicz [95] also used TanDEM-X data to study topographic changes at Pito de la Fournaise.

3) Rapid Posteruptive Assessment: It is not the goal of the TanDEM-X mission to provide data in near-real-time, and in some cases, data are not available for several months after acquisition. In these cases, it may be necessary to combine pre-eruption TanDEM-X data with other sources of posteruptive topographic data that are available in a more timely manner.

Pico do Fogo on Fogo Island is the most active volcano in the Cape Verde archipelago, about 800 km west of the coast of Africa. All islands of the archipelago have a volcanic origin caused by an underlying mantle plume [96]. The last eruption of Pico do Fogo started in November 2014 after almost 20 years of quiescence, and the eruption lasted until early February 2015. Voluminous and fast-moving lava flows, fed by strombolian activity along a 1.2 km-long fissure, almost completely destroyed the villages of Portela and Bangaéira [97]. Whereas TanDEM-X data were acquired before the eruption, no dataset was available directly after the eruption ended. Bagnardi et al. [98], therefore, used very-high-resolution tristereo optical imagery acquired by the Pléiades-1 satellite constellation [85] to generate a 1-m resolution posteruptive DEM of Pico do Fogo. It should be mentioned that this study was the first to use Pléiades-1 tristereo imagery in a volcanic environment. Differentiating of the post-eruptive Pléiades DEM with the pre-eruptive TanDEM-X DEM indicated a lava flow area of 4.8 km^2 and a total volume of 45.83 ± 0.02 × 10^6 m^3. These results compare well with other estimates made using Landsat-8 operational land imager (OLI) data [98] and coherence maps from TerraSAR-X InSAR for the area covered by lava [100]. The volume estimated by [100] using DEMs from terrestrial LiDAR, SfM, and photogrammetry (i.e., 44 ± 5 × 10^6 m^3) agrees with the TanDEM-X/Pléiades estimates, and also those inferred from SO2 measurements [101] (46–55 × 10^6 m^3).

F. Uncertainties

To give an insight in the quality of the TanDEM-X data used to study active volcanism, we conclude the present section with a summary of uncertainty analyses and results. Numerous authors have investigated the uncertainty in TanDEM-X DEMs, especially with respect to the ability to detect topographic change over time. In most circumstances, TanDEM-X DEM differences can resolve changes that exceed 2 m, although this varies depending on characteristics such as surface slope, snow cover, and vegetation.

Most authors who have generated TanDEM-X DEM difference maps at volcanoes have examined the topographic variation in areas of no topographic change to assess uncertainty. At Kilauea, the standard deviation of elevation differences calculated using TanDEM-X DEMs with respect to a reference DEM was 2 m in barren areas that had not been impacted by lava flows between the times of the two DEMs. This increased to 8 m in heavily vegetated areas, probably because the radar return was a combination of scatterers located within the trees and on the ground [36]. The quality of the TanDEM-X-based estimates at Tolbachik was assessed from four reference areas without topographic change, including both barren and vegetated areas. All calculated elevation differences were centered around zero with a mean of −0.21 m and a standard deviation of 1.63 m. Differences between DEMs from data acquired in summer and winter became obvious, but the standard deviation in the vegetated areas was not significantly higher [42]. For Jebel et Tair, the DEM difference in areas where topographic change occurred had a standard deviation of 1.9 m [92]. Uncertainty was less at Pito de la Fournaise and El Reventador, where height errors were estimated to be 0.31 m (1σ) [38] and ±0.7 m [74], [75], respectively.

Uncertainty has also been assessed using independent reference data. TanDEM-X DEMs from Nyamulagira and Nyiragongo were compared to Global Positioning System (GPS) measurements collected from 42 sites. The mean error when comparing the GPS and TanDEM-X elevations was 1.58 m, and the standard deviation was estimated to be 0.98 m [68]. Also at Nyamulagira and Nyiragongo, point-to-point comparison with high-resolution optical images was used to assess the horizontal accuracy of the TanDEM-X DEMs. Local targets in a TanDEM-X amplitude image were compared to a 1 m resolution IKONOS image that was orthorectified and georeferenced using the GPS points. Measuring the distance between selected points in both images resulted in a standard deviation of 5.4 m in the east and 1.9 m in the north component, and a total root-mean square error of 12.6 m [68].

Perhaps the most comprehensive assessment of uncertainty involved the analysis of 19 DEMs from a quiescent period at Colima volcano. All images were acquired with the same geometry from the descending orbit, with an incidence angle of about 32.4°. The data pairs had effective baselines ranging between 47.4 and 161.9 m, and respective heights of ambiguity of between 108.3 and 30.7 m. The elevation differences in three reference areas, all of which were located within a 2 km radius of the summit, revealed standard deviations of 0.62 m for the flattest areas (i.e., with a slope of 7°) and 2.94 m for the steepest areas (i.e., with a slope of 40°) [44].

IV. FROM BETTER DEMS TO BETTER FORECASTING

Calculating volume changes through topographic differencing is an obvious direct application of datasets like TanDEM-X to volcanology. Derived products from these data also provide critical input to volcanological studies, especially hazards assessment and physicochemical modeling of subsurface processes.
Topography is perhaps the most fundamental volcanological dataset given the importance of topographic controls on volcanic hazards. For example, topography is the most basic requirement of forecasting tools designed to assess the spatial extent and potential impact of PDCs (e.g., [102], [103]), lava flows (e.g., [104]), and lahars (e.g., [105]–[107]). Bistatic data from SRTM [1] provided some of the first widespread input data for such hazards models, and the TanDEM-X WorldDEM vastly improved the resolution of globally accessible topographic data [29]—important for developing more accurate hazards forecasts.

A study by [108] highlights the fact that the performance of volcanic mass flow models depends strongly on the resolution and accuracy of the input DEM. Nevado del Ruiz in Colombia is one of the most active volcanoes in the Andes and was the site of one of the deadliest volcanic disasters in recent history [109], [110]. In 1985, a small eruption with a Volcanic Explosivity Index (VEI) of 3 caused lahars that were responsible for more than 23 000 fatalities. The activity of Nevado del Ruiz has continued during the 2000s, with observable surface deformation, higher levels of seismicity, higher levels of gas extrusion, and ash plumes [111]. Because the DEMs available for Nevado del Ruiz were not sufficient for flow modeling (SRTM and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data did not have sufficient accuracy and contained gaps), Deng et al. [108] combined TanDEM-X data with terrestrial radar interferometry and SfM to generate a 10-m spatial resolution DEM of the volcano. By comparing the simulated inundation zones of lahars and pyroclastic flows using the 30-m SRTM DEM and the newly generated DEM, Deng et al. [108] demonstrated the advantage of the higher resolution and gap-free DEM. The simulated extent and run-out distance of lahars and PDCs would likely be underestimated using the lower resolution 30 m SRTM DEM, which could have severe consequences during a crisis.

Topographic change is a natural consequence of volcanic eruptions, and existing datasets are outdated as soon as an eruption occurs, since the emplacement of new deposits will change the course of future deposits (e.g., [100], [112]). For this reason, constant revision of topographic information is vital for updating hazards assessments at frequently active volcanoes—a task ideally suited to repeat acquisition of bistatic data, like TanDEM-X. Kilauea Volcano provides an instructive example. Steepest-descent calculations have long been used to forecast the paths of lava flows at the volcano (e.g., [113], [114]), but persistent lava flow activity constantly modified the topography and changed the paths that flows were likely to follow. When lava flows began advancing from the Pu’u ‘O’o eruption site toward the coast in 2016 after a three-year hiatus of activity in that area, it was unclear exactly where the flows would go—information that was critical to civil defense officials who needed to understand how the lava would impact transportation and infrastructure and homes. The existing topographic data were from 2005—outdated and inappropriate for forecasting flow paths due to lava flow activity that modified the topography between 2005 and 2013. By updating the topography using TanDEM-X data, new models of lava flow paths were computed—models that proved accurate and were of great use to civil defense officials [115] (see Fig. 10).

Insights derived from TanDEM-X data are also crucial input to physicochemical models of magmatic systems. These models provide constraints on the volumes and rates of magma accumulation and the volatile composition of the magma and source region—information that is valuable for understanding the likely course of future eruptive activity. For example, using effusion-rate data derived from TanDEM-X coupled with other gas emission and deformation data, Anderson and Poland [116] quantified temporal variations in magma supply rate from the mantle to Kilauea Volcano. At El Reventador volcano, Arnold et al. [74] inferred the volume of the magma reservoir and constrained possible recharge rates from only deformation and effusion-rate data, the latter derived in large part from TanDEM-X.

At the most silicic end of the compositional spectrum, Delgado et al. [80] employed deformation data and time-lapse DEMs, including many derived from TanDEM-X imagery, to model magma compressibility of the rhyolite magma reservoir at Puyehue–Cordón Caulle. These insights, which in the cases of Puyehue–Cordón Caulle and El Reventador required no ground-based observations at all, would not have been possible without the consistent, repeated, high-resolution topographic information provided by TanDEM-X. If such data were consistently available for volcanoes worldwide, physicochemical models of volcanic eruptions, and magma plumbing systems—currently

![Fig. 10. Steepest descent lines indicating likely lava flow paths during the 1983–2018 Pu’u ‘O’o-Kupaianaha eruption along Kilauea’s middle East Rift Zone. Blue lines show paths based on topographic data from 2005, whereas red lines are flow paths that were updated in 2013 using topographic information derived from bistatic TanDEM-X SAR imagery. The area shown is almost the same as indicated in Fig. 7 and is highlighted with the red rectangle in the map of Hawaii shown in the lower right corner. Figure from [115].](image-url)
on the cutting edge of volcanology and a vital tool in eruption forecasting [117]—would be possible on a global basis, even for volcanoes where no ground-based data were acquired.

V. CHALLENGES OF USING TANDEM-X TO STUDY ACTIVE VOLCANOES

Bistatic TanDEM-X data have many advantages compared to other methods for DEM generation and also allow the estimation of additional volcanological parameters with respect to repeat-pass InSAR studies. Nonetheless, there remain numerous challenges in using these data to study different types of volcanism. The following section summarizes these challenges and their consequences, and highlights where more research is needed to improve the utilization of bistatic TanDEM-X data in volcano research.

A. Data Processing

We have listed the software tools available to process the bistatic CoSSC TanDEM-X data in Section II. This seems to be a rather long list, but only includes DORIS as a noncommercial tool. Particularly, the InSAR Scientific Computing Environment (ISCE) and GMTSAR (open source GNU General Public License) InSAR processing system designed for users familiar with Generic Mapping Tools (GMT), which are widely used for processing monostatic data, are to date not able to process bistatic TanDEM-X data. Many volcano observatories do not have any access to commercial tools, highlighting the need for more easily accessible software. In the absence of such software, the Committee on Earth Observation Satellites (CEOS) has facilitated access to processed datasets.

The processing of interferometric (and other) data related to topography is still a challenge, highlighting the need for the development of new open-source tools to support datasets that could come from innovative missions like ESA’s Earth Explorer 10 candidate mission Harmony [25], [26]. Another solution would be to provide topography as a data product itself to facilitate the utilization of up-to-date topographic information by volcano observatories worldwide.

B. Extracting Topography From Vegetated Areas

The presence of vegetation can influence the analyses of satellite SAR imagery in several ways. First, volume scattering can hinder the extraction of the lava flow areas using coherence or backscatter information. This affected the lava-flow masks at Tolbachik, Kilauea, and Puyehue–Cordón Caulle, and in each case, external data were required to extract the affected area [36], [42], [80].

When considering a time-series of DEMs, differences in summer and winter vegetation need to be taken into account. At Tolbachik, for instance, the area surrounding the lava flow is mainly composed of dense scrub and taller trees. Larch and birch change their appearance from summer to winter by loosing needles and leaves, and this has a strong impact on the backscatter and, thus, on the final DEMs. As TanDEM-X uses X-band, the electromagnetic waves are scattered by the forest’s canopy when the trees have leaves in summer (i.e., when larches carry needles in summer), but the radar waves can reach the ground surface in winter time, resulting in elevation differences of up to 11 m [42], [118].

During the 2014–2015 Pāhoa lava flow crisis at Kilauea, lava moved into communities in the Puna District on the east side of the Island of Hawaii [114], [119]. The lava flow traversed a densely forested area (see Fig. 11), which made the DEM differencing approach as applied to study the lava volumes of Kilauea as described in Section III-B1 inapplicable. The pre-eruption TanDEM-X DEM indicates the top of the forest canopy (or slightly below due to limited penetration of the electromagnetic waves), while the post-eruption DEM indicates the level of the lava flow, which burned down the trees. Differencing of DEMs, thus, results in negative elevation values (see Fig. 11), showing the need for a pre-eruption bare-Earth DEM or some means of removing the height of the forest from the prelava-flow TanDEM-X DEM. Lundgren et al. [23] demonstrated that LiDAR data can provide such base-Earth topographic data, but such information is not uniformly, or even commonly, available on volcanoes around the world.

C. Geometric Distortions

A very common source of error is the geometric distortion when steep-sided stratovolcanoes are imaged by side-looking radar. This phenomenon is not new (see, e.g., [120]), but fundamentally affects the TanDEM-X data and derived DEMs. Kubanek et al. [43] analyzed DEMs of Merapi and its currently dormant neighbor Merbabu to evaluate the applicability of bistatic TanDEM-X data in mountainous terrain, highlighting that TanDEM-X data are helpful to study topographic changes at stratovolcanoes, but that errors due to the side-looking slant-range geometry are unavoidable. Kubanek et al. [57] used the backscatter magnitude to identify areas of geometric distortion of the fissured summit topography of Merapi that was left after the 2010 eruption. The generated masks helped to asses volumetric changes in the summit area caused by the eruption, but necessarily led to an underestimation of the volume loss. Mosaicking of different DEMs as performed by [108] to generate a high-resolution, gap-free DEM of Nevado del Ruiz could be a solution, but the effort needed to acquire SF and/or terrestrial laser scanning data in the field does not allow for a regular acquisition of topographic information in most cases. An alternative solution, which does not involve ground-based data collection in potentially hazardous areas, is to use TanDEM-X data acquired from opposite acquisition geometries (ascending and descending) and, if possible, acquired with different incidence angles to generate more reliable DEMs in steep topography. TanDEM-X data are often acquired in ascending and descending geometries on consecutive days, which facilitates this approach. The data could be fused using a variety of methods (see [121]–[123] as example). Multiple images acquired with different imaging geometries were also used for generating the final WorldDEM product from TanDEM-X data. For generating DEMs during an ongoing eruption, however, the number of acquisitions that can be used for a single DEM will always be limited by the volcanic
Fig. 11. Topographic change derived from TanDEM-X DEM differences in the eastern part of Kilauea Volcano, Hawaii, between June 27, 2014 and December 3, 2015. The map in the upper left corner shows the Island of Hawaii and the red rectangle denotes the area shown in the two bigger panels. Left panel shows pre-June 27th false-color Landsat image of the region; gray areas are barren lava flows, green denotes vegetated areas, white areas are clouds, and dark patches are cloud shadows. Right panel is TanDEM-X DEM difference map. Black polygon in both panels is the Hawaiian Volcano Observatory’s outline for the area covered by the so-called June 27th lava flow, which was active during 2014–2015 and threatened populated areas [114]. Negative elevation change (blue colors in the topographic change image) is indicated where the lava flow overran heavy vegetation, because the lava flow destroyed the trees that had defined the reflection surface in the pre-lava-flow TanDEM-X-derived DEM. This example illustrates the challenge in mapping topographic change in vegetated areas on volcanoes.

activity. Alternatively, other satellite-based DEMs, such as the Pléiades DEMs [98] or the ArcticDEMs [72] could be used to fill gaps.

D. Temporal Frequency of Acquisitions

The repeat-pass interval of TanDEM-X for acquisitions with similar parameters is 11 days. This means that a DEM can theoretically be generated every 11 days from the ascending orbit, and every 11 days from the descending orbit. In some cases, different data can be acquired with different incidence angles, which would lead to a shorter repeat interval. As illustrated here, this repeat is sufficient for analyzing discrete events or long-term eruptive activity. However, for very active systems, such as a growing lava dome with high extrusion rates, a shorter temporal repeat would be required to understand, for example, variations between effusive and explosive behavior, and also for the generation of physicochemical models. Delgado et al. [80], for instance, concluded that the temporal resolution is too long to properly discriminate the emplacement of a shallow laccolith and lava flow extrusion during the Cordón Caulle eruption, highlighting the need for more frequent repeats of topographic information. The two Sentinel-1 satellites are providing interferometry data every 6–12 days over most volcanoes. An equivalent topographic dataset would be required to build a time series of major changes during ongoing eruptions.

E. Acquisitions Over Snow and Ice

The study by [88] performed an in-depth quality analysis to assess the accuracy of TanDEM-X DEMs of Bárðarbunga, with a special emphasis on the X-band signal propagation into snow-covered grounds. They found that the changing properties of snow can have an effect on the results, and TanDEM-X data acquired during different seasons can, therefore, have biases of up to meters. TanDEM-X data from snow-covered areas should, thus, be interpreted with care.

VI. FUTURE SATELLITE MISSIONS

Finally, we consider the potential for future satellite missions to provide frequent measurements of topographic change. To demonstrate the ability of a short mission to measure topographic change at a number of volcanoes, we pick a representative year and estimate how many eruptions would have had measurable topographic change due to, for example, lava flow or dome extrusion. In 2018, 78 eruptions took place, of which we estimate at least 27 involved processes that we might expect to cause measurable topographic changes. The list includes 21 eruptions with lava flows, 8 with PDCs, 6 with lava lakes, and 6 lava domes with 3 collapse events. Thus, even a one-year observation window would be sufficient to produce a range of height change maps for a variety of volcanoes and eruption types. However, if the scientific goal is to observe changes in eruption rates, and eruptions typically last for several years, multiple years of data may be required to capture changes in eruption rate [12].

We consider various scenarios for topographic change as follows:

1) the growth of volcanic domes;
2) the emplacement of lava flows; and
3) volcanic collapses.

For these observation scenarios, we consider the resolution and accuracy required to make scientifically useful measurements of 1) total volume change and 2) the distribution of height change. Since no analytical models exist for the processes considered, we describe our observation scenarios using a set
of representative case studies using data collected by aerial photogrammetry and TanDEM-X.

We focus on the candidate Earth Explorer 10 mission “Harmony,” which is currently in the end of phase 0 of development by ESA [25]. Harmony would consist of two identical spacecrafts carrying receive-only radar instruments as their main payload and flying in a reconfigurable formation with Sentinel-1 C or D, which will be used as the “active” satellite. In a cross-track interferometry configuration, Harmony will provide DEMs every 12 days. In particular, we consider the choice of pixel size, with options of 6 m, 20 m (which is the best possible considering the properties of Sentinel-1), and 50 m (which would reduce the spatial resolution but offer improved vertical accuracy).

A. Dome Growth

For volcanic dome growth, we consider the case study of Mt. St. Helens, USA, in 2004–2005 using DEMs available through [124]. Fig. 12(a)–(d) shows the DEM from December 11, 2004—61 days after lava first appeared at the surface. At resolutions of 1 m or 6 m, the images clearly show a 150 m high, 350 m long whaleback spine (known as spine 3), and a longitudinal fracture separating the spine into two parts. At 20 m resolution (best possible for Harmony), the spine is still clearly visible, but the longitudinal fracture is not. Given the spine is 150 m high, we do not expect vertical accuracy to be a limitation in this case, but test the 50 m resolution product for consistency. At this resolution, all that is visible is a “lump,” but it cannot be identified as having whaleback morphology.

Next, we consider the potential for measuring the topographic change associated with dome growth. We take the difference between the DEMs collected on October 13 and November 4, 2004, and scale to a repeat interval of 12 days, consistent with the Sentinel-1 acquisition plan [see Fig. 12(e)–(h)]. As before, the spatial pattern of height change is discernible at 6 or 20 m, but not at 50 m. Simply summing the height change of each pixel in the original DEM and multiplying by the pixel area gives a value of $1.19 \times 10^6$ m$^3$. Interestingly, the volume change estimates at lower resolution are very similar: $1.18 \times 10^6$ m$^3$ at 20 m and $1.16 \times 10^6$ m$^3$ at 50 m. This corresponds to percentage changes of 1% and 2%, respectively, significantly less than the difference between our simple estimate and the value of [2]. We conclude that resolutions up to 50 m would be sufficient to measure the volume change associated with dome growth over a 12 d interval, but a resolution of at least 20 m is required to discern the spatial distribution of the height changes, and hence, the morphology of volcanic features of comparable dimensions.

B. Lava Flows

For lava flow emplacement, we consider the lava flow field at El Reventador, Ecuador, which has been erupting semicontinuously since 2002. We use TanDEM-X data published in [12] and [75] to produce the DEM difference between July 24, 2012 and April 14, 2013. Arnold et al. [75] identify eight flows during this time period with a maximum thickness of $\sim 20$ m and lengths of 0.6–1.8 km. We consider the DEM difference within the lava flow field at pixel sizes of 6 m (original), 18 m, and 48 m. Estimates of the total flow volume vary by less than 1% ($10.16 \times 10^6$ m$^3$, $10.19 \times 10^6$ m$^3$, and $10.15 \times 10^6$ m$^3$, respectively).

Lava flow advance is controlled by the interaction of numerous factors, including lava effusion rate, vent geometry, underlying slope, topographic barriers, and flow rheology. To understand these factors, it is necessary to study the morphology as well as the total volume of the flow. Fig. 13 shows a series of cross-sections through the flow field that clearly demonstrate the complex structure when viewed at the original pixel size of 6 m. We reproduce this profile at pixel sizes of 18 m and 48 m, and with simulated accuracies of 1.5 m, 3 m, and 6 m. Note that the standard deviation of the simulated noise on the DEM
Fig. 13. Height change in the lava flow field at El Reventador Volcano, Ecuador between July 24, 2012 and April 14, 2013 based on TanDEM-X imagery. Data are resampled to consider resolution and accuracy of future missions. Row 1 (a, b, c) shows the lava flow field at different resolutions. Row 2 (d, e, f) simulated accuracy of 1.5 m, row 3 (g, h, i) simulated accuracy of 3 m and row 4 (j, k, l) simulated accuracy of 6 m. Column 1 (d, g, j) shows the original pixel size of 6 m, Column 2 (e, h, k) pixel size of 18 m and column 3 (f, i, l) pixel size of 48 m. The standard deviation of the simulated noise is $\sqrt{2}$ times the accuracy to account for DEM differencing, and we assume no spatial correlation.

The growth of volcanic edifices is often interrupted by episodes of flank collapse, accompanied by catastrophic debris avalanches, lateral eruptions, and volcanigenic tsunamis [125]. The multitemporal topographic information can help us to study these often devastating events and can help modeling the evolution, inner architecture, and dynamics of volcanic systems. We use the example of Anak Krakatau, Indonesia where a flank collapse in December 2018 caused a tsunami, which resulted in > 400 fatalities and displaced > 45 000 people. There are no post-eruptive DEMs available for the flank collapse, and the geological interpretation is based on changes in Sentinel-1 amplitude imagery and pre-eruptive DEMs [126]. The total volume of the collapse is estimated at 0.1 km$^3$, with a maximum vertical height change of 80 m and a lateral extent of ∼400 m. The collapse was followed by a three-week reconstruction phase that included PDCs, vent migration, and further small collapses. Either 20 m or 50 m resolution would be sufficient to provide detailed maps of topographic change associated with the collapse and reconstruction. For very large topographic changes, the high gradient between pixels could cause an issue, but the gradient of 4 m per 20 m pixel or 10 m per 50 m is well below the expected height of ambiguity.

C. Volcanic Collapse

The growth of volcanic edifices is often interrupted by episodes of flank collapse, accompanied by catastrophic debris avalanches, lateral eruptions, and volcanigenic tsunamis [125]. The multitemporal topographic information can help us to study these often devastating events and can help modeling the evolution, inner architecture, and dynamics of volcanic systems. We use the example of Anak Krakatau, Indonesia where a flank collapse in December 2018 caused a tsunami, which resulted in > 400 fatalities and displaced > 45 000 people. There are no post-eruptive DEMs available for the flank collapse, and the geological interpretation is based on changes in Sentinel-1 amplitude imagery and pre-eruptive DEMs [126]. The total volume of the collapse is estimated at 0.1 km$^3$, with a maximum vertical height change of 80 m and a lateral extent of ∼400 m. The collapse was followed by a three-week reconstruction phase that included PDCs, vent migration, and further small collapses. Either 20 m or 50 m resolution would be sufficient to provide detailed maps of topographic change associated with the collapse and reconstruction. For very large topographic changes, the high gradient between pixels could cause an issue, but the gradient of 4 m per 20 m pixel or 10 m per 50 m is well below the expected height of ambiguity.

VII. CONCLUSION

This review summarizes the last ten years of TanDEM-X data acquisitions and analysis for volcanological applications. The unique characteristics of the data—global coverage independent of time of day and weather conditions, without endangering people or equipment—have shown outstanding potential for monitoring and studying a range of volcanological phenomena.
The different studies presented in this article and the corresponding published articles show that the list of applications is extensive, spanning the compositional spectrum and including a range of hazardous volcanic processes.

We emphasize that repeat up-to-date topographic information is of unique value to study and monitor active volcanoes around the globe. Future satellite missions should, therefore, include the repeated acquisition of topographic information to help in fundamental research and crisis management. Although bistatic topographic data do suffer from some disadvantages, such as geometric distortions and effects due to vegetation, the examples presented earlier demonstrate the high value of bistatic radar data in volcano monitoring and research. These data and derived DEMs—used on their own or in combination with other remote-sensing or ground-based data—offer a unique opportunity for elucidating volcanic processes around the world and assessing associated hazards.

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