

Using satellite radar amplitude imaging for monitoring syn-eruptive changes in surface morphology at an ice-capped stratovolcano

Article

Accepted Version

Creative Commons: Attribution-Noncommercial-No Derivative Works 4.0

Arnold, D. W. D., Biggs, J., Wadge, G. and Mothes, P. (2018) Using satellite radar amplitude imaging for monitoring syn-eruptive changes in surface morphology at an ice-capped stratovolcano. *Remote Sensing of the Environment*, 209. pp. 480-488. ISSN 0034-4257 doi: <https://doi.org/10.1016/j.rse.2018.02.040> Available at <http://centaur.reading.ac.uk/75660/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.1016/j.rse.2018.02.040>

Publisher: Elsevier

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

www.reading.ac.uk/centaur

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

1 Using satellite radar amplitude imaging for monitoring syn-eruptive
2 changes in surface morphology at an ice-capped stratovolcano

3 D.W.D. Arnold^{a,*}, J. Biggs^a, G. Wadge^b, P. Mothes^c

4 ^aCOMET, School of Earth Sciences, University of Bristol, Queens Road, Bristol, BS8 1RJ, UK

5 ^bCOMET, Department of Meteorology, University of Reading, Earley Gate, P.O. Box 243, Reading, RG6
6 6BB, UK

7 ^cInstituto Geofísico, Escuela Politécnica Nacional, Quito, Ecuador

8 **Abstract**

Satellite-based measurements of synthetic aperture radar amplitude provide a method for monitoring volcanoes during unrest and eruptions even when visual observations are not possible, for example due to poor weather or at night, and when radar phase measurements are noisy or decorrelated. Here, we use high resolution radar amplitude images from the TerraSAR-X and COSMO SkyMed satellites to investigate surface changes associated with explosive eruptions of Cotopaxi volcano, Ecuador in August 2015. We generate change difference and amplitude ratio maps spanning the start of explosive activity at Cotopaxi, which show complex spatial variations in radar amplitude both on and around the summit ice-cap that we attribute to a number of processes related to the eruption. Observed amplitude decreases are caused by crater deepening, ashfall onto ice and surface smoothing by ashfall onto slopes facing away from the satellite, while amplitude increases are due to deposition of coarse lapilli and wet tephra, increased soil saturation due to geothermally driven glacier melting, and smoothing of slopes facing towards the satellite. We discuss the potential applications of radar amplitude images for monitoring and hazard evaluation at active volcanoes.

9 *Keywords:* Explosive Volcanism, Radar amplitude, SAR

*Corresponding author

Email address: david.arnold@bristol.ac.uk (D.W.D. Arnold)

1. Introduction

During periods of volcanic unrest and eruption, frequent observations of the volcano are required to monitor the development of activity, in order to update hazard assessments and protect local populations (e.g. Tilling, 1989; Scarpa and Tilling, 1996; Tilling, 2008). For instance, a volcano with a large, unstable, lava dome growing at the summit will be more prone to a gravitational collapse that could generate large, hazardous, pyroclastic density currents than a volcano without an active dome (e.g. Watts et al., 2002; Sparks, 2003), and changes in the ice-cap at a glaciated volcano could indicate melting that may lead to lahars (e.g. Pierson et al., 1990; Mothes and Vallance, 2015). Up-to-date observations of the morphology and surface state of an erupting volcano are therefore crucial for evaluating the current hazard level.

Observations of volcanoes can be made using a variety of techniques and sensors, but all methods have limitations on either the temporal and/or spatial resolution of information they can provide (e.g. Sparks et al., 2012; Pyle et al., 2013; Biggs and Pritchard, 2017; National Academies of Sciences Engineering and Medicine, 2017). Visual observations are not possible in poor weather conditions such as low lying cloud, which is especially a problem at volcanoes with high relief and/or in tropical regions (e.g. Wadge et al., 2005, 2011). Visual observations are also often not possible at night, and even passive sensors such as thermal IR cameras that can make observations in low light still require clear weather conditions. Ground-based geophysical sensors, such as seismometers and GPS, can make continuous observations regardless of weather conditions, however the information they provide is limited to single locations, and instruments are generally located distally from active vents, due to the difficulty and hazard of deploying, maintaining and preserving proximal instruments, (e.g. Voight et al., 1998; LaHusen et al., 2008; Werner-Allen et al., 2006).

Active radar sensors provide their own illumination, so can make observations at day and night, and operate at wavelengths that are not strongly absorbed or scattered by water droplets or aerosols, so can see through clouds. Synthetic Aperture Radar (SAR) observations can therefore provide additional observations that can complement other monitoring

38 techniques. Satellite-based SAR platforms are able to image areas tens to hundreds of
39 kilometres wide with repeat times of days to weeks, and are therefore ideally suited to
40 observations of volcanic systems, especially volcanoes that are difficult to monitor with
41 ground-based techniques due to practical or financial considerations. The frequency of SAR
42 observations can be increased by using images acquired by multiple satellite missions and
43 from different viewing geometries (Elliott et al., 2016).

44 SAR amplitude observations can provide important observations, even at volcanoes with
45 an established ground-based monitoring network. For instance, amplitude observations
46 showed that the lava dome at Soufrière Hills Volcano, Montserrat had not been desta-
47 bilised by a large Vulcanian explosion in 2008, thus allowing civil authorities to revoke a
48 precautionary evacuation ten days before visual confirmation was possible (Wadge et al.,
49 2011). Conversely, SAR images provided information about the rate of lava dome growth
50 during the 2010 eruption of Merapi, Indonesia and helped to inform a broader evacuation
51 that potentially saved thousands of lives (e.g. Pallister et al., 2013). SAR amplitude ob-
52 servations have also provided insights into lava flow distribution and morphology at poorly
53 monitored volcanoes (e.g. Wadge et al., 2012; Goitom et al., 2015; Wang et al., 2015), and
54 rockfall response to a tectonic earthquake (Ebmeier et al., 2014).

55 In this work, we use the August 2015 eruption of Cotopaxi, Ecuador to show the utility
56 of SAR amplitude images for monitoring changes to an ice-capped volcano during explosive
57 eruptions. Cotopaxi is a 5897 m high stratovolcano located approximately 50 km south of
58 Quito in the Interandean Valley (Fig. 1). Cotopaxi is one of the most active volcanoes in
59 Ecuador, with nine periods of major historically-observed eruption and at least eight more
60 minor eruptions (Pistolesi et al., 2011). Prior to 2015, the previous eruption of Cotopaxi was
61 a minor explosive episode in 1942 that was confined to the crater (Pistolesi et al., 2011). In
62 April 2015, Instituto Geofisico, Escuela Politecnica Nacional, Ecuador (IG-EPN) reported
63 an increase in seismicity beneath Cotopaxi and SO₂ emissions began to increase in May
64 2015, accompanied by up to 3 cm of surface uplift (Morales Rivera et al., 2017). Released
65 seismic energy remained above background levels until August 2015, when there was a rapid
66 increase in seismic activity on 13 August 2015 that culminated in four phreatic explosions

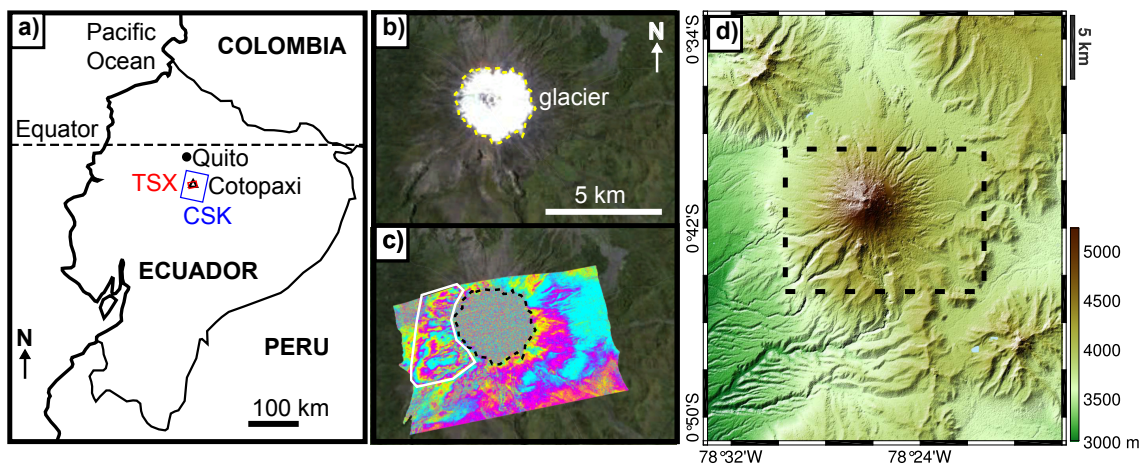


Figure 1: **a)** Map of Ecuador showing the location of Cotopaxi volcano (black triangle). The red rectangle shows the footprint of the TerraSAR-X (TSX) spotlight image and the blue rectangle shows the area covered by the COSMO-SkyMed (CSK) stripmap acquisitions. **b)** Google Earth image of Cotopaxi, with the yellow dashed line outlining the snow and ice covered summit. **c)** Interferogram formed from TSX acquisitions on 9 and 20 August 2015. No useful information can be retrieved over the ice-cap (black dashed line) due to phase incoherence. The white polygon west of the glacier shows phase changes due to atmospheric water vapour changes associated with orographic forcing of prevailing westerly winds. Similar phase anomalies are observed in Envisat and Radarsat-2 interferograms spanning 2002–2013, when there was no surface activity at Cotopaxi. **d)** Hillshaded Digital Elevation Model (DEM) of Cotopaxi. The dashed black box shows the location of **b)** and **c)**.

67 on 14 August 2015. These explosions were followed by a two week period of near continuous
68 ash and steam venting, before activity declined at the beginning of September 2015, with
69 the eruption ending in November 2015 (Bernard et al., 2016; Gaunt et al., 2016).

70 **2. Data and methods**

71 Satellite SAR data involves the transmission of electromagnetic radiation at microwave
72 wavelengths (between 1 mm and 1 m) from the satellite towards the ground surface. On
73 contact with the ground, the radar signal is scattered, with a portion of the signal backscat-
74 tered toward the satellite, which records a complex number for each pixel imaged. The
75 amplitude of this complex number represents the intensity of the radar signal received and
76 constitutes the proportion of the transmitted energy that was backscattered. The phase of
77 the complex number is equivalent to the fraction of the wavelength (between 0 and 2π) and
78 represents the distance between the satellite and the ground surface, wrapped by modulo
79 2π (e.g. Massonnet and Feigl, 1998).

80 The phase difference between two radar acquisitions separated in time and/or space is
81 frequently used to provide information about the shape of the land surface or the magni-
82 tude and spatial extent of ground deformation associated with volcanic processes (e.g. Pinel
83 et al., 2014). In areas where the land surface changes rapidly, for example due to vegeta-
84 tion growth or emplacement of volcanic deposits, the phase difference between neighbouring
85 pixels observed by Interferometric Synthetic Aperture Radar (InSAR) will appear random
86 (incoherent), and therefore no meaningful information can be retrieved (Fig. 1c). Phase
87 delays introduced by variation in atmospheric water vapour content can also introduce sig-
88 nificant noise that can obscure ground deformation signals (e.g. Parker et al., 2015)(Fig. 1c).

89 The amplitude component of a SAR image represents the power of the backscattered
90 radar signal observed by the satellite. This amplitude is a function of local slope relative to
91 the SAR incidence angle, the surface roughness on the length scale of the radar wavelength,
92 and the dielectric constant of the surface material, which changes most with the presence
93 or absence of water (Wadge et al., 2011). In addition the SAR amplitude is a function of
94 the relative radar polarization (Zebker et al., 1987; Saepuloh et al., 2012; Solikhin et al.,

95 2015). However, due to data availability, in this study we only consider single polarization
96 data (HH).

97 The dielectric constant of a material is a measure of how polarizable that material is,
98 and is defined as an effective complex relative permittivity, $\epsilon = \epsilon' - i\epsilon''$, where ϵ' is the real
99 and ϵ'' is the complex component of relative permittivity (e.g. Adams et al., 1996). For a
100 given material, ϵ' and ϵ'' are both dependent on the material density and shape, as well as
101 its temperature and the frequency of incident electromagnetic radiation.

102 In practice it is not possible to estimate the dielectric constant of the ground surface from
103 the power of radar amplitude in a single image, or predict the radar amplitude if the dielectric
104 constant is known, since the amplitude is dependent on the sum of all scatterers within a
105 ground resolution element (pixel). Variations in the satellite viewing geometry with time
106 mean that for any given pixel the backscattered power will be the sum of a slightly different
107 set of scatterers at each time step, resulting in a pixel-by-pixel speckle pattern. However, by
108 comparing broader scale amplitude variations over multiple neighbouring pixels, changes in
109 observed radar amplitude can still provide useful information about areas that are affected
110 by volcanic eruptions, even when the surface has changed enough to decorrelate SAR phase
111 (Fig. 1).

112 Lab measurements of ϵ' and ϵ'' exist for some materials of interest — for andesitic ash,
113 at X-Band frequency (9.6 GHz), ϵ' is between 5 and 6 and ϵ'' is between 0.1 and 0.2 (Adams
114 et al., 1996; Oguchi et al., 2009). For dry snow at X-band frequency ϵ' is 1–2 and ϵ'' is less
115 than 10^4 (Tiuri et al., 1984; Mätzler and Wegmüller, 1987). We would therefore expect a
116 surface covered by andesitic ash to have a higher magnitude radar amplitude return than a
117 surface of identical slope and roughness covered by dry snow.

118 Snow is a mixture of air, ice and water, and the dielectric constant of snow is highly
119 dependent on the relative proportion of water, which dominates the value of ϵ (Tiuri et al.,
120 1984). There is sufficient empirical data to derive a parameterisation of ϵ' and ϵ'' for wet
121 snow, based on W_v , the proportion of water in the snow by volume (Tiuri et al., 1984;
122 Kaatze, 1989; Artemov and Volkov, 2014). From this parameterisation, we would expect
123 the snow covered ice-cap of Cotopaxi to have higher ϵ' compared to the snow-free part of

124 the andesitic edifice if $W_v > 0.3$ and a higher ϵ'' if $W_v > 0.03$. The relative permittivity of
125 andesitic ash also increases substantially when covered with thin films of water, however as
126 yet there is no empirical relationship for this behaviour (Oguchi et al., 2009).

127 We investigated radar amplitude changes at Cotopaxi using data from two satellite SAR
128 missions, TerraSAR-X (TSX) and COSMO-SkyMed (CSK) that were acquired through the
129 Committee on Earth Observation Satellites' Ecuador Volcanoes Supersite. TSX has a repeat
130 observation frequency of 11 days and CSK is a constellation of four satellites, which each
131 have a repeat time of 16 days. Both satellites operate at X-band frequency (wavelength 3.1
132 cm). TSX images were acquired in spotlight viewing mode, which has a 10×10 km image
133 size and a horizontal pixel spacing of 2 m. CSK images were acquired in stripmap mode,
134 which acquires a swath 40 km wide at a pixel spacing of 3 m. Both TSX and CSK data
135 were acquired in HH polarisation.

136 We processed data from both satellites using the Caltech/JPL InSAR Scientific Com-
137 puting Environment (ISCE) software (Rosen et al., 2012). TSX data were provided as
138 single-look complex (SLC) images, while CSK data were provided as raw data, which were
139 focused into SLCs with one look in range and azimuth directions to keep full image reso-
140 lution. We coregistered SLC images using a subpixel amplitude correlation algorithm and
141 resampled the post-eruptive image to the geometry of the pre-eruptive scene (Rosen et al.,
142 2012). We only consider the amplitude component of the SAR images, since at Cotopaxi,
143 the phase component of interferograms decorrelates rapidly on the glaciated ice-cap, and
144 is subject to high atmospheric noise elsewhere (Fig. 1). Sequential images also have large
145 perpendicular baselines, which reduces the phase coherence in interferograms (e.g. Zebker
146 and Villasenor, 1992).

147 We keep the SAR images in radar viewing geometry due to the lack of a high resolution
148 digital elevation model (DEM) that could be used to geocode the images and to avoid warp-
149 ing of the image that occurs in inaccurately geocoded images at rapidly changing summits of
150 erupting volcanoes (e.g. Wadge et al., 2011; Ebmeier et al., 2013; Arnold et al., 2016). SAR
151 images in radar viewing geometry are subject to geometric distortion compared to orthorec-
152 tified geocoded images. Slopes that face towards the satellite sensor will appear brighter and

153 compressed, while slopes that face away from the radar look direction will appear darker
 154 and stretched. Where the angle of the slope is steeper than the satellite incidence angle,
 155 slopes facing away from the satellite will cast a radar shadow. The height of the feature
 156 casting the shadow is given by

$$h = w_{range} \cos \theta \quad (1)$$

157 where h is the height of the feature, w_{range} is the width of the shadow in the range direction
 158 in satellite radar geometry, and θ is the satellite incidence angle. Conversely, for slopes facing
 159 the satellite that are steeper than the normal to the incidence angle, returns from multiple
 160 backscatterers will overlap to create radar layover. The height of the feature causing layover
 161 is given by

$$h = \frac{w_{range} \sin \alpha}{\sin(\alpha - \theta)} \quad (2)$$

162 where α is the gradient of the feature causing layover.

163 Changes in surface reflectivity between two radar images are easier to visualise when
 164 plotted either as ratio maps (Wadge et al., 2002) or change difference maps (Wadge et al.,
 165 2011). A map of the pixel-by-pixel ratio between two images suppresses the influence of
 166 the local slope on amplitude in areas that do not change between images, and decreases
 167 the effect of speckle (e.g. Wadge et al., 2002; Bovolo and Bruzzone, 2005). To reduce the
 168 contrast between high and low intensity pixels, the change in ratio \mathbf{X}_R is given in decibels
 169 by taking the base 10 logarithm of the ratios (Rignot and van Zyl, 1993).

$$\mathbf{X}_R = 10 \log_{10} \left(\frac{\mathbf{X}_2}{\mathbf{X}_1} \right) \quad (3)$$

170 where \mathbf{X}_1 is the intensity of the earlier image and \mathbf{X}_2 is the intensity of the later image.
 171 Pixels in the ratio map with a value greater than 0 dB represent an increase in amplitude
 172 between the two acquisition dates, while pixels less than 0 dB have a decreased amplitude.

173 Alternatively, we can display differences in backscatter intensity as a change difference
 174 image. Change difference images are easier to interpret than ratio maps, but display reduced
 175 changes in areas of high amplitude, such as slopes facing towards the satellite (Rignot and
 176 van Zyl, 1993; Wadge et al., 2011). To generate a change difference image, we create a

177 three-colour component image. Following Wadge et al. (2011); Ebmeier et al. (2014) we
178 assign the earlier image to the red band, the later image to the green band and the scaled
179 difference between the two images to the blue band. Surfaces that have increased reflectivity
180 between the two acquisition dates will appear cyan in a change difference image, surfaces
181 that have decreased reflectivity will appear magenta, and surfaces that have not changed
182 reflectivity will appear yellow.

183 **3. Results**

184 We form change difference and ratio maps spanning the initial explosive activity at
185 Cotopaxi on 14 August 2015 (Figs. 2 and 3). Both maps show complex spatial variations
186 in radar amplitude associated with the eruption, on the ice-cap near the crater and on the
187 flanks and plateau surrounding Cotopaxi, below the ice-cap.

188 *3.1. Crater morphology*

189 The most significant amplitude changes observed at Cotopaxi were at the summit, within
190 approximately 1 km of the crater. Both TSX and CSK images observe a large decrease in
191 amplitude inside the crater (A in Fig. 2, B in Fig. 4). The spatial pattern of the amplitude
192 decrease is consistent with an increase in the width of shadow cast by the crater wall closer to
193 the satellite. Using equation 1, we find that the height of the crater wall increased by 58 ± 4
194 m in the TSX imagery and 51 ± 5 m in CSK images. Since the geometry of the crater edge
195 remains effectively unchanged between pre- and post-eruptive images, this height change
196 must be caused by a lowering of the crater floor through removal of material by volcanic
197 explosions (Fig. 4c and d). Note that for both satellites the height change given is a lower
198 bound, as the shadow cast by the near crater wall is interrupted by layover.

199 If we make assumptions about the shape of the summit crater, then we can estimate
200 the volume of material that was removed by the explosive activity. The crater rim is ap-
201 proximately circular, with a radius of 90 ± 5 m (Fig. 2). If we consider the crater to be
202 conical, from the TSX images, the bulk volume removed between the start of eruption on 14
203 and 20 August 2015 was $5 \pm 2 \times 10^5$ m³. Alternatively, if we assume the crater has vertical

204 sides then the volume removed during this time period was $1.5 \pm 6 \times 10^6 \text{ m}^3$. Realistically
205 the actual volume removed from the crater is likely to be between these end member cases.
206 Bernard et al. (2016) estimated an erupted volume of $1.18 \pm 0.33 \times 10^5 \text{ m}^3$ between 14 and
207 15 August 2015, with little volume erupted between 15 and 22 August based on isopleth
208 maps of tephra mass. Our volume estimates for this time period are substantially greater
209 than that observed from tephra deposition, so a relatively large proportion of the volume
210 removed from the crater must have been deposited proximally to the crater, possibly as bal-
211 listic projectiles, which were observed on the upper slopes of Cotopaxi on 14 August 2015
212 (Bernard et al., 2016).

213 3.2. Proximal ash

214 Areas of bare rock within and proximal to the crater show a slight increase in amplitude
215 (B in Fig. 2), while ice and snow covered areas north, east and south of the crater all show
216 decreased amplitude (C in Fig. 2 and 4). Given the proximity to the eruptive vent and
217 the rapid lateral changes between areas of increased and decreased amplitude on the flanks
218 of Cotopaxi, it is likely that these differences were caused by variation in the pre-eruptive
219 surface (ice or rock), rather than significant differences in the deposition during the eruption
220 (Fig. 4e and f).

221 We assume that the erupted material in 2015 was similar in composition to previously
222 erupted products at this elevation on the edifice of Cotopaxi, therefore there should not
223 be any significant difference in dielectric constant between old and new deposits. The in-
224 creased amplitude on bare rock therefore suggests that the proximal post-eruptive surfaces
225 were rougher than the pre-eruptive surface. For X-band (3.1 cm wavelength) radar, surfaces
226 appear rough if the small scale height variation is greater than about 4 mm (Wadge et al.,
227 2011). While most of the erupted material from this time period was fine-grained tephra,
228 proximal deposits contained approximately 2 % lapilli (2–4 mm) and larger ballistic projec-
229 tiles were observed on the upper flanks (Bernard et al., 2016; Gaunt et al., 2016). For a given
230 pixel in a SAR image, the backscatter is dominated by the largest objects contained within
231 that pixel (e.g. Ferretti et al., 2000; Hooper et al., 2004), therefore even a small proportion

232 of coarse grained lapilli and ballistics could be enough to increase the surface roughness at
233 radar wavelengths.

234 Ice and snow covered areas within 1 km of the summit crater show a clear decrease in
235 radar backscatter by over 5 dB (Fig. 2b and d). This decrease in reflected power would be
236 expected if the glacier was covered with tephra that had a lower dielectric constant than the
237 glacier. However, aerial photographs acquired on 18 August show little to no tephra on the
238 north, east and south flanks of the glacier. Instead, this change might be due to changes
239 in the ice-cap, such as fresh dry snow covering older wet snow at high altitudes. While the
240 greatest thickness of ash deposits were on the west flank of Cotopaxi, the radar information
241 provide little information about the ice-cap on the west flank, which suffers from layover in
242 ascending TSX images, and is almost entirely in shadow in descending CSK images.

243 *3.3. Ice-cap and crevasses*

244 We observed crevasses on the west flank (D in Fig. 2 and 4) that provided a reflective
245 surface facing the CSK satellite. The steep sided crevasses appear as patches of layover,
246 which more than halved in width between the pre-eruptive and post-eruptive images. If we
247 assume that the crevasses have vertical sides, then using equation 2, we estimate that they
248 decreased in height from 15 ± 2 m to 6 ± 2 m. Increased geothermal heating from below
249 combined with conductive heat transfer from tephra deposited on top of the glacier resulted
250 in high rates of glacier melting between August 18 and October 8 2015 compared to the
251 background rate (Ramón et al., 2016). However, it is highly unlikely that the observed 9
252 m decrease in crevasse height was due to melting, since this height decrease across the west
253 flank of the ice-cap would generate a very large volume of meltwater, which wasn't observed
254 at the time (IG-EPN special reports).

255 The 9 m decrease in crevasse depth could be due to infill by tephra and lapilli, however
256 the measured tephra mass for this time period was 7600 g m^{-2} at the nearest location to
257 the glacier (Fig. 3g) (Bernard et al., 2016). The measured ash deposit density was $1343 \pm$
258 128 kg m^{-3} (Bernard et al., 2016), which gives a deposit thickness of 6 mm — orders of
259 magnitude less than required to account for the change in crevasse height. However, glacier

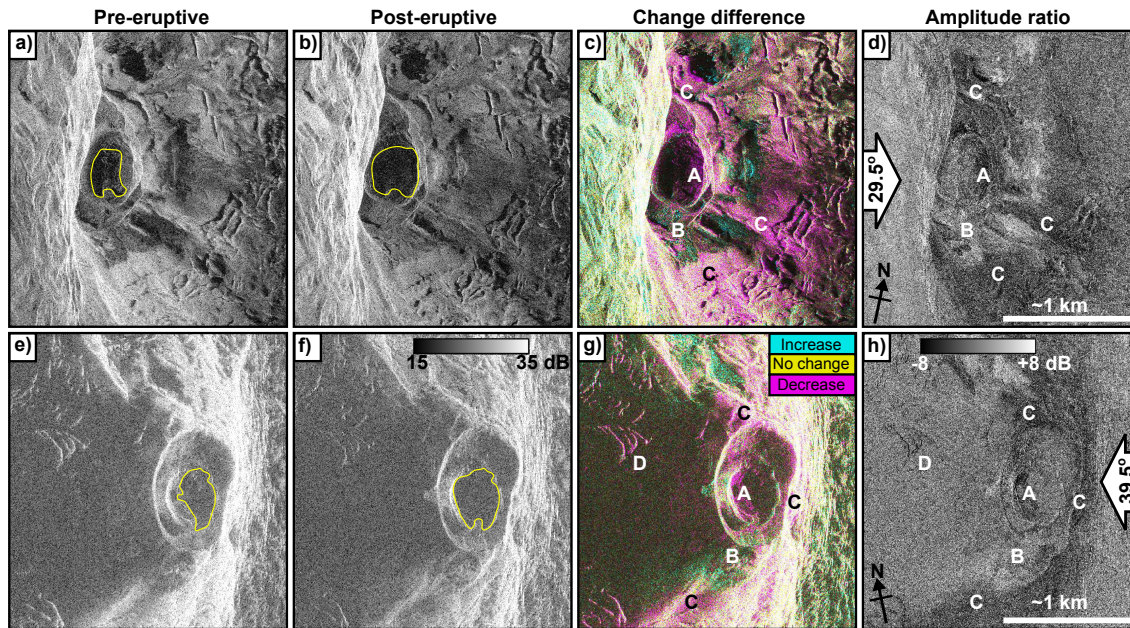


Figure 2: TSX (top) and CSK (bottom) images of the summit of Cotopaxi volcano during the August 2015 eruption. **a)** and **e)** pre-eruptive images; **b)** and **f)** post-eruptive images; **c)** and **g)** change difference maps; **d)** and **h)** amplitude ratio maps. TSX images were acquired on ascending passes in spotlight mode on 9 August 2015 (**a**) and 20 August 2015 (**b**). CSK images were acquired in stripmap mode on descending passes on 12 August 2015 (**e**) and 28 August 2015 (**f**). Images are in radar viewing geometry, with the white arrows showing the satellite look direction and incidence angle. Yellow polygons in **a)**, **b)**, **e)** and **f)** indicate the area of radar shadow in the summit crater. The scale bars are approximately accurate in the azimuth direction (perpendicular to the look direction), but are not valid on sloped topography in the range direction (parallel to the look direction). See main text for references to labels A-D.

260 meltwater or precipitation could wash tephra deposits into the crevasses, where they would
261 accumulate a much greater thickness than if tephra was just deposited by airfall. Partial
262 collapse of the crevasse sides, potentially induced by partial melting, would also move ice
263 from the top of the crevasse to the base, reducing the height of the crevasse side causing the
264 layover (Fig. 4g and h).

265 On the north, east and south side of the glacier is a ring of amplitude increase in both
266 TSX and CSK imagery (C in Fig. 3, A in Fig. 4). These areas were upwind of the summit,
267 and not affected by ashfall (Bernard et al., 2016), however visual observations on 18 and 23
268 August observed increased moisture and streams of water descending from the basal edge of
269 the glacier (Fig. 4a; Ramón et al., 2016). Increasing the water content of the area around the
270 glacier would increase the permittivity of the reflecting surface, resulting in the increased
271 amplitude observed (Oguchi et al., 2009). The paired inner ring of decreased amplitude
272 observed in Fig. 3b cannot be explained by the same mechanism, but could be due to the
273 presence of dry snow in the pre-eruptive image that had melted by the later image.

274 *3.4. Distal amplitude changes*

275 Changes in radar amplitude were observed up to 10 km away from the summit and below
276 the glacier. The area to the west of the summit, a few kilometres distal from the glacier edge,
277 shows increased amplitude in the CSK image, but is not covered by the smaller footprint
278 of the spotlight TSX image (A in Fig. 3). This area was covered by the greatest thickness
279 of tephra deposits, with over 7000 g m^{-2} of ash deposition between 14 and 28 August 2015
280 (Bernard et al., 2016), and is immediately downwind of the Cotopaxi summit. Given the
281 fine-grained nature of the tephra fallout (Gaunt et al., 2016), we would expect the surface
282 roughness to decrease when covered by a layer of tephra (e.g. Wadge et al., 2011).

283 We propose two possible mechanisms to explain the localised amplitude increase that is
284 spatially correlated with the thickest tephra deposits. The first mechanism involves initially
285 lowering the surface roughness through tephra deposition. The tephra deposits are poorly
286 consolidated and therefore more rapidly eroded than older, more consolidated, deposits by
287 post-depositional rainfall, which creates micro-relief that is rougher than the pre eruption

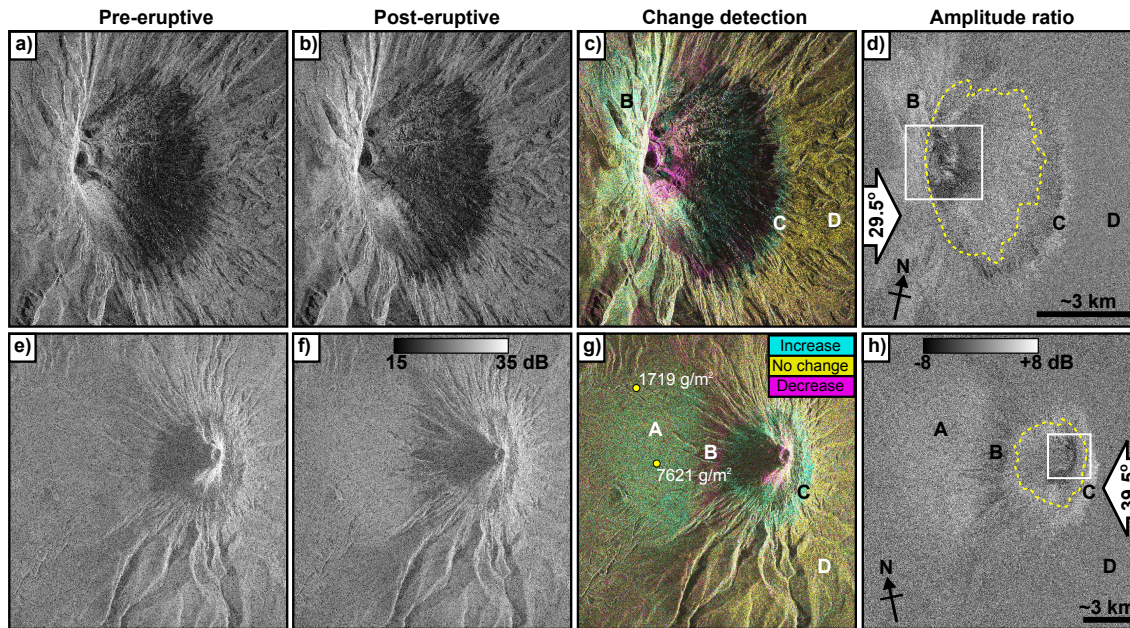


Figure 3: TSX (top) and CSK (bottom) images of the flanks of the August 2015 eruption of Cotopaxi. **a)** and **e)** pre-eruptive images; **b)** and **f)** post-eruptive images; **c)** and **g)** change difference maps; **d)** and **h)** amplitude ratio maps. TSX images were acquired on ascending passes in spotlight mode on 9 August 2015 (**a**) and 20 August 2015 (**b**). CSK images were acquired in stripmap mode on descending passes on 12 August 2015 (**e**) and 28 August 2015 (**f**). Images are in radar viewing geometry, with the white arrows showing the satellite look direction and incidence angle. The scale bars are approximately accurate in the azimuth direction (perpendicular to the look direction), but are not valid on sloped topography in the range direction (parallel to the look direction). Yellow dashed lines in **d)** and **h)** show the edge of the ice-cap, and white boxes show the extent of Fig. 2. See main text for references to labels A-D.

288 surface (combining steps b and d from Fig. 1 of Wadge et al. (2011)). While we cannot rule
289 out this mechanism, the nearest weather station (located 30 km to the southwest at Cotopaxi
290 International Airport in Latacunga) recorded very little precipitation between 14 and 28 Au-
291 gust 2015 (NOAA Global Surface Summary of the Day records, available online at [https://](https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD&resolution=40)
292 www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD&resolution=40). There were
293 also near continuous ash emissions during the last week in August (Bernard et al., 2016;
294 Gaunt et al., 2016), therefore providing constant resurfacing of the surface that would mit-
295 igate against this effect.

296 Alternatively, the effective permittivity of andesitic ash greatly increases when covered
297 by a thin film of water (Oguchi et al., 2009). If the erupted ash was covered by a coat of
298 water, either acquired from meteorological clouds or a hydrothermal or phreatic source, and
299 the deposited tephra had not dried out by the time the second SAR image was acquired,
300 the area covered by ash would have an increase in radar backscatter, even if the surface
301 roughness was decreased. Given the phreatic nature of the initial explosive phase (Gaunt
302 et al., 2016), high glacier melt rates (Ramón et al., 2016), and frequent orographically forced
303 cloud around the summit of Cotopaxi (Fig. 4a), we suspect this “wet ash” mechanism is
304 more likely than post-depositional erosion. Wetted ash could also explain the amplitude
305 increase seen near to the crater (B in Fig. 2), even if the proximal ash was fine-grained.

306 Closer to the summit, west and northwest of the glacier there were amplitude changes
307 in both TSX and CSK imagery, but with differing sign (B in Fig. 3, E in Fig. 4). The TSX
308 pair shows amplitude increase, while the CSK pair shows decreased amplitude in the same
309 area. This area is on the flank of Cotopaxi, which slopes 20–30° to the west. Covering
310 the slope with ash will decrease the surface roughness, which will change the amount of
311 backscattered energy received by the satellite depending on the incidence angle of the SAR
312 signal. Reducing roughness will cause the surface to act more like a specular reflector,
313 which will reflect more energy back towards the east-looking, ascending pass (TSX) while
314 more energy will be reflected away from the west looking, descending pass (CSK) causing a
315 reduction in SAR amplitude (Fig. 4i and j).

316 To the north, east and south, and at distances greater than 5 km from the summit of

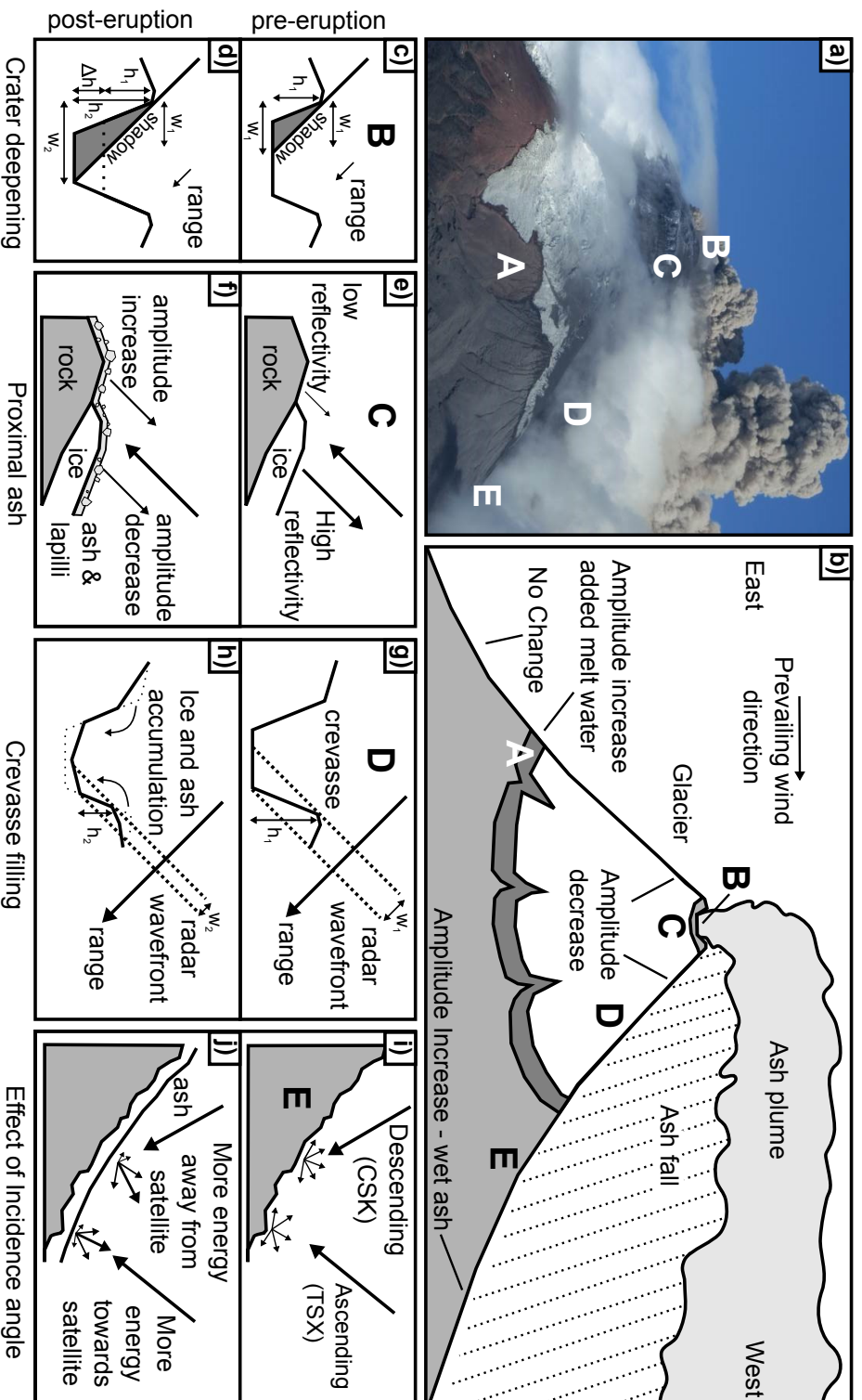


Figure 4: **a)** Photograph of the eruption of Cotopaxi taken by P. Mothes at 3:45 pm, on 23 August 2015. The photo was taken from the north of Cotopaxi looking south and the ash plume was heading west-southwest. See main text for references to labels A-E. **b)** Sketch of surface changes at Cotopaxi observed by radar amplitude. **c)–j)** Sketch interpretations of amplitude changes observed between pre- (top) and post- (bottom) eruptive SAR images. **c)** and **d)** Increased shadow width, caused by deepening of the summit crater (A in Fig. 2). w_1 and w_2 are the pre- and post- eruptive shadow widths, respectively. h_1 and h_2 are the pre- and post-eruptive crater depths, respectively, and Δh is the difference between h_1 and h_2 . Note that due to radar layover on the far crater wall, w_2 and h_2 are lower bounds only. **e)** and **f)** Relative difference in amplitude between glaciated (C in Fig. 2) and non-glaciated (B in Fig. 2) areas within 1 km of the summit. Post-eruptive ash deposits in **f)** contain coarse ballistic clasts. **g)** and **h)** Decreased layover width of crevasses, likely due to partial collapse of the crevasse walls and accumulation of ice and volcanoclastic material at the bottom of the crevasse. **i)** and **j)** Effect of satellite look direction on observed amplitude change (B in Fig. 3). The smoother ash-covered post-eruptive surface acts more like a specular reflector, and therefore backscatters more energy towards satellites looking approximately orthogonal to the slope, but less energy towards satellites looking at an oblique angle.

317 Cotopaxi, there are no significant amplitude changes in either TSX or CSK imagery (D in
318 Fig. 3), showing that these areas were unaffected by the eruption.

319 *3.5. Baseline measurements of amplitude change*

320 In addition to volcanic activity, radar amplitude can be affected by changes in precipi-
321 tation and vegetation cover, and we would therefore expect to observe amplitude variations
322 during inter-eruptive periods (e.g. Wadge et al., 2011; Kubanek et al., 2017). These am-
323 plitude changes can vary systematically throughout the year due to seasonal changes in
324 vegetation growth and precipitation (Kubanek et al., 2017) however, we would not expect a
325 strong seasonal signal at a high altitude equatorial volcano such as Cotopaxi.

326 In order to determine which amplitude changes are due to eruptive activity, we need
327 background measurements during periods of quiescence to establish a baseline of typical
328 amplitude changes. To create this baseline, we use eight TSX scenes to form four image
329 pairs, each with 11 day separation, acquired throughout the year following the eruption
330 (there is not a sufficiently long catalog of pre-eruptive X-band imagery at Cotopaxi to form
331 a pre-eruption baseline). We follow the same data processing scheme detailed in Section 2
332 to create four additional post-eruptive change difference images (Fig. 5) that we compare
333 with the syn-eruptive images shown in Figs. 2 and 3.

334 In the post-eruptive change difference images, we observe amplitude variations with dif-
335 ferent spatial patterns to those seen in the syn-eruptive imagery (Fig. 5a and f). Amplitude
336 changes on the glacier appear more spatially homogenous, such as between 7 and 18 April
337 2016 (Fig. 5c and h) and between 4 and 15 July 2016 (Fig. 5d and i), where there is an
338 amplitude increase across the entire Cotopaxi glacier. Post-eruptive images also show no
339 change in amplitude west of the summit, supporting our interpretation that the syn-eruptive
340 amplitude changes on the western flank were due to ashfall.

341 Proximal to the Cotopaxi crater, between 22 October and 2 November 2016 (Fig. 5e) we
342 observe amplitude variations that have a similar spatial pattern to the syn-eruptive changes,
343 with decreased amplitude on ice covered ground and decreased amplitude on exposed rock.
344 Since there was no eruptive activity at Cotopaxi in 2016, the pattern in the post-eruptive

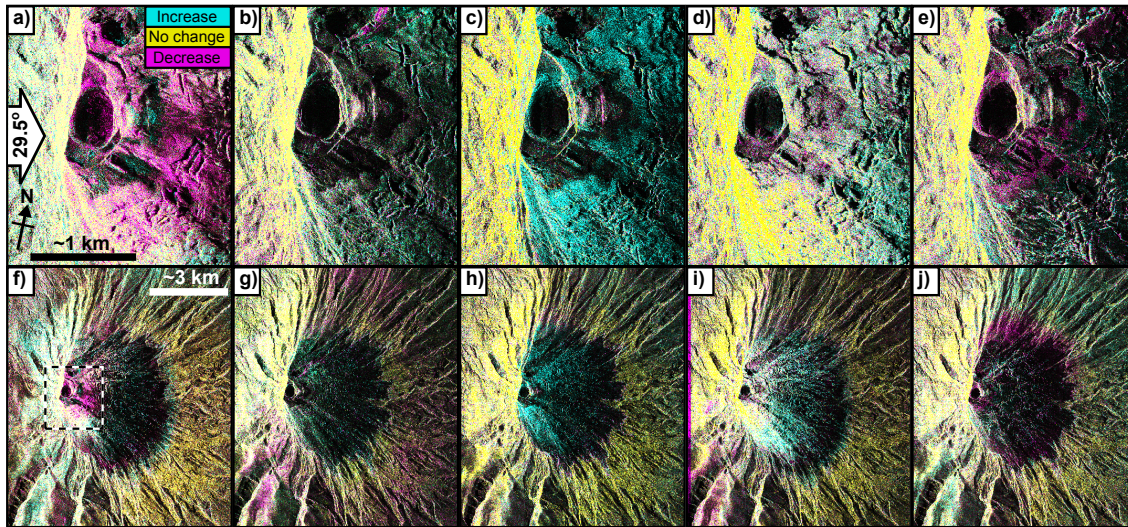


Figure 5: Change difference images of Cotopaxi formed from the 11-day TSX image pairs acquired on ascending passes in spotlight mode. **a)** and **f)** are the syn-eruptive images from 12 – 28 August 2015 (Fig. 2c and 3c). **b)–e)** and **g)–j)** are post-eruptive image pairs collected throughout 2016. **b)** and **g)** 10 – 21 January 2016; **c)** and **h)** 7 – 18 April 2016; **d)** and **i)** 4 – 15 July 2016; **e)** and **j)** 22 October – 2 November 2016. The dashed black and white box in **f)** give the location of zoomed images **a)–e)**.

345 imagery cannot be due to deposition of ash and lapilli (Fig. 4e and f). However, snowfall
 346 between the two image acquisition dates could cause a similar pattern, with snow deposited
 347 onto rock causing an amplitude increase, while depositing fresh dry snow onto wetter snow
 348 would appear as an amplitude decrease. Fig. 5j shows that there are concentric amplitude
 349 variations on the cone, which are likely due to altitude and temperature differences in the
 350 structure and water content of fresh snowfall between the images (Tiuri et al., 1984; Kaatze,
 351 1989; Artemov and Volkov, 2014).

352 4. Discussion

353 4.1. Application of radar amplitude to volcanoes

354 Here we have demonstrated the ability of radar amplitude images to record changes in
 355 surface character associated with explosive eruptive activity at a glaciated volcano. Radar
 356 amplitude was used to retrieve information about changes to the crater and ice-cap of Co-
 357 topaxi, even where radar phase was incoherent (Fig. 1c). Only processing the amplitude

358 component of SAR images also provides a substantial reduction in processing time, which
359 can be crucial when responding to a rapidly evolving volcanic system. In particular, the
360 computationally expensive steps of topographic flattening, filtering and phase unwrapping
361 can all be skipped when only dealing with amplitude imagery (e.g. Werner et al., 2000;
362 Rosen et al., 2004, 2012).

363 Previous work has shown the benefit of the amplitude images for tracking lava dome
364 growth (Wadge et al., 2011; Pallister et al., 2013; Wang et al., 2015), lava flow development
365 (Wadge et al., 2012; Goitom et al., 2015, Chapters 3 and 4), rockfalls (Ebmeier et al.,
366 2014), and pyroclastic density current and block-and-ash flow deposition (Wadge et al.,
367 2011). Results presented here represent one of the first cases of using radar amplitude to
368 study explosive volcanism and tephra dispersion, and additionally show changes in glacier
369 morphology associated with volcanic activity.

370 We also show the benefit of comparing results from different satellite sensors and viewing
371 geometries. Higher resolution spotlight TSX imagery was better at observing small scale,
372 localised changes on the glacier and at the summit crater. However, the larger footprint of
373 the stripmap CSK images enabled us to observe more distal ash depositions that fell outside
374 the TSX footprint.

375 The interpretation of amplitude images can be greatly aided by validation data, such as
376 field measurements of ashfall thickness (Bernard et al., 2016). For example, the edge of the
377 area that shows significant amplitude variation due to ashfall (A in Fig. 3) approximately
378 intersects with a location where Bernard et al. (2016) measured 1719 g m^{-2} of tephra
379 deposition during the same time period. Using their measured density of $1343 \pm 128 \text{ kg}$
380 m^{-3} give a tephra thickness of $1.28 \pm 0.12 \text{ mm}$. Therefore X-band radar amplitude could be
381 used to map tephra deposits of similar composition and with a thickness greater than ~ 1
382 mm. Optical images (e.g. Fig. 4a) of the eruption also aid with the interpretation of changes
383 on and around the glacier, such as increased melt water at the base of the glacier, and
384 confirming that ash deposition was almost entirely concentrated to the west of the summit.

385 More detail about syn-eruptive changes in volcano morphology could be obtained by
386 adding data from other SAR platforms that operate at different wavelengths. Sentinel-1

387 and ALOS-2 both acquire data with a pixel size of 10–20 m, which would be less well
388 suited to tracking small scale, proximal changes. However, the swath width of Sentinel-1 is
389 250 km and ALOS-2 is 350 km, therefore both systems could be better suited to tracking
390 distal ashfall. Since the frequency dependence of surface roughness and dielectric constant
391 is known generally in volcanic terrains (e.g. Ford et al., 1998), observations of the same
392 area at X-band ($\lambda = 3.1$ cm, e.g. CSK, TSX), C-band ($\lambda = 5.6$ cm, e.g. Sentinel-1) and
393 L-band ($\lambda = 23.6$ cm, e.g. ALOS-2) should make it possible to better attribute changes
394 in radar amplitude to either changes in surface roughness or dielectric constant. However,
395 quantitative interpretation of amplitude changes requires more laboratory measurements of
396 how the dielectric constants of surfaces change when covered by volcanic products of different
397 types (e.g. Ulaby and Long., 2014).

398 *4.2. Volcanic hazard*

399 Radar amplitude imaging can be a valuable tool for volcano monitoring, and can either
400 supplement other observation techniques, or provide critical information about volcanic haz-
401 ard when visual observations are not possible (e.g. Wadge et al., 2011; Pallister et al., 2013).
402 As demonstrated here, radar amplitude can be particularly useful for assessing changes at
403 ice-capped volcanoes, where radar phase rapidly decorrelates. Given that both the deadliest
404 (Nevado del Ruiz, 1985: 23000 fatalities, e.g. Pierson et al., 1990) and the most costly (Ey-
405 jafjallajökull, 2010: \$5 billion, e.g. International Air Transport Association, 2011) eruptions
406 of recent decades have both involved volcano-ice interactions, ice-capped volcanoes, such as
407 Cotopaxi, pose a much greater potential hazard through primary lahar generation than sim-
408 ilar volcanoes that do not have an ice-cap, and generally generate smaller secondary lahars
409 (e.g. Tungurahua: Loughlin et al., 2015; Mothes and Vallance, 2015).

410 The amplitude images presented here can readily be processed within hours of receiving
411 the satellite data, and incorporated into real-time volcano monitoring. Due to a five day la-
412 tency period between satellite acquisition and image delivery by DLR, IG-EPN were unable
413 to incorporate TSX images into their real-time monitoring procedures, however later radar
414 amplitude images confirmed aerial and ground-based observations that had been made im-

415 mediately after the 14 August 2015 eruption. Image delivery times are more rapid for other
416 SAR platforms — CSK interferograms were successfully incorporated into IG-EPN daily
417 briefings during a period of unrest at Volcan Chiles-Cerro Negro in October 2014 (Ebmeier
418 et al., 2016, Pritchard et al., in prep.), and Sentinel-1 interferograms have been included in
419 IG-EPN special reports on unrest at Cerro Azul in March 2017 (IG-EPN, 2017).

420 When interpreting amplitude changes, frequent image acquisitions can aide interpreta-
421 tion (e.g. Wadge et al., 2011). Any amplitude changes observed are the cumulative sum of
422 all changes that occurred between the first and second date, therefore attributing amplitude
423 changes to a specific event or time period can be more difficult for change difference maps
424 spanning a longer time interval. Having access to local meteorological records could prove
425 very useful in this regard. However, amplitude changes can be measured even when there
426 are large temporal or perpendicular baselines between images. So, unlike differential In-
427 SAR, ratio maps can be generated even if the previous image was acquired months or years
428 previously, which can be a serious limitation for differential InSAR (e.g. Ebmeier et al.,
429 2013).

430 5. Conclusion

431 We use radar amplitude images from the high resolution TerraSAR-X and COSMO
432 SkyMed satellites to track changes associated with mild explosive volcanism at Cotopaxi,
433 Ecuador in August 2015. We observe spatially complex variations in radar backscatter with
434 adjacent areas showing simultaneous increases and decreases in radar amplitude. We also
435 show that some amplitude changes, due to smoothing of surfaces on sloped topography, are
436 dependent on the radar incidence angle. These surfaces show increased amplitude for satel-
437 lites facing orthogonal to the slope and decreased amplitude for satellites looking obliquely
438 at the slope. We attribute changes in radar amplitude to a variety of processes, including
439 changes in summit crater morphology and deepening of the crater floor, deposition of ash
440 and lapilli on the summit ice-cap, accumulation of ice and volcaniclastic material at the base
441 of crevasses, increased melt water at the base of the glacier and downwind deposition of wet
442 ash. Radar amplitude images presented here can provide critical information about changes

443 to volcanic systems, even when radar phase provides no useful information, and could be
444 used to supplement volcano monitoring observations at other eruptions across the range of
445 terrestrial volcanic settings and eruption styles.

446

447 **Acknowledgements**

448 We thank K. Cashman and T. Walter for useful feedback and discussion. Comments
449 from E. Kasischke and one anonymous reviewer greatly improved the manuscript. DA is sup-
450 ported by NERC studentship Ne/L501554/1. JB and GW are supported by NERC COMET
451 and JB is supported by STREVA. COSMO-SkyMed data were provided by the Italian Space
452 Agency (ASI) and TerraSAR-X images were provided by Deutsches Zentrum für Luft- und
453 Raumfahrt e. V. (DLR; German Space Agency). Satellite data were made available through
454 the Group on Earth Observation's Ecuador Volcanoes Geohazard Supersite. This work forms
455 part of the Committee on Earth Observation Satellites (CEOS) Volcano Pilot for Disaster
456 Risk Management.

457

458 **References**

- 459 Adams, R.J., Perger, W.F., Rose, W.I., Kostinski, A., 1996. Measurements of the complex dielectric constant
460 of volcanic ash from 4 to 19 GHz. *J. Geophys. Res.* 101, 8175. URL: [http://www.geo.mtu.edu/~raman/
461 papers/AdamsJGR.pdf](http://www.geo.mtu.edu/~raman/papers/AdamsJGR.pdf), doi:10.1029/96JB00193.
- 462 Arnold, D.W.D., Biggs, J., Wadge, G., Ebmeier, S.K., Odbert, H.M., Poland, M.P., 2016. Dome growth,
463 collapse, and valley fill at Soufrière Hills Volcano, Montserrat, from 1995 to 2013: Contributions from
464 satellite radar measurements of topographic change. *Geosphere* 12, 1300–1315. URL: [http://geosphere.
465 gsapubs.org/lookup/doi/10.1130/GES01291.1](http://geosphere.gsapubs.org/lookup/doi/10.1130/GES01291.1), doi:10.1130/GES01291.1.
- 466 Artemov, V.G., Volkov, A.A., 2014. Water and Ice Dielectric Spectra Scaling at 0C. *Ferroelectrics* 466,
467 158–165. URL: <http://arxiv.org/abs/1308.1229>[http://www.tandfonline.com/doi/abs/10.1080/
468 00150193.2014.895216](http://www.tandfonline.com/doi/abs/10.1080/00150193.2014.895216), doi:10.1080/00150193.2014.895216, arXiv:1308.1229.
- 469 Bernard, B., Battaglia, J., Proaño, A., Hidalgo, S., Vásconez, F., Hernandez, S., Ruiz, M., 2016. Relationship
470 between volcanic ash fallouts and seismic tremor: quantitative assessment of the 2015 eruptive period
471 at Cotopaxi volcano, Ecuador. *Bull. Volcanol.* 78, 80. URL: [http://link.springer.com/10.1007/
472 s00445-016-1077-5](http://link.springer.com/10.1007/s00445-016-1077-5), doi:10.1007/s00445-016-1077-5.
- 473 Biggs, J., Pritchard, M.E., 2017. Global Volcano Monitoring: What Does It Mean When Volcanoes Deform?

474 Elements 13, 17–22. URL: <http://elements.geoscienceworld.org/content/13/1/17>, doi:10.2113/
475 gselements.13.1.17.

476 Bovolo, F., Bruzzone, L., 2005. A detail-preserving scale-driven approach to change detection in multitem-
477 poral SAR images. *IEEE Trans. Geosci. Remote Sens.* 43, 2963–2972. URL: <http://ieeexplore.ieee.org/document/1542367/>, doi:10.1109/TGRS.2005.857987.

479 Ebmeier, S.K., Biggs, J., Mather, T.A., Amelung, F., 2013. Applicability of InSAR to tropical vol-
480 canoes: insights from Central America. *Geol. Soc. London, Spec. Publ.* 380, 15–37. URL: <http://sp.lyellcollection.org/content/380/1/15.short>, doi:10.1144/SP380.2.

482 Ebmeier, S.K., Biggs, J., Muller, C., Avarid, G., 2014. Thin-skinned mass-wasting responsible for widespread
483 deformation at Arenal volcano. *Front. Earth Sci.* 2, 1–10. URL: [http://journal.frontiersin.org/
484 article/10.3389/feart.2014.00035/abstract](http://journal.frontiersin.org/article/10.3389/feart.2014.00035/abstract), doi:10.3389/feart.2014.00035.

485 Ebmeier, S.K., Elliott, J.R., Nocquet, J.M., Biggs, J., Mothes, P., Jarrín, P., Yépez, M., Aguaiza, S., Lund-
486 gren, P., Samsonov, S.V., 2016. Shallow earthquake inhibits unrest near Chiles-Cerro Negro volcanoes,
487 Ecuador-Colombian border. *Earth Planet. Sci. Lett.* 450, 283–291. URL: <http://www.sciencedirect.com/science/article/pii/S0012821X16303338>, doi:10.1016/j.epsl.2016.06.046.

489 Elliott, J., Walters, R., Wright, T., 2016. The role of space-based observation in understanding and re-
490 sponding to active tectonics and earthquakes. *Nat. Commun.* 7, 13844. URL: <http://www.ncbi.nlm.nih.gov/pubmed/28004655>, doi:10.1038/ncomms13844.

492 Ferretti, A., Prati, C., Rocca, F., 2000. Nonlinear subsidence rate estimation using permanent scatterers
493 in differential SAR interferometry. *IEEE Trans. Geosci. Remote Sens.* 38, 2202–2212. URL: <http://ieeexplore.ieee.org/document/868878/>, doi:10.1109/36.868878.

495 Ford, J., Blom, R., Jr, J.C., Farr, T., Plaut, J., 1998. Radar geology, in: Henderson, F., Lewis, A.
496 (Eds.), *Princ. Appl. imaging radar. Man. Remote sensing, Vol. 2.* John Wiley and Sons, Inc., Somerset,
497 NJ (United States), pp. 511–560. URL: [https://scholar.google.co.uk/scholar?q=Ford%7D2C+J.P.
498 +%7D281998%7D29+Radar+geology.&btnG=&hl=en&as%7Dsdt=0%7D2C5](https://scholar.google.co.uk/scholar?q=Ford%7D2C+J.P.+%7D281998%7D29+Radar+geology.&btnG=&hl=en&as%7Dsdt=0%7D2C5).

499 Gaunt, H.E., Bernard, B., Hidalgo, S., Proaño, A., Wright, H., Mothes, P., Criollo, E., Kuep-
500 pers, U., 2016. Juvenile magma recognition and eruptive dynamics inferred from the analysis
501 of ash time series: The 2015 reawakening of Cotopaxi volcano. *J. Volcanol. Geotherm. Res.*
502 328, 134–146. URL: [http://www.sciencedirect.com/science/article/pii/S0377027316301858?np=
503 y&npKey=93070ef3896dbf4803f0c5b235a6a2d7154de09fd4443ce6de78255becdbd0f2](http://www.sciencedirect.com/science/article/pii/S0377027316301858?np=y&npKey=93070ef3896dbf4803f0c5b235a6a2d7154de09fd4443ce6de78255becdbd0f2), doi:10.1016/
504 j.jvolgeores.2016.10.013.

505 Goitom, B., Oppenheimer, C., Hammond, J.O.S., Grandin, R., Barnie, T., Donovan, A., Ogubazghi, G.,
506 Yohannes, E., Kibrom, G., Kendall, J.M., Carn, S.A., Fee, D., Sealing, C., Keir, D., Ayele, A., Blundy,
507 J., Hamlyn, J., Wright, T., Berhe, S., 2015. First recorded eruption of Nabro volcano, Eritrea, 2011.

508 Bull. Volcanol. 77, 85. URL: <http://link.springer.com/10.1007/s00445-015-0966-3>, doi:10.1007/
509 s00445-015-0966-3.

510 Hooper, A., Zebker, H., Segall, P., Kampes, B., 2004. A new method for measuring deformation on volcanoes
511 and other natural terrains using InSAR persistent scatterers. *Geophys. Res. Lett.* 31, 1–5. URL: <http://doi.wiley.com/10.1029/2004GL021737>, doi:10.1029/2004GL021737.

512

513 IG-EPN, 2017. Informe Especial Cerro Azul No. 2 - 2017 - Instituto Geofísico - EPN. URL: [http://www.
514 igepn.edu.ec/servicios/noticias/1473-informe-especial-cerro-azul-no-2-2017](http://www.igepn.edu.ec/servicios/noticias/1473-informe-especial-cerro-azul-no-2-2017).

515 International Air Transport Association, 2011. Volcanic Ash. Ashes to AshesWhat has been learned from
516 recent volcanic eruptions and where does the industry go from here? URL: [http://airlines.iata.
517 org/analysis/volcanic-ash](http://airlines.iata.org/analysis/volcanic-ash).

518 Kaatze, U., 1989. Complex permittivity of water as a function of frequency and temperature. *J.*
519 *Chem. Eng. Data* 34, 371–374. URL: <http://pubs.acs.org/doi/pdf/10.1021/je00058a001><http://pubs.acs.org/doi/abs/10.1021/je00058a001>, doi:10.1021/je00058a001.

520

521 Kubanek, J., Westerhaus, M., Heck, B., 2017. TanDEM-X Time Series Analysis Reveals Lava Flow Volume
522 and Effusion Rates of the 20122013 Tolbachik, Kamchatka Fissure Eruption. *J. Geophys. Res. Solid Earth*
523 122, 7754–7774. URL: <http://doi.wiley.com/10.1002/2017JB014309>, doi:10.1002/2017JB014309.

524 LaHusen, R.G., Swinford, K.J., Logan, M., Lisowski, M., 2008. Instrumentation in Remote and Dangerous
525 Settings; Examples Using Data from GPS Spider Deployments During the 20042005 Eruption of Mount
526 St. Helens, Washington. A volcano rekindled renewed Erupt. Mt. St. Helens, 2004-2006 , 335–345URL:
527 <https://pubs.usgs.gov/pp/1750/chapters/pp2008-1750{ }chapter16.pdf>.

528 Loughlin, S.C., Vye-Brown, C., Sparks, R., Brown, S.K., Barclay, J., Calder, E., Cottrell, E., Jolly, G.,
529 Komorowski, J.C., Mandeville, C., Newhall, C., Palma, J., Potter, S., Valentine, G., 2015. An introduction
530 to global volcanic hazard and risk, in: Loughlin, S.C., Sparks, S., Brown, S.K., Jenkins, S.F., Vye-Brown,
531 C. (Eds.), *Glob. Volcan. Hazards Risk*. Cambridge University Press, Cambridge, pp. 1–80. URL: <http://ebooks.cambridge.org/ref/id/CB09781316276273A013>, doi:10.1017/CB09781316276273.003.

532

533 Massonnet, D., Feigl, K.L., 1998. Radar interferometry and its application to changes in the Earth’s surface.
534 *Rev. Geophys.* 36, 441. URL: <http://doi.wiley.com/10.1029/97RG03139>, doi:10.1029/97RG03139.

535 Mätzler, C., Wegmüller, U., 1987. Dielectric properties of fresh-water ice at microwave frequencies. *J.*
536 *Phys. D. Appl. Phys.* 20, 1623–1630. URL: [http://stacks.iop.org/0022-3727/20/i=12/a=013?key=
537 crossref.08de7f831b696e8f0116e5958739ce37](http://stacks.iop.org/0022-3727/20/i=12/a=013?key=crossref.08de7f831b696e8f0116e5958739ce37), doi:10.1088/0022-3727/21/11/522.

538 Morales Rivera, A.M., Amelung, F., Mothes, P., Hong, S.H., Nocquet, J.M., Jarrin, P., 2017. Ground
539 deformation before the 2015 eruptions of Cotopaxi volcano detected by InSAR. *Geophys. Res. Lett.*
540 URL: <http://doi.wiley.com/10.1002/2017GL073720>, doi:10.1002/2017GL073720.

541 Mothes, P.A., Vallance, J.W., 2015. Lahars at Cotopaxi and Tungurahua Volcanoes, Ecuador: High-

lights from Stratigraphy and Observational Records and Related Downstream Hazards, in: *Volcan. Hazards, Risks, Disasters*. Elsevier, pp. 141–168. URL: <http://linkinghub.elsevier.com/retrieve/pii/B978012396453300006X>, doi:10.1016/B978-0-12-396453-3.00006-X.

National Academies of Sciences Engineering and Medicine, 2017. *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing*. National Academies Press, Washington, D.C. URL: <https://www.nap.edu/catalog/24650>, doi:10.17226/24650.

Oguchi, T., Udagawa, M., Nanba, N., Maki, M., Ishimine, Y., 2009. Measurements of dielectric constant of volcanic ash erupted from five volcanoes in Japan. *IEEE Trans. Geosci. Remote Sens.* 47, 1089–1096. URL: <http://ieeexplore.ieee.org/document/4798218/>, doi:10.1109/TGRS.2008.2008023.

Pallister, J.S., Schneider, D.J., Griswold, J.P., Keeler, R.H., Burton, W.C., Noyles, C., Newhall, C.G., Ratdomopurbo, A., 2013. Merapi 2010 eruption-Chronology and extrusion rates monitored with satellite radar and used in eruption forecasting. *J. Volcanol. Geotherm. Res.* 261, 144–152. doi:10.1016/j.jvolgeores.2012.07.012.

Parker, A.L., Biggs, J., Walters, R.J., Ebmeier, S.K., Wright, T.J., Teanby, N.A., Lu, Z., 2015. Systematic assessment of atmospheric uncertainties for InSAR data at volcanic arcs using large-scale atmospheric models: Application to the Cascade volcanoes, United States. *Remote Sens. Environ.* 170, 102–114. URL: <http://www.sciencedirect.com/science/article/pii/S0034425715301267>, doi:10.1016/j.rse.2015.09.003.

Pierson, T.C., Janda, R.J., Thouret, J.C., Borrero, C.A., 1990. Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow and deposition of lahars. *J. Volcanol. Geotherm. Res.* 41, 17–66. URL: <http://linkinghub.elsevier.com/retrieve/pii/037702739090082Q>, doi:10.1016/0377-0273(90)90082-Q.

Pinel, V., Poland, M., Hooper, A., 2014. Volcanology: Lessons learned from Synthetic Aperture Radar imagery. *J. Volcanol. Geotherm. Res.* 289, 81–113. URL: <http://www.sciencedirect.com/science/article/pii/S0377027314003084>, doi:10.1016/j.jvolgeores.2014.10.010.

Pistolesi, M., Rosi, M., Cion, R., Cashman, K.V., Rossotti, A., Aguilera, E., 2011. Physical volcanology of the post-twelfth-century activity at Cotopaxi volcano, Ecuador: Behavior of an andesitic central volcano. *Bull. Geol. Soc. Am.* 123, 1193–1215. URL: <http://gsabulletin.gsapubs.org/cgi/doi/10.1130/B30301.1>, doi:10.1130/B30301.1.

Pyle, D.M., Mather, T.A., Biggs, J., 2013. Remote sensing of volcanoes and volcanic processes: integrating observation and modelling - introduction. *Geol. Soc. London, Spec. Publ.* 380, 1–13. URL: <http://sp.lyellcollection.org/content/380/1/1.full>, doi:10.1144/SP380.14.

Ramón, P., Vallejo, S., Almeida, M., Gomez, J.P., Caceres, B., 2016. Increased Melting of Glaciers during Cotopaxi volcano awakening in 2015, in: *EGU Gen. Assem. 2016*, held 17-22 April. 2016 Vienna Austria,

576 p.10769, p. 10769. URL: <http://adsabs.harvard.edu/abs/2016EGUGA...1810769R>.

577 Rignot, E.J.M., van Zyl, J.J., 1993. Change Detection Techniques for ERS-1 SAR Data. *IEEE Trans. Geosci.*
578 *Remote Sens.* 31, 896–906. URL: <http://ieeexplore.ieee.org/document/239913/>, doi:10.1109/36.
579 239913.

580 Rosen, P.A., Gurrola, E., Sacco, G.F., Zebker, H.A., 2012. The InSAR scientific computing environment,
581 in: *Synth. Aperture Radar, 2012. EUSAR. 9th Eur. Conf., [IEEE], Nuremberg, Germany.* pp. 294–297.
582 URL: <http://ieeexplore.ieee.org/abstract/document/6217174/>.

583 Rosen, P.A., Hensley, S., Peltzer, G., Simons, M., 2004. Updated repeat orbit interferometry pack-
584 age released. *Eos, Trans. Am. Geophys. Union* 85, 47–47. URL: [http://doi.wiley.com/10.1029/](http://doi.wiley.com/10.1029/2004E0050004)
585 2004E0050004, doi:10.1029/2004E0050004.

586 Saepuloh, A., Koike, K., Omura, M., 2012. Applying bayesian decision classification to Pi-SAR polari-
587 metric data for detailed extraction of the geomorphologic and structural features of an active volcano.
588 *IEEE Geosci. Remote Sens. Lett.* 9, 554–558. URL: <http://ieeexplore.ieee.org/document/6129474/>,
589 doi:10.1109/LGRS.2011.2174611.

590 Scarpa, R., Tilling, R.I., 1996. *Monitoring and Mitigation of Volcano Hazards.* Springer, Berlin, Heidelberg.
591 URL: <http://link.springer.com/10.1007/978-3-642-80087-0>, doi:10.1007/978-3-642-80087-0.

592 Solikhin, A., Pinel, V., Vandemeulebrouck, J., Thouret, J.C., Hendrasto, M., 2015. Mapping the 2010 Merapi
593 pyroclastic deposits using dual-polarization Synthetic Aperture Radar (SAR) data. *Remote Sens. Envi-*
594 *ron.* 158, 180–192. URL: <http://www.sciencedirect.com/science/article/pii/S0034425714004386>,
595 doi:10.1016/j.rse.2014.11.002.

596 Sparks, R.S.J., 2003. Forecasting volcanic eruptions. *Earth Planet. Sci. Lett.* 210, 1–
597 15. URL: <http://www.sciencedirect.com/science/article/pii/S0012821X03001249>, doi:10.1016/
598 S0012-821X(03)00124-9.

599 Sparks, R.S.J., Biggs, J., Neuberg, J.W., 2012. Monitoring Volcanoes. *Science* (80-.). 335, 1310–1311. URL:
600 <http://science.sciencemag.org/content/335/6074/1310>, doi:10.1126/science.1219485.

601 Tilling, R.I., 1989. Volcanic hazards and their mitigation: Progress and problems. URL: [http://doi.](http://doi.wiley.com/10.1029/RG027i002p00237)
602 [wiley.com/10.1029/RG027i002p00237](http://doi.wiley.com/10.1029/RG027i002p00237), doi:10.1029/RG027i002p00237.

603 Tilling, R.I., 2008. The critical role of volcano monitoring in risk reduction. *Adv. Geosci.* 14, 3–11. URL:
604 <https://hal.archives-ouvertes.fr/hal-00297038/>, doi:10.5194/adgeo-14-3-2008.

605 Tiuri, M., Sihvola, A., Nyfors, E., Hallikaiken, M., 1984. The complex dielectric constant of snow at mi-
606 crowave frequencies. *IEEE J. Ocean. Eng.* 9, 377–382. URL: [http://ieeexplore.ieee.org/document/](http://ieeexplore.ieee.org/document/1145645/)
607 1145645/, doi:10.1109/JOE.1984.1145645.

608 Ulaby, F.T., Long, D.G., 2014. *Microwave Radar and Radiometric Remote Sensing.* Artech House. URL:
609 <http://titlealert.alkemlibrary.com/attachments/546/ArtechHouseABI-Mar15-Ulaby.pdf>.

610 Voight, B., Hoblitt, R.P., Clarke, A.B., Lockhart, A.B., Miller, A.D., Lynch, L., McMahon, J., 1998.
611 Remarkable cyclic ground deformation monitored in real-time on Montserrat, and its use in eruption
612 forecasting. *Geophys. Res. Lett.* 25, 3405–3408. URL: <http://doi.wiley.com/10.1029/98GL01160>,
613 doi:10.1029/98GL01160.

614 Wadge, G., Cole, P., Stinton, A., Komorowski, J.C., Stewart, R., Toombs, A., Legendre, Y., 2011. Rapid
615 topographic change measured by high-resolution satellite radar at Soufriere Hills Volcano, Montserrat,
616 20082010. *J. Volcanol. Geotherm. Res.* 199, 142–152. URL: [http://www.sciencedirect.com/science/
617 article/pii/S0377027310003434](http://www.sciencedirect.com/science/article/pii/S0377027310003434), doi:10.1016/j.jvolgeores.2010.10.011.

618 Wadge, G., Macfarlane, D., Robertson, D., Hale, A., Pinkerton, H., Burrell, R., Norton, G., James, M.,
619 2005. AVTIS: A novel millimetre-wave ground based instrument for volcano remote sensing. *J. Vol-
620 canol. Geotherm. Res.* 146, 307–318. URL: [http://www.sciencedirect.com/science/article/pii/
621 S0377027305000739](http://www.sciencedirect.com/science/article/pii/S0377027305000739), doi:10.1016/j.jvolgeores.2005.03.003.

622 Wadge, G., Saunders, S., Itikarai, I., 2012. Pulsatory andesite lava flow at Bagana Volcano. *Geo-
623 chemistry, Geophys. Geosystems* 13, n/a–n/a. URL: <http://doi.wiley.com/10.1029/2012GC004336>,
624 doi:10.1029/2012GC004336.

625 Wadge, G., Scheuchl, B., Stevens, N.F., 2002. Spaceborne radar measurements of the eruption of Soufriere
626 Hills Volcano, Montserrat. *Geol. Soc. London, Mem.* 21, 583–594. URL: [http://mem.lyellcollection.
627 org/content/21/1/583.short](http://mem.lyellcollection.org/content/21/1/583.short), doi:10.1144/GSL.MEM.2002.021.01.27.

628 Wang, T., Poland, M.P., Lu, Z., 2015. Dome growth at Mount Cleveland, Aleutian Arc, quantified by time
629 series TerraSAR-X imagery. *Geophys. Res. Lett.* 42, 10614–10621. URL: [http://doi.wiley.com/10.
630 1002/2015GL066784](http://doi.wiley.com/10.1002/2015GL066784), doi:10.1002/2015GL066784.

631 Watts, R.B., Herd, R.A., Sparks, R.S.J., Young, S.R., 2002. Growth patterns and emplacement
632 of the andesitic lava dome at Soufriere Hills Volcano, Montserrat. *Geol. Soc. London, Mem.* 21,
633 115–152. URL: <http://mem.lyellcollection.org/content/21/1/115.short>, doi:10.1144/GSL.MEM.
634 2002.021.01.06.

635 Werner, C., Wegmüller, U., Strozzi, T., Wiesmann, A., 2000. Gamma SAR and interferometric processing
636 software. *Proc. ERS-Envisat Symp* URL: [http://citeseerx.ist.psu.edu/viewdoc/download?doi=
637 10.1.1.20.6363{&}rep=rep1{&}type=pdf](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.20.6363{&}rep=rep1{&}type=pdf).

638 Werner-Allen, G., Lorincz, K., Welsh, M., Marcillo, O., Johnson, J., Ruiz, M., Lees, J., 2006. Deploying
639 a wireless sensor network on an active volcano. *IEEE Internet Comput.* 10, 18–25. URL: [http://
640 ieeexplore.ieee.org/document/1607983/](http://ieeexplore.ieee.org/document/1607983/), doi:10.1109/MIC.2006.26.

641 Zebker, H.A., Villasenor, J., 1992. Decorrelation in interferometric radar echoes. *IEEE Trans. Geosci.
642 Remote Sens.* 30, 950–959. URL: <http://ieeexplore.ieee.org/document/175330/>, doi:10.1109/36.
643 175330.

644 Zebker, H.A., van Zyl, J.J., Held, D.N., 1987. Imagin Radar Polarimetry From Wave Synthesis. J.
645 Geophys. Res. 92, 683-701. URL: <http://doi.wiley.com/10.1029/JB092iB01p00683>, doi:10.1029/
646 JB092iB01p00683.