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# Measurement of three-dimensional surface deformation by Cosmo-SkyMed X-band radar interferometry: Application to the March 2011 Kamoamoa fissure eruption, Kīlauea Volcano, Hawai'i

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A B S T R A C T

Three-dimensional (3D) surface deformation is retrieved for the March 6–10, 2011 (UTC dates), Kamoamoa fissure eruption along the East Rift Zone of Kīlauea Volcano, Hawai'i, through the integration of multi-temporal synthetic aperture radar (SAR) interferometry (InSAR) and multiple-aperture interferometry (MAI) measurements from the COSMO-SkyMed X-band SAR. The measurement accuracies of 1) the individual and multi-stacked MAI interferograms and 2) the 3D deformation, which is measured from COSMO-SkyMed data, are assessed using continuous GPS stations. The root-mean-square (RMS) errors of individual MAI interferograms for descending and ascending data are $2.97 \pm 0.6$ cm and $3.20 \pm 0.62$ cm, respectively. The MAI interferograms stacked from multi-temporal observations can produce better results by emphasizing surface deformation signals, with the RMS errors of 1.06 and 1.24 cm for descending and ascending data, respectively. The empirical equations for measurement uncertainties are determined with respect to interferometric coherence for individual and stacked MAI interferograms. An assessment of the 3D components of deformation was performed as well, and RMS errors of 0.75, 0.83, and 0.68 cm were estimated in the east, north, and up directions. A performance test of magma source model parameter estimations was carried out by using the InSAR and 3D measurements. From the 3D deformation field, we found that the magma chamber source at the Kīlauea caldera should be modeled by the spheroid source rather than the simple point source. The performance comparison between the InSAR and 3D modeled results showed that the 3D deformation field allows for precise model parameter estimation.


## 1. Introduction

Synthetic aperture radar (SAR) interferometry (InSAR) is a powerful technique that allows for the precise measurement of surface deformation and provides vital clues pertaining to the mechanism of Earth surface activities, such as earthquakes (Hu et al., 2012; Shen et al., 2009), volcanic eruptions (Lu et al., 2010; Jung, Lu, Won, Poland, & Miklius, 2011), tectonic movements (Jo, Won, Kim, & Jung, 2010), and ground subsidence (Choi et al., 2011; Zhang et al., 2012), to name a few. However, the conventional InSAR method can only measure one-dimensional deformation along the antenna's line-of-sight (LOS) direction. A better understanding of Earth surface deformation sources through geophysical models requires precise three-dimensional (3D) surface deformation maps.

Numerous studies have focused on the measurement of 3D surface deformation by InSAR over the past decade (Fialko, Simons, & Agnew, 2001; Gourmelen et al., 2011; Hu et al., 2012; Jung et al., 2011; Wright, Parsons, & Lu, 2004) and the strengths and weaknesses of each method were very clearly summarized by the previous research (Hu et al., 2014). In this study, 3D measurements were divided into three categories: offset-based, multi-looking and multiple-aperture interferometry (MAI)-based methods.

The offset-based method (Fialko et al., 2001) integrates azimuth offset measurements from cross-correlation and LOS phase measurements from InSAR using one interferometric pair from an ascending orbit and one pair from a descending orbit. This method has been widely used for 3D deformation measurements: however, the along-track displacements estimated from the cross-correlation are much less precise than the LOS displacements from InSAR. This method has low measurement precision of more than 12 cm as well as low computational efficiency (Bechor & Zebker, 2006; Fialko et al., 2001; Gourmelen et al., 2011; Jung, Won, & Kim, 2009).

The multi-looking approach (Bürgmann, Hilley, Ferretti, & Novali, 2006; Cakir, Akoglu, Belabbes, Ergintav, & Meghraoui, 2005; Wright et al., 2004) reconstructs the 3D deformation field from multiple interferograms with different incidence angles from ascending and

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descending orbits. While it has the advantage that it can improve deformation models of geological events such as earthquakes and volcanic activity, this method has a limitation in that it measures along-track deformation with low precision, which is similar to the offset-based method. The multi-looking method also has a disadvantage in that the number of interferometric pairs required is larger than other methods. Recently, a Kalman-filter-based approach was proposed for resolving time-series 3D displacements (Hu et al., 2013). This method achieved much higher temporal resolution of measurements by integrating multi-sensor, multi-path, and multi-temporal InSAR measurements, but low precision of the displacements in the north direction can be the main weakness, the same as for other multi-looking approaches.

The measurement accuracy of 3D surface deformation has been remarkably improved by the multiple-aperture interferometry (MAI) technique (Gourmelen et al., 2011; Hu et al., 2012; Jung et al., 2011). MAI allows for the measurement of the precise along-track deformation by means of split-beam InSAR processing (Bechor & Zebker, 2006; Jung, Lee, & Zhang, 2014; Jung, Lu, & Zhang, 2013; Jung, Won and Kim, 2009; Jung, Yun, & Jo, 2015). The precision of the MAI measurements for ERS and ALOS interferometric pairs are about 5.5 and 3.6 cm, respectively, which correspond to about 1.1% and 0.8% of the azimuth resolution of SAR single look complex (SLC) image (Jung et al., 2011, 2013). The MAI-based 3D reconstruction method (Gourmelen et al., 2011; Hu et al., 2012; Jung et al., 2011) exploits the MAI measurements that are two to three times better than the pixel offset measurements.

For further improvement of 3D deformation measurement, an MAI stacking method has been proposed by Jo et al. (2015). The MAI Stacking multi-temporal observation approach is one of the temporal ensemble averaging techniques. Since MAI stacking can reduce the inteferometric phase noise as well as mitigate ionospheric artifacts, it improves the MAI measurement precision and accuracy. Jo et al. (2015) showed that the measurement precision achieved by the MAI stacking method using Envisat ASAR data is about 1 cm/year in all the three-dimensional directions. In addition, MAI measurements using data from an X-band SAR system can obtain more precise surface deformation because the MAI sensitivity is a function of the effective antenna length (Bechor & Zebker, 2006), with a shorter antenna providing more precise MAI observations. Since the antenna lengths of X-band SAR systems such as TerraSAR-X and COSMO-SkyMed (Lombardo et al., 2005) are approximately half those of C- and L-band SAR systems such as ERS-1/2, Envisat ASAR and ALOS PALSAR, it would be expected that the improvement factor of the MAI measurement precision is approximately two. Despite the expected improvement in accuracy for X-band MAI measurements, 3D deformation reconstruction using X-band interferometric pairs has not been investigated due to high temporal decorrelation in such SAR systems.

The COSMO-SkyMed system is comprised of four satellites in the same orbital plane with uneven temporal separation ($t = 0$, 1, 4, 8 days), each with a 16-day repeat interval, which gives the system a powerful capability to minimize temporal resolution and maximize coherence. This leads to MAI interferograms with higher coherence, and it is expected that precise 3D surface deformation can be generated from COSMO-SkyMed data by the MAI-based approach. To evaluate the performance of COSMO-SkyMed X-band system using an MAI approach, a three-step test for precision is performed through a comparison with continuous GPS data: 1) test the precision of along-track deformation estimated from the MAI technique, 2) evaluate the precision of stacked along-track deformation measured by the multi-temporal MAI staking method, and 3) access the precisions of the east, north and up components of the 3D surface deformation measurements. Moreover, the empirical equations of measurement uncertainties for MAI and MAI stacking of COSMO-SkyMed data are derived with respect to the continuous GPS data.

Therefore, the objectives of this study are 1) to measure the precise 3D surface deformation from multi-temporal COSMO-SkyMed InSAR pairs, 2) to validate the measurement performance of the 3D deformation using GPS observations and 3) to determine optimal model parameters for a magma source using the 3D deformation. Most of all, the important issue for this study is to investigate how much the parameter estimation for a volcanic model can be improved by the precise 3D surface deformation measured from integration of the InSAR and MAI stacking methods. For this, we reconstruct 3D surface deformation fields associated with the March 6–10, 2011, Kamoamoa fissure eruption of Kīlauea Volcano, Hawai'i from ascending and descending multi-temporal COSMO-SkyMed data sets. The precise 3D measurements of the Kamoamoa event over Kīlauea Volcano are used to estimate the model parameters of a magma source geometry and condition. Finally, model parameters from the 3D measurements are compared with model parameters from the conventional InSAR measurements.

## 2. Dataset and processing

### 2.1. Study area and data set

Kīlauea Volcano is one of the youngest and most active volcanoes in the world, and is the focus of continuous monitoring and research because of the high level of volcanic activity and dynamically changing surface deformation. There have been many studies to explore the magma behavior at Kīlauea Volcano using geodetic data (Baker & Amelung, 2012; Lundgren et al., 2013; Montgomery-Brown et al., 2010; Poland, Miklius, Sutton, & Thornber, 2012), each estimating magma reservoir or dike models.

To obtain precise 3D measurements of surface deformation and optimum model parameters of volcanic activity, we used multi-temporal interferometric pairs of COSMO-SkyMed SAR data from ascending and descending orbits at Kīlauea Volcano, Hawai'i. The COSMO-SkyMed satellite which was launched by the Italian Space Agency (ASI) and the Italian Ministry of Defence (MoD) consisting of a constellation of four mid-sized satellites, are equipped with a high-resolution X-band SAR sensor (Covello et al., 2010). The stripmap-mode data used for this study has a resolution of ~3 m in the range and azimuth directions and an image size of 40 × 40 km for a single scene. The details of sensor parameters of the COSMO-SkyMed data used for this study are summarized in Table 1.

A shaded relief map for the study area (Fig. 1), depicts the observation frames of the ascending and descending paths. All master and slave images were collected before and after the March 5–9 (local time) eruption, from November 2010 to April 2011, to measure the surface deformation caused by the Kamoamoa eruptive episode. A few InSAR pairs from an ascending orbit cover only partial period of the eruption event, but do not cover the entire period. However, the US Geological Survey (USGS) reported that most of the deformation from the eruption event occurred within a day of the eruption start on March 5, 2011 (Orr et al., 2015). The fissure's propagation was finished as well within 12 hours, although dike and fissure opening continued throughout the eruption (Lundgren et al., 2013). Included in the InSAR

**Table 1**
System parameters of COSMO-SkyMed Strip-map mode data.

| COSMO-SkyMed parameters | |
|---|---|
| Orbit height (km) | 619.6 |
| Effective azimuth antenna dimension (m) | 5.7 |
| Effective Doppler bandwidth (Hz) | 2024 |
| Chirp bandwidth (MHz) | 91.8 |
| Carrier frequency (GHz) | 9.6 |
| Nominal incidence angle (deg) | 25–50 |
| Azimuth resolution (m) | ~3 |
| Ground range resolution (m) | ~3 |