Advanced interferometric synthetic aperture radar (InSAR) time series analysis using interferograms of multiple-orbit tracks: A case study on Miyake-jima

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[1] InSAR time series analysis is an effective tool for detecting spatially and temporally complicated volcanic deformation. To obtain details of such deformation, we developed an advanced InSAR time series analysis using interferograms of multiple-orbit tracks. Considering only right- (or only left-) looking SAR observations, incidence directions for different orbit tracks are mostly included in a common plane. Therefore, slant-range changes in their interferograms can be expressed by two components in the plane. This approach estimates the time series of their components from interferograms of multiple-orbit tracks by the least squares analysis, and higher accuracy is obtained if many interferograms of different orbit tracks are available. Additionally, this analysis can combine interferograms for different incidence angles. In a case study on Miyake-jima, we obtained a deformation time series corresponding to GPS observations from PALSAR interferograms of six orbit tracks. The obtained accuracy was better than that with the SBAS approach, demonstrating its effectiveness. Furthermore, it is expected that higher accuracy would be obtained if SAR observations were carried out more frequently in all orbit tracks. The deformation obtained in the case study indicates uplift along the west coast and subsidence with contraction around the caldera. The speed of the uplift was almost constant, but the subsidence around the caldera decelerated from 2009. A flat deformation source was estimated near sea level under the caldera, implying that deceleration of subsidence was related to interaction between volcanic thermal activity and the aquifer.


1. Introduction

[2] Crustal deformation is important information for understanding magma behavior under a volcano. We monitor such deformation by volcanic observation networks that have GPS, tiltmeters, and strainmeters. Such ground-based observations have high temporal resolution but are usually too sparse to fully resolve the spatial variations in deformation associated with shallow magma migration. One solution of this problem is to construct a denser observation network, but this is not realistic. Therefore, we utilize interferometric synthetic aperture radar (InSAR) to compensate for the insufficiency of density observations. InSAR can detect spatially detailed crustal deformation and has been used in crustal deformation studies of volcanoes worldwide [e.g., Massonnet et al., 1995; Amelung et al., 2000; Sigmundsson et al., 2010]. However, InSAR is usually disturbed by atmospheric, ionospheric, and other noise sources [e.g., Goldstein, 1995; Gray et al., 2000; Mattar and Gray, 2002]. Such noise obscures the crustal deformation signal and sometimes causes misinterpretation of crustal deformation.

[3] Simulating atmospheric delay with numerical weather models has become more useful with model improvements. Ozawa and Shimizu [2010] obtained an accuracy of 5 to 13 mm at 1-sigma confidence in a case study of atmospheric delay simulation of Mt. Fuji, the highest mountain in Japan. However, this is not always sufficient for understanding volcanic deformation. InSAR time series analyses such as the small baseline subset (SBAS) approach [Berardino et al., 2002] and permanent scatterer InSAR (PS-InSAR) approach [Ferretti et al., 2001] have enabled us to obtain precise deformation time series. In particular, SBAS has been used in many studies, since it has an advantage in application to non-urban areas. For example, Berardino et al. [2002] applied SBAS to the Campi-Flegrei volcano and found continuous subsidence of several centimeters per year. Furthermore it was revealed that continuous subsidence rapidly changed to uplift in 2000. Schmidt and Bürgmann [2003]
applied this approach to the Santa Clara Valley and found a maximum uplift of 4 cm in eight years. Such successful results demonstrate the usefulness of SBAS.

Basicallly, SBAS uses interferograms obtained for a single-orbit track and reduces noise by the least squares method with smoothing. Theoretically, noise that depends on the observation time, such as atmospheric and ionospheric delays, is not reduced as an effect of the least squares method, but is reduced only by the smoothing effect. If the average effect is added to an InSAR time series analysis, we will be able to reduce such noises more precisely. Furthermore, since simple SBAS analyzes interferograms for a unique orbit track, individual analysis for each orbit track is needed. In order to improve the accuracy of deformation detection and to avoid such an inconvenience, we devised an advanced InSAR time series analysis method using interferograms of multiple-orbit tracks. In this paper, we propose an advanced InSAR time series approach and demonstrate its usefulness based on a case study on a Japanese volcanic island.

2. Method

A given area is generally included in several SAR frames by different orbit tracks, different off-nadir angles, and different SAR sensors. Thus, an area is observed several times in a certain period. The idea of the proposed InSAR time series analysis is to estimate a deformation time series using interferograms generated from these observations.

The slant-range change $\Delta \rho$ obtained from InSAR is expressed by the inner product of a deformation vector $(d_x, d_y, d_z)$ and the unit vector of the radar incidence direction $(u_x, u_y, u_z)$:

$$\Delta \rho = u_x d_x + u_y d_y + u_z d_z. \tag{1}$$

If slant-range changes are available for more than three different incidence directions, a three-dimensional displacement vector can be estimated from them. However, for most present SAR sensors observation is carried out by transmitting radar in the right-downward direction (right-looking), and the variation is small in an incidence direction close to north–south except in the polar region (Figure 1). Therefore sensitivity for this direction is low. For more detail, the direction that has the lowest resolution is the direction perpendicular to the best-fitted plane for all incidence directions (called the “co-plane” in this paper). To indicate its sensitivity, we consider the incidence directions of two incidence angles (10° to 60°) for ascending and descending orbits (four incidence directions) and calculate the maximum difference angle of the incidence direction from the co-plane. We obtained a maximum difference of 10° (Figure 2). Furthermore, most of the present SAR observations are carried out at incidence angles of 20° to 50°, and the maximum difference is approximately 5° when interferograms with incidence angles of 20° and 50° are used. This result indicates negligible sensitivity of the perpendicular component of the co-plane. Note that this discussion is inapplicable to the polar region, where the orbit configuration is different. If interferograms for both right- and left-looking observations from ascending and descending orbits are available, sensitivity in the north–south direction may be obtained. However, such data is not available in most areas. Another approach to obtaining the sensitivity of the perpendicular component of the co-plane is the offset-tracking method [Michel et al., 1999]. However, the accuracy of offset estimation using PALSAR data is about 70 mm [Sandwell et al., 2008], and this is not sufficient to detect deformation within a few centimeters. Estimating three-dimensional deformation is thus difficult. Inversely, the assumption that all incidence directions for only right- (or only left-) looking SAR observations are included in the co-plane is reasonable. Under this assumption, all slant-range changes can be expressed by two components in the co-plane: the horizontal component in the co-plane, which is almost east-west (called the quasi-east-west (QEW) component in this paper), and the vertical component, which slightly inclines to the south (called the quasi-up-down (QUD) component in this paper) when interferograms by right-looking SAR observations are used.

![Figure 1](image1.png)

**Figure 1.** Schematic geometry of incidence directions and the co-plane.

![Figure 2](image2.png)

**Figure 2.** Maximum difference from the co-plane in four incidence directions. The circle denotes the maximum difference for general SAR observation (incidence angles of 20° to 50°), and the triangle denotes that for the case study on Miyake-jima.
Their components are the same as those in 2.5-D proposed by Fujiwara et al. [2000]. Our approach estimates these two components by inversion analysis.

[7] In two dimensions in the co-plane, a slant-range change can be expressed as

$$\Delta \rho = u_{\text{ew}} d_{\text{ew}} + u_{\text{ad}} d_{\text{ad}},$$

(2)

where \((d_{\text{ew}}, d_{\text{ad}})\) denotes the QEW and QUD components of a displacement vector and \((u_{\text{ew}}, u_{\text{ad}})\) denotes those of a unit vector of the radar incidence direction in the co-plane. With this approach, we estimate two components of deformation for each epoch, dividing the entire estimating period by the specified time step. Additionally, the apparent slant-range change due to error of a digital elevation model (DEM) appears in an interferogram. The observed slant-range change \(\Delta \rho_{\text{obs}}\) is then expressed as

$$\Delta \rho_{\text{obs}} = \sum_{i=1}^{N} c_i \Delta \rho_i + \frac{\Delta h_{\text{err}} B_i}{\rho \sin \theta},$$

(3)

Here, \(B_i\) is the perpendicular component of the orbit difference (perpendicular baseline), \(\rho\) is the slant range, \(\theta\) is the incidence angle at a pixel, \(N\) is the number of estimation epochs, and \(c_i\) is a coefficient related to the SAR observation date and is determined assuming that the temporal change of deformation in a period is linear. Although apparent slant-range changes are induced from other noise sources, they can be removed in the generation of interferograms. If most of the remnant noise component is due to atmospheric delay, it is reasonable to assume that the noise component is temporally distributed at random. We can then estimate the time series of the slant-range change and DEM error from inversion analysis of equation (3). When the time series of the slant-range change is estimated from interferograms of a unique orbit track, it is the analysis of the SBAS approach. In the advanced InSAR time series analysis, the time series of the slant-range change due to error of a digital elevation model (DEM) \(\Delta h_{\text{err}}\) appears in an interferogram. The observed slant-range change \(\Delta \rho_{\text{obs}}\) can be removed in the generation of interferograms. If most of the remnant noise component is due to atmospheric delay, it is reasonable to assume that the noise component is temporally distributed at random. We can then estimate the time series of the slant-range change and DEM error from inversion analysis of equation (3). When the time series of the slant-range change is estimated from interferograms of a unique orbit track, it is the analysis of the SBAS approach. In the advanced InSAR time series analysis, the time series of the slant-range change is obtained in all orbit tracks, and we select SAR frames for six orbit tracks based on an equation that substitutes equation (2) into equation (3).

[8] \(M\) observed slant-range changes can be described in the vector form as

$$d^T = [\Delta \rho_1 \ldots \Delta \rho_M].$$

(4)

and the estimated values can be described, such as the following \(2N + 1\) vector:

$$m^T = [d_{\text{ew},1} \ldots d_{\text{ew},N} d_{\text{ad},1} \ldots d_{\text{ad},N} \Delta h_{\text{err}}].$$

(5)

The observation equation can then be described as

$$d = Gm + v,$$

(6)

where \(v\) is the error vector of the observed slant-range change and \(G\) is an \(M \times (2N + 1)\) dimensional coefficient matrix calculated as

$$G = \begin{pmatrix}
    c_{1,1} u_{\text{ew}} & \ldots & c_{1,N} u_{\text{ew}} & c_{1,1} u_{\text{ad}} & \ldots & c_{1,N} u_{\text{ad}} & B_{1,1} \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
    c_{M,1} u_{\text{ew}} & \ldots & c_{M,N} u_{\text{ew}} & c_{M,1} u_{\text{ad}} & \ldots & c_{M,N} u_{\text{ad}} & B_{M,1} \\
    \end{pmatrix}.$$

(7)

If SAR images for all repeat cycles are obtained in all orbit tracks, they can be estimated precisely by a simple least squares analysis. However, this is not a realistic case. Therefore, we use the constraint that the temporal change of deformation is smooth. Additionally, we strongly constrain deformation in the first epoch to zero, in order to stabilize the solution. The final solution can then be calculated from

$$m_{\text{est}} = (G^T G + \alpha^2 D^T D + \beta^2 F^T F)^{-1} G^T d,$$

(8)

where \(D\) is the matrix for the smoothing constraint:

$$D = \begin{pmatrix}
    1 & -1 & 0 & \ldots & 1 & -1 & 0 & \ldots & 0 \\
    0 & 1 & -1 & 0 & \ldots & 0 & 1 & -1 & 0 & \ldots & 0 \\
    0 & \ldots & 1 & -1 & 0 & \ldots & 1 & -1 & 0 & \ldots & 0 \\
    \end{pmatrix},$$

(9)

and \(F\) is the matrix to constrain deformation of the first epoch to zero:

$$F^T = (1 \ 0 \ \ldots \ 1 \ 0 \ \ldots \ 0).$$

(10)

Here, \(\alpha\) and \(\beta\) are hyperparameters for the strength of the constraint. We determine \(\alpha\) by minimizing the Akaike Bayesian Information Criterion [Akaike, 1980], and we set \(\beta\) to a large value for a strong constraint. Basically, the smoothness constraint could degrade temporal resolution. If many interferograms are input to the analysis, ABIC weakens the constraint. Then it is expected that sensitivity for short temporal change is improved.

3. Area of the Case Study and SAR Data

[9] To demonstrate the usefulness of the proposed InSAR time series analysis, we apply it to Miyake-jima, a Japanese volcanic island located 180 km south of Tokyo (Figure 3a). The island is nearly circular with a diameter of 8 km. Eruptions have occurred at roughly 20-year intervals [Miyazaki, 1984], and a large eruption occurred in 2000. In the 2000 eruption, the summit suddenly collapsed just before the eruption [Geshi et al., 2002]. After that, it began to emit a large amount of volcanic gas, and this continues today [Kazahaya et al., 2004]. We monitor the volcanic activity by a volcano observation network with single-frequency GPS receivers, tiltmeters, and seismometers (Figure 3b). Observation indicates that high seismicity is located under the caldera. The Japanese nationwide GPS network (GEONET) operated by the Geospatial Information Authority of Japan (GSI) has four GPS stations with dual-frequency receivers on the island [Sagiya et al., 2000]. We combined the GPS data of our network with the GEONET data and found crustal deformation of a few centimeters per year (Figure 3b). In this case study, we seek to detect the time series of such deformation.

[10] We use SAR data observed by the Phased Array type L-band Synthetic Aperture Radar (PALSAR) in this analysis. PALSAR is an L-band SAR sensor on board the Advanced Land Observing Satellite (ALOS), and its data are available from mid-2006 to April 2011. Miyake-jima is included in several PALSAR frames, and we select SAR frames for six orbit tracks (Figure 3a and Table 1). Descending tracks are
paths 54, 55, 57, and 58, and ascending tracks are paths 407 and 410. The off-nadir angle of paths 57, 58, and 407 is 34.3°, which is the standard observation mode of PALSAR, and that of the others is 41.5°. Estimating the best-fit plane for all incidence directions (co-plane), QEW is almost east-west, and QUD inclines 10° from vertical to the south. The direction of the co-plane is different at each pixel, but variations of the QUD and QEW directions are 0.1° in Miyake-jima. Differences in incidence directions from the co-plane are less than 1° (Table 1). Therefore, it is reasonable to assume that all incidence directions are included in the co-plane. Additionally, we tried to use Envisat and Radarsat SAR interferograms (C-band SAR), but the coherence of their interferograms was very low because of dense vegetation. Therefore, we do not use those interferograms in this analysis.

4. InSAR Processing

[11] Two-hundred and thirty-two pairs of PALSAR data are analyzed in this study. The relationship between interferometric pairs and the perpendicular baseline is depicted in Figure 4. Because the perpendicular baseline increases with time, the InSAR application condition for a pair with a long time interval is very bad. An orbit maneuver was performed in mid-2008, and the orbit just after that was close to that in 2006. However, high coherence was not always obtained for such pairs because of decorrelation due to dense vegetation. Therefore, few interferometric pairs overlap during the maneuver period. Furthermore, there is a possibility that such a systematic orbit shift may cause misestimation due to correlation between deformation time series and DEM error. To avoid such problems, interferograms with long perpendicular baseline and with short temporal baseline were included in this analysis.

[12] To subtract the topographic phase from the initial interferogram, we use the two-pass differential InSAR technique [e.g., Gabriel et al., 1989] with DEM released from GSI. The pixel spacing of the DEM is 0.4 arc-seconds. The DEM of Miyake-jima was modified based on surveys carried out in 2003. Topographic change after that is limited to particular areas where the caldera wall collapsed and where a landslide occurred.

[13] We choose the number of looks in interferogram generation so that the ground-range resolution for the along- and cross-track directions would be roughly the same as that of the DEM. The obtained interferogram is filtered with a spectrum filter with a parameter of 0.8 and a window size of 64 pixels [Goldstein and Werner, 1998]. Such a filter generally reduces spatial resolution, but local deformation is not our target. All interferograms are converted into a geodetic coordinate with a pixel spacing of 2 arc-seconds from the radar coordinate. The InSAR time series analysis is carried out in this coordinate.

Table 1. Parameters for the Radar Incidence Direction for Each Orbit Track

<table>
<thead>
<tr>
<th>Path</th>
<th>Heading</th>
<th>Incidence Angle°</th>
<th>Difference From Co-plane°</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>N171°W</td>
<td>48°</td>
<td>0.7°</td>
</tr>
<tr>
<td>55</td>
<td>N171°W</td>
<td>46°</td>
<td>0.4°</td>
</tr>
<tr>
<td>57</td>
<td>N170°W</td>
<td>41°</td>
<td>-0.4°</td>
</tr>
<tr>
<td>58</td>
<td>N170°W</td>
<td>38°</td>
<td>-0.9°</td>
</tr>
<tr>
<td>407</td>
<td>N10°W</td>
<td>39°</td>
<td>-0.6°</td>
</tr>
<tr>
<td>410</td>
<td>N9°W</td>
<td>47°</td>
<td>0.6°</td>
</tr>
</tbody>
</table>

*Angle at the crater center.
One of the greatest noise sources in deformation detection is atmospheric delay. To reduce this noise, we simulate the atmospheric delay from the numerical weather model with a 10 km mesh (5 km mesh from 7 April 2009) released from the Japan Meteorological Agency (Meso-Scale Model (MSM)). We evaluated this noise reduction method with interferograms of Mt. Fuji that crustal deformation was negligible, and the standard deviations of the pseudo slant-range changes were 5 to 13 mm [Ozawa and Shimizu, 2010]. In particular, it was confirmed that the noise component, which correlates with topography, was reduced well.

The orbit information included in PALSAR data is highly accurate [Iwata, 2007], but slight misestimation of slant-range change due to orbital differences induces a phase ramp. In a small area such as Miyake-jima, this is assumed to be a uniformly inclined phase change. Ionospheric delay is also a large error source, and we also assume it to be a uniformly inclined phase change in this small area. Assuming the phase change to be a plane inclining in longitude and latitude directions, we estimate its parameter by adjusting GPS displacements that were derived from an 11-day average centered on the SAR observation date. The reference site of the GPS displacements is Mikura-jima, located 20 km south-southeast of Miyake-jima. Therefore, the obtained interferograms indicate the slant-range change relative to Mikura-jima. Comparing interferograms with their noise reductions with GPS deformations, the root mean square (RMS) of the difference was 8.4 mm.

5. Results and Discussion

5.1. Comparison of InSAR and GPS Time Series

Figures 5a and 5b present the obtained interferograms. An obvious slant-range extension can be identified around the caldera, but crustal deformation in other areas is obscured by noise. Applying the advanced InSAR time series analysis to these interferograms, we estimate the temporal change of deformation at pixels which obtained unwrapped phases in all interferograms. In this analysis, we set the initial time to 12 March 2006, which is 87 days before the observation date of the earliest SAR data. There is no observation for the first epoch which is constrained to zero. Time interval is set to 46 days equal to ALOS recurrence time. If more SAR data with different observation timing are available, higher temporal resolution will be obtained by setting shorter time interval.

Figures 6 and 7 indicate the estimated deformation time series and the two-dimensional vector distribution of deformation between 12 June 2006 and 8 August 2010. An eastward motion of a few centimeters which dominates over the entire island is due to relative motion between Miyake-jima and Mikura-jima, where the reference site is located. Subsidence around the caldera and uplift around the west coast are observed, and these increase with time. A brief interpretation will be included in the next section. In this section, we discuss its accuracy. Figure 8 compares time series by the advanced InSAR time series analysis and GPS. The zero point is adjusted to the average of each time series. They are in good agreement, and the RMS of the differences is less than 8 mm. Although correspondence among them was found in short variations of time series, this would be because the contribution of adjustments to the GPS time series is large. The amplitude of high-frequency noise is different at each station, due to a difference of the strength of smoothing determined by ABIC. The trend of the QUD component of the Tsubota station is slightly different with the GPS time series. We discuss this inconsistency below. Figure 9 indicates the estimated DEM error in the InSAR time series analysis. A significant DEM error was estimated in the eastern flank. In this area, vegetation was dead due to volcanic gas, and landslides are occurring. Sand is continuously flowing and has accumulated in a wide area of the eastern flank. The estimated DEM error will show the thickness of the accumulated sand. The Tsubota station is located at the margin of its area, and the station is actually surrounded by flowing sand. As one interpretation, we suspect that the InSAR time series analysis detected movements of such sand. In contrast, GPS observation is not affected by the sand because the GPS station is fixed to the ground under the flowing sand. Thus, trends for InSAR and GPS may be different. However, we cannot reject the possibility.
Figure 5a. Interferograms used in this study.
<table>
<thead>
<tr>
<th>Path Number</th>
<th>Observation Date (yymmdd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>050706 060821 061006</td>
</tr>
<tr>
<td></td>
<td>060607 060607 060607</td>
</tr>
<tr>
<td>55</td>
<td>060607 060607 060723</td>
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<td></td>
<td>060907 060907 061023</td>
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<td>56</td>
<td>060723 060907 061023</td>
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<tr>
<td></td>
<td>061031 061031 061204</td>
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<td>57</td>
<td>061011 061011 061126</td>
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<td>061126 070226 070226</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>070226 070226 070226</td>
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<td></td>
<td>070226 070226 070226</td>
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</tbody>
</table>

**Figure 5b.** Information of SAR data for the interferograms in Figure 5a. The top is the path number of the orbit track, and the mid and bottom are observation dates (yymmdd) of used SAR data.
that there is a misestimation due to correlation with DEM error, as mentioned in section 4. Actually, it seems that the DEM error is larger than the intuitive thickness, though there is no measurement involving the thickness. To understand the reason for this, more ground truth data are necessary.

[18] To compare the results by advanced InSAR time series analysis and by SBAS, we applied SBAS to interferograms for paths 57, 58, and 407. The strategy for the analysis is the same as for the advanced InSAR time series analysis, except for the observation equation. Equation (3) was used for the observation equation. Figure 10 compares SBAS results and GPS deformations. Its consistency is obviously worse than that of the advanced InSAR time series analysis. Figure 11 compares the frequency distribution of differences from GPS displacement for results of the two-pass InSAR seen in Figures 5a and 5b, SBAS, and advanced InSAR time series analysis. Standard deviations are 8.4 mm for two-pass InSAR, 6.8 mm for SBAS, and 5.3 mm for the advanced InSAR time series analysis. We also carried out analyses of SBAS with other strategies, and there were cases in which the consistency with GPS was often improved because of differences in smoothing strength. However, we did not find a case in which the standard deviation was better than 5.3 mm for advanced InSAR time series analysis. This result confirms that the accuracy of SBAS is better than that of two-pass InSAR, and that the accuracy of the advanced InSAR time series analysis was enhanced more than that of the SBAS approach. Since there were fewer than three SAR data in most periods, the averaging effect by a least squares analysis would be small. If SAR observation is carried out more frequently, it is expected that higher accuracy will be obtained.

5.2. Geophysical Interpretation of the Obtained Deformation Time Series

[19] In this section, we briefly interpret the obtained deformation data. Uplift was found around the west coast, and its temporal change was almost linear at 2 cm/yr (Figures 12b and 12c). Investigation of its mechanism should be the focus of future study, but accumulation of magma under Miyake-jima is suggested. Remarkable subsidence with contraction was observed in the caldera bottom. Such subsidence was also found in the pre-eruption period by JERS-1 InSAR, but it was much smaller, 4 to 6 mm/yr [Furuya, 2004]. The maximum subsidence was located to the north of the caldera center, not around the volcano vent, which is located near the southern caldera wall. Although local deformation may have also occurred around the volcano vent, this could not be observed due to radar shadow, layover, and DEM error. The obtained subsidence center is close to the starting point of the caldera collapse in the 2000 eruption [Geshi et al., 2002]. Therefore, such a collapse with the caldera bottom falling out may be continuing. For four years, subsidence at its center was approximately 50 cm, and that in the neighborhood of the north caldera wall was approximately 10 cm. Such a large difference over a short distance (800 m) suggests a deformation gap. Therefore,
Figure 8. Comparison of time series by the advanced InSAR time series analysis (solid circles) and GPS (gray triangles).
The constant for the inflation of the source (latitude and longitude) are estimated by a grid-search algorithm. The upper depth is estimated to be at a shallow depth (Table 2), and this is inconsistent with the condition of the closed source, meaning that it is an inappropriate model. For a spherical source, we use the formula by Mogi [1958], and its location (latitude, longitude, and depth) is estimated by a grid-search algorithm. The volume change and biases for the QEW and QUD components are estimated by the least squares method. The obtained result does not explain the observed deformation, as with cylindrical sources (Figure 13c and Table 2). Therefore, this source type is also unsuitable for deformation in the neighborhood of the caldera. For a flat source, we use the formula by Okada [1985], and its location (latitude, longitude, and depth), length, width, and strike are estimated by a grid-search algorithm. The dip angle is fixed to zero. The tensile dislocation and biases for the QEW and QUD components are estimated by the least squares method. A deflation source under the caldera is estimated, and the simulated deformation sufficiently explains the observed one (Figure 13d and Table 2). Thus, the flat source model is most suitable for the deformation in the neighborhood of the caldera. The depth of the deflation source is estimated to be near sea level. Generally, an aquifer such as the Ghyben-Herzberg Lens is formed at sea level depth under an island, and therefore, we suspect that subsidence around the caldera is related to such an aquifer. Actually, a large amount of steam has been emitted with volcanic gas from the volcano vent located near the south caldera, and such an aquifer may be a water supply source. One interpretation is that deceleration of subsidence in and around the caldera may be related to the balance of the water supply to the aquifer and hydrothermal activity.

6. Summary

In this paper, we propose an advanced InSAR time series analysis that estimates two components of a deformation time series in the best-fit plane of all incidence angles from interferograms of multiple-orbit tracks. One advantage of this analysis is improvement of accuracy using SAR data of multiple-orbit tracks. Another advantage is that interferograms for different incidence directions can be integrated. To demonstrate the efficiency of the advanced InSAR time series analysis, we applied it to Miyake-jima and obtained a deformation time series corresponding to GPS observation from PALSAR interferograms of six orbit tracks. The obtained accuracy was better than that of SBAS, confirming the efficiency of the advanced InSAR time series analysis. If more interferograms of different orbit tracks become available, the accuracy will be improved further. Actually, small targets, such as Miyake-jima, can be observed from multiple orbit tracks. Furthermore, several SAR missions have been planned recently (e.g., ALOS-2), and it is expected that observations from multiple directions will increase. The advanced InSAR time series analysis can...
Figure 10. Comparison of estimated SBAS time series (solid circle) and GPS (gray triangle) time series. (a) Path 57. (b) Path 58. (c) Path 407.
Figure 11. Frequency distribution of differences from GPS displacement. (a) Two-pass InSAR result (shown in Figure 5). (b) SBAS. (c) Advanced InSAR time series analysis.

Figure 12. (a) Locations of pixels for deformation time series in Figures 12b and 12c. Colors of the circles correspond to those of the time series. (b) Time series of estimated QUD component of deformation around the coast. (c) Time series of estimated QEW component of deformation around the coast. (d) Locations of pixels for deformation time series in Figures 12e and 12f. Colors of the circles correspond to those of the time series. (e) Time series of estimated QUD component of deformation around the caldera. (f) Time series of estimated QEW component of deformation around the caldera.
Figure 13. (a) Observed deformation used in the modeling. Deformation in the shaded area was not used in the source estimation. (b) Simulated deformation and the residual in the model considering an open cylindrical source. The purple circle denotes the location of the estimated source. (c) Simulated deformation and the residual in the model considering a spherical source. The purple circle denotes the location of the estimated source. (d) Simulated deformation and the residual in the model considering a flat source. The purple rectangle denotes the location of the estimated source.
easily combine interferograms obtained from such SAR missions, and will enable us to obtain detailed deformation with higher accuracy.

[22] The obtained deformation in the case study indicates uplift in the west coast and subsidence with contraction around the caldera. It reveals that the subsidence around the caldera decelerated from 2009. Its deformation source is estimated to be a flat source located near sea level under the caldera, suggesting that deceleration of subsidence is related to the interaction between volcanic thermal activity and the aquifer.

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