RESEARCH ON CRUSTAL DEFORMATION IN SOUTHWESTERN JAPAN USING SAR INTERFEROMETRY

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ABSTRACT

Detection of small displacements requires processing of many SAR interferograms to increase the signal-to-noise ratio. To efficiently perform this kind of analysis, we first developed an InSAR processing system that automatically outputs reliable SAR interferograms. Then, we performed InSAR analyses on two regions in Southwestern Japan: 1) Kinki region, central Honshu, and 2) Sakurajima volcano, southern Kyushu. The aim of the first target area was to detect secular deformation associated with subduction of the Philippine Sea Plate under Honshu. It became clear that the temporal decorrelation effect is not critically severe for long-term interferograms. It became clear also, however, that ionospheric noise was often dominant and deformation signals were not easy to be captured. The aim of the analysis on Sakurajima volcano was to map the detailed deformation pattern associated with its volcanic activity, which provides one of the most fundamental data for evaluating its future forecast. The InSAR results were in excellent consistency with the leveling results obtained along the coastal route. It became clear that removing altitude-dependent tropospheric artifacts would be important for accurately measuring the deformation further on areas where the topographic relief is important.

1. INTRODUCTION

The Disaster Prevention Research Institute, Kyoto University, conducts researches related to both earthquakes and volcanoes. In this RA2 project, we have proposed to conduct interferometric synthetic aperture radar (InSAR) analyses as one of the principal tools to monitor and study crustal deformation associated with tectonic strain accumulation, earthquakes and volcanic activities.

The final objectives of our project were as follows. 1) Develop an integrated and automated system of InSAR processing useful for routine monitoring and efficient study of crustal deformation. 2) Unravel the mechanisms of tectonic events such as earthquakes and volcanoes by using InSAR and other kinds of data.

The next section describes the development of the automated InSAR processing system. As to the analysis target areas, we concentrated on studying 1) the strain accumulation process due to plate subduction by analyzing a long strip in Kinki region, central Japan, and 2) Sakurajima volcano in Kyushu. The main results of these two studies are summarized in Sections 3 and 4, respectively.

2. AUTOMATED INSAR PROCESSING

As the amount of available data is increasing nowadays, we developed an integrated system of precise and efficient automatic InSAR processing. Our aim was to find an optimal way of automatic processing that could be adapted to any target fields, in order to use such a system for our study on crustal deformation. The flow chart of our developed processing chain, every step of which is automatically performed through a script called gm_PALSAR_auto, is described in Figure 1.

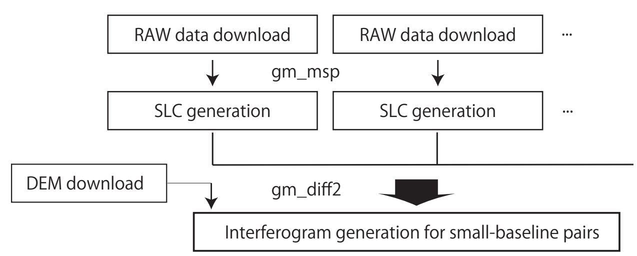

Fig. 1. Flowchart of the automated processing system.

1: Preparation of raw SAR data. First, raw SAR products (Level 1.0) are downloaded online or copied to the computer from DVDs. This process cannot be automated in case the data are downloaded from the AUIG website because of its design, but the system can automatically download multiple scenes through http or ftp when the data are stored in some data server in systematic ways (systematic naming of the files, etc.).

2: SLC generation. A script named gm_msp is invoked by the main script gm_PALSAR_auto to perform SLC generation. This script calls lower-level functions that are part of the commercial GAMMA software [1]. The processing steps taken care by gm_msp include concatenation of the neighboring frames if necessary, Doppler frequency estimation, range compression, filtering out of radio frequency interference, and azimuth compression. gm_PALSAR_auto automatically invokes gm_msp repeatedly if there are multiple scenes to be processed.

3: Preparation of the digital elevation model. Before proceeding to interferogram computation, the digital elevation model (DEM) is prepared. Any kind of DEM can be used, but the DEMs of the Geographical Authority of Japan (GSI), those of the space-shuttle topography mission (SRTM) [2], and hole-filled version of the SRTM DEMs [3] are ready to be used by our automated system without the necessity of format conversion. The original and hole-filled SRTM DEMs, available to the public online, can be downloaded automatically so that the users do not even have to know which region of the DEM is needed for the processing. The preparation of the DEM for the interferogram processing (format conversions, mosaicing and cropping of the DEMs) is done within gm_PALSAR_auto by calling some MATLAB functions that we developed.

4: Interferogram generation. A script named gm_diff2 performs two-pass differential interferometry using the SLCs computed in the second step and the DEM obtained in the third step. Samely as gm_msp, gm_diff2 calls low-level functions of the GAMMA software. It also calls a number of MATLAB functions that we developed. For example, removal of anomalous ground control points used for orbit tuning is taken care by a MATLAB function. gm_PALSAR_auto automatically selects pairs that are small both temporally and spatially and computes all the small-baseline interferograms. If specified, gm_diff2 performs multiple aperture (MAI) interferometry processing [4,5] and offset-tracking analyses [6].

3. STRAIN ACCUMULATION IN KINKI REGION

In Southwest Japan, the Philippine Sea Plate subducts under Honshu Island, located on the Eurasian Plate, at rates of 3-4 cm/year. Certain areas of the plate interface are coupled, which eventually get decoupled by releasing the strain energy (earthquakes). The coupling in interseismic periods deforms the overriding Eurasian Plate. Our interest is in whether it is possible to detect the deformation by using InSAR.

We used SAR images of the path 414, frames 660 to 700 (5 frames) that are concatenated at the pre-processing stage (Figure 2). This long strip traversing the Honshu Island enables us not only to measure the deformation in a wide area but also to properly evaluate the effects of ionospheric and orbital artifacts that somewhat appear systematically in the InSAR results.

We used all the FBS and FBD products of this strip that were available up to date, meaning that we used SAR images acquired 23 times between October 8, 2006 and October 16, 2011. We formed interferograms of 80 pairs that had small baselines (Figure 3). Our tentative definition of the small baselines is such that the spatial (perpendicular) baseline is less than 1500 meters for FBS-FBS pairs and 750 meters otherwise.

The most dominant characteristics of the interferograms are as follows.

1) The mean coherence of the interferograms was generally as good as larger than 0.5 when the spatial baseline was less than 500 meters (Figure 4). We got some coherent interferograms for long-interval interferograms, indicating that the temporal decorrelation effect is not severe.
2) The artifacts that appear to be caused by ionospheric disturbance are often large (Figure 5). While there is

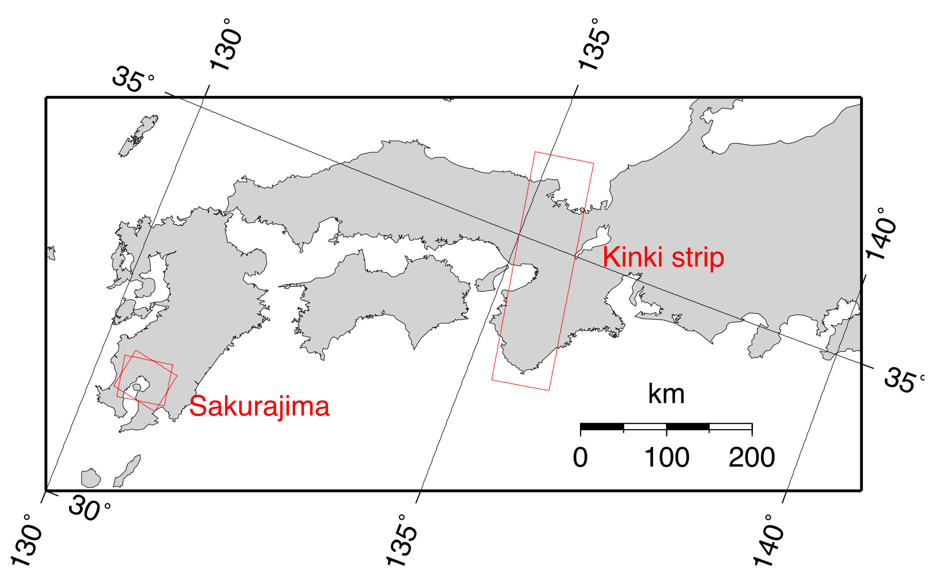

Fig. 2. Extensions of the scenes analyzed in this project. Kinki strip: path 414, frames 660-770 (five frames). Sakurajima: path 73, frame 2980 (descending) and path 424, frame 620 (ascending).

no direct evidence that this kind of noise is of ionosphere origin, there is a general correlation of the noise amplitude and the perturbation in the total electron content (TEC) in the atmosphere. The fact that this kind of fluctuating noise is not usually seen in C-band interferogram also supports that the noise is caused by some ionospheric activity.

3) Linked to the above, it is still difficult, albeit not impossible probably, to detect the strain accumulation due to subduction of the Philippine Sea Plate.

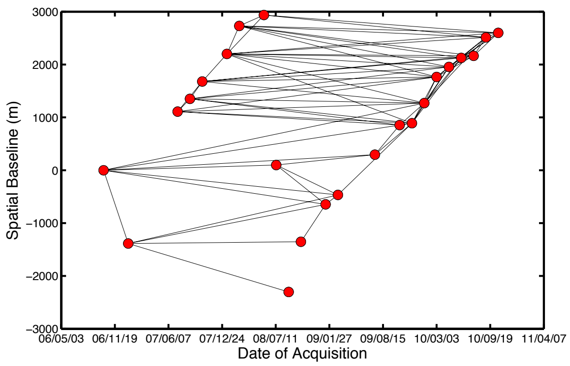

Fig. 3. Date of acquisition and spatial baseline for the Kinki strip. Each red dot denotes SAR acquisition. Each line segment indicates an interferogram computed in this study. Total of 80 interferograms were computed.

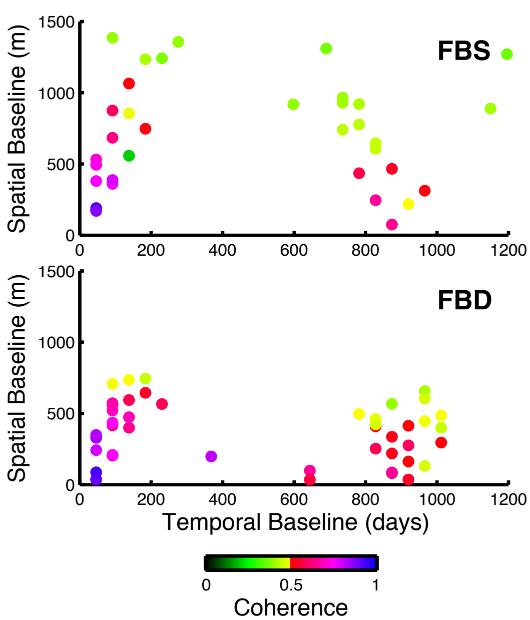

Fig. 4. Mean coherence as a function of temporal and spatial baselines, both for FBS-FBS interferograms (top) and FBD-FBS and FBD-FBD interferograms (bottom).

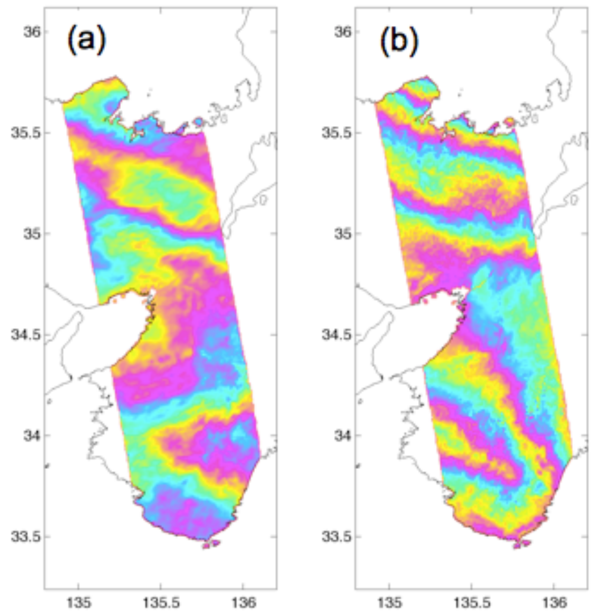

Fig. 5. Example of interferograms affected by ionospheric disturbance. (a) Aug. 2007 – Oct. 2007. (b) Jan. 2008 – May 2008. One fringe corresponds to 11.8cm of LOS displacements, but the observed number of fringes is much more than expected.

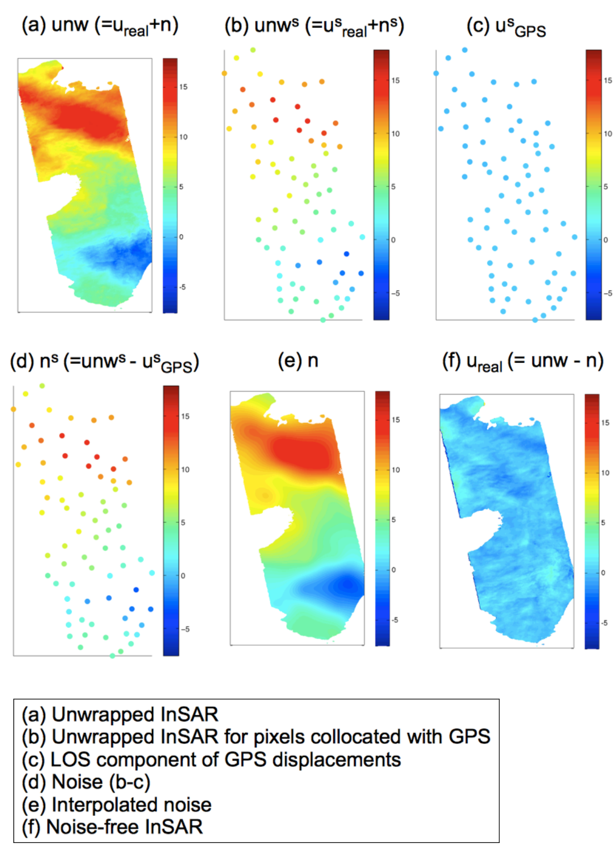

Fig. 6. (a-f) Steps of the algorithm to reduce long-wavelength noise that appears in interferograms.

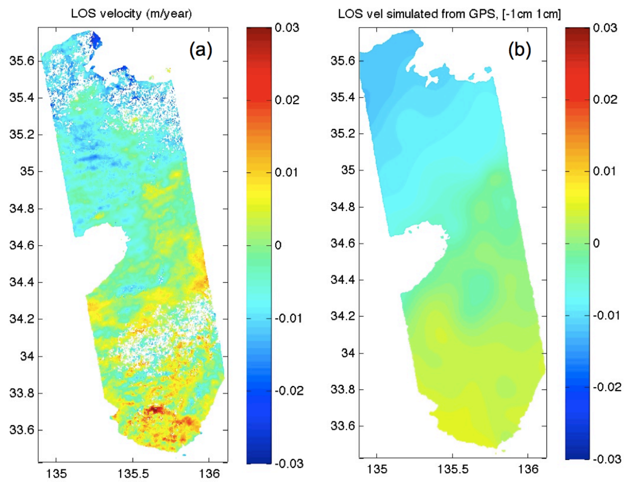

Fig. 7. (a) The mean LOS velocity obtained from 12 interferograms. (b) The LOS velocity simulated from the GPS displacements.

GPS displacement time-series of the permanent network GEONET operated by the Geographical Authority of Japan (GSI) capture the deformation associated with the subduction. The spatial spacing of the GEONET network is approximately 20 to 25 km, so that the deformation measured by the network can be regarded as the low-pass filtered version of the true deformation field. The ionospheric noise component that appears in the interferograms can be estimated by subtracting the low-pass filtered displacement pattern simulated from the GPS data from the original interferograms. This removes not only the ionospheric noise, but also all the other noise components that has longer wavelength than the GPS station intervals.

We apply the correction individually to each interferogram. Our algorithm is as follows (Figure 6) [7]. (a) First, extract the unwrapped InSAR values (displacements) of pixels that are collocated with GPS stations. (b) Project the three-dimensional displacements observed at each GPS station along the line-of-sight (LOS) direction of the InSAR observation. (c) Subtract the LOS component of GPS displacements (b) from the InSAR displacements (a). The result contains only noise as long as the GPS displacements are accurate. (d) Interpolate the noise component (c) to all the InSAR pixels. (e) Finally, subtract the interpolated noise component (d) from the original interferogram to get a noise-free interferogram (f).

Figure 7a shows the mean LOS velocity obtained from 12 interferograms. By nature of our method, the long-wavelength pattern is identical to the pattern simulated from the GPS displacements (Figure 7b). Our correction method enables extracting detailed displacements in a scale smaller than the GPS observation spacings. One must note, however, that there are smaller scale tropospheric and other noise components as well, which cannot be removed by our method. Elaborating this method should be able to be useful for detection of small changes in the deformation pattern.

4. DEFORMATION OF SAKURAJIMA VOLCANO

Sakurajima volcano located in southern Kyushu (Figure 8) has been very active and has repeatedly caused disasters including a large eruption in 1914 that killed 58 people. After a few years of quiet period, the volcano is recently in an active stage and caused 896 explosions in the year of 2010.

We started to use InSAR, by using the opportunity of this RA2 project, as a tool to monitor the ground deformation associated with the volcanic activity in Sakurajima.

SAR acquisitions for this volcano have been made both from the ascending (path 424) and descending (path 73) orbits. Figure 9 shows four unwrapped interferograms of path 424 and one interferogram from path 73. Long-wavelength fringes had been removed because we are only interested in local signals surrounding Sakurajima.

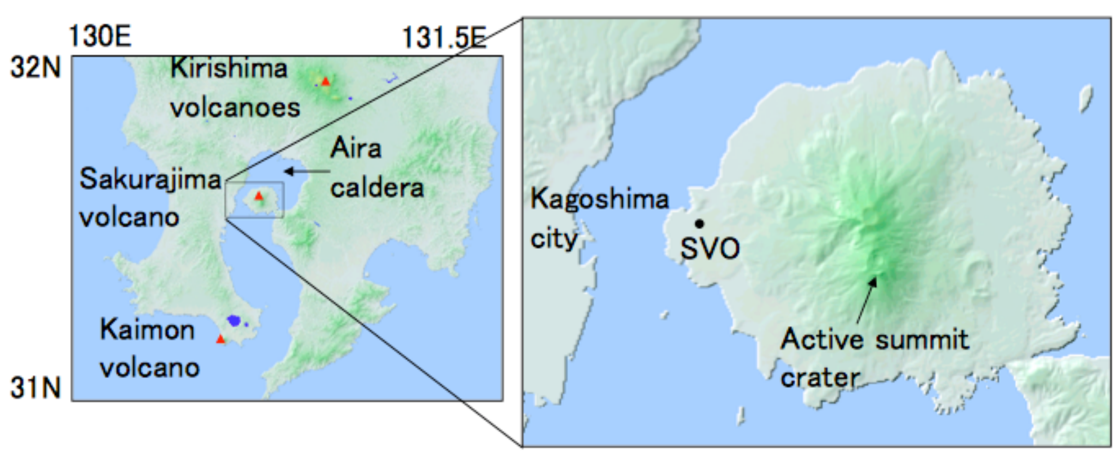

Fig. 8. Location and close-up figure of Sakurajima Volcano.

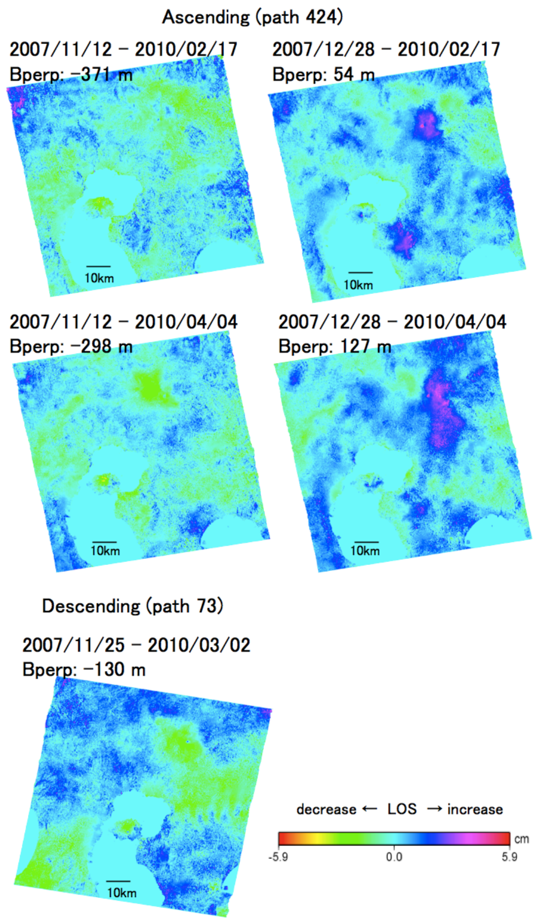

Fig. 9. Unwrapped interferograms that include Sakurajima volcano, four obtained using ascending data, one obtained from descending data.

Although we only show interferograms that are little affected by ionospheric perturbance, the interferograms still contain considerable amount of noise that are probably due to tropospheric phase delay.

We stacked the four ascending interferograms to better obtain the average displacement pattern between late 2007 and beginning of 2010 (approximately 2 years and 3 months interval). Then we applied a 2.5-dimension analysis [8] on the descending and stacked ascending interferograms to obtain the quasi-vertical and EW component of the displacements (Figure 10).

We can recognize a concentric pattern in the eastward motion (Figure 10b), which is not consistent with the ground-based data. This implies that the interferograms still contain significant amount of atmospheric noise correlated with the altitude. On the other hand, if we compare our results with the leveling measurements performed along the coast (that is, the vertical displacements along a flat route), the two kinds of measurements agree quite well with only a few mm of discrepancy (Figure 11). This is rather an encouraging result; if we can remove the altitude-correlated tropospheric noise, we can obtain accurate and spatially continuous deformation pattern on the whole Sakurajima.

We are initiating a new project on the method of mitigating the tropospheric noise.

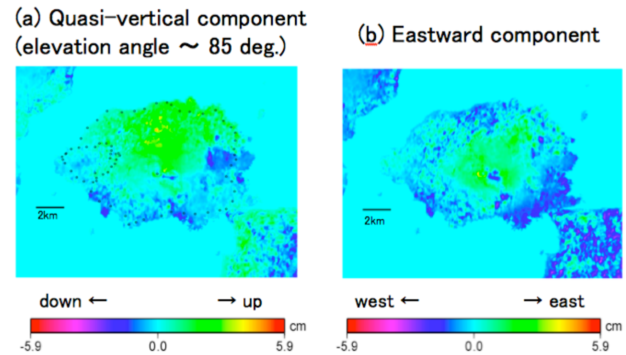

Fig. 10. Quasi-vertical (a) and eastward (b) components obtained from a 2.5-D analysis of the data shown in Figure 9.

5. CONCLUDING REMARKS

The RA2 project gave us an excellent opportunity to investigate the potential of PALSAR products on measuring small ground deformation of various scales.

From the analysis of a long strip in the Kinki region, it was found that the interferograms are often severely affected by ionospheric perturbance. We tested a method to mitigate the nuisance effect by using the GPS data. It is debatable if application of this correction provides new findings on the deformation associated with plate subductions, because the expected signals are of long wavelength that can be captured by the operating GPS network. The method is probably useful, however, to detect finer-scale deformation, for example, around active faults. The fact that the temporal decorrelation was not severe is a positive result toward monitoring of long-term deformation using InSAR.

From the analysis on the Sakurajima volcano, we found an excellent consistency between the results of InSAR and leveling surveys along a flat route. The next step would be to remove the tropospheric noise correlated with the altitude. Further challenge should be done to detect deformation on a wider area to get the whole picture of inflation and deflation of the magma chamber believed to lie north of Sakurajima.

6. ACKNOWLEDGEMENT

We are grateful to the Geographical Authority of Japan for the GPS solutions used in this study. This project was fruitful in a sense that it provided us a number of research seeds that should be tackeled toward detecting subtle deformation signals using InSAR technique. The authors fully acknowledge JAXA for giving us this opportunity.

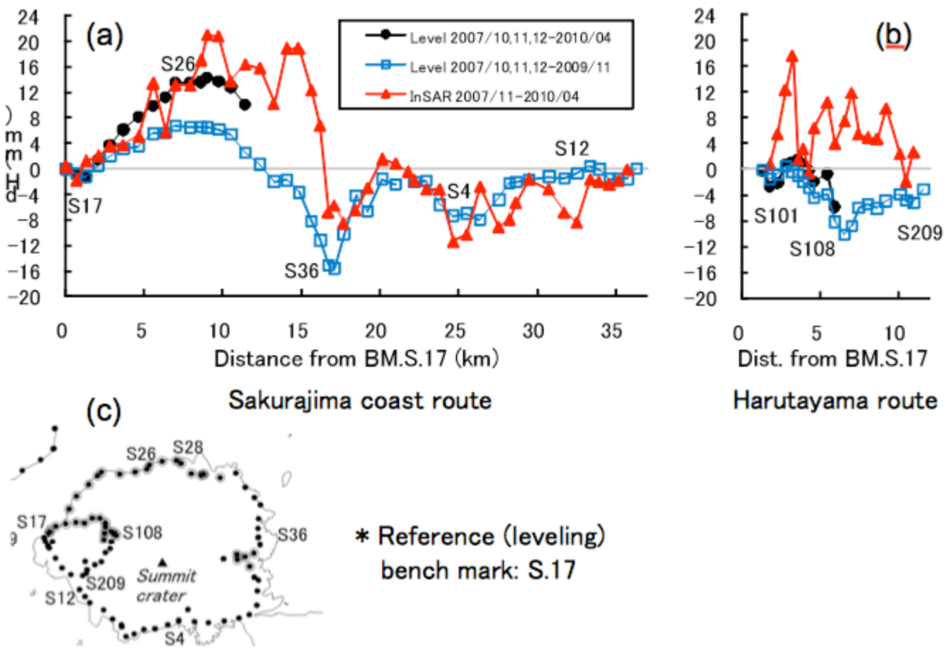

Fig. 11. Comparison of leveling and InSAR results. (a) On a route along the coast. (b) On a mountaineous route around Harutayama. (c) Map of the leveling routes.

7. REFERENCES

[1] U. Wegmüller, and C.L. Werner, "Gamma SAR processor and interferometry software", *Proc. the 3rd ERS Symposium*, ESA, SP-414, 1686-1692, 1997.

[2] T.G. Farr, and M. Kobrick, "Shuttle Radar Topography Mission produces a wealth of data", *Eos Transactions*, American Geophysical Union 81 (48), 583–585, 2000.

[3] A. Jarvis, H.I. Reuter, A. Nelson, and E. Guevara, "Hole-filled SRTM data V4", International Centre for Tropical Agriculture (CIAT), 2008. http://www.srtm.csi.cgiar.org

[4] N.B.D. Bechor, and H.A. Zebker, "Measuring two-dimensional movements using a single InSAR pair", *Geophys. Res. Lett.*, 33, L16311, doi:/10.1029/2006GL 026883, 2006.

[5] S. Barbot, Y. Hamiel, and Y. Fialko, "Space geodetic investigation of the coseismic and postseismic deformation due to the 2003 Mw7.2 Altai earthquake: Implications for the local lithospheric rheology", *J. Geophys. Res.*, 113, B03403, doi:10.1029/2007JB005063, 2008.

[6] R. Michel, J.-P. Avouac, and J. Taboury, "Measuring ground displacementsfrom SAR amplitude images: application to the Landers earthquake", *Geophys. Res. Lett.*, 26(7), 875-878, 1999.

[7] Y. Fukushima, and M. Hashimoto, "On detection of crustal deformation associated with plate subductions with ALOS/PALSAR data", *3rd ALOS Joint PI Symposium*, Kona, Hawaii, 2009.

[8] S. Fujiwara, T. Nishimura, M. Murakami, H. Nakagawa, and M. Tobita, "2.5-D surface deformation of M6.1 earthquake near Mt Iwate detected by SAR interferometry", *Geophys. Res. Lett.*, 27(14), 2049-2052, 2000.