Observation of Surface Subsidence by Interferometric SAR Time Series Analysis in Chiba Prefecture

Ryota Aoto (1), Keiji Imaoka (1), Hidenori Shingin (1), Kakuji Ogawara (1)

[1]Yamaguchi Univ., 2-16-1 Tokiwadai, Ube, Yamaguchi, Japan
Email: i001vd@yamaguchi-u.ac.jp; k.imaoka@yamaguchi-u.ac.jp; shingin@yamaguchi-u.ac.jp; ogawara@yamaguchi-u.ac.jp

KEY WORDS: Interferometric SAR (InSAR), Small Baseline Subset algorithm (SBAS), Zenith Tropospheric Delay (ZTD)

ABSTRACT: A Synthetic Aperture Radar (SAR) is a powerful tool for crustal deformation with a method called Interferometric SAR (InSAR). In this study, we conducted a time series analysis of InSAR for Chiba Prefecture in Japan where significant ground subsidence has been reported, and compared the results with leveling surveys by Chiba Prefecture and the GNSS Earth Observation Network System (GEONET) data by Geospatial Information Authority of Japan to evaluate the accuracy. We used Level 1.1 products of the Phased Array Type L-band SAR (PALSAR) onboard the Advanced Land Observing Satellite (ALOS) provided by the Japan Aerospace Exploration Agency (JAXA). In total, 27 descending scenes were available during the years 2005-2011. GMTSAR, an open source analysis software, was used for InSAR processing. In this analysis, we tried two methods. One is a simple averaging of multiple unwrapped interferograms (hereafter stacking analysis). In the stacking analysis, three interference pairs were selected with a perpendicular baseline within 500 m and an observation interval of about 3 years, and the annual average movement of the ground surface during the data period was calculated. The other is a time-series analysis by the Small Baseline Subset algorithm (SBAS) that uses many SAR interferograms with short perpendicular baseline to minimize the spatial decorrelation. In the SBAS analysis, 78 interference pairs were selected with the perpendicular baseline within 800 m and the observation interval within 1000 days. The annual average movement and the time series fluctuation were calculated. The comparison between the annual average movements from the stacking analysis and the leveling survey showed the slope of 0.76 and the residual root-mean-square (rms) of 3.0 mm/year. Although the stacking analysis tends to underestimate the changes, it could be used to identify an area of 20 mm subsidence yearly, which is the criteria given by the Ministry of the Environment for subsidence monitoring. The same comparison for the SBAS analysis showed the residual rms of 3.5 mm/year, and somewhat unreasonable spatial distribution in some areas. Also, the comparison of time-series variations with GEONET showed that the SBAS analysis failed to track the subsidence particularly at the station with large changes. GMTSAR itself does not provide the functions to correct various errors including satellite orbit errors and propagation delay due to water vapor contained in the atmosphere. Although the SBAS analysis is designed to minimize the atmospheric effects, step-by-step corrections for independent error factors should improve the results. Therefore, we tried to apply the instantaneous correction of water vapor delay by using zenith tropospheric delay estimates in the GEONET data. As a result, the correction reduced fluctuations in unwrapped phases to some extent, while the result of the SBAS analysis was not affected much.

1. INTRODUCTION

In recent years, the measurement of surface displacements for monitoring natural disasters (e.g., earthquakes and volcanic activities) and human activities (e.g., groundwater use) and managing infrastructures has become increasingly important. Synthetic Aperture Radar (SAR) interferometry or Interferometric SAR (InSAR) has been attracting attention in recent areas above as an observation technique to obtain wide-area and area information at once.

However, InSAR has various error causes such as an orbit error and propagation delay errors due to tropospheric and ionospheric disturbances. In order to reduce the atmospheric delay errors, various studies have been done. A typical technique for the atmospheric correction uses the atmospheric-elevation correlation. A significant effect was obtained with the correlation function between altitude and atmospheric delay by dividing the atmospheric delay into hydrostatic pressure and wet terms. However, it was found that more accurate correction was required for each InSAR image due to different regional weather conditions (Fujiwara et al., 1999). In a later study, a processing tool using the output from a numerical weather model was developed by Geospatial Information Authority of Japan (GSI). As a result, the atmospheric delay error was effectively reduced by using the numerical meteorological model even in the InSAR image where the effect of the reduction processing was small in the atmosphere-elevation correlation method (Kobayashi et al., 2014). However, because of the large difference in spatio-temporal resolution between the numerical weather model and SAR data, the atmospheric condition at the exact time and place of SAR image cannot be reproduced sufficiently. The other method is to use the atmospheric delay derived through the analysis of the Global Navigation Satellite Systems (GNSS) data (e.g., Yu et al., 2018). Although this method provides direct information of atmospheric delay, one of the major issues is the spatial sparsity. Recently, researches on time-series analysis have been progressed. The method called Persistent Scatterer InSAR (PSInSAR) observes the ground surface subsidence using temporal changes in the phase of pixels with low noise (Ferretti et al., 2002). The Small Baseline Subset algorithm (SBAS) uses many SAR interferograms with short perpendicular baseline to minimize the spatial decorrelation (Berardino et al., 2002). The method called multi-temporal InSAR that combines these two methods had also been developed (Hooper, 2008). These time-series analyses can reduce the atmospheric noise by using multiple interference pairs. However in the past studies, no perfect method was established for correcting the atmospheric delay in single InSAR pair. In this study, we applied simple averaging of multiple unwrapped interferograms (hereafter stacking analysis) and the SBAS technique for the significant subsidence over Chiba Prefecture in Japan, and assessed the errors by comparing with independent measurements. Also, we tried to apply the instantaneous correction of atmospheric delay by using the GNSS Earth Observation Network System（GEONET) data.

2. DATA AND STUDY AREA

2.1 Data

Details of the data used in this study are shown below.

2.1.1 Satellite data: We used Level 1.1 products of the Phased Array Type L-band SAR (PALSAR) onboard the Advanced Land Observing Satellite (ALOS) provided by the Japan Aerospace Exploration Agency (JAXA). In total, 27 descending scenes were available during the years 2005-2011 over the study area. To minimize the effect of ionosphere, we only selected the descending scenes for this study. To cover the study area with identical condition, we used the scenes with same path/frame numbers.

2.1.2 Leveling surveys: The leveling survey has been conducted by Chiba Prefecture. The results of the survey have been published annually on the Chiba Prefecture website.

2.1.3 GEONET: GEONET data were provided by the Geospatial Information Authority of Japan. The altitude values of GEONET stations were extracted from the daily coordinates [F3] and the zenith tropospheric delay (ZTD) were from 3-hourly tropospheric delay estimates.

2.2 Study Area

The study area is over Chiba Prefecture, Japan as shown in Fig. 1. The area covers the range of 35.34° N to 35.977° N and 139.722° E to 140.6°E.

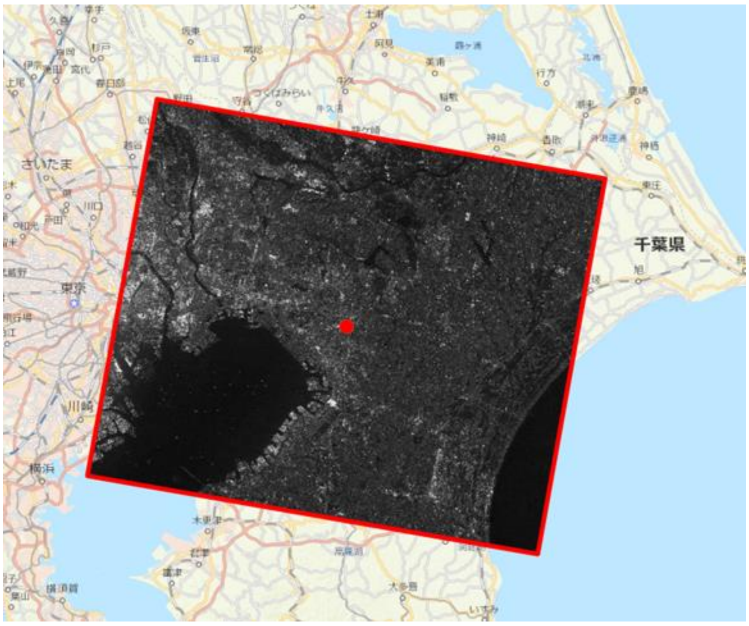

Figure 1. Study Area

3. METHODOLOGY

3.1 InSAR processing

GMTSAR, an open source analysis software, was used for InSAR processing including preprocessing, image alignment, creating interferogram, phase filtering and unwrapping, geocoding, and SBAS analysis. The procedures of stacking analysis and tropospheric delay correction were written in the form of c-shell script and incorporated in the software. In this study, derived line-of-sight (LOS) displacement was simply converted to vertical component by using the incidence angle at the scene center. The typical value is around 38.75 degrees for the scenes selected.

3.2 Selection of InSAR pairs

Figure 2 shows the time series of relative perpendicular baselines for all scenes. The blue lines show InSAR pairs for stacking analysis and blue/red lines show for SBAS analysis. The InSAR pairs were selected based on the condition of baseline length and temporal separation of two scenes. For the stacking analysis, the pairs with baseline length of less than 500 m and temporal separation of around 3 years were selected to keep good correlation and enough subsidence signals at the same time. Selected pairs were listed in Table 1. For the SBAS analysis, the pairs with baseline length of less than 800 m and temporal separation of less than 1000 days to keep good correlation and enough number of pairs for time-series analysis.

Table1. Interferograms pairs used in stacking

Observation date (master)	Observation date (slave)	Baseline [m]
2007/07/22	2009/12/04	-200.2
2007/11/29	2010/07/22	33.1
2008/01/14	2010/09/06	182.0

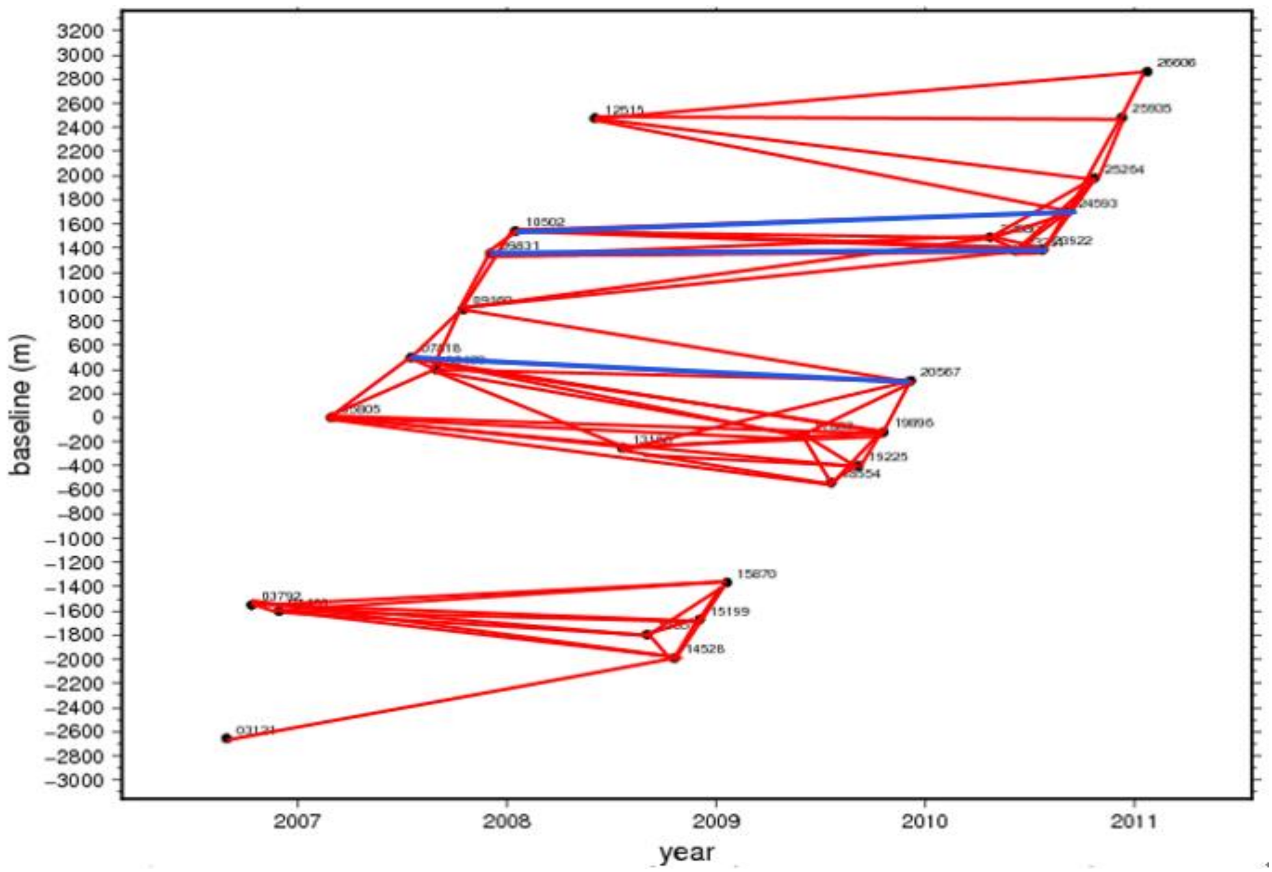

Figure 2. Combination of interference pairs (blue lines for stacking analysis and blue/read lines for SBAS analysis).

3.3 Tropospheric delay correction

The interferometric phase Δϕ in InSAR processing can be written by the changes in slant range and propagation delay as (Yu et al., 2018):

$$\Delta\phi = \frac{4\pi}{\lambda}(r_2 - r_1) - \frac{4\pi}{\lambda}(\Delta L_2 - \Delta L_1) \qquad (1)$$

where λ is the wavelength of the radar signal; r_1 and r_2 are slant range length corresponding to the first and second acquisitions, respectively; ΔL_1 and ΔL_2 are the atmospheric propagation delays of radar signals in the LOS direction. The values of ΔL_1 and ΔL_2 were obtained from the ZTD estimates in the GEONET tropospheric delay estimates. Since only the 3-hourly estimates were available, we linearly interpolated the data in time and obtained the value at the time of PALSAR data acquisition. Since the typical spatial interval of the GEONET stations is about 20 km, we also interpolated the data in the spatial domain by using adjustable tension continuous curvature splines (Smith and Wessel, 1990) implemented in the Generic Mapping Tools (GMT).

4. RESULTS AND DISCUSSION

4.1 Stacking result

Figure 3 shows the spatial distribution of the annual mean velocity in the LOS direction obtained by the stacking analysis. Figure 4 is a scatter plot between surface subsidence by leveling surveys and stacking analysis. The slope and intercept of the regression line are about 0.76 and 3.6, respectively. The residuals from the regression line indicates the root-mean-square (rms) value of 3.0 mm/year. From the result, although the stacking analysis provides systematically smaller velocities than by leveling, the rms error is reasonable to some extent.

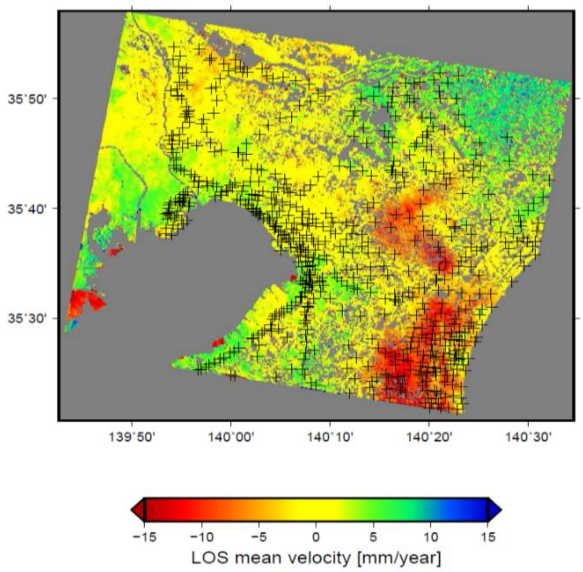

Figure 3. Annual mean velocity in LOS direction obtained by stacking analysis. Crosses indicate the locations of leveling survey.

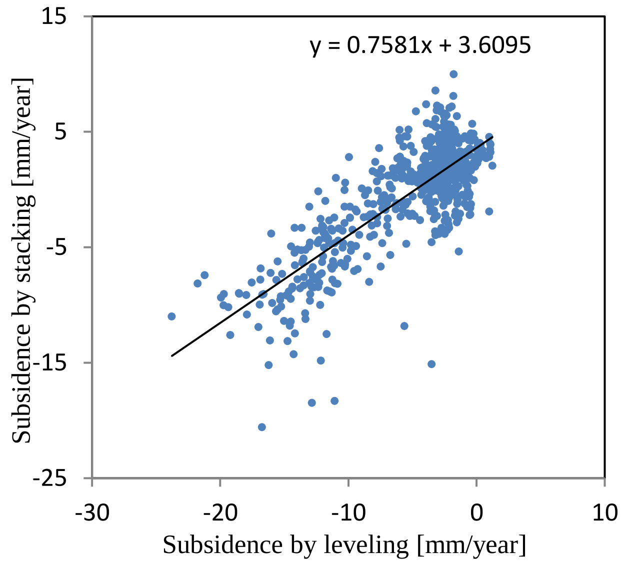

Figure 4. Scatter plot between annual mean surface subsidence obtained by leveling and stacking analysis.

4.2 SBAS result

Figures 5 and 6 are same as Fig. 3 and 4, but with the results obtained by SBAS analysis. The slope and intercept of the regression line in Fig. 6 are about 0.45 and 2.4, respectively. The residuals from the regression line indicates the rms value of 3.5 mm/year. By comparing the spatial distribution in Fig. 3 and 5, we can see that the SBAS analysis did not capture the subsidence in southern latitude areas, while the patterns in other areas are similar. This inconsistency is the major reason skewing the scatter plot. We also compared the temporal changes of the surface subsidence between SBAS analysis and GEONET data (not shown). For the GEONET stations without significant subsidence, although the SBAS analysis also provides the insignificant trend, the fluctuation and bias are large. For "Oamishirasato" GEONET station, where the significant subsidence is observed, the SBAS analysis could not capture the trend. Further investigations are necessary to improve the accuracy of the SBAS analysis.

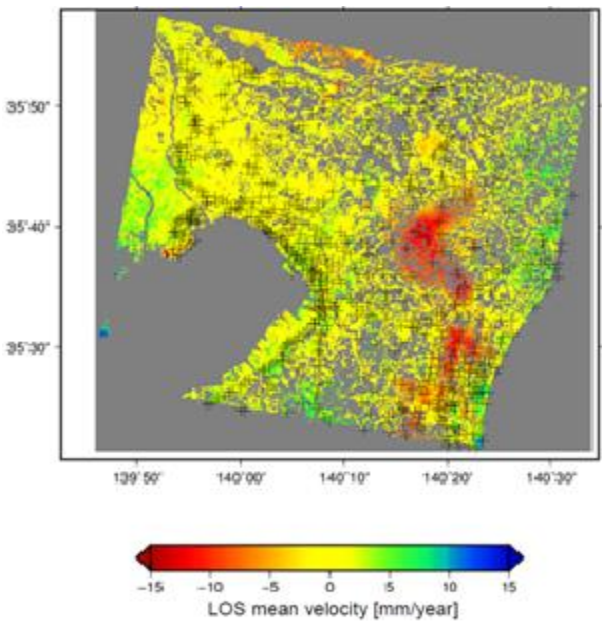

Figure 5. Same as Fig. 3, but for SBAS analysis.

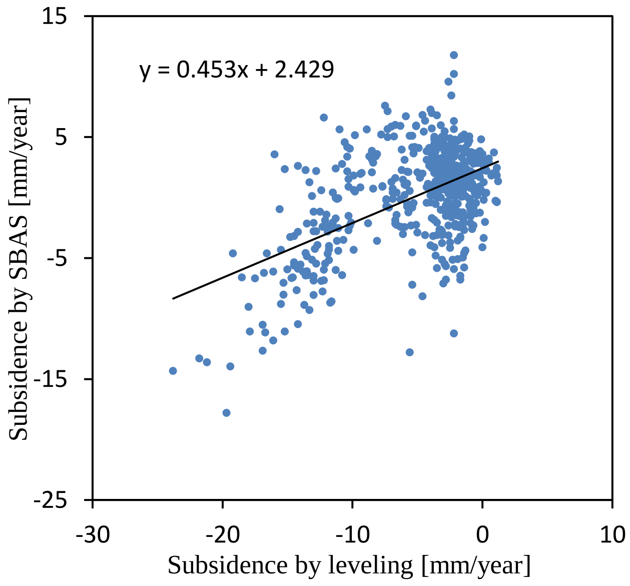

Figure 6. Same as Fig. 4, but for SBAS analysis.

4.3 Tropospheric delay correction

Figure 7 shows the examples of unwrapped phase and corresponding tropospheric phase delay difference derived from the GEONET ZTD. This interferogram was selected for the ease of comparison because of the small effect of orbit error. For these examples, unwrapped phase and tropospheric phase delay difference exhibit the similar spatial patterns to some extent. Among the 7 pairs with small orbit error, some of them shows reasonable agreement but some of them does not. Probably, coarse spatial resolution due to the sparse distribution of GEONET stations and temporal interpolation from 3-hourly data are the potential reasons.

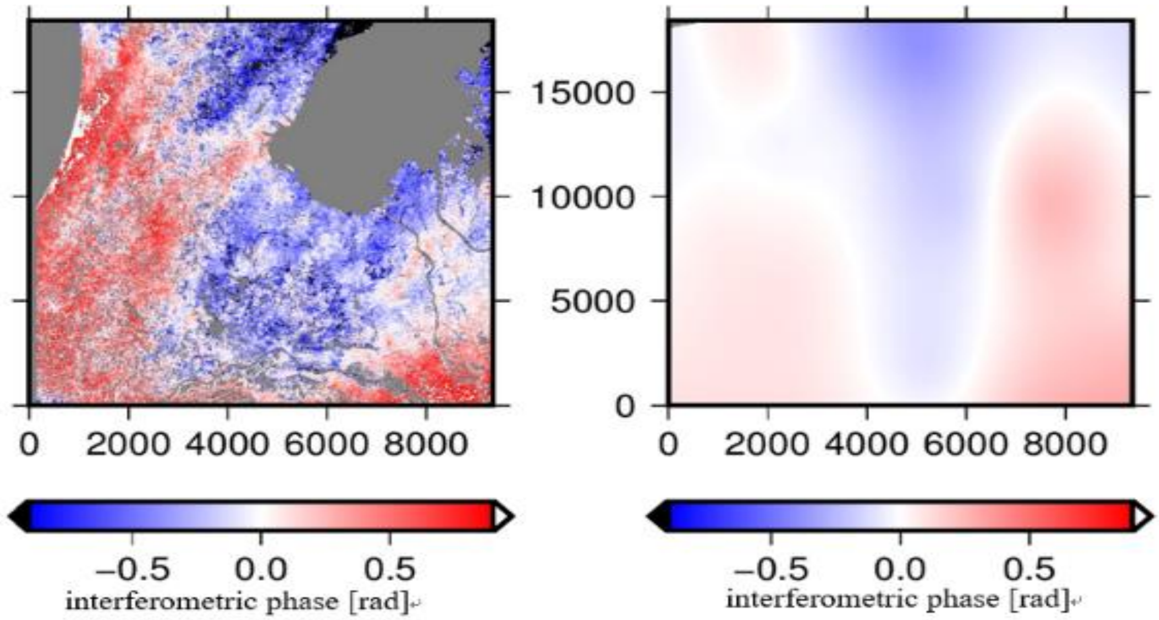

Figure 7. Example of unwrapped phase (left) and tropospheric phase delay difference to be subtracted from the unwrapped phase (right).

Figure 8 shows the average and the standard deviation of unwrapped/detrended phase for all InSAR pairs before the tropospheric delay correction by Eq. (1). Figure 9 is same as Fig. 8, but after the tropospheric correction. Except around the areas with significant subsidence seen in Fig. 3 and 5, appropriate tropospheric correction may reduce the inhomogeneous patterns both in average and standard deviation. From the comparison of Fig. 8 and 9, we can recognize some reductions of fluctuations both in average and standard deviation maps, particularly noticeable around the center and southwest of the image. We performed the SBAS analysis by using the InSAR pairs with tropospheric delay correction. The correction slightly improved the time-series variation, but slightly deteriorate the annual mean velocity in the LOS direction.

In the present correction, we just spatially interpolate the ZTD estimates. The ZTD estimate is a representative value computed from the signals of multiple GNSS satellites. The original GNSS data contain some information of directional inhomogeneity. In the previous study, a procedure for estimating the water vapor distribution around GNSS stations on a scale of several km by utilizing the slant path delay was reported (Shoji et al., 2014). Such technique can be tested for creating tropospheric delay with better spatial resolution. Also, we can process from the original data called the Receiver Independent Exchange Format (RINEX) to create the tropospheric delay value close to the time of SAR measurement.

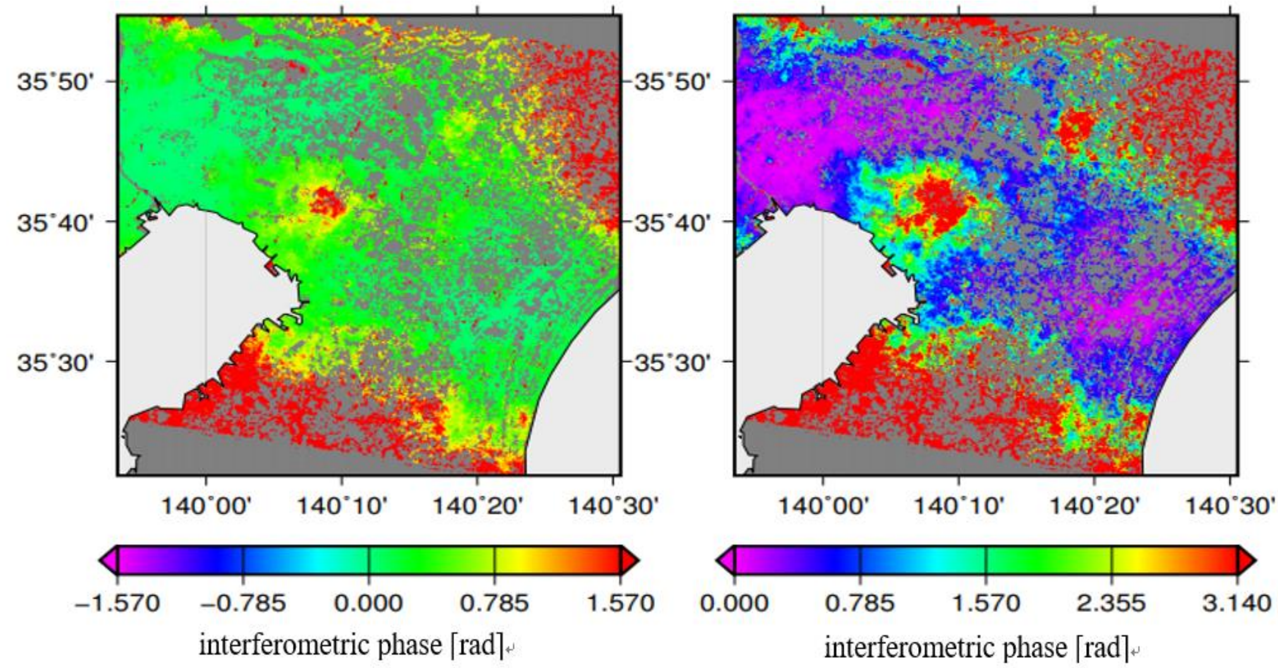

Figure 8. Average (left) and standard deviation (right) of unwrapped/detrended phase for all InSAR pairs before tropospheric delay correction.

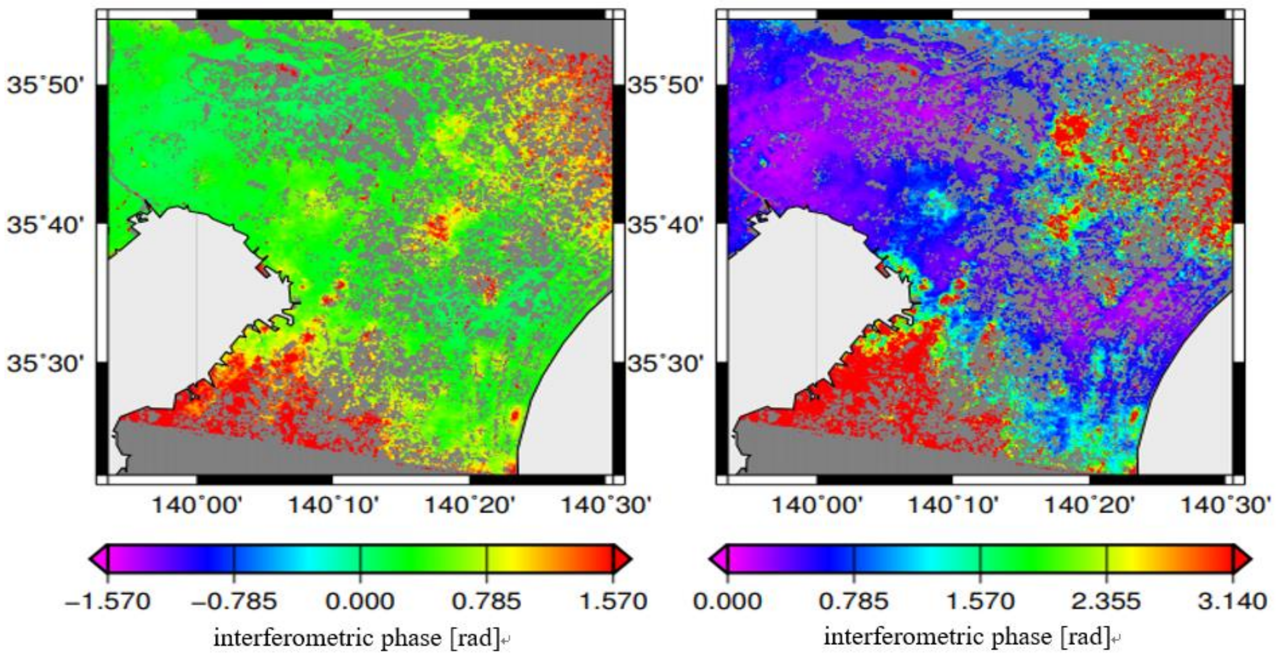

Figure 9. Same as Fig. 8 but after tropospheric delay correction.

5. CONCLUSION

In this study, we conducted InSAR analysis for Chiba Prefecture in Japan where significant ground subsidence has been reported, and compared the results with leveling surveys and the GEONET data. The stacking analysis provided the reasonable result for annual mean subsidence, while the SBAS analysis inferior to the stacking result. The tropospheric delay correction was tested by using the ZTD estimates in GEONET data. The correction reduced some fluctuations in unwrapped/detrended phases, but the effect in SBAS results is limited or for the worse direction. The potential next step is to create tropospheric delay values with better spatial and temporal sampling by using the slant path delay information.

REFERENCES

Berardino, P., Fornaro, G., Lanari, R., and Sansosti, E., 2002. New algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. IEEE Transactions on Geoscience and Remote Sensing, 40 (11), pp.2376-2378.

Ferretti, A., Prati, C., and Rocca, F., 2001. Permanent scatterers in SAR interferometry, IEEE Transactions on Geoscience and Remote Sensing, 39 (1), pp. 8-20.

Fujiwara, S., Tobita, M., Murakami, M., Nakagawa, H., and Rosen, P. A., 1999. Baseline determination and correction of atmospheric delay induced by topography of SAR interferometry for precise surface change detection. Journal of the Geodetic Society of Japan, 45 (4), pp. 315-325.

Hooper, A., 2008. A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches. Geophysical Research Letters, 35, L16302, doi:10.1029/2008GL034654.

Kobayashi, T., Ishimoto, M., Tobita, M., and Yarai, H., 2014. A tool for reduction of atmosphere-related noises included in an InSAR image, incorporating a numerical weather model. Journal of the Geospatial Information Authority of Japan, 125, pp. 31-38.

Shoji, Y., Yamauchi, H., Mashiko, W., and Sato, E., 2014. Estimation of local-scale precipitable water vapor distribution around each GNSS station using slant path delay. SOLA, 10, pp. 29−33.

Smith, W. H. F, and Wessel, P., 1990. Gridding with continuous curvature splines in tension. Geophysics, 55, pp. 293-305.

Yamanaka, M., Morishita, Y., and Osaka, Y., 2013. Detection of ground subsidence by InSAR time series analysis. Journal of the Geodetic Society of Japan, 124, pp. 1-14.

Yu, C., Li, Z., and Penna, N. T., 2018. Interferometric synthetic aperture radar atmospheric correction using a GPS-based iterative tropospheric decomposition model. Remote Sensing of Environment, 204, pp. 109–121.

ACKNOWLEDGEMENT

Original PALSAR data were provided by JAXA (some of them were provided under the framework of research collaboration between JAXA and Yamaguchi University). The leveling survey data and GEONET data were provided by Chiba Prefecture and GSI, respectively.