MONITORING OF 3-D LAND SUBSIDENCE INTEGRATING PSI AND GPS DATA BY WLS

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ABSTRACT: Analysis of Synthetic Aperture Radar (SAR) satellite images using persistent scatterer interferometry (PSI) is one of the most effective approaches to the detection of land subsidence, but it has a limitation that the detected displacement is only along the radar line-of-sight (LOS) direction. It is necessary to estimate three-dimensional (3-D) displacement to monitor the subsidence accurately and one of the solutions is combining multi-directional observation. In this paper, we estimate 3-D displacement velocities by combining PSI, leveling and global positioning system (GPS) survey results. In this regard, we applied weighted least square method by considering the difference of data accuracies used. We applied the method to 2nd Airport Island of Kansai International Airport. The root mean squared errors (RMSEs) in east-west, north-south and vertical direction were 6, 13, and 10 mm/year, respectively. This result indicates that the combination of PSI and geodetic results is effective to monitor land displacement accurately with high spatial resolution.

1. INTRODUCTION

Land subsidence is one of the causes for flood and damaging infrastructure, and early detection of the subsidence is important. There are some method proposed to estimate 3-D displacement from SAR images (Hu, et al, 2012; Samsonov, et al, 2007). One of the methods by Ito et al. (2018), firstly, estimates two radar LOS direction velocities from multi-temporal SAR images observed on ascending- and descending-orbits. Then, it interpolates the 3-D direction from GPS survey and leveling data by interpolation; ordinary kriging. Finally, ordinary least square method (OLS) estimates 3-D direction velocity by interpolation and estimate 3-D direction velocity with high accuracy and resolution. However, the OLS-based combination does not consider the difference of accuracy. It is assumed that the accuracies of different data are same. If the assumption is not reasonable, the estimation is influenced by lower accuracy data. To solve the problem, we apply weighted least square method (WLS) to combine. In this paper, we estimate the 3-D displacement combining PSI velocity and interpolated velocity by WLS and confirm the validity of WLS.

2. METHOD

Here, we introduce how to estimate the 3-D displacement. First, the method estimates the velocity in the LOS direction from SAR images by PSI. From SAR images on ascending- and descending-orbit, we have two LOS velocities. Next, we interpolate the 3-D velocity from GPS data by kriging. Then, we set up observation equations by combining these velocities, shown in Equation (1).

$$\begin{bmatrix} V_{ASC} \\ V_{DES} \\ V_{GPS}^{e} \\ V_{GPS}^{n} \\ V_{GPS}^{u} \end{bmatrix} = \begin{bmatrix} u_{ASC}^{e} & u_{ASC}^{n} & u_{ASC}^{u} \\ u_{DES}^{e} & u_{DES}^{n} & u_{DES}^{u} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} V^{e} \\ V^{n} \\ V^{u} \end{bmatrix} \quad (1)$$

Here, V_{ASC} and V_{DES} are the absolute velocities by PSI along the LOS of ascending- and descending-orbit, respectively. V_{GPS}^{e}, V_{GPS}^{n}, and V_{GPS}^{u} are the interpolated velocities in the direction of east-west, north-south, and vertical, respectively. $[V^e, V^n, V^u]^T$ is the vector of estimated velocity in each direction, $[u_{ASC}^e, u_{ASC}^e, u_{ASC}^e]$ and $[u_{DES}^e, u_{DES}^e, u_{DES}^e]$ are unit vectors to convert the LOS direction velocity to 3-D direction velocity. Finally, we derive the 3-D displacement by minimizing the sum of squared errors with unique weight.

Now, we consider WLS with different weights. In surveying, the traditional error adjustment theory assumes that the weight is reciprocal number of variances of measurement error. Following this theory, we calculate the weight for PSI results by Equation (2).

$$\begin{gathered} \varepsilon_i = \frac{V_{ps}}{u_u} - V_{GPS}^u, \\ \sigma_{ps}^2 = \frac{1}{\mathrm{n}}\sum_{n=1}^{n}(\varepsilon_i - \bar{\varepsilon}), \\ w_{ps} = \frac{1}{\sigma_{ps}^2}. \end{gathered} \tag{2}$$

In Equation (2), V_{PS} means V_{ASC} *or* V_{DES}, ε_i is measurement error, σ_{ps}^2 is error variance, and w_{ps} is the weight. On the other hand, the weights for interpolation results are calculated by selecting one interpolated point from all interpolation points and treating the difference at the selecting point between the estimation the others interpolate and the true value of the point as error. Then, we calculate the weight for interpolation by Equation (3).

$$\begin{gathered} \varepsilon_i = V' - V_{GPS}, \\ \sigma_{kriging}^2 = \frac{1}{\mathrm{n}}\sum_{n=1}^{n}(\varepsilon_i - \bar{\varepsilon}), \\ w_{kriging} = \frac{1}{\sigma_{kriging}^2}. \end{gathered} \tag{3}$$

In Equation (3), V' is interpolated velocity, V_{GPS} means V_{GPS}^{e}, V_{GPS}^{n} *or* V_{GPS}^{u}, $\sigma_{kriging}^2$ is error variance, $w_{kriging}$ is the weight for interpolated velocity. Finally, the proposed method solves Equation (1) by WLS and estimates the displacement velocities $[V^e, V^n, V^u]$ in each direction.

3. STUDY AREA AND USED DATA

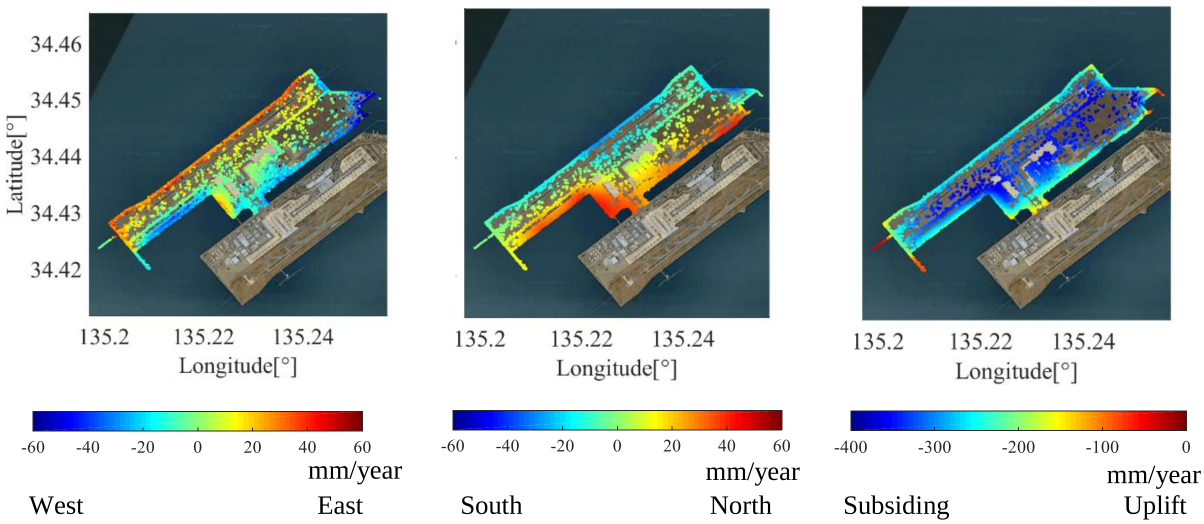
We selected 2nd Airport Island in Kansai international airport (KIX), Japan as our study area. KIX has been subsided since the open and 1st and 2nd Airport Island subsided 6 cm/year and 34 cm/year, respectively (Kansai Airports., n.d., 2015). In this experiment, we applied to only 2nd Airport Island because the GPS data on 2nd Airport Island are available to us.

We used 13 SAR images taken by Advanced Land Observing Satellite 2 (ALOS2) / Phased Array type L-band SAR 2 (PALSAR2), developed and operated by Japan Aerospace Exploration Agency (JAXA), on ascending orbit from September 2014 to March 2018 and 17 SAR images taken by ALOS2/PALSAR2 on descending orbit from March 2015 to May 2018. We also used 10 m mesh digital elevation model (DEM) that Geospatial Information authority of Japan publishes to remove the topography influence on interference phase (GSI, n.d., 2019). Then we used 26 GPS data on the study area surveyed by Kansai Airport Corporation, and we treated 18 data for interpolation and the others for validation. In addition, Kansai Airport Corporation surveyed 54 leveling data with

GPS, and we treated 32 data for interpolation and 22 data for validation. Therefore, we had 50 interpolation data and 30 validation data in vertical.

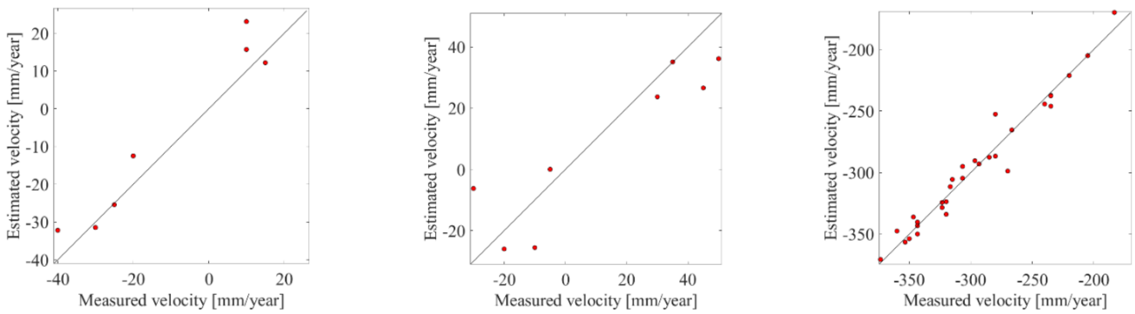
4. RESULTS

First, we estimated displacement velocity in the direction along LOS using permanent scatterer interferometry (PSI) (Ferretti et al., 2000), divide the velocity by cosine of the incident angle to the vertical velocity and compare it with validation data. In this research, we used a software developed by Earth Observation Research Center (EORC), JAXA (EORC, 2019). The RMSEs of the velocities from ascending- and descending-orbit SAR data were 22 mm/year and 19 mm/year, respectively. For comparison, we considered the nearest PS point within 100 m from validation point is same position as validation point. The average distance of each PS was 7 m and 95 % of PSs were within 20 m away from validation points. The RMSEs of the interpolation were 8 mm/year, 13 mm/year, and 33 mm/year in the direction of east-west, north-south and vertical, respectively. Figure 1 shows the results of WLS that combines PSI and interpolation results using $\boldsymbol{w}$ and Figure 2 shows the accuracy in graph. The root mean square errors (RMSEs) using WLS were 6, 13, and 10 mm/year in east-west, north-south, and vertical directions and the RMSEs using OLS were 5, 13, and 16 mm/year in each direction, respectively.



(a) (b) (c)

Figure 1 Results of integration by WLS. (a) In east-west, (b) in north-south, and (c) in vertical direction. Map data ©2018 Google, ZENRIN.



(a) (b) (c)

Figure 2 Accuracy of the WLS results. (a) In east-west, (b) in north-south, and (c) in vertical direction

5. DISCUSSION

It was shown that WLS is more effective than OLS to combine PSI results and interpolation ones. The RMSEs in east-west of estimates by WLS and OLS are almost same, and the RMSEs in north-south are same. However, that in vertical using WLS is 6 mm/year less than that of OLS. It was confirmed that the accuracy of vertical velocity estimated by WLS is better than that estimated by OLS. These things show that WLS does not influence the estimation of horizon velocity, but greatly improves the estimation accuracy of vertical velocity. In addition, WLS eases the influence of smoothing effect of interpolation; ordinary kriging. Smoothing effect is the trend of kriging to estimate small value larger and large value smaller. It was indicated the northwest area of KIX is more shifted toward east in Figure 1 than the result obtained by OLS. WLS can estimate the more local displacement than OLS in east-west and vertical. Therefore, it is showed that WLS can improve the estimation of the direction in east-west and vertical.

Now, we discuss why WLS generates better accuracy of the estimates. At calculating the weight, we calculate each error variance; σ_{ASC}^2, σ_{DES}^2, $\sigma_{GPS,e}^2$, $\sigma_{GPS,n}^2$, and $\sigma_{GPS,u}^2$. At the result, σ_{ASC}^2 and σ_{DES}^2 are approximately $5.0 * 10^{-4}$, $\sigma_{GPS,e}^2$ and $\sigma_{GPS,n}^2$ are approximately $1.0 * 10^{-3}$, and $\sigma_{GPS,u}^2$ is approximately $1.0 * 10^{-2}$. From these error variances, the estimation in horizon by PSI is twice as accurate as that by kriging and that in vertical by PSI is 20 times as accurate as that by kriging. As the result, using WLS to combine PSI results that is more accurate affect the result of LS and interpolation results that is poor less affect that, the accuracy in vertical is greatly improved and the accuracy improves the accuracy in the east-west direction.

6. CONCLUSIONS

In this research, it is appeared that WLS improves the accuracy of estimation of vertical displacement and detects more locally displacement in vertical and east-west, compared with OLS. However, there are problems to apply this proposed method to other area. One of them is that there are many and high-density GPS data on KIX, but in other area, the number is less and sparse. To solve the problem, turning bands simulation that can interpolate using less data is valid instead of kriging. In the future, we try interpolation by turning bands simulation and estimate the displacement combining PSI and the interpolation results by WLS.

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