An Evaluation of the Performance in Ground Settlement Monitoring in Hong Kong Using Satellite Radar Remote Sensing Technology

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Abstract. In recent years, Persistent Scatters (PS) Synthetic Aperture Radar Interferometry (InSAR) technology has been proved to be a powerful tool that can provide high resolution information on topology and ground displacement monitoring of up to millimetric accuracy. In this project, we studied the ground deformation of the area of interest (AOI) in Hong Kong urban area by means of PSInSAR technology with multi-temporal techniques. The deformation map of AOI showed a relatively stable status with 0~-15mm/year subsidence in partial regions. For evaluating the millimetric accuracy performance of monitoring outcomes, a set of corner reflectors (CR) are deployed in the monitoring region. For the validation test, the CRs are either lifted or lowered, and the displacements are recorded by optical leveling. The accuracy of PSInSAR monitoring is then evaluated quantitatively by comparing the estimated displacement from SAR images with optical leveling data. The results of CR test showed a very high correlation between the displacement retrieved from InSAR analysis and that from ground survey; the deviation is less than one millimeter. In conclusion, PSInSAR method is validated for its capability of achieving millimeter level accuracy, meanwhile much more convenient than conducting ground survey in monitoring ground subsidence.

1. Introduction

In recent years, Synthetic Aperture Radar interferometry (InSAR) technology has proved its capability in deriving high accuracy ground deformation information from Synthetic Aperture Radar (SAR) images [1][2]. Comparing with traditional leveling method and the new GPS method, InSAR technology is favored for its unique characteristics of all-time, all-weather and wide-area monitoring. Moreover, for the purpose of overcoming the major limiting factors of InSAR technique, namely geometric and temporal decorrelation plus atmospheric phase screen (APS) disturbance, the persistent scatterer (PS)-InSAR technique was proposed and has since became the core concept in precisely measuring earth deformation from a time series of SAR images [3][4][5]. Reliable deformation information with millimetric accuracy can thus be obtained and extracted from searching persistent scatterers from long temporal series of interferometric pairs.

Since then, PSInSAR have been widely applied in ground deformation monitoring especially of urban areas, and a series of monitoring works have been applied in China [6]~[9]. Among these, Hong Kong stands as one of the most prosperous mega-cities around the world, and is especially famous for its dense skyscrapers, ceaseless new construction projects and massive area of reclaimed lands, which are all possibilities for causing surface subsidence over a long time period [10]. Monitoring the stability over urban region thus becomes very important for providing valuable information and assessing the impact of ground movement. In this project, for the first time, we analyzed a relatively large region of Hong Kong urban area and provided the deformation map to a millimetric accuracy applying the PSInSAR technology. Furthermore, the capability of the technique was evaluated by deploying a set of corner reflectors in the monitoring area. The heights were adjusted manually, and the result was compared with the result derived from PS analysis. The field data agreed with theoretical analysis with a deviation of 1.2 millimeter, revealing that fact that InSAR can definitely reach the millimetric level that could be expected from such an analysis and meanwhile apply to large region urban area ground monitoring works.

2. Study Area and Dataset

The study area belongs to the urban areas in Hong Kong as marked in blue rectangle in Figure 1. In this study, a total of 61 TerraSAR-X and 11 TanDEM-X images acquired between October 2008 and June 2012 were exploited. The two satellites for generating the images process an active phases array X-band SAR antenna with a wavelength of 31mm and frequency of 9.6GHz, with a resolution of up to 1 meter. The minimum interval between the two consequent acquisitions is 11 days. The TSX sensor acquires images over Hong Kong at about 6:25pm, along an ascending orbit with an incidence angle of approximately 37 degrees.

Figure 1 shows the coverage of TerraSAR-X images and the study area of interest (AOI) regarding this research. Later on the deformation map of AOI and time series analysis of Persistent Scatterers were generated and geocoded in SARPROZ [11] and displayed in Google Earth.

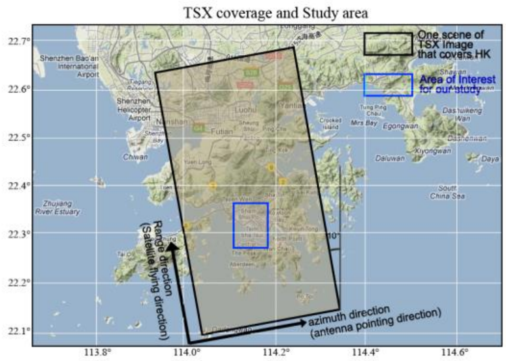

Figure 1. Spatial coverage of TerraSAR-X and TanDEM-X satellite with the studying area of interest of urban area in Hong Kong.

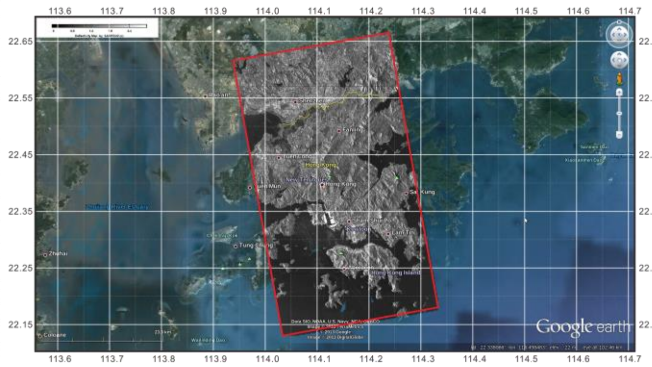

Figure 2. The reflectivity map of TerraSAR-X and TanDEM-X images overlay in Google Earth.

3. Methodology

The processing methodology can be divided into two steps: PS analysis and CRs validation test. Before the PS time series analysis, the reflectivity map was firstly generated by averaging the intensity of 72 satellite images as shown in Figure 2. After the procedure, the satellite image generally acquired midway through the monitoring period was selected as the master image, in this case, the acquisition on the 11th of June, 2010. Later on, the displacement of the radar targets are retrieved as a function of time with respect to the Master image. By processing the phase of SAR images with PSInSAR algorithm, two results can be retrieved: the three dimensional localization of PS's with 1m precision, and the estimated millimetric displacement of PS's along the satellite line of sight.

In order to evaluate the performance of PSInSAR monitoring techniques and the accuracy of ground monitoring results with artificial targets, a set of CRs are deployed in the monitoring region. For the validation test, the CRs are either lifted or lowered manually, and its displacement is recorded by optical leveling. We will then evaluate the accuracy of PSInSAR monitoring by comparing the displacement detected by SAR images and by optical leveling. The validation period is from February 2012 to June 2012, and 12 images are used for validation analysis.

4. Deformation Results

Figure 3 shows the final outcomes of the analysis, namely the annual velocity of the linear displacement map for PSs that have a height within the region ranging from -5 meters to 5 meters. In the first place, PS points at the low level or close to the ground are more relevant to the demonstration of monitoring ground settlement. The overall annual velocity around the area are mostly stable, with partial regions vary from -10mm/year to 5mm/year, for example, the west corridor in our AOI shows approximately -5mm/year displacement trend. Here we represent one representative PS point in the area in Figure 4. It shows the three-dimensional representations of the PS location in the AOI in Google earth. The target is located at ground level along the coast, close to an undergoing construction site for railway lines and stations. The target shows a linear displacement of the terrain: -5.2mm/year.

Figure 3. The annual velocity of the linear displacement map for PSs that have a height within the region of [-5,5] meters, urban area in Hong Kong.

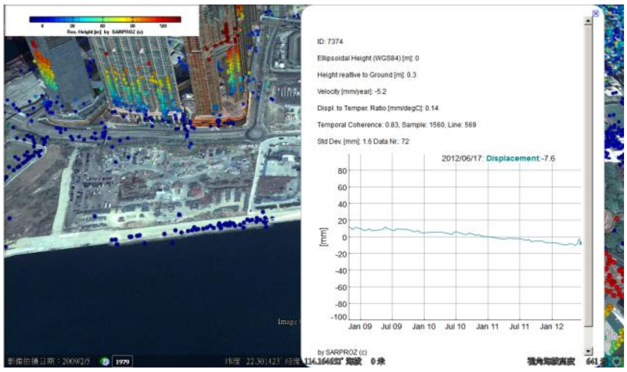

Figure 4. A representative PS's detected along the coastal area and near to a railway construction site. The target shows a moving velocity of 5.2mm/year.

5. Validation Experiment

5.1. Design and Deployment of Corner Reflector

A general type of corner reflector discussed in [12] was designed and deployed for the validation test. The corner reflectors are designed as rectangular trihedral reflector with 0.5m wide basement and 0.75m height, holed plate and adjustable basement. For deploying the corner reflectors, the CR's are installed in a region that presents a low background radiation to guarantee a good signal to noise ratio (SNR). In addition, in order to avoid possible unexpected relative motions and to keep the atmospheric noise as limited as possible, the corners are kept 50 meters from each other. One is selected as the reference target for the process.

5.2. Displacement of Corner Reflector

To estimate the displacement of the CRs, the other factors adding up to the phase should be removed. First of all, the interferometric phase can be decomposed into the following terms:

$$\Delta\varphi = \Delta\varphi_{displacement} + \Delta\varphi_{height} + \Delta\varphi_{atmosphere} + \Delta\varphi_{noise} \qquad (1)$$

In sequence, the four parameters are possible displacement, height of targets, atmosphere and noise. In this case, the height of the target was provided by the ground survey. The atmospheric delay and the noise (assuming a low noise level here within a small area) can be neglected in the case since the 4 CRs are placed relatively close to each other. So the displacement can be computed as:

$$d = \frac{\Delta\varphi - \Delta\varphi_{height}}{4\pi} \cdot \lambda \cong \frac{\Delta\varphi_{displacement}}{4\pi} \cdot \lambda \qquad (2)$$

Meanwhile, for the TerraSAR-X, given the wavelength λ equal to 3.1cm and the ambiguity of interferometric phase, the displacement retrieved from the interferometric phase will be

$$d = d \pm k15.5mm \quad (k = 1, 2, 3, ...) \qquad (3)$$

From which formulas we will approach the real-data study in our case.

5.3. Result of the detected displacement

The final results of displacement for corner reflectors are reported in Table 1. For each CR the time series of displacement detected by survey team and SAR images are being compared. For CR4E, the displacement time series show no movement, since the target has been selected as reference. The displacement detected by SAR images is provided by the common processing chain of SARPROZ. By comparing the deviation between two measurements in the table, we can have a first insight that most deviations are within one millimeter. A statistical analysis is followed in the next section.

Table 1. The comparison of vertical displacements between SAR images results and surveyed results

Date of Satellite Images	Vertical displacement detected by SAR images (mm)				Actual Vertical displacement Surveyed (mm)				Deviation between ground survey and SAR images(mm)			
	CR 1E	CR 2E	CR 3E	CR 4E	CR 1E	CR 2E	CR 3E	CR 4E	CR 1E	CR 2E	CR 3E	CR 4E
06/Feb/12	0	0	0	0	0	0	0	0	0	0	0	0
17/Feb/12	8.4	8.9	4.4	0	10	10	5	0	1.6	1.1	0.6	0
21/Mar/12	-5.2	19.6	9.6	0	-5	19	8	0	0.2	-0.6	-1.6	0
1/Apr/12	-5.7	18.8	5.6	0	-5	18	5	0	0.7	-0.8	-0.6	0
12/Apr/12	-0.3	26.9	-0.2	0	-1	26	-1	0	-0.7	-0.9	-0.8	0
23/Apr/12	2.1	19.3	8.5	0	3	20	8	0	0.9	0.7	-0.5	0
4/May/12	2.0	26.5	17.9	0	1	25	15	0	-1	-1.5	-2.9	0
15/May/12	2.0	9.3	37.7	0	1	9	35	0	-1	-0.3	-2.7	0
26/May/12	13.5	-0.6	37.7	0	12	-1	35	0	-1.5	-0.4	-2.7	0
06/Jun/12	18.0	-0.8	33.3	0	16	-3	30	0	-2	-2.2	-3.3	0
17/Jun/12	21.6	-4.0	30.4	0	18	-5	27	0	-3.6	-1.0	-3.4	0

5.4. Deviation of the detected displacement

Figure 5 shows the linear regression statistical analysis on the deviation of the detected displacement between the surveyed and SAR detected vertical displacements. For each target in the graph, the x-axis value indicates the vertical displacement measured by the leveling survey, and the y-axis value indicates the vertical displacement detected by SAR images.

The updated outcome of the linear regression is

$$y=1.0602x+0.30467 \qquad (4)$$

which shows a bias of about 0.3 millimeter and a deviation from the linear relation of about 6%.

The linear correlation coefficient, R^2, is equal to 0.99151, stating univocally the linear correlation between the displacements detected by InSAR and by the leveling survey. The root mean square error (RMSE) has a value of 1.2 mm, confirming the fact that the accuracy of PSInSAR measurement can reach the millimetric level.

5.5. Analysis of the results of Corner Reflector test

From Table 1 we can see that the results retrieved from InSAR in May and June for the three corner reflectors are not matching as well as before the leveling survey. However, the discrepancy between InSAR and leveling in May and June is not irregular; on the contrary, the results appear clearly shifted, revealing a neat bias. This evidence proves that some factors occurred and influenced the results.

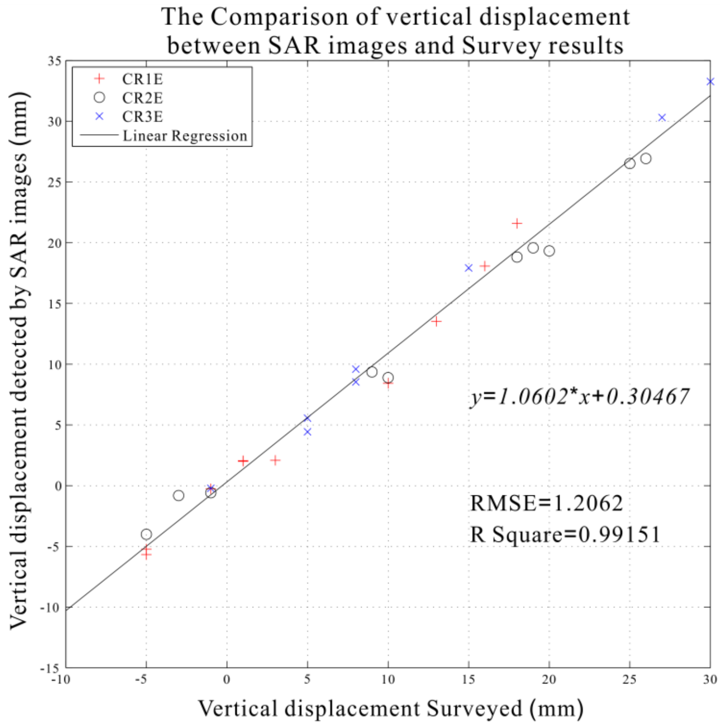

Figure 5 The statistical analyses on the deviation between the displacements detected by InSAR and by leveling survey measurement.

It is important to investigate the reasons for such bias. When ruling out the possibilities caused by precipitations and thermal expansion, the most possible explanation could be the movement of the terrain. As a matter of fact, we know that the area where the corner reflectors have been installed (which lies within the area of Figure 4) is moving. We also observed a drift of CR4E (the reference reflector) in May-June which is compatible with the bias we observed. It has to be noted here that, while the manual movement carried out by ground survey is sensitive only to vertical movements, the InSAR estimated displacement can be affected by both vertical and horizontal components. Thus, a possible explanation of the detected bias could be a horizontal movement, recorded by InSAR but not by the ground survey. The assumption has also been proved by the ground GPS RTK records of the four corner reflectors that the reference corner was actually moving away from the other three.

6. Conclusion

In this research, we analyzed the ground deformation trend in Hong Kong urban area. In the first place, the reflectivity map of the local area is shown. Buildings in urban area and four CRs for validation can be clear seen on the image. In the second place, the deformation map is generated, and the result shows an overall stable state with partial regions undergoing a subsiding trend from -10~5mm/year. To further validate the accuracy of the PS analysis, a corner reflector test is conducted inside our AOI. The results showed a very high coefficient between the displacement between the InSAR analysis and the ground survey result and a deviation of close to 1mm. In addition, as stated above, if the area of CR settlement is not moving, the accuracy of validation should even be higher. In conclusion, PS technique is definitely showing the capability of achieving the same level of ground survey, meanwhile much more convenient than conducting ground survey in monitoring ground subsidence. The method can achieve high accuracy for a wide monitoring area. In the future, the technique should be an important method and reference for ground monitoring.

7. Acknowledgement

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