ABSTRACT

The TerraSAR-X SAR system provides high spatial resolution and geometric accuracy imagery which supports well the mapping of the 3-D structure of the city and its motions (4-D). In this work, we have evaluated potential of the very high resolution (VHR) satellite observations for monitoring and detecting ground deformation due to large-scale civil infrastructure constructions. Two case studies were carried out in test sites of the Shenzhen Metro Line 4 and the Lantau Link Hong Kong, which are characterized by different triggering mechanisms of land subsidence: one induced by subway tunnelling constructions and the other by land reclamation from the sea. A total of 15 TerraSAR-X scenes were used in an elaborated PSI processing chain e.g. the DEM-assisted coregistration, the spectral shift filtering, the phase ramp correction and multi-master stacking analysis. The preliminary results indicate a remarkably high density of PS points (>2,500 PS point/km$^2$) to be identified and a quick land subsidence (> 15 cm within approximately half of year) to be detected. The high detail level of deformation filed and the high sensitivity regarding displacements, coupled with the good long-term coherence of man-made features (e.g. roads and buildings), make TerraSAR-X interferometry an remarkable potential EO technique to enable the detection of the ground deformation related to civil infrastructure constructions.

KEYWORDS

TerraSAR-X interferometry; Ground Deformation; Civil Infrastructure Construction; Persistent Scatterers Interferometry; Shenzhen Metro Line 4; Hong Kong Lantau Link.

1 Introduction

Satellite Interferometric Synthetic Aperture Radar (InSAR) is a revolutionary technique that can provide ground deformation data faster and more economically than traditional ground-based observation techniques\cite{1}. And recent advances in SAR interferometry have demonstrated the robustness and precision of some Advanced InSAR approaches (referred to also as Persistent Scatterers Interferometry, PSI) to overcome the intrinsic limitations of conventional InSAR. The PSI technique has been particularly useful for monitoring tiny urban ground displacement, i.e. land subsidence induced by the over-exploitation of groundwater\cite{2}. However, for the current standard SAR systems (e.g. ERS and ENVISAT) with relatively coarser pixel resolutions and longer repeatedly visiting circles, identification and interpretation of point-likely targets (Persistent Scatterers, PS) are still a challenge for monitoring ground deformation due to construction activities of large-scale civil infrastructure (e.g. subway tunneling and reclamation). Such land subsidence is generally
characterized by a high deformation rate or involves a single building. The new-generation SAR systems, e.g. TerraSAR-X and COSMO-SkyMed, have the enhanced capabilities in terms of spatial resolution and temporal revisit time, and therefore offer a potential to monitor and detect such rapid land subsidence. The InSAR technique with these new-generation SAR images profits from the shorter radar wavelength, the high PS density, the high sensitivity regarding displacements (e.g. 1.5 cm/cycle) and the coherent rough surfaces of man-made features, e.g. roads and buildings.

In this work, the main aim was to evaluate the potential of TerraSAR-X observations of ground deformation due to large-scale civil infrastructure constructions. A total of 15 TerraSAR-X Stripmap images between May 2008 and January 2009, acquired over both Shenzhen and Hong Kong, have been applied in two case studies that characterized by different triggering mechanisms of land subsidence: one induced by subway underground constructions and the other by land reclamation from the sea. And a small-baseline subset PSI analysis was performed to retrieve mean deformation velocity and displacement time series in the selected test sites.

2 Test Sites and Sar Dataset

Two test sites were selected in Shenzhen and Hong Kong (see Figure 1). The first site is located in the tunnel section from Lianhuabei Station and Shangmeilin Station (LS Section), which is a part of Shenzhen Metro Line 4 Phase 2 project (Metro L4 P2). The Metro L4 P2 is approximately 15.8 km long, consisting of 5 km of underground section and 10.8 km of at-grade and elevated sections. It has 10 stations and is expected to complete by mid 2011. The specific section of interest in the study, the tunnel section from Lianhuabei to Shangmeilin, was designed as two Tunneling Boring Machine (TBM) tunnels. Until March, 2009, one of the two TBM tunneling constructions was completed and the second one had also commenced. In addition, the main station box structures of the two underground stations were completed in late 2008. Quick land subsidence, in conjunction with construction activities and due to ground water changes, was expected in the section during and after tunneling and building constructions. For this selected site there is a real monitoring demand and ground based geodetic measurements available that could be used for comparison studies and validation.

The second site lies in a section of the Lantau Link of Hong Kong, a series of infrastructures linking Hong Kong International Airport to the Hong Kong urban areas. The section of interest consist of main transportation infrastructures from Kap Shui Mun Bridge to Shum Shui Kok, such as North Lantau Highway, Airport Express and one railway station (Sunny Bay Station), as well as the Kap Shui Mun Bridge, a cable-stayed bridge linking Ma Wan to Lantau Island. These infrastructures were mostly developed in reclaimed land, and therefore still experiences land settlement even more than ten of yeas passed since the reclamation.

Figure 1 The location of two test sites. (a) TerraSAR-X Stripmap imagery; (b) Test site of Shenzhen Metro Line 4 Phase 2; (c) Test site of Lantau Link of Hong Kong TerraSAR-X, a German high resolution radar satellite launched on the 15th of June 2007, is capable of acquiring data in three different imaging modes with different resolution: Stripmap mode (SM), Spotlight mode (SL and HS) and ScanSAR mode. The platform’s nominal orbit height at the equator is 514 km, orbit inclination 97.44° and the orbit repeat cycle is 11 days. The range bandwidth reaches a value of maximum 150 MHz for the standard mode, while for the experimental mode this parameter is up to 300 MHz. Moreover, the instrument can operate in single (HH, VV) or dual polarization mode (HV, VH). Table 1 summarizes the characteristic parameters of SM mode.

Table 1 the Characteristic Parameters of SM Mode of TerraSAR-X

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground range (ground range)</td>
<td>6 km for single pol (3 km for dual pol)</td>
</tr>
<tr>
<td>Normal LAI product length</td>
<td>50 km</td>
</tr>
<tr>
<td>PSI performance incidence angle range</td>
<td>20°-45°</td>
</tr>
<tr>
<td>Data mean incidence angle range</td>
<td>30°-40°</td>
</tr>
<tr>
<td>Number of iteration loops</td>
<td>27 (27 ft/pixel)</td>
</tr>
<tr>
<td>Azimuth resolution</td>
<td>33 in for single pol; 16.8 in for dual pol</td>
</tr>
<tr>
<td>Ground range resolution</td>
<td>0.9 to 3.9 m at 45°-70° incidence angle</td>
</tr>
<tr>
<td>Notation</td>
<td>HH or VV (single)</td>
</tr>
</tbody>
</table>

In this study, a total of 15 Stripmap ascending scenes (VV polarization) over the region of Hong Kong and Shenzhen were used to monitor the land subsidence in two test sites. The TerraSAR-X Single Look Slant Range Complex (SSC) data covers approximately 30 x 50 km², and has a pixel spacing of 0.9 m in slant-range and 2.0 m in azimuth. These data were programmed and ordered in the framework of the TerraSAR-X General AO project CAL_0390.
3 TerraSAR-X Interferometry

TerraSAR-X mission was designed to have high-resolution EO mapping and monitoring capabilities, particularly in the aspect of repeat-pass interferometric applications\(^4\). Most of the current InSAR processing algorithms, developed and optimized for widely available ERS-1/2, Envisat/ASAR and Radarsat-1 data, can be applied to TerraSAR-X data without the need for fundamental modifications. However, in the case of the higher spatial resolution and shorter wavelength data, certain processing steps of the "conventional" InSAR processing algorithms cannot be applied directly in TerraSAR interferometry. And the biggest problems could be associated to a conventional coregistration and spectral filtering modules, especially for processing Spotlight data\(^6\).

In order to achieve optimal interferometric results, coupled with a limitation of small number of TSX data available, the following key processing steps are emphasized and proposed in this study:

1. the coregistration procedure assisted with an extended-DEM
2. the spectral filtering and 2-D quadratic phase model using the least-squares error criterion
3. the multi-master stacking analysis with small-baseline subset

More specifically, the DEM-assisted coregistration approach considers the terrain heights in the SLC co-registration and utilizes the imaging geometry information and a-priori information of the topography\(^6\). It can achieve a higher accuracy of co-registration than that obtained by the so-called cross-correlation co-registration method. In particular, a high-resolution local DEM of the study area was used for the coregistration, as well as the removal of topography phase and geocoding. The DEM has a vertical resolution of 2 m and a regular grid spacing of 5 m that is comparable with pixel size of 4x4 multi-look TerraSAR images. In our test, offsets determined by DEM-assisted method showed a very low standard deviation below 0.05 SLC pixels, however, the method based on smooth wrap models such as 2-D polynomials of low degree can not ensure the sub-pixel coregistration accuracy in most cases. Errors occurring during coregistration result generally in a loss of coherence\(^5, 7\). The influence of misregistration on coherence is illustrated in Figure 2. For instance, the peak of the Tai Yam Teng experiences low conference in the case of TerraSAR-X InSAR pair coregistered in the congenital way (Figure (a)), but relatively high value in DEM-assisted coherence map (Figure (b)). The improvements in coregistration are also clearly visible in the area corresponding to the Lantau Link and its adjacent slopes.

Another important processing step is the 2-D quadratic phase fit using the least-squares criterion after the spectral filtering in slant range and azimuth. When calculating and unwrapping the differential interferograms, we found evident phase circle trends (phase fringe) within the area corresponding to flat topography in several interferograms, particularly the one with a large perpendicular baseline. For example, Figure 3 (a) and (c) show the phase fringe of the unwrapped differential phase along the Lautau Link. An initial inference is that the inaccurate orbit state vector data might result in the fringe due to phase flattening influence. We will further investigate the reason in the next study. Here we carried out a 2-D quadratic phase fit for the fringe correction. The fit was modeled by a linear and quadratic phase function in range and azimuth, and then the modeled phase ramp was subtracted from the differential interferogram. Generally, this phase fit correction is enable to result in a removal of the fringes (see Figure 3 (b) and (d)).

The last key processing step is the multi-master stacking analysis with small-baseline subset for retrieval of mean deformation velocity and displacement time series. The land subsidence due to civil infrastructure constructions is characterized by high deformation rates with significant spatial deformation gradients. In the past PSI analysis need large number of time-series SAR images and was not very successful under these conditions. In this study, for the optimizing the PSI processing in the case of high deformation gradients and non-uniform motion, a multi-master stacking analysis was applied to a subset of interferometric combinations of the 15 available scenes especially with shorter time intervals (11- to 44 days) and smaller perpendicular baselines (less than 200 m). In addition, the formation scheme of multi-master interferograms can also increase the number of the resultant interferograms. For these shorter baseline pairs spatial phase unwrapping for the point...
network was possible. In particular, the result achieved could significantly profit from the remarkably high point density, short time interval of 11 days and high spatial resolution of 1 m order of the TerraSAR-X data.

4 Preliminary Results

4.1 Test Site 1: Subway Line 4 in Shenzhen

Figure 4 shows the line-of-sight deformation between 13-May-2008 and 21-Jan-2009 over the test site 1, which was derived from 15 scenes of TerraSAR-X data series in the multi-master PSI processing. Subsidence values larger than 15 cm were observed near the two stations of Shangmeilin and Lianhuabei. A total of more than 13,000 points were ultimately identified and interpreted for this test site of Metro L4 P2 in Shenzhen which is approximately 5 km$^2$ (> 2500 PS point /km$^2$). Most of these detected points were suited on individual buildings and even over roads. Generally, moderate (light green and yellow, -5 to -10 cm) to strong (red, <-15 cm) subsidence was observed in the region where subway constructions are in progress, particularly near the two stations of Shangmeilin and Lianhuabei. It is interesting to note that the results did not show an evident subsidence related to constructions in the tunneling section from Lianhuabei to Shangmeilin. It is possible since the tunneling started the end of 2008 when our TerraSAR-X data used in this work were acquired in Jan, 2009. The validation of the result will be carried out with the geodetic measurements in near future.

4.2 Test Site 2: Lantau Link in Hong Kong

Figure 5 shows the line-of-sight deformation rate between 13-May-2008 and 21-Jan-2008 derived from TerraSAR-X data series in the multi-master PSI processing over the test site of Hong Kong. Remarkably, large amount of PS points were found over the transportation infrastructures of the Lantau Link, e.g. North Lantau Highway, Airport Express railway and the Kap Shui Mun Bridge. The X-band and high spatial resolution of TerraSAR-X data, enabling road surface to have high coherence, significantly contribute to the capacity of PS identification. As we expected, a relatively clear settlement pattern was detected in the reclaimed land of the Lantau Link. In contrast, the sectors corresponding to the area excavated from original land (dashed black ellipses 1 and 2 in Figure 5) appear quite stable. Maximum of reclamtion settlement (< -15 mm/yr) was observed within the Sunny Bay Station area.
Conclusions and Prospective

The TerraSAR-X SAR system is characterized by the high spatial resolution and the unchallenged geometric accuracy which supports well the mapping of the 3-D structure of the civil infrastructures and its deformations. Our preliminary results have demonstrated the applicability and potential of TerraSAR-X data for the detection of land subsidence induced by large-scale infrastructure construction in two cases of Shenzhen and Hong Kong. The applicability and capacity of TerraSAR-X interferometry benefits from the high PS density, the shorter repeat cycle of eleven days and the high sensitivity regarding displacement as the result of the shorter radar wavelength. However, some algorithmic adaptation in interferometric processing chains such as the coregistration and the spectral shift filtering are required in order to cope with the high resolution especially the complex imaging characteristics of the Spotlight model. In addition, layover ambiguities and multipath scattering effects particularly in high density urban areas are still open issues. Our main focus in the next work will be on an elaborate PSI analysis with an increased stack of scenes and on validation of results with ground surveying measurements.

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