Height Estimation for High-rise Buildings based on InSAR Analysis

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Abstract— **Owing to the remarkable improvements that have been made in radar sensors, it becomes possible to obtain the information for a single structure from high-resolution SAR images. In our previous research, a method for detecting the heights of low-rise buildings automatically was proposed using 2D GIS data and a single high-resolution TerraSAR-X intensity image. However, this method is difficult to apply for high-rise buildings due to surface/material conditions of their exterior walls. In this study, a new method was developed for estimating the heights of high-rise buildings based on the results from an Interferometric SAR (InSAR) analysis. The characteristics of phases in the InSAR result were investigated and used for extracting the potential layover areas of target buildings. Then, the heights were estimated according to their layover lengths. The developed method was tested on two TerraSAR-X images for San Francisco, USA, in the HighSpot mode. Comparing the result with Lidar data, the detected heights were found to be reasonable.**

I. INTRODUCTION

Recently, data from the new high-resolution (HR) SAR sensors, e.g., Cosmo-SkyMed (CSM) and TerraSAR-X (TSX), have provided us with more detailed surface information. It became available to obtain the features of an individual urban structure, especially its height, from these HR SAR images. Because SAR sensors can observe the earth surface despite of weather and sunlight conditions, they are more suitable for periodic monitoring than optical sensors. Thus, deriving cartographic information for urban areas from SAR images is a highly attractive issue.

Several methods related to height detection from HR SAR images have been proposed. Franceschetti et al. [1] proposed a method for extracting building height information based on a radiometric analysis of the double-bounce contribution. This method was tested on an airborne SAR sensor image [2], and a TSX image of Shanghai, China [3]. Because priori knowledge of the material and surface roughness properties of the background are required, it cannot be used in different areas. Bolter and Leberl [4] and Thiele et al. [5] extracted buildings and their heights from multiple Interferometric SAR (InSAR) datasets. These methods, however, require at least two SAR data pairs that represent different flight angles. Height detection was also carried out using the geometrical characteristics of layover and radar-shadow areas. Simonetto et al. [6] extract building heights by stereoscopic measures from three SAR intensity images with different incident angles. Brunner [7] estimated building heights by matching simulated SAR images with a real image containing buildings of various heights, which is complicated and time consuming. The present authors [8] proposed a method to detect layover areas of low-rise buildings by a simple threshold value of the SAR backscattering intensity and a 2D GIS data. Then the building heights were calculated from the lengths of the detected layovers. However, this method could not work well for high-rise buildings due to the complicated reflection pattern of their exterior walls. In addition, the layover of a high-rise building usually overlaps with other buildings in a dense urban area. Thus, it is difficult to extract the layover areas only form the SAR intensity.

In this study, our proposed method is improved to estimate heights of high-rise buildings by introducing the results from an InSAR analysis. First, a flattened interferogram is obtained from two HR SAR data by the InSAR analysis. Then the characteristics of stable phases in layover areas are investigated using several sample buildings. The potential layover areas are extracted by three threshold values for InSAR phases. The final building heights are estimated by the template measurement that was proposed in the previous study, using the potential layover areas and building footprints. This method is tested on two TSX images of San Francisco in the HighSpot mode, and the accuracy is verified by comparing with Lidar data.

II. STUDY AREA AND IMAGE DATA

The study area focuses on a part of San Francisco, CA, USA, as shown in Fig. 1(a). The two TSX data taken on December 5 and 27, 2007, respectively, were used to estimate building heights. They were taken by the HH polarization in the HighSpot mode from the descending path. The incident angle at the center was 39.87°. The data were recorded as single-look slant-range complex (SSC) products including the amplitude and phase information. The azimuth resolution was about 1.10 m and the slant-range resolution was about 0.92 m. A color composite of the two amplitude images in the slant range is shown in Fig. 2(a). It can be observed that the most of the layover areas for high-rise buildings overlap with the backscattering echoes from the surrounding buildings.

A digital surface model (DSM) and a digital elevation model (DEM) taken by a Lidar flight in June 2010 were used

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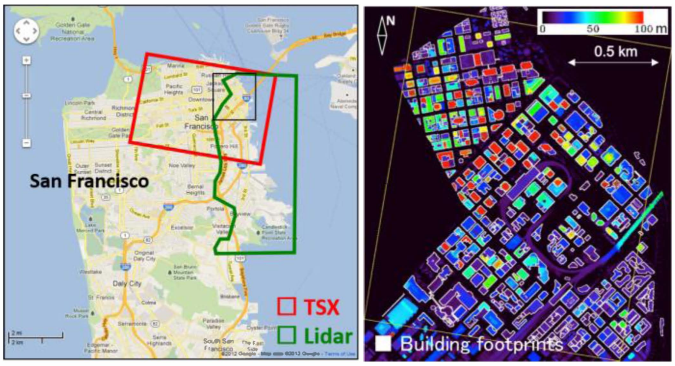
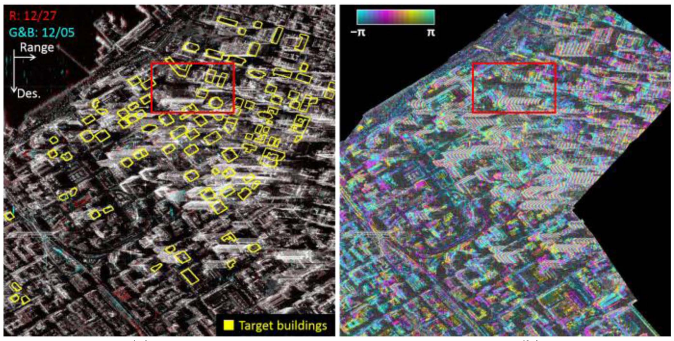


(a) (b)

Fig. 1. The study area along the bay coast of San Francisco with the shooting ranges of the TSX and Lidar data (a); the reference heights calculated from the Lidar data with the building footprints that were downloaded from the website of San Francisco City government [9] (b).



(a) (b)

Fig. 2. Color composite of the two temporal TSX intensity images, overlaid by the footprints of the target buildings over 50 m (a); the obtained interferogram by the InSAR analysis (b). Note that the both images are shown in the slant range.

as a reference for the building heights. The horizontal accuracy of the Lidar data was about 2.0 m and the vertical accuracy 0.12 m. The DSM and DEM data were resampled as 0.5 m/pixel. Since the shooting range for the TSX data and the Lidar data were different, the target area was selected from the common range as the black square shown in Fig. 1(a). The reference building heights were calculated by the difference between the DEM and DSM data, as shown in Fig. 1(b). It is seen that in a financial district, many high-rise buildings over 100-m high are standing in a small but dense area.

In addition, a GIS data of building footprints was downloaded from the website of San Francisco City government [9]. The footprint data in the target area are shown in Fig. 1(b) by the white frames. There exit 448 buildings, and 99 of them are higher than 50 m. The geo-referenced GIS data were transformed to the slant rang and matched with the TSX SSC data. The buildings higher than 50 m were selected as the targets in this study, shown in Fig. 2(a) by the yellow frames.

III. Methodology

In our previous study, a simple method was proposed for detecting the heights of individual buildings by measuring their layover lengths from a single HR SAR intensity image [7-8]. The potential layover areas were extracted by a threshold value of the backscattering coefficient. However, the backscattering intensity for the layover area of a high-rise building is generally overlapping on other buildings. In addition, the values are not stable due to the material of exterior walls and their complicated surfaces. It is difficult to extract the complete layover areas only using the SAR amplitude information. Thus, an InSAR result including phase information was introduced to improve the previous method. The flowchart of the new method is shown in Fig. 3.

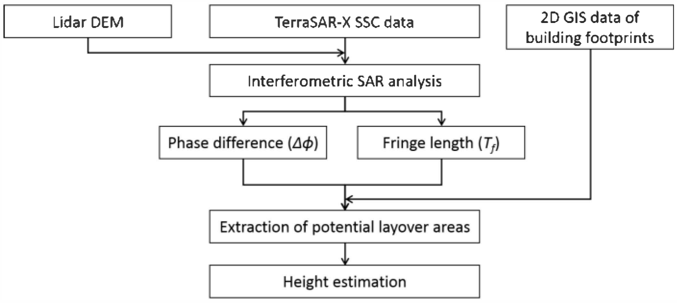


Fig. 3. Flowchart of the improved method to estimate the heights of high-rise buildings by introducing InSAR analysis results.

A. *Interferomtertic SAR (InSAR) analysis*

First, an InSAR analysis was carried out for the two TSX complex data using *ENVI/SARscape* software. The image taken on December 5, 2007 was set as the master whereas the one on December 27, 2007 as the slave. The look number for the compress step was set as one in both the azimuth and range directions. The high accuracy Lidar DEM data were used to remove topographic fringes. Then a flattened phase image was obtained by removing orbital fringes and noises using the Goldstein filter. After removing the orbit, topographic fringes and noise effects, the residual fringes represent only building heights. Owing to the short acquisition interval (22 days), highly coherent fringes were obtained for the whole target area, as shown in Fig. 2(b).

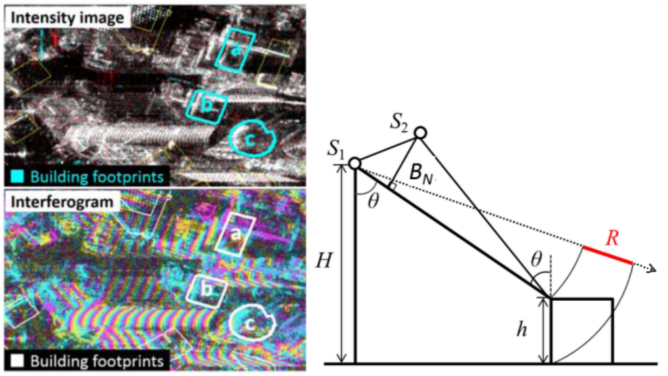
A close-up of Fig. 2 is shown in Fig. 4(a), where three high-rise buildings are selected as examples. The layover of Building ***c*** with strong backscattering is possible to extract by the pervious method. However, the backscattering intensities in the layover areas of Buildings ***a*** and ***b*** are not strong enough to be extracted. On the contrary, the phases in their layover areas are stable and continuous despite of low backscattering. Thus, the phase characteristics are considered to be useful for the extraction of layover areas.

B. *Extraction of potential layover areas from phases*

According to the shooting model shown in Fig. 4(b). The relationship between the phase angle (ϕ) and the building height (h) can be expressed by (1). Furthermore, the relationship between the building height (h) and the layover length (R) in a slant-rang image can be expressed by (2). Thus, the phase difference within the building layover is represented by (3), which is obtained by combining (1) and (2).

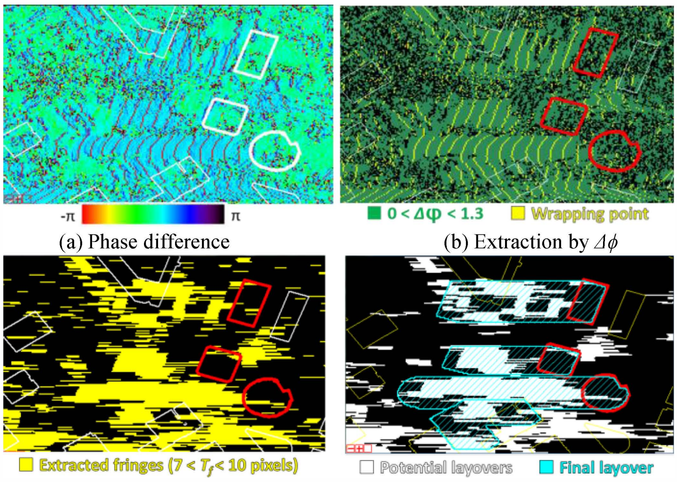
$$\frac{d\phi}{dh} = \frac{4\pi B_N}{\lambda H \tan\theta} \tag{1}$$

where λ [m] is the radar wavelength and H [m] is the satellite altitude; θ [rad] is the incident angle, and B_N [m] is the perpendicular baseline distance.



(a) (b)

Fig. 4. Comparison of the backscattering intensity and the interferogram for three sample buildings (a), which is the close-up of Fig. 2; a schematic image of geometrical characteristics for a building in a slant-range SAR image (b).



(a) Phase difference (b) Extraction by $\Delta\phi$

(c) Extraction by T_f (d) Extracted layover areas

Fig. 5. Extraction of potential layover areas from the interferogram: phase difference (a); the extracted stable phases and wrapping points using the threshold value of phase difference (b); the fringes of the lengths within the threshold value of T_f (c); the final potential layover objects extracted by both (b) and (c) after removing the small objects (d).

$$h = \frac{R}{\cos\theta} \quad (2)$$

$$\Delta\phi = \frac{4\pi B_N}{\lambda H \sin\theta}\Delta R \quad (3)$$

Since the perpendicular baseline distance between the two TSX images was 561.6 m, a fringe from –π to π represents 11.6 m in height. The phase difference ($\Delta\phi$) within one pixel in the layover areas of the slant-range TSX image was a constant value as 0.65 rad/pixel, with the pixel size 0.91 m. In additional, the length of one fringe cycle (T_f) was also a constant value as about 10 pixels. Thus, the parameters $\Delta\phi$ and T_f are used to extract layover areas from the interferogram.

The phase differences were calculated by subtracting the next pixel's value in the range direction. To extract the potential layover areas, two threshold values were set. The threshold value for $\Delta\phi$ was set as between 0 and 1.3 considering its theoretical value (0.65). The wrapping points between two fringes were also extracted by the phase difference smaller than –π. Then the fringe length was measured according to the distance between two wrapping points in the range direction. The threshold value for T_f was set as plus-minus 3 pixels around the theoretical value (10 pixels).

An example of the extraction is shown in Fig. 5. The phase difference was calculated firstly as shown in (a). The stable layover areas were extracted according to the threshold value of $\Delta\phi$, as shown in the green areas in (b). The wrapping points (yellow) were extracted in this stage. Then the fringes with the length within the threshold range of T_f were connected as shown in (c) as yellow. The areas extracted by both the phase difference and the fringe length were considered as potential layover areas. To remove noises, an object-based filter was applied. Considering the minimum size of layover areas for tall buildings, the extracted objects less than 50 pixels were removed after segmentation. The final potential layover areas are shown in (d) as white.

C. Height estimation

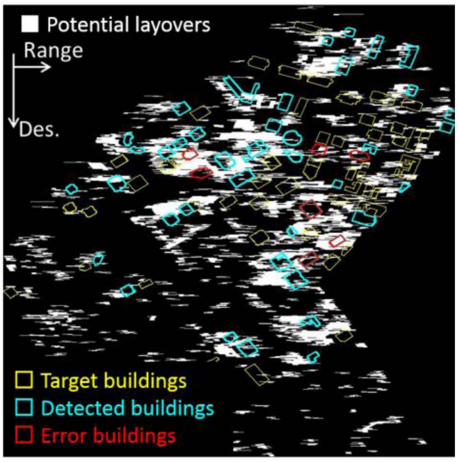
The template measuring proposed in the previous study was carried out to estimate the building heights from layover areas [8]. A template was created according to the building footprints, with one pixel width in the range direction. To reduce noises, the template was set as two pixels smaller than the original shape in the azimuth direction, one pixel to each side. Considering to the complicated environment in the ground floor, the initial template location was set as 5 pixels (about 6 m in height) in front of the building footprint along the rang direction. If a potential layover object exists within the initial template, the template measuring will start.

The template was shifted to the range direction pixel by pixel. In each shift, the percentage (P_L) of the extracted layover pixels within the template was calculated. When the value of P_L gets smaller than the threshold value, the shifting will stop. The building height was estimated from the number of shifted pixels using (2). In the previous study, a limitation of the shifting distance was set to avoid overestimation. For low-rise buildings, 30 m was set as the height limit. However, it is difficult to set such a limit for high-rise buildings. Thus in this study, the template measuring will stop when it reaches the other target building. By investigating 11 sample buildings, the threshold value of P_L was set as 11%. The finally estimated layovers for the three sample buildings are shown in Fig. 5(d) by the cyan frames.

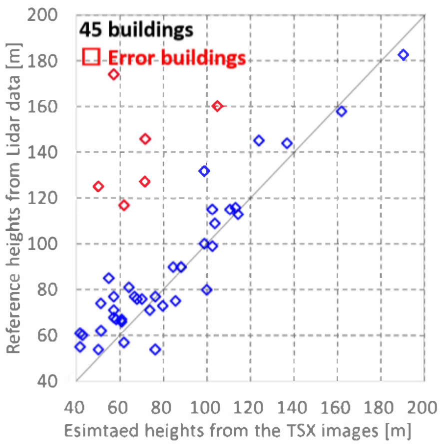
IV. Result and Discussion

The improved method was tested on the whole target areas. The potential layover areas were extracted using the threshold values for the phase difference and fringe length. After applying the filter, the layover objects larger than 50 pixels were detected and shown in Fig. 6(a). There were 99 target buildings in the study area, and the heights of 45 ones could be estimated successfully.

Three reasons are considered mainly causing the failure in the estimation. The first one is the high built-up density of buildings. When a target building stands close to its front target buildings in the range direction, there was no enough space for the template measuring. This problem also occurred



(a)



(b)

Fig. 6. Extracted potential layover objects from the interferogram, overlaid by the building footprints (a); comparison of the detected result versus the reference values (b).

in the previous study for low-rise buildings. The second reason is the complicated forms of the target buildings. Although the potential layover areas for high-stories were extracted successfully, the layover areas for first- and second-stories with complicated facade could not be detected. Thus, the template measuring did not start from the initial location. Irregular surfaces of exterior walls would also cause the failure in extraction. When the backscatters from those walls do not interfere, the layover areas cannot be extracted from the interferogram. The third reason is due to the facing directions of buildings. When the observable surfaces of a building to the range direction are limited, the layover areas become narrow and are difficult to be detected.

A comparison of the detected heights and the reference heights from the Lidar data is shown in Fig. 6(b). In the detected buildings, 87% were between 50 m and 100 m. Most of the estimated heights are around the isometric line, except for five points shown in red. All of those buildings were higher than 100 m, but their estimated heights were 50 m lower than the reference. The locations of these five buildings are shown in Fig. 6(a). Due to their heights, those layover areas overlaid on other target buildings. The template measuring stopped when reaching the footprints of their front buildings, and hence the heights were underestimated.

Excluding the five buildings, the absolute average error was 6.6 m, less than two-stories of ordinary office building. The RMS error was 13 m. The correlation coefficient between the estimated height and the reference was 0.93. Most of the estimated results were smaller than the Lidar data due to the phase disturbance by roofs. Considering the densely built-up environment of the target area, our result is still promising.

V. Conclusions

In this study, the method proposed previously by the present authors was further enhanced to estimate the heights of high-rise buildings from high-resolution TerraSAR-X images. An InSAR analysis was introduced to supplement the limitation of the SAR backscattering intensity. The method was tested on two 1-m resolution SAR images of San Francisco, taken within one month period. 99 buildings higher than 50 m were selected as targets, and 40 buildings were detected from the interferogram successfully.

The building heights obtained from Lidar data were used as a reference to examine the accuracy of the proposed method. Excluding five outliers, the average difference between the detected results and the reference values was 6.6 m, the RMS error 13 m, and the correlation coefficient 0.93. The accuracy of our method depends on the surrounding condition of a target building. In the future, by combining these two methods for low-rise and high-rise buildings, we will try to estimate all the building heights at once.

Acknowledgment

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