GEODETIC TOMOSAR – FUSION OF SAR IMAGING GEODESY AND TOMOSAR FOR 3D ABSOLUTE SCATTERER POSITIONING

Xiao Xiang Zhu[(1,2)], *Sina Montazeri*[(1,3)], *Christoph Gisinger*[(4)], *Ramon Hanssen*[(3)], *Richard Bamler*[(1, 2)]

(1) Remote Sensing Technology Institute (IMF), German Aerospace Center (DLR), Oberpfaffenhofen, D-82234 Wessling, Germany
(Email: xiao.zhu@dlr.de)
(2) Chair of Remote Sensing Technology, Technische Universität München (TUM)
(3) Department of Geoscience and Remote Sensing, Delft University of Technology
(4) Institute of Astronomical and Physical Geodesy (IAPG), TUM

ABSTRACT

In this paper, we propose a framework referred to as "*geodetic TomoSAR*" that fuses the SAR image geodesy and TomoSAR approaches to obtain absolute 3D positions of a large amount of natural scatterers. The methodology is applied on four Very High Resolution (VHR) TerraSAR-X spotlight image stacks acquired over the city of Berlin. Since the TomoSAR estimates are referred to the identical reference point whose absolute 3D positions are retrieved by means of Stereo-SAR, the point clouds from ascending and descending orbits are automatically fused. To assess the accuracy of the position estimates, the resulting absolute shadow-free 3D TomoSAR point clouds are compared to a DSM obtained by airborne LiDAR.

Index Terms— Geodetic TomoSAR, Stereo-SAR, TerraSAR-X, SAR Tomography

1. INTRODUCTION

Using stacked very high resolution (VHR) SAR images delivered by modern spaceborne SAR sensors, tomographic SAR inversion (TomoSAR) allows us to retrieve not only the 3D geometrical shape but also the undergoing temporal motion of individual buildings and urban infrastructures in the centimeter or even millimeter scale [1]. The resulting 4D point clouds have a point (scatterer) density that is comparable to LiDAR. Experiments using TerraSAR-X (TS-X) high-resolution spotlight data stacks show that a scatterer density in the order of 1 million pts/km^2 can be achieved by TomoSAR. However, similar to conventional InSAR and PSI, the elevation and deformation rates are estimated with respect to a previously chosen reference point which makes them *relative 3D* estimates [1]-[3].

Another attractive feature of modern SAR sensors, in particular of TerraSAR-X and TanDEM-X, is the precise orbit determination and high geometrical localization accuracy. After compensating for the most prominent geodynamic and atmospheric error sources, the *absolute 2D* (range and azimuth) positions of targets such as corner reflectors and persistent scatterers can be estimated to centimeter-level accuracy – a method called "SAR imaging geodesy" [6] [7]. Using two or more SAR observations acquired from different satellite orbits, absolute 3D positions of scatterers can be retrieved by means of stereo-SAR [4]. However, common scatterers that appear in SAR images acquired from different geometries, in particular from cross heading orbits, are very rare. This limits the application in 3D absolute scattering positioning.

In this paper, we propose a framework referred to as "geodetic TomoSAR" that fuses the SAR image geodesy and TomoSAR approaches to obtain *absolute 3D positions* of a large amount of natural scatterers. We work on four stacks of TS-X high resolution spotlight images over the city of Berlin, among them two are acquired from ascending and two from descending orbits. Fig.1 shows the mean scene coverage of each individual stack overlaid on an optical image of Berlin. Firstly, tens of opportunistic (or: natural) point scatterers that appear in all image stacks are manually identified; their *absolute* SAR range and azimuth measurements are calculated using imaging geodesy by compensating all the error sources; their absolute 3D positions are calculated using Stereo-SAR; the most precisely localized point target is then chosen as reference point for the follow-on TomoSAR processing. Since then the TomoSAR estimates are referred to the identical reference point whose absolute 3D positions are known, the resulting point clouds are automatically fused; finally, to assess the accuracy of the position estimates, the resulting absolute 3D TomoSAR point clouds are compared to a DSM obtained by airborne LiDAR.

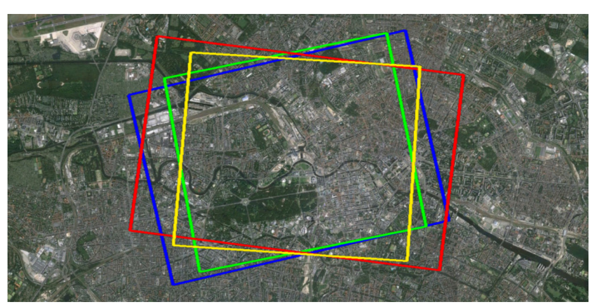
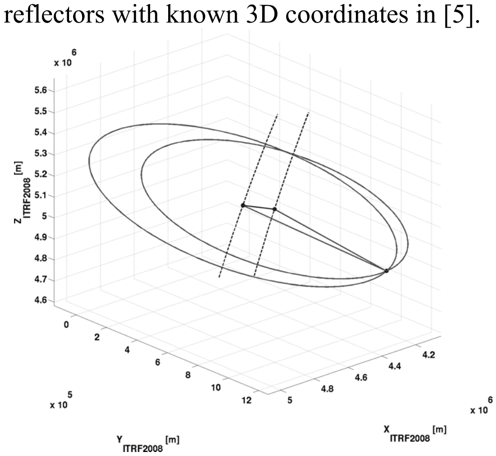


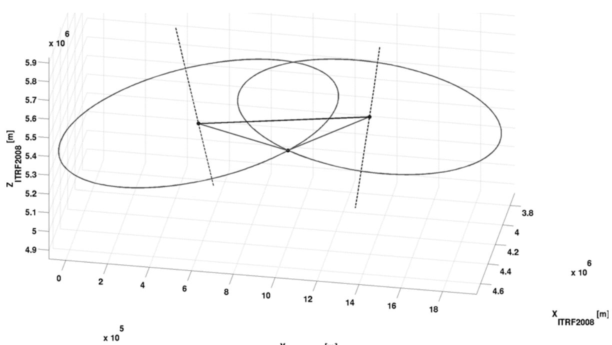
Fig.1. Optical image of the city of Berlin (©Google Earth). Rectangles mark the coverage of the four TS-X data stacks.

2. STEREO-SAR FOR 3D SCATTERER POSITIONING

Stereo-SAR makes use of two or more SAR observations of the same scene acquired from different satellite orbits for 3D retrieval of ground surface [4]. The retrieval of absolute 3D coordinates requires the computation of the intersection of two circles at angles $\Delta\theta$. To determine absolute azimuth and range time observations, highly accurate orbit determination and high geometrical localization accuracy of the sensor' phase center are required. Delays caused by propagation of the SAR signal in different layers of atmosphere and position changes due to geodynamic phenomena must be accounted for [5]-[8]. Finally, the absolute 3D scatterer position can be estimated by finding the intersection of the circles defined by the range-Doppler equations [5]. Fig. 2 illustrates the 3D stereo solution for a point target computed using different orbit stereo configurations, i.e. from the same heading orbits (two ascending orbits, left) and from cross heading orbits (one ascending and one descending orbit, right). Experiments using measurements from the same heading orbits revealed an absolute 3D accuracy and repeatability below 4 cm for corner reflectors with known 3D coordinates in [5].



(a) same heading orbits



(b) cross heading orbits

Fig.2. Different orbit stereo configurations taken into account for 3D scatterer reconstruction in Berlin

In our experiment, a dozen of opportunistic bright scatterers that appear at least in two stacks are manually identified. Using tens of images from the same stack, an absolute positioning precision of 7-10 cm for the 14 natural scatterers was found in city of Berlin [5]. Eventually, the most precisely localized point target which is a street lamp that appears in all four stacks was chosen as the reference point which is visualized in Fig.3. Its absolute positions in the ITRF 2008 reference frame are as follows:

$$[X\ Y\ Z] = [3783630.014 \pm 0.010\text{m} \quad 899035.0040 \pm 0.010\text{m} \quad 5038487.589 \pm 0.011\text{m}] \tag{1}$$

It has to be emphasized that the listed 1 cm level uncertainties refer to the variance-covariance information provided by the position computation with Stereo-SAR. Thus, these values are a measure for the consistency of the stereo-based scatterer retrieval. It is most likely that satellite illuminate different sides of the lamp post from ascending and descending orbit. Regarding the absolute accuracy of the reference point, we expect a bias in the order of 20 centimeters which depends on the diameter of the lamp post [5].

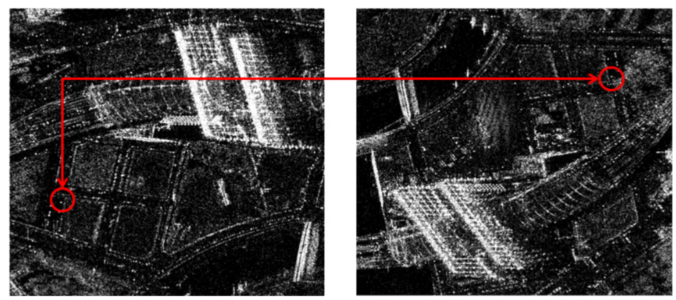


Fig.3. Selected common point target visible in all ascending and descending data stacks. The point can be observed as a bright dot inside the red circles.

3. TOMOSAR PROCESSING

After choosing the aforementioned absolutely geo-positioned scatterer as reference point for all the four stacks, the InSAR stacking and TomoSAR processing were done by the PSI-GENESIS [9] and Tomo-GENESIS system [10] [11] of the Remote Sensing Technology Institute of DLR. Starting from SLCs, for an input data stack, the Tomo-GENESIS system retrieves the following information: number of layovered scatterers inside each azimuth-range pixel, amplitude and phase, topography and motion parameters (e.g. linear deformation velocity and amplitude of thermal dilation induced seasonal motion) of each detected scatterer. The final elevation estimates of the four data stacks using the same reference point are shown in Fig. 5. The elevation is color-coded. Since the TomoSAR estimates are referred to the identical reference point whose absolute 3D position is known from the previous step, the resulting point clouds are automatically fused. In this manner, the resulting first absolute 3D TomoSAR point cloud fused from the four stacks in the ITRF 2008 reference frame is shown in Fig.6. The coverage of the test area is approximately 10km×5km and the number of the retrieved point scatterers is about 63 million.

4. LOCALIZATION ACCURACY ANALYSIS

To validate the absolute position accuracy of the resulting point clouds, a reference Digital Surface Model (DSM) is calculated from a point cloud obtained from aerial Laser scanning. Fig. 7 gives a zoom-in of a small area where the resulting point cloud (colored according to heights) is overplotted onto the LiDAR DSM (gray). Compared to this highly absolutely accurate LiDAR DSM, it is found that the positioning precision of the resulting point clouds obtained from the proposed approach is in the order of several deci meters for the horizontal components and a couple of meters for the vertical component. This is consistent with the relative elevation estimation accuracy of InSAR methods that are limited by the number of acquisitions available, signal to noise ratio and orbit spread [1].

5. CONCLUSION

In this paper, we proposed the "geodetic TomoSAR" framework that fuses SAR image geodesy and SAR tomography to obtain *absolute* 3D positions of a large amount of scatterers. The first absolute 3D TomoSAR point cloud with 63 million points covering an area of 10km×5km over the city of Berlin is presented. Compared to high precision LiDAR DEM, the absolute positioning accuracy of the proposed approach reaches a couple of meters. It demonstrates the applicability of the proposed approach. Future work concentrates on: 1) automatic identification of common scattering objects appearing in SAR images obtained from different geometries, e.g. by exploring the regular pattern attributed to building façades (for same heading orbits) or street lamps (for cross heading orbits); 2) investigation on absolute deformation estimates for large area, e.g., by cooperating GPS measurements.

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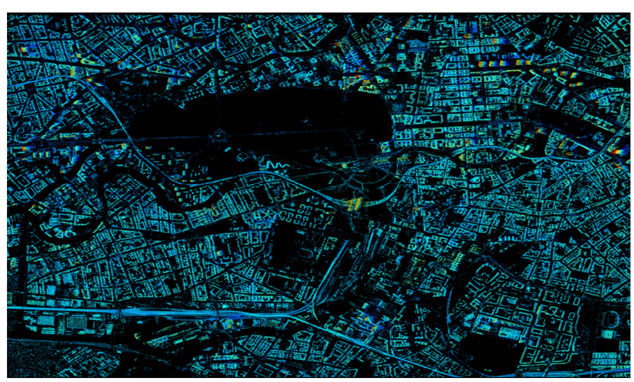
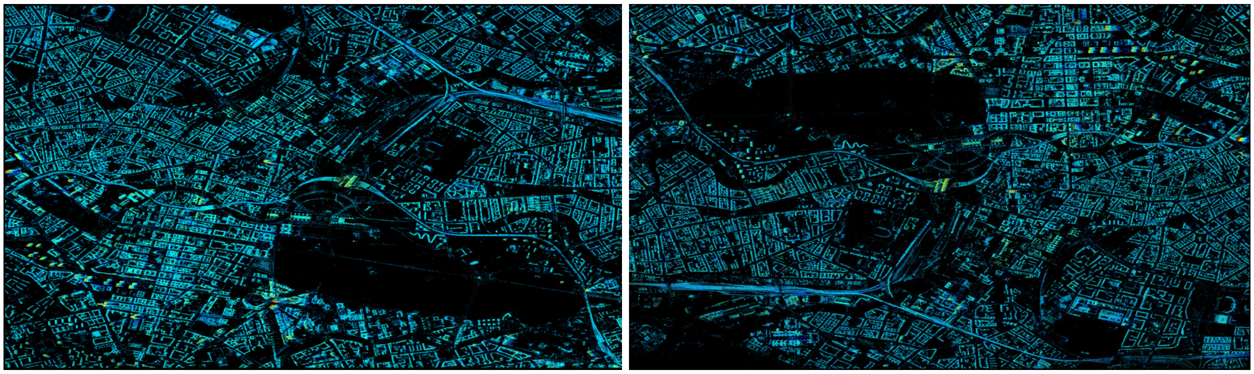
(a) beam 42, descending



(b) beam 57, ascending



(c) beam 99, descending (b) beam 85, ascending

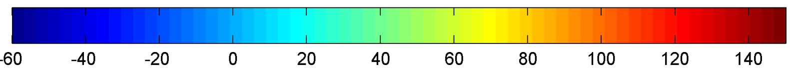


Fig. 5. TomoSAR results: elevation estimates of all stacks using the same reference point; elevation is color-coded.

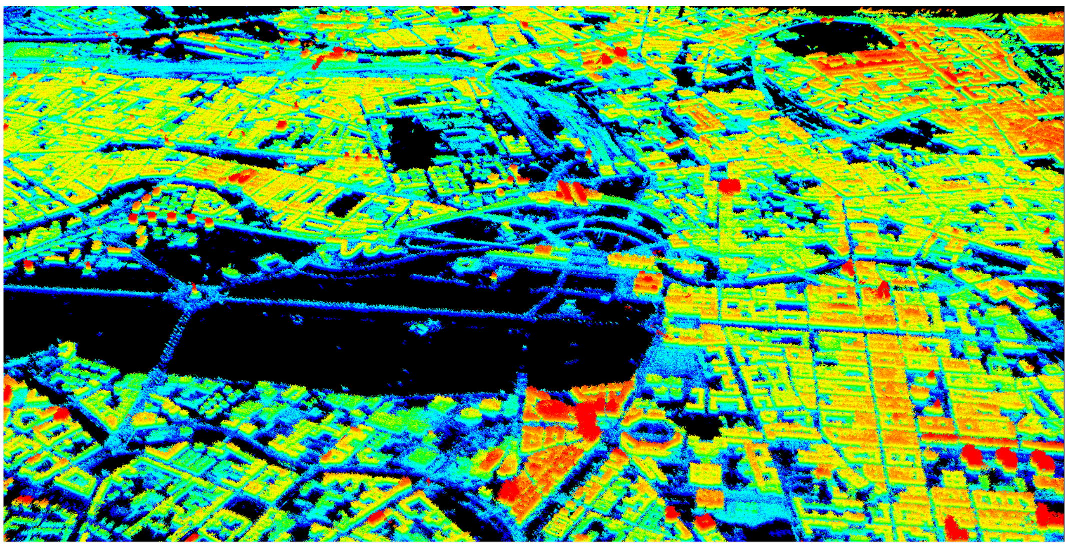


Fig. 6. Geodetically fused 3D absolute positioned TomoSAR point clouds in 3D.

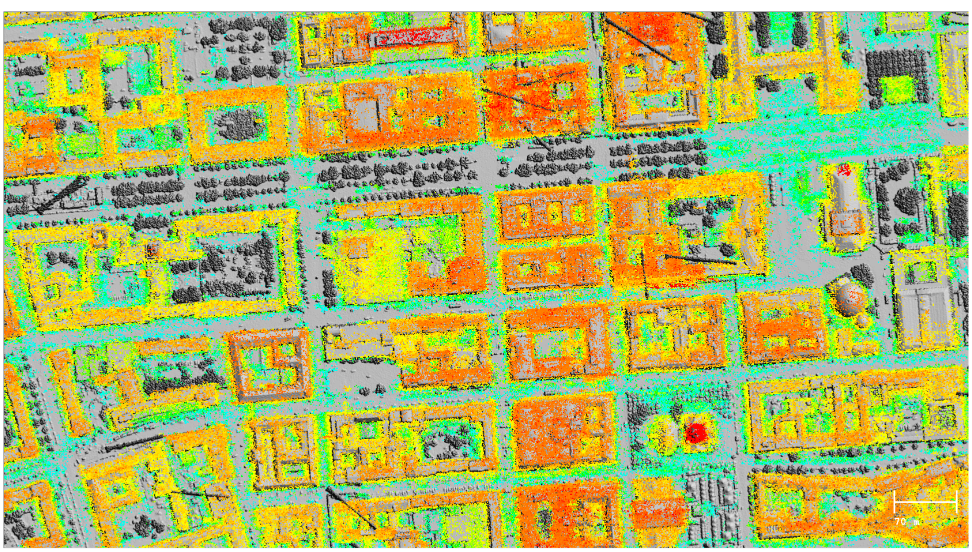


Fig. 7. TomoSAR point clouds vs. LiDAR DEM