Stereo-SAR Technique without Using Control Points to Estimate Terrain Height

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Abstract— Estimation of terrain profiles remains very interested in the applications of remote sensoring. In particular, the high-resolution images obtained by the Airborne or satellite-borne synthetic aperture radars (SARs) were effectively used in conjunction with the applications of stereo techniques to perform the estimation. Many simulation models were thus developed and applied in the stereo techniques to process the optical images to estimate terrain profiles such as the digital elevation model (DEM) and digital terrain model (DTM). Some typical examples of technologies revealed in the literatures are summarized in the following. The works in proposed a new hybrid radar grammetric model as a function of terrain's slope to establish the stereo DEM without the need of using any reference cartographic data. The accuracy was examined by using the topographic 1959 DEM, and Ice, Cloud, and land Elevation Satellite (ICESat) data. It was applied to ice-covered areas with 1-sigma 25- or 18-m accuracy over less than 30° or 5° slopes, respectively. In addition, a systematic elevation lowering of around 10 m computed between 1959 DEM and recent elevation data (R-2 and ICESat) could be due to icefield wastage over the last 50 years.

1. INTRODUCTION

Estimation of terrain profiles remains very interested in the applications of remote sensoring. In particular, the high-resolution images obtained by the Airborne or satellite-borne synthetic aperture radars (SARs) [1–3] were effectively used in conjunction with the applications of stereo techniques to perform the estimation. Many simulation models were thus developed and applied in the stereo techniques to process the optical images to estimate terrain profiles such as the digital elevation model (DEM) and digital terrain model (DTM). Some typical examples of technologies revealed in the literatures are summarized in the following. The works in [4] proposed a new hybrid radar grammetric model as a function of terrain's slope to establish the stereo DEM without the need of using any reference cartographic data. In [5, 6] stereo-techniques using a reference point to estimate the height difference relative to the reference point are developed. In particular, [5] employs a known profile as the reference to find the profile of desired terrain. The reference point is selected in the vicinity of the target point in an one-to-one correspondence. Instead, [6] starts with a single reference point. The target point most close to the reference point is first estimated. Afterward, this target point is used as a new reference point to estimate the next target point in a sequential order. A systematic bias [5] based on a conjecture of being proportional to the height difference between the target area and the reference area is developed to improve the accuracy. The estimated height error can be reduced to 1 m or less by correcting such bias if the target points are near the center row. The approach of using a single reference point dramatically simplifies the systematical structure at the cost of estimation accuracy.

The work presented in this paper is most related to [5, 6] by estimating the height difference between the target point and a reference point. The important progress achieved in this works is that the reference profile is established from the SAR range information of the desired terrain's profile under estimation instead of using the existing and known profiles. This approach simplifies the estimation procedure because the known profile of reference terrain may not be available at the time of processing. Beside the known profile of reference terrain might be also obtained from estimation, where the estimation errors exist in the profile. The use of such reference profile may accumulate errors in the subsequent estimation.

2. STEREO-SAR TECHNIQUE

2.1. Review of SAR Technique

The range-Doppler SAR algorithm [7, 8] used in this work is illustrated which is a two-stage processing procedure to process the range and azimuth compressions in a sequential order. According to the illustration, the received data, $s(t, \tau)$, obtained by SAR is first employed to conduct a range compression, where t and τ denote the receiving time and variables, respectively. In this procedure, the data is first transformed in the range domain by applying the fast Fourier transform (FFT) algorithm over the variable t, $\tilde{s}(\omega, \tau) = F_t\ [s(t, \tau)]$.

2.2. The Developed Processing Algorithm

The algorithm is developed based on the difference of range information obtained by two receivers of SAR satellites, which can be obtained from two different satellites flying in one pass or a single satellite flying in two passes along two different paths as illustrated in Fig. 1(a). Here the altitudes of the two different flight paths are assumed to be same and equal to h so that a trigonometric relationship can be established between the receivers, S_1 and S_2, on the two flight paths, and the target under estimation. This assumption will avoid the possibility of forming any collinear relationship between the three points, and assure the validity of algorithm. Here the coordinate system is therefore selected for S_1 and S_2 to be $(0, 0, h)$ and $(r_d, 0, h)$, respectively. Thus S_1 serves as a reference point of coordinates with the vector of $\overrightarrow{S_1S_2}$ pointing to $\hat{x}$, which makes the along-track separation is zero, and the across-track separation is r_d.

As mentioned in Section 1, the algorithm presented in this work builds up its own reference profile by using the same set of SAR data obtained from the target terrain profile. The scheme is illustrated by the geometrical illustration in Fig. 1(b), where a reference point, P_r, in the same range cell of the target, P_t, is selected. The reference is at a postspacing distance, Δx to P_t with a height z_r. Fig. 1(b) also shows four dummy circular circles, which are plotted with respect to the centers at the two satellites on S_1 and S_2. In particular, the radii of F_{1r} and F_{2r} are the distances, R_{1r} and R_{2r} measured from P_r while those of F_1 and F_2 are the distances R_1 and R_2 measured from P_t. To establish the reference, the range information, R_{1r} and R_{2r}, is considered. The processing algorithm is developed according to the differential information received between those at S_1 and S_2. The development starts with the expressions of R_{1r} and R_{2r} by

$$R_{1r} = \sqrt{x_r^2 + y_r^2 + (h - z_r)^2} \tag{1}$$

and

$$R_{2r} = \sqrt{(x_r - r_d)^2 + y_r^2 + (h - z_r)^2}, \tag{2}$$

respectively. Note that if one considers the strip profile in the vicinity of $y_r = 0$, where in practice x_r, $h \gg y_r$, (1) and (2) can be approximated as

$$R_{1r} \cong \sqrt{x_r^2 + + (h - z_r)^2} + \frac{1}{2} \frac{y_r^2}{\sqrt{x_r^2 + + (h - z_r)^2}} \tag{3}$$

and

$$R_{2r} \cong \sqrt{(x_r - r_d)^2 + (h - z_r)^2} + \frac{1}{2} \frac{y_r^2}{\sqrt{(x_r - r_d)^2 + (h - z_r)^2}}, \tag{4}$$

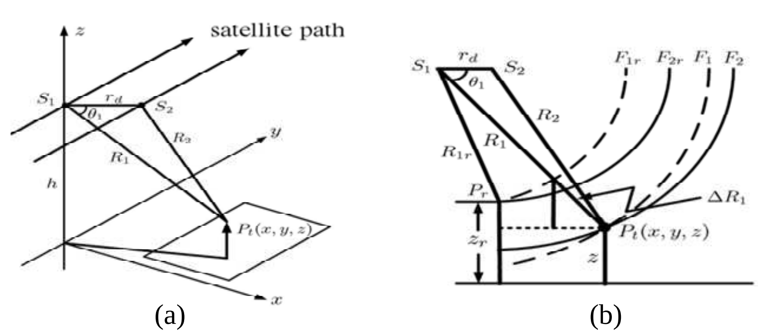


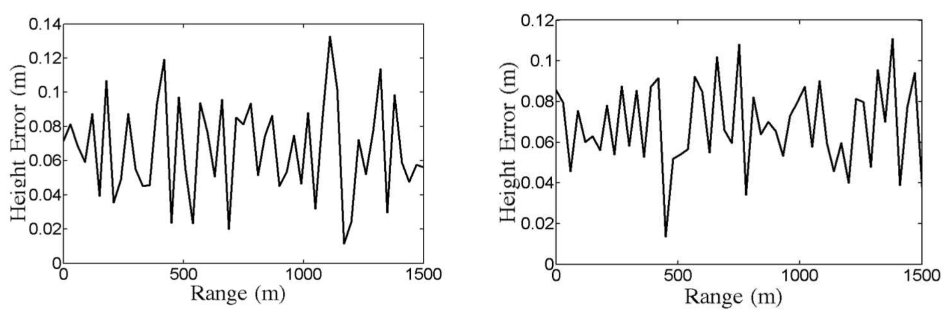
Figure 1: Configuration of dual satellite path and estimation of target height using the receiving data along two paths. (a) Configuration of dual satellite paths over a target area. (b) Estimation of θ_1 using R_1, R_2 and r_d.

2.3. Calibration of SAR Range Information Base Two Known Terrain Profiles

The range information obtained by SAR technique experiences the estimation errors, which will affect the estimation accuracy of terrain's profile when the information is used to evaluate the height of terain via any algorithm. It is assumed that the errors are solely caused by the SAR satellite's performance for simplification. Thus given a set of satellite's system parameters, the relative errors can be considered to be roughly the same regardless the terrain's profile under estimation. In this work, this relative error is first examined by using two known terrains' profiles, which will be used to correct the estimation errors and improve the accuracy.

3. NUMERICAL EXAMPLES

Examples are presented to demonstrate the utilization of this technique and validate the feasibility. The relevant parameters of the TerraSAR-X satellite [9], which is used in our simulations. The target area has a size of $1500 \times 150\,\mathrm{m}^2$ with the center located at $(x_c, y_c) = (350,\ 0)\,\mathrm{km}$. The altitude of satellite is 750 km. Thus the angular variation of any point in the target area, when it is observed from the satellite, is significantly small and can be ignored as having been assumed in Section 2. From the satellite, a total of 8192 pulses are emitted along the track, and the pulse repetition interval is chosen to be $\Delta\tau = 43.86\,\mu\mathrm{s}$, making an effective aperture length of $L = 8192V\Delta\tau = 2560\,\mathrm{m}$. The target area of the terrain is discretized into square cells of $\Delta x \times \Delta y$, where $\Delta x = 30\,\mathrm{m}$ and $\Delta y = 30\,\mathrm{m}$ are used to create 306 sample points. In this case, the range resolution of SAR is in the order of $\Delta R = c/2Bw \cong 2\,\mathrm{m}$ while the azimuth resolution is in the order of $\Delta R_a = \lambda R/(2L) \cong 5\,\mathrm{m}$. The three terrain profiles selected for the examinations are shown in Figs. 2(a), (b), which are the contoured maps and images of: (a) Mountain area, Highland Experimental Farm, National Taiwan University, Nantou County, Taiwan; (b) Batura Glacier, Batura Valley Passu, Gojal, Gilgit-Baltistan, Pakistan. These three regions experienced special influences by the global weather changes or were used to perform the related studies. In the simulation, six rows of height data at the sampled points are recorded, with each row containing 51 data points.



(a) (b)

Figure 2: Height error along the center row of the strip area in (a) Mountain area, Highland Experimental Farm, National Taiwan University, Nantou County, Taiwan, (b) Batura Glacier, Batura Valley Passu, Gojal, Gilgit-Baltistan, Pakistan.

4. CONCLUSIONS

A stereo-synthetic aperture radar (stereo-SAR) technique is proposed to reconstruct the height profile of terrains, requiring only one reference point. The technical parameters of TerraSAR-X satellite is chosen to simulate over three different types of terrain. The rms error of height estimation can be reduced to one meter, making this technique practical for certain applications.

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