Calibration of the Relative Heights Measurements of Radarclinometry into Absolute Heights

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Abstract: **3D heights or Digital Elevation Models (DEMs), among other spatial data, are currently one of the most important data used for geo-spatial analysis. In Synthetic Aperture Radar (SAR) remote sensing, DEMs are used to resample the SAR images to well known coordinate systems. The Radar clinometry technique deals with the recovery of shape of an object through a gradual variation of shading encoded in the image. Radar shape-from-shading (SFS) algorithm outputs relative heights, which are scaled to an arbitrary datum. This paper will focus on a new calibration model for transformation of relative SFS measurements into absolute surface heights. Ground truth data in term of ground Control Points (GCPs) are used to estimate the coefficients of the model. Results from the experiment have shown that the new calibration model has a significant effect on the overall accuracy of the final absolute heights. The new model was implemented using MATLAB programming language and applied to RADARSAT-1 image. The performance of the algorithm was tested visually and numerically. Experiments showed that the algorithm is more efficient and accurate as indicated by RMSE and R2 (17.49m and 0.972, respectively).**

Keywords - Clinometry, Calibration Modeling, 3D Extraction, SFS, SAR Imageries

INTRODUCTION

1.1 CLASSIC SFS

The first systematic study of SFS was reported by Horn (1975) and his colleagues (Liu 2003). SFS deals with the process of finding the object's 3D shape from a single image of that object. The use of a single image cannot always ensure the uniqueness of the shape of an object. Therefore, there will be relatively little effect devoted to exploiting the exact 3D shape reconstruction from the shading information of one image (Ming et al. 2004). This problem is resolved by introducing ancillary information to the SFS process. The basic assumption underlying SFS is a uniform surface reflectivity (Lambert). Several studies investigating Lambertian reflectance model have been carried out on SFS (Kimmel and Bruckstein 1992, Wilson and Hancock 1999, and Prados and Faugeras 2005).

From a computational viewpoint, SFS involves solving the image irradiance equation to recover a set of surface normals or surface slopes (Worthington 1999). Horn (1975) was the first researcher, who had formulated SFS problem and found the solution as a nonlinear first-order partial differential equation (PDF). This equation is known as the image irradiance equation and is the basic equation for any SFS technique. It relates the image irradiance to the scene radiance as shown in Equation 1 below:

$$E(x,y) = R(\hat{n}(x,y)) \tag{1}$$

Where $E(x,y)$ is the image irradiance at a point (x,y), R is the reflectivity, and $\hat{n}$ represents the three components of unit surface normal.

The recovered surface can be expressed in four types (Durou 2008); surface height (elevation) $z(x,y)$, surface normal (n_x, n_y, n_z), surface slope (p,q), and surface slant Φ and tilt ϴ. The depth can be considered either as the relative distance from the camera or antenna to the surface points, or the relative surface height above the xy plane. This implies that "(1)," can also be written as follows:

$$E(x,y) = R(p,q) \tag{2}$$

where $(p,q) = (dz/dx , dz/dy)$

1.2 Radarclinometry

Extraction of DEM from a pair of SAR images is well known. Due to some decorrelations (temporal or spatial) between images, the elevations estimated by these methods sometimes defer from the real. Toutin and Graey (2000) have grouped these methods or techniques for extracting relative or absolute elevations from radar images to four methods; Stereoscopy, Shape from shading (Radarclinometry), Interferometry, and Polarimetry. Each method has its advantages and disadvantages.

Although there are well-developed methods for recovering surface heights from more than one radar images, there has been limited attention paid to the extraction of terrain topography from one image. Guindon (1990) proposed an algorithm to recover elevation heights by generating independent elevation profiles for each image range line. It has been concluded that image radiometry is a strong indicator of the range component of terrain slope. Bors et al. (2000a and 2000b) derived a maximum log-likelihood and a maximum likelihood feature detector from the image statistics. The detected topographic features with a DEM corresponding to the images have been used to derive empirical model for the recovery of surface normals. Later, Bors et al. (2003) have derived Lambertian corrections so that a conventional shape from shading algorithm can be applied to SAR images. In order to avoid the impossibility of the classic assumptions of shape from shading, Hégarat-Mascle et al. (2005) replaced the traditional Lambertian model with a backscattering diagram provided by the integral equation model (IEM). Ghayourmanesh and Zahng (2008) adapted Pentland's (1990) linear shape from shading technique for SAR imagery by applying Taylor expansion, to obtain a linear estimation of the reflectance function. The major objection to radar SFS is the ambiguity from uncertain backscatter properties. Involving some constraints can remove or reduce this ambiguity. In iterative minimization radar SFS technique, the output is relative heights. In most applications these relative heights need to scale to a specific vertical datum.

2. METHODOLOGY

The study area is the Kassala state in the east of Sudan. The area is comprised of water body, mountain, vegetations, and man-made buildings and roads. Therefore, the surface topography and reflectivity materials of the area are relatively complex. The data sets for this study consist of subset of RADARSAT-1 imagery and different sets of Ground Control Points (GCPs). The subset of RADARSAT-1 imagery, depicted in Figure 1 is Standard 7 (S7) mode. The area of the subset was approximately 10 km^2. The purpose of choosing this subset was that it contained sufficient features to analyze and evaluate the performance of the algorithm. These features include building, vegetation, water body and mountain as mentioned above. Thus, they provided a complex surface presentation, having a wide range between minimum and maximum surface elevations. It is interesting to note that the highest height values of mountain are located in the center of the figure. The real height values of minimum and maximum are found to equal 400m and 1040m, respectively.

The relative SFS surface heights were computed using iterative minimization SFS algorithm that involve radar reflectance model proposed by Mobarak et al. (2010) below.

$$R = \rho \frac{(\cos(\alpha_i))A^2}{(1-(\cos^2(\alpha_i))A^2)^{\frac{3}{2}}} \tag{3}$$

where, α_i is the incidence angle; ρ is the average radar backscatter; and A is the illuminated area.

The output from radar SFS model is the relative heights. They are measured relative to the first pixel of the radar subset image, located in the extreme upper-left corner. Due to the normalization of the reflectance model and the observed image intensity in the Fourier domain, the average heights of some parts of surface terrain could not be recovered. Also the relative SFS measurements are scaled arbitrarily. Therefore, they are needed to relate to a specific vertical datum to provide significant results. To get such results, the relative height measurements from SFS were calibrated into absolute surface heights using the new model represented by "(5),". GCPs were involved to estimate the coefficients of the new model. It is interesting to note that this model is a further development of Liu's (2003) calibration model "(4)," which it was used originally for calibration of relative SFS measurements from optical images. Radar backscatter σ° and brightness β° were added (after applying speckle filtering to them) to the old model as new parameters.

$$H = A + Bx + Cy + Dz \tag{4}$$

$$H = A + Bx + Cy + Dz + E\sigma^\circ + F\beta^\circ \tag{5}$$

Where,

H is the calibrated absolute height values; A, B, C, D, E, & F are the model coefficients; x and y are the horizontal coordinates; z is the relative SFS height; σ° is the radar backscatter coefficient; and β° is the radar brightness.

"Equation (5)" contains six parameters to be fitted. Consequently, more than six GCPs are required to establish least-squares solution for the unknowns. In this work, the MATLAB backslash operator (**mldivide**) was used to solve a system of simultaneous linear equations for unknown coefficients. The advantage of this MATLAB function is its usage of stable numerical algorithm to avoid unacceptable rounding errors. The reconstructed absolute heights were evaluated graphically by analyzing the contour plot of them. Regression analysis between the real and the estimated absolute heights was also performed to assess the accuracy of the final absolute heights numerically.

3. RESULTS AND DISCUSSIONS

3.1 Results

The calibration model represented by Equation 4 was first used to transform radar SFS height measurements into absolute heights. This model works well under the assumption that the image formation is dominated by the surface normal orientation. In radar imagery, the formation of the image is affected by many factors, including the surface normal orientation. Therefore, to achieve better results, "(5)," was applied to calibrate the relative radar SFS measurements into absolute heights. The coefficients of the parameters of the new model *A, B, C, D, E,* and *F* were found to be: 131263.65, -0.0387, -0.0720, -1.2260, -1.7580, and -6.5955, respectively. The procedure employed to examine the new model was to compare between the heights estimated from the two calibration models and that of real one.

Figures 2 and 3 show images of the absolute height values, obtained from the new and old calibration model, respectively. Upon detail analysis, the figures give multiple findings. First, the location of the peak of the mountain is somewhat near the center with average value of 1040m as mentioned previously. The average height value of this particular location is approximately 1009m and 750m in Figures 2 and 3, respectively. The finding of Figure 2 is in agreement with that finding reported for Figure 1 which located the peak of mountain in the center of the figure.

What is clearly unexpected is that the highest height value in Figure 3 is located in the lower-left corner marked with a black ellipse shape. Secondly, the shape variation among surface topography types changes very smoothly in the same figure. The slope of the terrain starts almost from the centre of the figure, distributing out in all directions systematically. In other words, the overall shape of the surface heights appears over-smoothened, meaning losing surface details.

The next important finding is that removing the Beta parameter in the calibration model has led to decrease in the maximum absolute height from 1009m to 970m and increase in the minimum from 393m to 424m. In comparison, removing the Sigma parameter in the model has resulted in decrease of the maximum absolute height to 954m and increase of the minimum to 402m. Thus, removing Beta and Sigma parameters separately from the calibration model has affected the results slightly. The corresponding images depicting the results of these separate removals are presented in Figures 4 and 5. It is clear from the comparison of these two figures that the absolute height was more affected by the removal of the beta parameter rather than sigma.

Validation of the calibration model was done numerically through the computations of both RMSE and R^2 between the real and the respective calibrated heights derived from the calibration model without Beta, without Sigma, without Beta and Sigma, and with Beta and Sigma. As shown in Table 1 the respective RMSE values are 24.86m, 22.52m, 24.93m, and 17.47m and R^2 values are 0.948, 0.953, 0.751, and 0.972. It is clear that removing of Beta or Sigma parameters separately has an insignificant effect on the final absolute height reconstructions. The most interesting finding numerically is that there is a significant difference between the old and the new calibration models. Figure 6 illustrates the differences between the new and old calibration models graphically, showing considerable differences in heights between them.

3.2 Discussions

The impact of the new calibration model on the absolute SFS surface height estimates was investigated as mentioned in the previous section. The results showed that the new parameters, Beta and Sigma, were found to improve the accuracy of the final absolute heights. This is obvious from observations made in Figures 2, 3, 4 and 5 and computed values of RMSE and R^2 listed in Table 1. These positive results could be due to the fact that both parameters represent the average reflectivity of a horizontal material. However, they are affected by the surface topography.

Another important finding is that the effect of removing of Beta or Sigma separately was proven insignificant. A possible explanation for this could be attributed to the closeness in behavior of both parameters. This is clear from the fact that the only difference between the two parameters is at the place of normalization of the radar reflectivity. Strictly speaking, normalization of Sigma is in the ground range, while Beta is normalized in the slant range (local surface topography and the Geoid for Beta and Sigma, respectively). Strong evidence of the difference between the two models was found, when removing both Beta and Sigma at the same time.

4. CONCLUSION

In this paper, a new calibration model was developed to transform the relative radar SFS measurements into absolute heights. Interesting findings were revealed, when the new calibration model (for SAR) was replaced by the old one (for optical). A considerable difference on qualitative accuracy of the absolute heights between the two models was revealed. Statistically, the accuracy of the new model was higher than that of the old one, as indicated by the RMSE and R^2 of 17.47m and 0.972 and 24.93m and 0.751 for the new and the old model, respectively.

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Table 1: Validation of the Calibration Model

Calibration Model	Without Beta	Without Sigma	Without Beta and Sigma (Liu 2003)	With Beta and Sigma (Proposed)
RMSE (m)	24.86	22.52	24.93	17.47
R^2	0.948	0.953	0.751	0.972

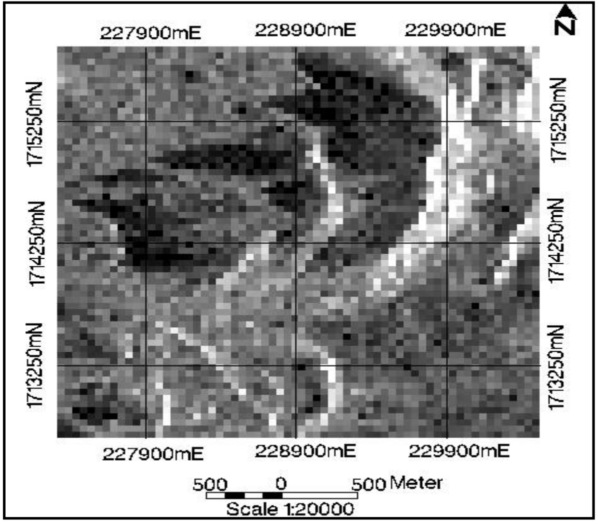

Figure 1: Subset from RADARSAT-1 S7 Mode Image

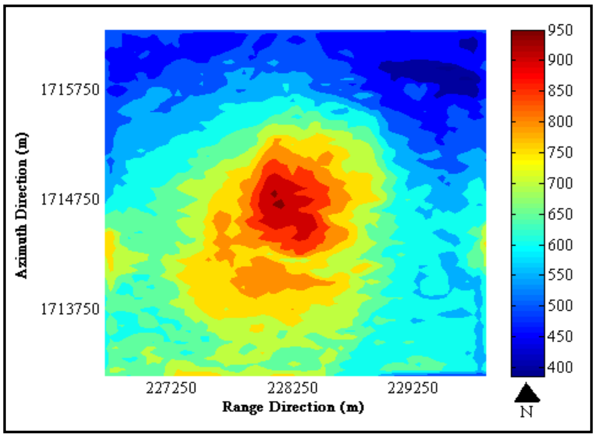

Figure 2: Absolute Heights Reconstructions Using the New Calibration Model

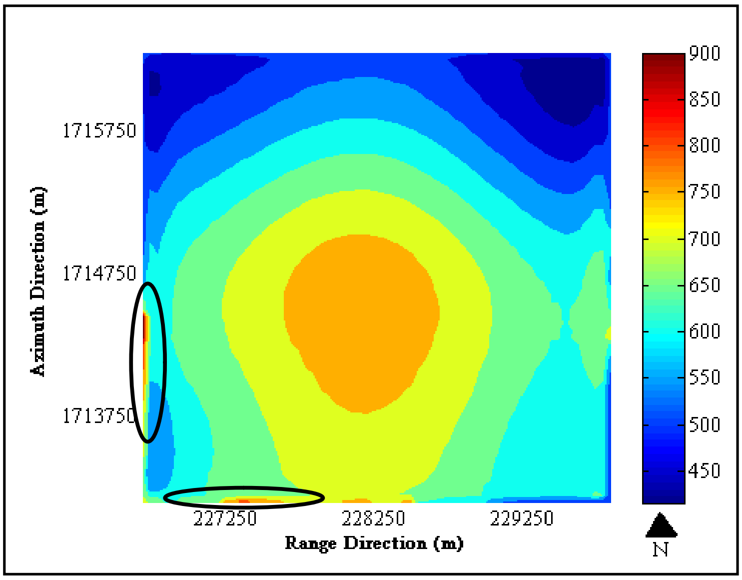

Figure 3: Absolute Height Reconstructed Using the Old Calibration Model

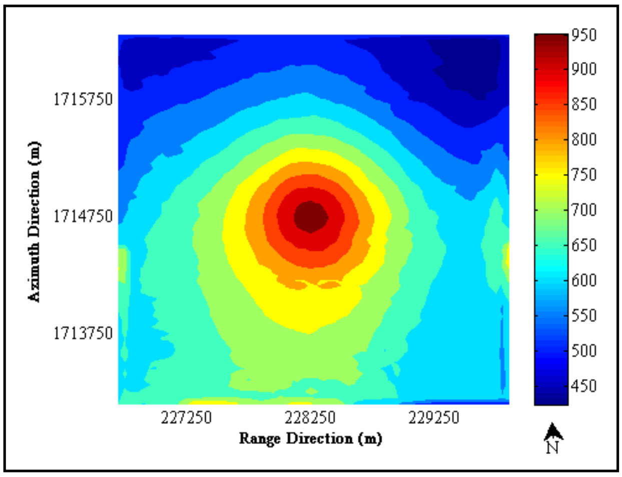

Figure 4: The Effect of Beta Removal in the Final Absolute Heights

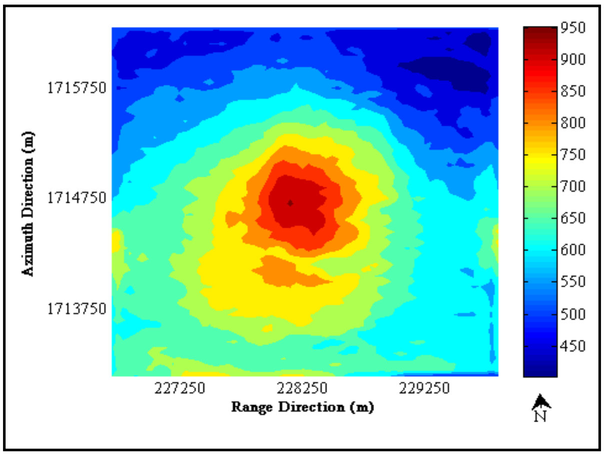

Figure 5: The Effect of Sigma Removal in the Final Absolute Heights

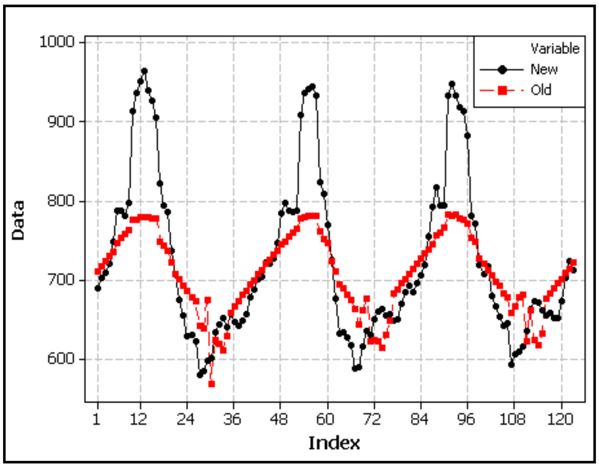

Figure 6: Height Differences between Liu's 2003 (Old) and the Proposed Calibration Models