3D GEOMETRIC MODELING OF RADARSAT-2 ULTRA-FINE MODE USING DIFFERENTIAL GPS DATA

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ABSTRACT

The geometry and the accuracy of the three-dimensional (3-D) cartographic localization of RADARSAT-2 images are being evaluated as part of the Canadian Space Agency’s Science and Operational Applications Research program. In a first step, the Toutin’s 3-D physical model, previously developed for Radarsat-1, was adapted to Radarsat-2 sensor and applied to two ultra-fine mode images (U2 and U25) acquired over a hilly area in Beauport, Quebec. Both the 3-D modeling computed with only 8 ground control points and its geometric localization were evaluated with different check data: (1) independent check points; (2) the two quasi-epipolar images; (3) the two ortho-images; and (4) 1-m accurate ortho-photos. All four results and validations are in agreement and confirm that the 3-D geometric localization and restitution accuracy is better than 1.5 m in planimetry and elevation. In addition the relative error computed from the comparison of the quasi-epipolar images provided a high level of confidence that the precision of Toutin’s 3-D radargrammetric model is better than 0.25 m.

I. INTRODUCTION

This paper will investigate the adaptation of Toutin’s 3-D radargrammetric model, previously developed at the Canada Centre for Remote Sensing for Radarsat-1 single, stereo or block images [1]-[3] and its application to high-resolution Radarsat-2 modes. The paper will then addresses the processing of an ultra-fine mode (3-m resolution) stereo-pair and validate: (a) the precision of the modeling computed with ground control points (GCPs); (b) the accuracy of the two-dimensional (2-D) positioning accuracy of the ortho-images; (c) the accuracy of the 3-D positioning of extracted points.

II. STUDY SITE AND DATA SET

The study site, north of Québec City, Québec, Canada spans different environments: urban and residential, semi-rural and forested (Fig. 1). The elevation ranges almost from sea level at the southeast, to more than 600 m in the Canadian Shield, located to the north. The northern and western parts are mainly covered by forests (deciduous, conifer and mixed) with a hilly to mountainous topography while the south-east part is urban and residential areas with a semi-flat topography.

Figure 1. Radarsat-2 SAR C-HH ultra-fine mode image (U2; 3.3 × 3 m resolution; 30.8°-32° east look angle; 20 km × 20 km; 1.56 × 1.56-m pixel spacing; SGF format; ground range presentation) acquired June 30 2008 displays the study site. Beauport city is in the southeast. "RADARSAT-2 Data © MacDONALD, DETTWILER AND ASSOCIATES LTD. (2008) – All Rights Reserved” and Courtesy of Canadian Space Agency.

The Radarsat-2 data set includes two images U2 (Fig. 1) and U25 (20 by 20 km) acquired with the C-band ultra-fine mode (about 3 by 3 m ground resolution) in HH polarization from descending orbits. U2 and U25 were acquired June 30 and July 04 2008 with view angles of 30.8°-32° and 47.5°-48.3° at the near-far edges, respectively. The images were processed as SGF product (1 by 1 look; 1.56-m pixel spacing), ground range presentation (ellipsoid projection without relief correction), orbit oriented, coded in 16 bits without any radiometric processing. The ephemerides were also provided.

Ground control points GCPs input data were collected from a differential Global Positioning System (GPS) survey with accuracy of 10-20 cm. GCPs are mainly road intersections and electrical poles. The topographic data, obtained from the Ministère des Ressources naturelles du Québec, Canada were a digital elevation
model (DEM) generated from the 5-m contour lines digitized from 1:20,000 scale maps. The DEM was used in the ortho-rectification of the U2 and U25 images.

III. EXPERIMENT

A. Toutin’s radargrammetric model

Since the Toutin’s 3-D radargrammetric model was already well described in [1]-[2], only the bases are summarized. It was developed as an integrated and unified geometric modeling to geometrically process SAR images [1] and recently adapted to Radarsat-2 data. This sub-metre accuracy model has been operationally applied with few (3-6) GCPs over various landscapes and topographic relief to most of the satellite radar data and medium/high-resolution optical data.

B. Processing steps

Before the statistical evaluation of the model and 2-D/3-D positioning accuracy, there are three processing steps:

1. Acquisition and preprocessing of images and their metadata to determine orbit osculatory parameters and approximate values for each parameter of the Toutin’s 3-D radargrammetric model(s);

2. Collection of ground points with 2-D images coordinates and 3-D cartographic coordinates. The ground points (mainly roads intersection and other accurate and well-defined features such as electrical poles) were collected from differential GPS and distributed over the full study site to avoid extrapolation in planimetry and in elevation: 89 and 113 ground points for U2 and U25, respectively. The image pointing accuracy was about 1 pixel, and the cartographic coordinates was 10-20 cm accuracy.

3. Computation of Toutin’s model(s), initialized with the approximate values and refined by an iterative least-squares adjustment with GCPs and orbital constraints. The equations are used as observation equations and weighted as a function of input errors (both ground point coordinates and image point coordinates). On the other hand, the orbital constraint equations are weighted as a function of the orbit knowledge and accuracy. The images can be computed independently or simultaneously as a stereo-pair.

C. Validation

Different validations can be performed to evaluate Toutin’s radargrammetric modeling for Radarsat-2 data. The first validation tests were performed on the computation of the model with 8 GCPs and the remaining points as independent check points (ICPs). The adjustment was performed for U2 and U25, independently (monoscopic) and simultaneously (stereoscopic).

The second validation compared the quasi-epipolar images generated from U2 and U25 using the radargrammetric model. These quasi-epipolar images are resampled into a geometry where all systematic geometric distortions (orbit and sensor related, Earth curvature) were corrected but not the elevation distortions. Consequently, there is no parallax in the line direction between the two quasi-epipolar images but only the parallax related to the elevation remained in the column direction. The relative comparisons of quasi-epipolar images can then be used for evaluating the performance and the precision of the radargrammetric model. The third validation compared the two ortho-images generated from U2 and U25 using the 3-D radargrammetric model and the topographic DEM. The last validation compared the ortho-images with the ortho-photos.

IV. RESULTS

A. Validation with GCPs/ICPs

The use of overabundant GCPs (six is the theoretical minimum for SAR images) in the least-squares bundle adjustment reduced or even cancelled the propagation of input data errors (image pointing and map) into the 3-D Toutin’s radargrammetric model; conversely these input errors are reflected in the residuals [1]-[3]. It is thus normal and “safe” with 3-D physical models, such as the Toutin’s 3-D radargrammetric model, to obtain GCP residuals converging to the same order of magnitude as the GCP errors when overestimation is used with many GCPs: the radargrammetric models are thus more accurate than the RMS residuals because the input error did not propagate into the radargrammetric model.

In operational environments, many GCPs were never used. Consequently, the radargrammetric models where computed using only 8 GCPs, which spanned the full ranges of landscapes and terrain (including low and high elevations), such as the ICPs. Table I summarizes the final results of the model computation. With the RMS Max. errors (in metres) computed over ICPs. ICPs, being not used in the 3D stereo model calculation, enabled an unbiased validation of the model accuracy to be performed. The two monoscopic tests and the stereoscopic test (Table I) gave coherent RMS errors (better than 1.5 m in X, Y and Z axes). The 1.5-m RMS errors were good when compared to 3-m SAR resolution and with a same-side stereo-pair [2]. RMS errors were generally in the same order of magnitude as the input data error, mainly the image pointing or feature extraction error (1 pixel). The precision of the mono/stereo models was thus better, less than 1 m. The
Max. errors were also less than three times the RMS errors, showing coherency, robustness and stability without generating local errors over the full images and the stereo-pair. However, a small bias (1 m in X and Y) was computed. In conclusion these adjustment tests overall results (better than 1.5 m) for monoscopic or stereoscopic adjustments not only demonstrate the applicability of the Toutin’s 2-D and 3-D radargrammetric model to Radarsat-2 ultra-fine mode data, but also show a good stability and robustness without systematic and random errors regardless of the beam (e.g. look angle).

Table 1: Number of GCPs/ICPs and their RMS errors (in meters) computed on ICPs from bundle adjustments of the two images processed independently (monoscopic) or simultaneously (stereoscopic).

<table>
<thead>
<tr>
<th>Test</th>
<th>GCP</th>
<th>ICP</th>
<th>ICPs RMS Errors (m) X, Y, Z</th>
<th>Absolute ICPs Max. Errors (m) X, Y, Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>U2</td>
<td>8</td>
<td>81</td>
<td>1.5, 1.4, NA</td>
<td>3.9, 3.4, NA</td>
</tr>
<tr>
<td>U25</td>
<td>8</td>
<td>70</td>
<td>1.4, 1.3, NA</td>
<td>4.2, 3.2, NA</td>
</tr>
<tr>
<td>U2 &amp; U25</td>
<td>8</td>
<td>81</td>
<td>1.3, 1.2, 1.6</td>
<td>3.2, 2.4, 3.4</td>
</tr>
</tbody>
</table>

B. Validation with quasi-epipolar images

The U2/U25 quasi-epipolar images (1.5-m spacing), represented as anaglyph (Fig. 2: U25 in red and U2 in blue), were reprojected using Toutin’s radargrammetric model previously computed. The quasi-epipolar reprojection canceled the registration error or parallax in the Y-direction (all systematic distortions corrected), while the elevation parallax in the X-direction remained (the higher is the elevation the larger is the X-parallax). The anaglyph can thus be viewed in stereo with red/blue glasses for 3-D feature extraction, for automatic DEM extraction and for precision evaluation of the radargrammetric model: the more accurate was the 3-D computed radargrammetric model, the less is the Y-parallax and the better is the stereo-viewing. The red bleedings noticeable in the column direction corresponded to the elevation parallaxes between U2 and U25, as mentioned previously. There was, however, no bleeding in the line direction, corresponding thus to an accurate quasi-epipolar stereo reprojection and consequently to an accurately-computed 3-D radargrammetric model. Using red/blue glasses, Fig. 2 gives a precise stereo viewing with sharp features and edges due to an accurate correction of the systematic geometric distortions. The water bodies appeared black in stereo without bleeding and their shorelines were also very sharp in 3-D.

Fig. 3 is an anaglyph sub-image of the quasi-epipolar images oversampled with 0.5 m spacing, which shows bright and well-defined backscatter of an electrical pole. Because there was less than half-line Y-parallax, as can be noticed when comparing/aligning the two bright red (U25) and blue (U2) backscatters of the electrical pole, it demonstrated an error less than 0.25 m in the correction of the systematic geometric distortions, and thus a precision of the Toutin’s 3-D radargrammetric model better than 0.25 m. This evaluation was performed on other poles spread over the full stereo-pair.

Figure 2. Red-blue anaglyph image (13 700 x 13 200 pixels; 1.5 m spacing) color coded with U25 (red) and U2 (blue) quasi-epipolar images, which have been reprojected using Toutin’s 3D radargrammetric model. The bleedings correspond to the elevation parallax and this anaglyph can thus be viewed in stereo with red/blue glasses. "RADARSAT-2 Products © MacDONALD, DETTWILER AND ASSOCIATES LTD. (2008) – All Rights Reserved"

Figure 3. Sub-image (220 x 80 pixels; 0.5 m spacing) of the anaglyph, which showed bright and well-defined backscatter of an electrical pole. No Y-parallax indicates an accurate correction of the systematic geometric distortions. "RADARSAT-2 Products © MacDONALD, DETTWILER AND ASSOCIATES LTD. (2008) – All Rights Reserved"
Fig. 4 shows U2 quasi-epipolar sub-image overlaid with 1:50,000 contour lines and water layer. The good superposition demonstrates the quality and accuracy of the radargrammetric model since no shift is apparent between the image and the vector data.

Figure 4. Sub-image (2000 x 1500 pixels; 1.5 m spacing) of the U2 quasi-epipolar images overlaid with 1:50,000 contour line (white) and water layer (blue). "RADARSAT-2 Products © MacDONALD, DETTWILER AND ASSOCIATES LTD. (2008) – All Rights Reserved"

C. Validation with the two ortho-images

The U2 and U25 ortho-images (1-m spacing) were corrected from all geometric distortions including the relief, and the quality of their overlay defines the accuracy of the Toutin’s 3-D radargrammetric model.

Fig. 5 displayed two sub-images with 1-m spacing extracted from the south-east part (Beauport City) and from the north-east part (mountains) of a color-composite with U2/U25 ortho-images. Regardless the area and its topography (flat terrain in the city or forested areas in mountains), the registration is good with less than 1-pixel error. The lakes and roads appeared black and sharp as well as the golf course in the bottom sub-image, and there is no blurring or bleeding due to the geometry. The only color variations, such as the cardinal effects affecting the top sub-image, were due to the different scattering mechanisms (houses, electrical poles along streets, trees, etc.) with different look and azimuth angles. Consequently, the registration of the two ortho-images is better than one pixel (1 m).

Figure 5. Sub-images (3000 x 3000 pixels; 1-m spacing) extracted from the south-east part (top) and north-centre part (bottom) of the color-composite of the U2/U25 ortho-images. "RADARSAT-2 Products © MacDONALD, DETTWILER AND ASSOCIATES LTD. (2008) – All Rights Reserved"

D. Validation with the ortho-photo

The ortho-photo and the corresponding part of the U25 ortho-image (Fig. 6 top) have been color-coded in blue/green and red, respectively (Fig. 6 bottom). The U25 ortho-image was pre-processed to enhance the roads before the superposition for facilitating the registration evaluation. Better than one pixel (1 m) was noticed for the registration. This registration error included the error of the ortho-photo.
V CONCLUSIONS

Toutin’s 3-D radargrammetric model was adapted to Radarsat-2 and tested on two ultra-fine mode images, U2 and U25 acquired over a hilly relief study site north of Quebec City. Using GCPs, the models were computed with an iterative least-squares adjustment for the images separately and simultaneously. All these adjustment tests demonstrated the applicability, stability and robustness of Toutin’s 3-D radargrammetric model to Radarsat-2 and gave consistent results: better than 1.5 m in the three axes. Three other validations were performed using (1) the quasi-epipolar images in anaglyph stereo-viewing; (2) the ortho-images comparison and registration; and (3) the comparison and registration of the U25 ortho-image with an ortho-photo. All validations, in combination with previous SAR experiments [1] - [3], gave a high level of confidence that:

1. The precision of Toutin’s 3-D radargrammetric model was better than 0.25 m
2. The 2-D and 3-D restitution accuracy was better than 1.5 m; and
3. The 3-D radargrammetric model and method will be applicable to other Radarsat-2 data acquired over different landscapes and relief.

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REFERENCES