Application of the RPC model for spaceborne SAR image geometric processing

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An increasing number of low, medium, and high resolution SAR satellites creates a demand for a generalized sensor model to replace the rigorous sensor model (RSM). The rational polynomial coefficient (RPC) model is a generic sensor model which accurately fits the object-image geometry for various sensor systems with different coefficient values. It has been widely used as an alternative to RSM for photogrammetric processing of optical images, but its applications to SAR images are rarely discussed in publications. In this paper, the feasibility and practicability of the RPC model for SAR images are studied. The RPC model can not only be used to replace the RSM (range-Doppler model for SAR), but also applied to the processing chain for SAR data, thus facilitating the processing of SAR and InSAR data for end users.

Keywords: RPC model; spaceborne SAR; orientation; orthorectification

1. Introduction

Sensor orientation modeling is required to determine the functional relationship between the satellite image space and 3D object space. It is a prerequisite for the geopositioning of satellite images, stereo reconstruction, and orthorectification. Sensor models are typically categorized into two types, namely, the rigorous sensor model (RSM) and generalized models (1). Being able to accurately represent the imaging geometry of object-to-image mapping, the RSM has been regarded as the most precise way for geometric processing of satellite images. As one of the most conventional methods of SAR image rectification, the range–Doppler (RD) model has become the standard positioning model for launched spaceborne SAR, as primarily indicated by Curlander and McDonough (2).

Based on the collinearity condition, the RSM is rigorous and normally capable of yielding high modeling accuracy. However, the RD model involves many mathematical calculations and high time costs as both the forward and inverse transformation of the RD model are an iteration process. Additionally, since different SAR systems exhibiting different engineering designs require various mathematical descriptions, the RD model has to vary all along because it is dependent on sensors and platforms. Meanwhile, with the increasing number of low, medium, and high resolution SAR satellites successfully launched one after another – such as ALOS, COSMO-SkyMed, TerraSAR-X, and Radarsat-2 – the uniqueness and complexity of each sensor model poses a real challenge to the implementation of the RD model. Therefore, naturally, a generalized sensor model independent of sensors and platforms is needed and should be adopted for simplification and generalization.

The rational polynomial coefficient (RPC) model is a generalized sensor model that is used as an alternative for the RSM. The RPC model relates object space coordinates in any system to image space coordinates through the geometrical relationship between the two systems. The model uses a pair of ratios from two cubic functions to approximate the collinearity condition equations that are based on the full employment of the auxiliary parameters of the satellite images. Over the past decade, the RPC model has been widely recognized as a replacement for RSM and thoroughly applied in high-resolution optical imagery, while few publications have discussed the application of the RPC model to SAR image processing (3). Similarly, the RPC adjustment model has been generally employed for optical stereo block adjustment since the early twenty-first century, but seems to be rare in the case of SAR images. A RPC-based model extended for RPC adjustment was first formulated by Fraser et al. (4) in 2002 corresponding to the least squares adjustment with the RSM. Ever since Radarsat-2 provided the coefficients of the RPC model in its image production, the usage of RPC model has spread to SAR images. A comprehensive evaluation of the use of the RPC model for SAR imagery’s RSM has been presented by Zhang et al. (5) in 2010. Their experi-
ments demonstrated that the RPC model can achieve high fitting accuracy for SAR images.

Based on the earlier investigations into the RSM model and the need for a replacement of the RPC model for RSM in photogrammetric processing of SAR images, this paper aims to present a comprehensive study of the RPC model, including its generation and applications to geometric processing corresponding to the RSM model. To begin with, we will provide a brief background on the RD model and RPC model as well as the substitutability analysis between them. In order to remove the orientation biases inherent in the RPC model that give rise to the geo-positioning errors, a bias-corrected model is subsequently derived. A review of applications involving stereo orientation, and orthorectification performed with this approach are described. These results of this work are quoted to verify the feasibility and reliability of this model. Finally, a summary and an outlook of the RPC model for SAR imagery’s further development are presented.

2. Sensor orientation models

2.1. RD model

The RD model accurately delineates object coordinates to image coordinates with respect to the geometry of a SAR image. The location of a point on the Earth’s surface in a digital image can be determined by solving the Doppler equation governing the image product’s geometry. The condition being that the radar timing annotations, including the time of first range sample, range sampling rate etc. as well as the state vectors describing the satellite’s trajectory are given during the time of data acquisition. In other words, it means searching for the azimuth time where the satellite’s position corresponds to the zero Doppler value (6).

With its specific advantages, RD model has become the mainstream solution for orthorectification and stereo orientation of spaceborne SAR images. Aimed at a cartographic accuracy standard, a weighted least-squares method enables a robust RD model for intersection of spaceborne SAR imagery (7). Likewise, the RD model has been widely applied to orthorectification (8, 9) in mainly two ways. One way is to optimize the RD model by selecting ground control points (GCPs) on a SAR image, relevant topographic maps, and DOM to complete rectification. However, in mountainous areas where DEMs are difficult to fix, a simulated image will be first generated by RD parameters and the corresponding DEM, then rectification is achieved by matching the real SAR image and simulate image, establishing the ground-to-image relationship for the real SAR data.

2.2. RPC model

A RPC model is capable of offering a simple, generic mapping from a 3D object space point to 2D image point by a set of equations. Mathematically, oscillation is the general weakness of polynomials, but the RPC model has better interpolation properties because it is typically smooth and spreads the approximation error evenly between exact fit points (1). In addition, the RPC model is independent of specific sensors and platforms. We can establish any sensor model with one set of constant equations and different coefficients. The RPC model approximates projective equations very well (10) and can achieve high fitting accuracy with adequate control information. The practicability and generalization of RPC model therefore is guaranteed by its typical merits.

2.2.1. Substitutable analysis of RPC model for RD model

Since RPC model has been applied successfully to optical images instead of the RD model because of its high fitting accuracy, there are questions about its suitability for SAR images. These issues can be resolved by a comparison of the two imaging geometry.

Push-broom optical imaging is composed via a line-by-line scanning procedure along the satellite’s orbit. All pixels on a scan line are collected at one time according to the perspective projection. The projection center varies from one scan line to another as the satellite moves forward. In a way, the SAR imaging resembles that of the push-broom sensors, which employ slant-range projection instead of perspective projection for the pixel location and every ground point is determined by its distance to the antenna. A range line is then formed in the SAR image at an azimuth time. The 2D image is determined as the satellite moves in the azimuth direction by the integration of these range lines. Similarly to the optical image, the slant-range projection for each scan line of SAR image can also be expressed by simple polynomials.

As illustrated by Figure 1, an active radar on the left only images one side on the antenna since its imaging is an oblique projection. On the right of Figure 1 is an optical device, most of which are typically push-broom sensors such as Ikonos. As push-broom sensor imaging is a perspective projection, it usually covers a large area beneath the satellite orbit, including both the left and right sides. The hillside on Figure 1 can be imaged by

![Figure 1. SAR image is half of an optical image.](image-url)
the radar and just one side by the optical sensor, so we may take SAR image as half of an optical image. Point “C” and “D” seem to be overlapped in the optical image while in the SAR image there is a great distance between them. Thus, an optical image looks like to give an inverse display of a SAR image.

The RPC model might be more applicable to SAR images as compared to optical images given that its geopositioning accuracy is independent of satellite attitude. Accordingly, the RPC model can be applied successfully to an optical image, so it is straightforward to implement the RPC model in SAR imagery.

However, a replacement sensor model must not only represent object to image mapping accurately, but perform the subsequent digital photogrammetric operations previously performed with the RSM model as well. Thus, the RPC model has also been implemented in stereo orientation and orthorectification and will be described in later sections.

2.2.2. The RPC model and its solution

As mentioned previously, the RPC model relates 3D object space to 2D image space through a set of equations for a variety of sensors with different RPC coefficients, as demonstrated in Figure 2.

The RPC model consists of two separate rational functions as presented below (11), where image coordinates (sample, line) are expressed as the ratios of polynomials of ground coordinates ($D_{\text{sin}}$, $D_{\text{tan}}$, $D_{\text{hei}}$). In order to strengthen the numerical stability of equations, the image coordinates and object coordinates are each offset and scaled to fit the range from -1.0 to 1.0.

\[
Y = \frac{N_1(P, L, H)}{D_1(P, L, H)} \\
X = \frac{N_5(P, L, H)}{D_5(P, L, H)}
\]  

where $N_1(P, L, H)$, $D_1(P, L, H)$, $N_5(P, L, H)$, and $D_5(P, L, H)$, are terms of the third-order polynomials of $(P, L, H)$. $X$ and $Y$ are the normalized image coordinates (sample, line) and $P$, $L$, $H$ are the normalized coordinates of corresponding object points in the 3D space. With the RSM available, the RPC coefficients can be solved by fitting the RSM as described in (12). A brief description is provided as follows. The resolution is carried out by generating 3D grid points determined based on the full range of 2D image space with a number of elevation layers. The corresponding coordinates in the image space are computed using the RD model. In this way, enormous virtual GCPs can be easily obtained for each image point corresponding to a number of ground points with different elevations. The RPCs can then be determined by solving the normal equations for RPC model that are established based on those GCPs, during which a least squares fitting approach is adopted. Given these coefficients, the values of (sample, line) can be computed quickly and precisely. Afterwards, the fitting accuracy of the developed RPC model can be evaluated by generating a set of check points (CKPs). These CKPs are collected in a manner similar to the GCPs, but the 3D object grid density is doubled in each dimension, which gives rise to the independence of CKPs from GCPs. With the RPCs calculated as above we can obtain the corresponding image positions of the CKPs. Consequently, the accuracy analysis can be accomplished by calculating the difference between the positions of the original image points and those obtained from the RPCs.

2.2.3. RPC accuracy for SAR imagery

Zhang et al. (5) used the algorithm above to establish the RPC model based on RD model with a series of high, medium, and low resolution satellite SAR images. They came to the conclusion that with 3D control grids consisting of five elevation layers, and each of them with a $500 \times 500$ pixels grid, a third-order RPC model with unequal denominators can give RMS values on the checkpoints of 0.00015 pixels in planimetry with a maximum error of 0.00037 pixels. This result is in compliance with that of the RD model for photogrammetric processing, which illustrates that the RPC model is available for SAR imagery and can achieve a high approximate accuracy.

2.3. Bias-corrected RPC model

Although the RPC model has demonstrated its potential as an accurate representation of the RD model, positioning accuracy is influenced by errors inherent in RPC since it is derived without the aid of ground control. To be specific, factors affecting positioning accuracy mainly including: (1) the sensor stability; (2) the accuracy of the platform ephemeris; and (3) the measurement accuracy of target ranging. An intimate analysis of the above three terms was discussed by Culander and McDonough (2) in 1991 in detail. Based on the knowledge of multiple satel-

![Figure 2. RPC model relates object space to image space using RPC coefficients.](image-url)
lite system parameters that might give rise to the geopositioning error, the biases which to be compensated are generally classified into two categories: a line offset parameter required to adjust for errors in the line direction and a sample offset parameter required to adjust for errors in the sample direction, each of which has the same net effect on the object–image relationship.

Generally, the systematic bias of RPC can be compensated by an empirical model using GCPs located on the image and the corresponding coordinate system to express the discrepancies between the nominal and the measured image-space coordinates. Thus, the bias-corrected RPC model proposed here employs an affine transformation (AT) defined in the image space to represent the two kinds of errors indicated above, whose form is consistent with the truncated polynomial model utilized by the Ikonos image (13). Figure 3 illustrates the process of mapping sequence for the RPC model. Given a ground control point \( P \) in the object space, the image coordinates \( (x_0, y_0) \) can be quickly computed using the RPC model. Afterwards, the bias of the image point \( (x_0', y_0') \) can then be compensated by the AT.

The model is expressed as follows (14):

\[
\begin{align*}
\Delta y = e_0 + e_1 \cdot s + e_2 \cdot l \\
\Delta y = f_0 + f_1 \cdot s + f_2 \cdot l
\end{align*}
\]

where \( \Delta x \) and \( \Delta y \) are the adjustable functions added to the RPC model to capture the discrepancies between the calculated and the measured coordinates of ground points; \( e_0, e_1, e_2 \) and \( f_0, f_1, f_2 \) are the adjustment parameters for a SAR image, and \( l \) and \( s \) are line and sample coordinates of the ground control point computed using the RPC model. It should be noted that the adjustment parameters are generated by combining multiple physical camera model parameters into single parameter, which are different from that of an optical satellite image. Obvously, each of them has absorbed the specific errors and should have physical significance.

Parameter \( e_0 \) absorbs all along-track errors causing offsets in the line direction, including the along-track position error, a line component of the Doppler shift resulting from the radial platform position error. All of which have the same effect of displacing images in line. Similarly, parameter \( f_0 \) absorbs cross-track errors causing offsets in the sample direction, including cross-track position error, a sample component of the change in look angle resulting from a radial platform position error and so on. Parameter \( e_2 \) and \( f_2 \) absorb the effects due to gyro drift in the sensor during the imaging scan. Parameters \( e_1 \) and \( f_1 \) absorb radial position error and interior orientation errors. Consequently, the bias-corrected RPC model does not present the numerical ill-conditioning problems of classical techniques.

3. Stereo orientation

The previously proposed approach can be extended to stereo orientation using stereo pairs. The spatial intersection performed with the RPC model is illustrated in Figure 4. The stereo pairs consist of two images each determined by its own set of RPC equations. Combining the conjugate image point coordinates \( (x_1, y_1) \) and \( (x_2, y_2) \), we can get four RPC equations, which can surely calculate the three unknowns of the corresponding object space coordinate \( (P, L, H) \).

Owing to the fact that the RPC model is generated without reference to GCP, its positioning accuracy is thus somewhat restricted. As mentioned above, the introduction of AT model into the RPC model namely, the bias-corrected RPC model can eliminate errors induced by various sensor parameters. The orientation of RPC model to accurate ground point is then guaranteed. In this way, the error of 3D positioning can be corrected during spatial intersection by AT model defined in image space, which causes a transformation of image coordinates (14),
whose implementation only calls for one or more quality GCPs. This approach is appeared in the figure as well.

The proposed method for stereo orientation by utilizing corner reflectors (CRs) as GCPs or CKPs has been validated (15). Images used for this study included TerraSAR-X and COSMO-SkyMed data. And the test scene was characterized by a rolling topography. The elevation range was from 0 to 270 m. Typical results are shown in Table 1. There are six CR points in the experiment changing between GCPs and CKPs for accuracy analysis. The values of $\sigma_{\text{plane}}$ which indicates that the bias-corrected RPC model error was 0.15 pixels for TerraSAR-X and 0.082 pixels for COSMO-SkyMed, respectively, in the worst case, manifesting that the proposed model can reach a relatively high orientation error modeling accuracy. The best results achieved using an increasing number of CKPs can be 0.032 m (RMS) error in planimetry and 0.028 m (RMS) in height for TerraSAR-X, and, for COSMO-SkyMed the results are 0.174 m in planimetry and 0.003 m in height. These tests show that the use of the bias-corrected RPC model for SAR stereo orientation can achieve an extremely high 3D positioning accuracy.

4. Orthorectification

As SAR images present typical geometric distortions such as layover, foreshortening, and shadow due to the special nature of radar imaging, orthorectification is of particular importance for SAR image processing. Previous work has also indicated the use of RPC model for orthorectification. This operation is accomplished using the bias-corrected RPC model and a DEM. Owing to various topographic conditions, the generation of the bias-corrected RPC model is different as well. For flat areas, ground points can be selected between a SAR image and a DEM to establish a bias-corrected RPC model. For hilly and mountainous areas, where the ground points are difficult to collect, a simulation operation is required. A simulated image is produced with SAR data and a DEM based on the RPC model, it is geometrically consistent with the real SAR image, while the differences in pixel location reflect the biases caused by sensor parameters. In this way, the bias-corrected RPC model can be generated by matching the two images (17). Hence, the ortho-rectification can be implemented with the bias-corrected RPC model and a DEM using the algorithm below.

As illustrated in Figure 5, the angular point of the original image is extracted and the RPC model is utilized to determine the range of output image. After that, the DEM needs to interpolate for the discrepancy in resolution between the DEM and the real SAR image. The SAR image coordinates can then be calculated by point-wise orientation of the interpolated DEM grid using the bias-corrected RPC model. Finally, the digital number value of each point is determined by the interpolation of the SAR image coordinates.

The method proposed above has been successfully verified (16), when TerraSAR-X and COSMO-SkyMed image data were acquired as experimental data. The study site covered different environments, including flat and hilly topography. Typical results are shown in Figures 6 and 7.

Results achieved using these data are: in flat areas, the planimetric accuracy of TerraSAR-X is 2.66 m, while the COSMO-SkyMed is 2.285 m. In hilly and mountainous areas, the planimetric accuracy of TerraSAR-X is 6.378 m, and the COSMO-SkyMed is 6.252 m.

After the analysis of the results, the accuracy of orthorectification for different kinds of data was authenti-

![Figure 5. The procedure for orthorectification with RPC model.](image)

| GCP item       | TerraSAR-X | COSMO-SkyMed |
|----------------|------------|--------------|
|                | $\sigma_{\text{plane}}$ | Planimetry | Height | $\sigma_{\text{plane}}$ | Planimetry | Height |
| 1 in center    | 0.129      | 0.789        | 3.036   | 0.048     | 1.125        | 0.783   |
| 2 in center    | 0.150      | 0.928        | 1.445   | 0.052     | 0.694        | 0.698   |
| 3 in center    | 0.070      | 0.122        | 0.181   | 0.064     | 0.475        | 0.347   |
| 4 in center    | 0.078      | 0.166        | 0.241   | 0.071     | 0.304        | 0.092   |
| 1 center, 4 corners | 0.084      | 0.032        | 0.028   | 0.072     | 0.174        | 0.003   |
Thus, the conclusion drawn indicates that the use of RPC model for orthorectification is feasible and reliable.

5. Summary and outlook

In this paper, a comprehensive study of the RPC model for spaceborne SAR image has been presented, including its feasibility and practicability. Because the RPC model accurately fits the object-image geometry for various sensor systems with computational efficiency, it has been widely used as an alternative of RD model for SAR images. Furthermore, it utilizes a single generic model with different coefficient values to model various sensor systems that would greatly simplify the development of commercial software and multisensor processing for SAR images. The only restriction stems from the accuracy of positioning described by the RPC error model. In order to compensate for the inherent orientation errors, a bias-corrected RPC model was proposed and applied to stereo orientation and orthorectification; the experimental results validated the practicability of the RPC model for SAR data without loss of accuracy. Since it is independent of sensors, highly efficient and highly fitting accuracy, there is no doubt that the RPC model should be recommended to the photogrammetric community as a generalized replacement sensor model.

It is believed that the RPC model, based on its bias compensation mode, is broadly applicable. For example, the RPC model can not only be used to replace the RSM, but also applied to the processing chain for SAR data, thus facilitating the processing of SAR data for end users. Moreover, InSAR is the synthesis of SAR and interferometry whose RSM is based on the RD equations and a phase equation. Since the RPC model has been successfully applied to SAR image’s RSM, it is suggested that the phase equation of InSAR be replaced by RPC model as well (17). Hence, the geometric processing of InSAR data such as DEM generation would be simplified. In addition, multisource data processing of SAR and optical images could be implemented through the universal RPC model, thus the stereo restitution based on the two systems can be expected as well.

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