Bias-compensated RPCs for Sensor Orientation of High-resolution Satellite Imagery

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Abstract
The demand for higher quality metric products from high-resolution satellite imagery (HRSI) is growing, and the number of HRSI sensors and product options is increasing. There is a greater need to fully understand the potential and indeed shortcomings of alternative photogrammetric sensor orientation models for HRSI. To date, rational functions have proven to be a viable alternative model for geo-positioning, and with the recent innovation of bias-compensated RPC bundle adjustment, it has been demonstrated that sensor orientation to sub-pixel level can be achieved with minimal ground control. Questions have lingered, however, as to the general suitability of bias-compensated rational polynomial coefficients (RPCs), and indeed rational functions in general. The purpose of this paper is to demonstrate the wide applicability of bias-compensated RPCs for high-accuracy geopositioning from stereo HRSI. The case of stereo imagery over mountainous terrain will be specifically addressed, and results of experimental testing of both Ikonos and QuickBird imagery will be presented.

Introduction
As a sensor orientation model for stereo satellite image configurations, rational functions have a history of application spanning nearly two decades (Dowman and Doloff, 2000). The use of the rational function model, with its 80 Rational Polynomial Coefficients, termed RPCs, primarily found application in military mapping, and it was not until the launch of the Ikonos high-resolution imaging satellite in September 1999 that the civilian photogrammetric community had to take note of this alternative or replacement model for sensor orientation and ground point determination from stereo line scanner imagery. Indeed, the commercial photogrammetric industry had little option but to embrace RPC-based restitution, since this was the only means provided by Space Imaging, Inc. for customers to extract accurate object space information from Ikonos imagery.

Although it is fair to say that there was initially some unease associated with the employment of RPCs, it quickly became clear that the metric accuracy potential of Ikonos would not be compromised through use of Space Imaging produced RPCs, which as reported by Grodecki (2001), modelled the rigorous sensor orientation to an accuracy of better than 0.05 pixels. Moreover, experimental testing with stereo and multi-image Ikonos Geo-image configurations had shown that sub-pixel ground point determination is readily achievable with Ikonos RPCs, once the inherent sensor orientation bias errors (which also affect the rigorous model) had been compensated (e.g., Hanley et al., 2002; Fraser & Hanley, 2003; Grodecki & Dial, 2003).

Notwithstanding the very impressive results obtained with Ikonos image restitution using the bias-compensated RPC approach, and the already demonstrated equivalence of the RPCs and the rigorous sensor orientation model from which they were derived, uncertainties persisted. Much of this can be attributed to the false association of vendor produced RPCs with those empirically determined by users through the use of ground control points (GCPs). More curious, however, were reports that RPCs supplied with the HRSI would be somehow influenced by the nature of the terrain being imaged (e.g., Cheng et al., 2003).

With the successful launch of the QuickBird satellite in October 2001, along with the decision by DigitalGlobe, Inc. to provide all associated orbit ephemeris, sensor attitude and camera model data with the imagery, the options for photogrammetric restitution of HRSI increased. It was now possible to utilize rigorous sensor orientation models, which were generally collinearity-based and which had previously been employed in the commercial photogrammetric sector with SPOT, MOMS, and IRS satellite imagery. RPCs are also supplied with QuickBird imagery, and Robertson (2003) has reported agreement between the rational function model and the rigorous sensor model of generally between 0.1 and 0.3 pixels RMSE for QuickBird imagery. He has also observed that such levels of discrepancy will typically be dwarfed by other errors in any orthorectification process. To the authors’ knowledge, a more comprehensive assessment of the integrity of QuickBird RPCs with respect to the rigorous model has yet to be reported.

Another interesting factor in any discussion of rigorous models versus RPC models is that some well-known digital photogrammetric systems which employ rigorous model approaches for stereo QuickBird imagery actually use system generated RPCs within the modelling process. It would thus appear that lingering concerns about the quality of RPCs, and especially those derived from the rigorous sensor orientation and supplied with the imagery, can be put aside. But, statements such as those by Cheng et al. (2003) concerning how RPCs do not have a very high degree of accuracy in high relief areas have the effect of casting some doubt upon the rational function approach. As a consequence, the authors aim in this paper to demonstrate that RPCs supplied with HRSI, for both Ikonos and QuickBird, can produce accuracies commensurate with rigorous model approaches irrespective of the nature of the scene topography or the size of the scene.
Errors in sensor orientation within HRSI can, fortuitously, be resolution, especially attitude, but also position and velocity. The answer to this lies both in the inherent limitations in directly modelling as biases in image space, primarily due to the very narrow field-of-view of the satellite line scanner (approaching a parallel projection for practical purposes) and the nature of the error signals. In the simplest case, small attitude or ephemeris errors are equivalent to shifts in image space coordinates. But, more than simple translation may be involved. Time-dependent errors in attitude sensors, for example, can give rise to drift effects in the image coordinates and even to displacement in the image coordinates and even to position shifts. But, in many cases, the shift-and-drift model (Case 2), the situation is slightly different, at least when the parameters \( A_1, B_1, A_2, B_2 \) are rarely significant. This means that one need only worry about providing one \( \text{GCP} \) to compensate for the shifts \( A_1, B_1 \) and \( A_2, B_2 \). With QuickBird imagery, the authors’ experience suggests that the shift-and-drift and affine AP models can in cases lead to measurable improvements in the accuracy of sensor orientation and geo-positioning using bias-compensated RPCs (e.g., Noguchi et al., 2004). Thus, there is a very slight prospect of the nature of the scene topography influencing the geo-positioning since the relative-to-absolute orientation process does not constitute a shape-invariant transformation.

Correcting the RPCs for Bias

The issue of achieving bias compensation in the RPCs provided with HRSI, and mainly with Ikonos Geo and QuickBird Basic imagery, would be largely academic were it not for the fact that a user can correct the RPCs for this bias and consequently obtain a sensor orientation model with an accuracy commensurate with the image resolution, that is about 1 m, in the case of Ikonos and QuickBird. The corrected RPCs can then be substituted for the originals in subsequent digital photogrammetric operations such as ortho-image generation and digital terrain model (DTM) extraction. The formula for generating bias-corrected RPCs is provided in Hanley et al. (2002) and Fraser & Hanley (2003), at least for the case of shift terms only. Where parameters beyond \( A_0, B_0, A_1, B_1 \) are significant, the RPCs must be re-estimated, rather than simply corrected. This can be carried out using the accepted technique outlined by Grodecki (2001). Moreover, to fully exploit bias-compensated RPCs, the digital photogrammetric workstation must support the RPC model. While this is generally the case with Ikonos imagery, it is not necessarily so at present with stereo QuickBird imagery, where some popular photogrammetric systems employ a rigorous model formulation (e.g., the BAE SOCT SET™ and Intergraph ImageStation™ solutions are based on a rigorous model).

Experimental Testing

Test Range Data

As mentioned, a primary aim of this paper is to demonstrate the high accuracy potential of bias-compensated RPCs for sensor orientation and geopositioning from HRSI.
in this exercise is the assumption that the RPCs do in fact constitute rigorous re-parameterisations of the rigorous sensor orientation model. Thus, the APs, $A_i - B_i$, will be modelling residual systematic error associated with biases. In order to demonstrate the effectiveness of the bias-compensated RPC approach, two test data sets of stereo HRSI are examined. One of these is a stereo triplet of Ikonos Geo-imagery, whereas the other is a QuickBird Basic stereo pair. Shown in Table 1 are the essential characteristics of the two HRSI data sets to be analysed. These are not the only stereo and multi-image Ikonos and QuickBird configurations that have been metrically evaluated by the authors, but they do represent two with GCP and image measurements of sufficient accuracy to highlight the error signal in sensor orientation at the sub-pixel level.

The Hobart test field covers a 120 km$^2$ area of the city of Hobart, Australia along with its surroundings. A prominent feature in the area, lying only 10 km or so from downtown Hobart is Mount Wellington, the peak of which is just below 1,300 m elevation. The test range was imaged in a stereo triplet of Ikonos Geo-imagery recorded in February 2003. Of the images forming the triplet, the two stereo images (elevation angles of 69°; base-to-height ratio of 0.8) were scanned in reverse mode, while the central image (elevation angle of 75°) was acquired in forward mode. Hobart was specifically chosen as a suitable test field due to its height range, and the fact that the scene covered was largely urban, thus providing excellent prospects for accurate image-identifiable GCPs. A total of 110 precisely measured ground feature points (mainly road roundabouts) served as GCPs and checkpoints. In order to ensure high-accuracy GCPs and image coordinate data, multiple GPS and image measurements were made for each GCP with the centroids of roundabouts being determined by a best-fitting ellipse to six or more edge points around the circumference of the feature, in both object and image space. The estimated accuracy of this procedure, described in Hanley & Fraser (2002), is 0.2 pixels. Four sample GCP image chips are shown in Figure 1.

The stereo pair of QuickBird Basic imagery covering the Melbourne test range, which exhibited a pixel size of 0.75 m and a base-to-height ratio of 1, was recorded in July 2003. The majority of the 81 GCPs used were also road roundabouts, with the remaining points being corners and other distinct features conducive to high precision measurement in both the imagery and on the ground. Roundabouts were measured as described above, and in the case of corners, the feature point was defined in image space by the intersection of best-fitting lines to edge points.

All RPC bundle adjustment runs, along with all image data processing and measurement operations, were performed with the BARISTA software package. This software system has been developed specifically to provide a practical data processing environment for HRSI sensor orientation and geopositioning, along with ortho-image generation and DTM extraction.

**Results with Ikonos**

The results obtained in the RPC bundle adjustments of the Hobart stereo triplet of Ikonos imagery are listed in Table 2. The first row of the table shows the RMS value of coordinate discrepancies obtained in a direct spatial intersection utilising the RPCs provided with the imagery. A major component of these checkpoint discrepancy values arises from the biases in the RPCs. Post transformation of the computed ground coordinates, utilizing three or more GCPs, could be expected to yield RMS accuracies at the 1 m level. The remaining rows of Table 2 list the accuracies attained in the RPC bundle adjustments with bias compensation for different AP sets. As can be appreciated, the resulting RMS values of checkpoint discrepancies will vary depending upon the particular GCPs employed. Those listed in the table are representative of the many that were obtained.

Of most practical interest are the results obtained in RPC bundle adjustments with the two shift parameters $A_0, B_0$. It can be seen that geopositioning accuracy to 30 cm (RMS, 1-sigma) in longitude, and 70 cm in latitude and height are obtained with just two GCPs, and indeed, this result is achievable with one GCP. Note for the case of a single GCP on the top of Mount Wellington, i.e., at a 1,200 m elevation difference from the majority of the 109 checkpoints, that accuracy in planimetry is again at the 0.3 pixel level in the cross-track direction. The error in height is marginally higher than in the two-GCP case, but this likely represents the effect of a bias of the adjusted position of the single GCP rather than any affine distortion in the relatively oriented three-image configuration. What is certainly clear in the RPC bundle adjustments with shift parameters is that terrain characteristics have no impact upon the results. As regards the individual positional biases in image

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**Table 1. Characteristics of the Two HRSI Imagery Test Fields**

<table>
<thead>
<tr>
<th>Testfield</th>
<th>Area</th>
<th>Elevation Range</th>
<th>Image Coverage</th>
<th>Number of GCPs</th>
<th>Notable Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ikonos, Hobart</td>
<td>120 km$^2$</td>
<td>sea level</td>
<td>Stereo triplet (69°, 75°, 69°)</td>
<td>110</td>
<td>Full scene; mountainous terrain</td>
</tr>
<tr>
<td></td>
<td>(11 × 11 km)</td>
<td>to 1280 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QuickBird, Melbourne</td>
<td>300 km$^2$</td>
<td>sea level</td>
<td>Stereo pair (approx. 63° each)</td>
<td>81</td>
<td>Full scene, low relief area</td>
</tr>
<tr>
<td></td>
<td>(17.5 × 17.5 km)</td>
<td>to 50 m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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and also object space, these ranged from 0.1 m to 4 m for the three images of the Ikonos Geo-triplet.

The plots of image coordinate residuals shown in Figure 2 provide an insight into the question of whether there may be additional bias error signal in the RPCs, for example from time-dependent drift effects. While Figures 2a and 2b show a quite random distribution suggesting the absence of any further systematic error, the right-hand stereo image, Figure 2c, appears to display residual systematic error in the along-track coordinate. Shown in Figure 2d are the image coordinate residuals for the same image which result from an RPC bundle adjustment with shift and shift parameters (the fourth row of Table 2). The drift terms, especially $A_1$, lead to a reduction in the RMS value of image coordinate residuals, from 0.32 to 0.25 pixels in the line coordinate direction, but this improvement does not lead to enhanced geopositioning accuracy. Grodecki & Dial (2003) have reported that with Ikonos imagery drift effects would be unlikely to be seen in strip lengths of less than 50 km. The results obtained in the Hobart test field are consistent with this view, notwithstanding the small residual systematic error pattern seen in Figure 2c.

Given the indications that the RPC bias has been adequately modelled by the two shift parameters $A_0$ and $B_0$, it is not surprising to see that the full affine additional parameter model does not lead to any accuracy improvement. The best indicator of the overall metric potential of the Ikonos stereo triplet is listed in the last row of Table 2. This is the case where the RPC bundle adjustment with shift parameters employs all GCPs as loosely weighted control, thus providing a solution that can be thought of as being equivalent to a free-network adjustment with inner constraints. Note here the RMS geopositioning accuracy of just 0.24 pixels in the cross-track direction while there is no impact in along-track or height accuracy. Similarly, the full affine model produces no accuracy improvement. Shown in Figures 2c and 2d are the residual vectors in image space for the adjustment with $A_0$ and $B_0$ biases reached magnitudes of 30 m in height. The results obtained in the Hobart test field are consistent with this view, notwithstanding the small residual systematic error pattern seen in Figure 2c.

As was the case with Ikonos, the achievement of sub-pixel geopositioning accuracy with QuickBird imagery required only the provision of $A_0$ and $B_0$ in the RPC bundle adjustment. However, the nature of the image coordinate residuals obtained in the bundle adjustment with shift parameters suggests that drift terms may also be warranted with QuickBird. The findings of Noguchi et al. (2004) support this view. The $A_0$ and $B_0$ biases reached magnitudes of 30 m in the QuickBird stereo images.

**Concluding Remarks**

The impressive geopositioning accuracy attained with the RPC bundle adjustment with bias compensation supports the view that this sensor orientation model has the same metric potential as rigorous model formulations for both Ikonos and QuickBird imagery. Implicit in this conclusion is that the RPCs produced by Space Imaging, Inc., and DigitalGlobe, Inc., are equivalent to the rigorous model, and thus there should be no concern regarding their applicability in stereo imagery covering any type of terrain.
In comparing the accuracy results after bundle adjustment with ground control, one finds not much difference between Ikonos and QuickBird. Both produce the highest accuracy in the cross-track direction. Also, in the test cases examined QuickBird yielded slightly higher accuracy in height, and Ikonos produced better along-track accuracy. The issue of residual systematic error in the along-track direction is of importance for users who wish to utilize sensor orientation models based on low-order empirical functions, such as the 3D affine model. Experience by the authors and others
Table 3. Results of RPC Bundle Adjustments with Bias Compensation for the QuickBird Basic Stereo Pair Covering the Melbourne Test Field

<table>
<thead>
<tr>
<th>RPC Solution</th>
<th>No. of GCPs (Number of Checkpoints)</th>
<th>RMS of ( l, s ) image residuals (pixels)</th>
<th>RMS Value of Ground Checkpoint Discrepancies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Latitude (along track)</td>
<td>Longitude (across track)</td>
</tr>
<tr>
<td>Spatial Intersection</td>
<td>None (81)</td>
<td>-</td>
<td>1.0 (1.3)</td>
</tr>
<tr>
<td>Shift: ( A_0 ), ( B_0 )</td>
<td>2 (79)</td>
<td>0.24</td>
<td>0.73 (1.0)</td>
</tr>
<tr>
<td>Drift: ( A_0 ), ( B_0 ), ( A_1 ), ( B_1 )</td>
<td>6 (75)</td>
<td>0.21</td>
<td>0.74 (1.0)</td>
</tr>
<tr>
<td>Affine: ( A_0 ) = ( B_1 )</td>
<td>9 (72)</td>
<td>0.19</td>
<td>0.74 (1.0)</td>
</tr>
<tr>
<td>Shift: ( A_0 ), ( B_0 )</td>
<td>81 (sigma = 2 m)</td>
<td>0.24</td>
<td>0.70 (0.9)</td>
</tr>
</tbody>
</table>

Figure 3. Image coordinate residuals from RPC bundle adjustments of QuickBird stereo imagery in the Melbourne testfield; (a) Left stereo image, APs \( A_0 \), \( B_0 \), (b) Right stereo image, APs \( A_0 \), \( B_0 \), (c) Left stereo image, APs \( A_0 \), \( B_0 \), \( A_1 \), \( B_1 \), and (d) Right stereo image, APs \( A_0 \), \( B_0 \), \( A_1 \), \( B_1 \).
(e.g., Fraser & Yamakawa, 2003; 2004; Noguchi et al., 2004; Hanley et al., 2002) has shown that success with such models is highly dependent on the absence of higher-order errors sources such as perturbations in scan velocity. While Ikonos reverse scanned imagery appears largely free of such effects, the same is not always the case for Ikonos forward scanned images and QuickBird imagery. Indeed the authors’ recent experience with QuickBird imagery suggests that standard low-order empirical models do not yield very impressive accuracy results. On the other hand, where a user has the opportunity of utilizing bias-compensated RPCs, they can do so with every confidence of achieving optimal accuracy.

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