AN ALTERNATIVE SENSOR ORIENTATION MODEL FOR HIGH-RESOLUTION SATELLITE IMAGERY

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ABSTRACT

As high-resolution satellite imagery (HRSI) attracts usage in a broader range of mapping and GIS applications, so the demand for higher 3D accuracy increases. One of the significant recent innovations in metric information extraction from HRSI has been the adoption of alternative sensor orientation models such as bias-compensated RPCs, the affine model and other linear model approaches. These have demonstrated that sub-pixel geopositioning accuracy can be achieved with minimal to modest ground control requirements. Indeed, only one ground control point is necessary for bias-compensated RPCs. Utilisation of this sensor orientation model allows users of HRSI to routinely realise accuracy with base-level imagery (eg. IKONOS *Geo* and QuickBird *Basic*) which has hitherto only been available with higher level image products at much higher cost.

This paper briefly reviews the RPC sensor orientation model with bias compensation, and discusses the results of experiments with two HRSI datasets. The experimental applications reported have not only concerned themselves with 3D point positioning accuracy but also with the use of bias-corrected RPCs for DSM generation and feature extraction from stereo imagery, and for ortho-image production and 3D building extraction from single images. The paper will provide a further insight into the potential and limitations of HRSI for large-scale mapping, while at the same time touching upon two current issues concerning sensor orientation for HRSI. These are the impact or non-impact of topography on the RPC model, as well as the issue of scanning mode. The latter issue can influence metric performance, with the effect being anticipated to be more pronounced with HRSI sensors such as QuickBird which dynamically vary their look-orientation during scene capture.

1. INTRODUCTION

Bias-compensated RPC bundle adjustment, where the ‘RPC’ in the name stands for Rational Polynomial Coefficients is a recent innovation in alternative sensor orientation modelling for high-resolution satellite imagery (HRSI). It has been shown in a number of practical applications that the rational functions-based approach can yield sub-pixel geopositioning with only a modest requirement for ground control, a single ground control point (GCP) being sufficient in some cases. The reader is referred to Hanley et al. (2002), Trisirisatayawong et al.,(2004), Grodecki & Dial (2003) and Fraser & Hanley (2003) for example applications.

Notwithstanding the impressive results obtained with IKONOS and QuickBird sensor orientation and geopositioning via the bias-compensated RPC bundle adjustment approach, some uncertainties have persisted regarding the universal applicability of this model. These are partially due to a false association of vendor produced RPCs with those empirically determined by users through the use of dense arrays of GCPs, a process which is not recommended. There have also been suggestions that RPCs supplied with HRSI could somehow be influenced by variations in the terrain within the scene (eg Cheng et al., 2003), though this would appear to be unlikely for any RPC determination which is based on the rigorously determined sensor orientation (Grodecki, 2001).

One area of justifiable concern relates to the impact of the scanning mode upon metric performance of RPCs. This is anticipated to be more pronounced with HRSI sensors in imaging modes where the look-orientation is varying during scene capture. For example, in the 'normal' Reverse scanning mode of IKONOS, the elevation angle of the sensor is near constant, yet in Forward scanning mode it is changing at close to 1^0/sec. For QuickBird, the sensor orientation is always varying, in either Forward or Reverse scanning mode. There is a higher likelihood of small residual components of systematic scan velocity errors in platforms that are dynamically re-orienting during image recording. This may well be a factor in the reported 0.1 to 0.3 pixel level of agreement between the rational function model and the rigorous sensor model for QuickBird imagery (Robertson, 2003).

In this paper, the bias-compensated RPC model in the form that accommodates first-order 'drift' effects as well as image space shifts induced by small biases in sensor exterior orientation is first briefly described. Practical examples of application of the RPC model to stereo HRSI are then summarised. In one of the examples, which utilised IKONOS imagery, it is demonstrated that the nature of the terrain being imaged has virtually no impact upon the metric performance of sensor orientation based on bias-compensated RPCs. The practical achievement of sub-pixel ground point determination is also demonstrated for base-level (most economical) IKONOS *Geo* and QuickBird *Basic* stereo imagery products. Also very briefly touched upon are automated DSM extraction, ortho-image generation and the determination of 3D building dimensions, the latter from single satellite images. These issues shed further light on the potential of HRSI for large-scale mapping.

2. BIAS-COMPENSATED RPC MODEL

The RPC model provides a direct mapping from 3D object space coordinates (typically offset normalised latitude, longitude and height) to 2D image coordinates (offset normalised line and sample values). The model incorporating bias compensation can be presented in the form:

$$\begin{aligned} l + A_0 + A_1 l + A_2 s &= \frac{F_1(U,V,W)}{F_2(U,V,W)} \\ s + B_0 + B_1 l + B_2 s &= \frac{F_3(U,V,W)}{F_4(U,V,W)} \end{aligned} \qquad (1)$$

where l and s are line and sample coordinates, and F_i are third-order polynomial functions of object space coordinates U, V and W. The A_i and B_i terms describe image shift and drift effects and they provide the 'bias-compensation'. Within this model there are three logical choices of 'additional parameter' (AP) sets to effect the bias correction: i) A_0, A_1, ... B_2, which describe an affine transformation; ii) A_0, A_1, B_0, B_1, which model shift and drift; and iii) A_0, B_0, which effect an image coordinate translation only. The solution of the APs in Eq. 1 can be carried out via a multi-image bundle adjustment, as developed by Fraser & Hanley (2003, 2004) and Grodecki & Dial (2003).

For IKONOS Reverse scanned imagery, the model with shift parameters A_0, B_0 alone is usually sufficient to yield 1-pixel level geopositioning. This AP set effects a shape-invariant transformation of the relatively oriented assemblage to an accurately, absolutely oriented model, even if the bias-induced shifts are different for each image. Only one GCP is required though additional GCPs will enhance precision. Their number and location is, however, not of major importance. It is apparent that this relative-to-absolute orientation process would not be influenced by terrain height or ruggedness, and it will be shown later that terrain seems to have no impact on the bias-compensated RPC approach, or even on the standard RPC forward intersection.

Time-dependent errors in attitude determination can give rise both to 'drift' effects in the image coordinates and to an affine distortion of the image. Experience suggests that these errors are rarely significant in IKONOS Reverse scanned imagery, but can be of practical significance in QuickBird imagery. In the case of the full affine correction model (Case i) and the shift-and-drift model (Case ii), the number and location of GCPs is therefore important, with a practical minimum number being 4-6. With QuickBird imagery, 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 geopositioning (eg Noguchi et al., 2004). Thus, there is a very slight prospect of the nature of the scene topography influencing ground feature point determination since the relative-to-absolute orientation process does not constitute a shape-invariant transformation.

The ability to determine the bias parameters A_0 and B_0 is very useful, but of more utility is incorporation of the bias correction into the originally supplied RPCs. This allows bias-free application of RPCs without reference to additional correction terms. The bias correction is very straightforward, as shown in Hanley et al. (2002) and Fraser & Hanley (2003). Bias-corrected RPCs, incorporating shift terms only in this case, are generated by carrying out the following corrections to the two numerator terms in Eq. 1; the denominator terms remain unchanged:

$$\begin{aligned} F_1(U,V,W) &= (a_1 - b_1 A_0) + (a_2 - b_2 A_0)\cdot V + \ldots + (a_{20} - b_{20} A_0)\cdot W^3 \\ F_3(U,V,W) &= (c_1 - d_1 B_0) + (c_2 - d_2 B_0)\cdot V + \ldots + (c_{20} - d_{20} B_0)\cdot W^3 \end{aligned} \tag{2}$$

Here, a_i, b_i, c_i and d_i are the RPC terms forming F_1 to F_4, respectively. It should be recalled that the distinction between image product levels offered for IKONOS, for example, has more to do with their absolute georegistration accuracy than with radiometric or local metric image properties. Thus, the ability to correct RPCs for inherent biases provides, effectively, the quality of higher level products at a base-level price, all for the modest additional cost of a single GCP in most cases.

3. APPLICATION EXAMPLES OF BIAS COMPENSATED RPCS

In order to demonstrate the effectiveness of the bias-compensated RPC approach, two test data sets of stereo HRSI have been 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 to have been metrically evaluated, but they constitute two with GCP and image measurements of sufficient accuracy to highlight any error signal in sensor orientation at the sub-pixel level.

The first testfield covers a 120 km^2 area of the city of Hobart. A very prominent feature in the area, lying only 10km or so from the downtown area, is 1300m high Mount Wellington. Of the images forming the triplet, the two stereo images (elevation angles of 69^o; base-to-height ratio of 0.8) were scanned in Reverse mode while the central image (elevation angle of 75^o) was acquired in Forward mode. Hobart was specifically chosen as a suitable testfield 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 road 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 Fraser & Hanley (2003), is 0.2 pixels.

The second testfield, for which there is both IKONOS and QuickBird stereo imagery, covers Melbourne. Here, only a stereo pair of QuickBird *Basic* images is considered. This pair exhibited pixel sizes of 0.75m and a base-to-height ratio of 1. The majority of the 81 GCPs used in the Melbourne testfield 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.

Testfield	Area	Elevation Range	Image Coverage (elevation angles)	Number of GCPs	Notable Features
IKONOS, Hobart	120 km^2 (11 x 11 km)	sea level to 1280 m	Stereo triplet (69^o, 75^o, 69^o)	110	Full scene; mountainous terrain
QuickBird, Melbourne	300 km^2 (17.5x17.5 km)	sea level to 50 m	Stereo pair (approx. 63^o each)	81	Full scene, low relief area

Table 1. Characteristics of the Hobart and Melbourne testfields.

3.1 IKONOS Results

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, utilising three or more GCPs, could be expected to yield RMS accuracies at the 1m level. The remaining rows of Table 2 list the accuracy attained in the RPC bundle adjustments with bias compensation, for different AP sets.

RPC Bundle Adjustment Solution	No. of GCPs (Number of Checkpoints)	RMS of *l, s* image residuals (pixels)	RMS value of ground checkpoint discrepancies. Units are metres and pixels		
			Latitude (along track)	Longitude (across track)	Height
Spatial Intersection	None (110)	-	2.9	1.2	4.0
Shift: A_0, B_0	2 (108)	0.24	0.67	0.29	0.70
Shift: A_0, B_0	1 at 1200m (109)	0.24	0.60	0.29	0.87
Drift: A_0, B_0, A_1, B_1	6 (104)	0.21	0.68	0.26	0.72
Affine: A_0 - B_2	9 (101)	0.20	0.59	0.25	0.78
Shift: A_0, B_0	*110 (sigma=2m)*	*0.24*	*0.54*	*0.26*	*0.54*

Table 2. Results of bias-compensated RPC bundle adjustments for the IKONOS *Geo* triplet covering Hobart.

The results obtained in RPC bundle adjustments with the two shift parameters A_0, B_0 are of most interest. These show that geopositioning accuracy to 30cm (RMS, 1-sigma) in longitude, and 70 cm in latitude and height are obtained with just 2 GCPs, and this result is also achievable with one GCP. For the case of a single GCP on Mount Wellington, i.e. at a 1200m elevation difference from the majority of the 109 checkpoints, accuracies in planimetry are again at the 0.3 pixel level in the cross-track direction. The RMS error in height is marginally larger than in the 2-GCP case, but this is likely due to the effect of a bias in the adjusted position of the single GCP rather than to any affine distortion in the relatively oriented 3-image model. It is clear that terrain characteristics have no impact upon the results for the RPC model with shift parameters. As for individual positional biases in object space, these ranged from 0.1 to 4m for the three images of the *Geo* triplet.

The plot of image coordinate residuals for the RPC model with shift terms only, for one of the stereo images, is shown in Fig. 1. Here there is no obvious presence of additional bias error signal in the RPCs, for example from time-dependent drift effects. 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 employed all GCPs as loosely weighted control points 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 below ¼ pixel in the cross-track direction, and close to ½ pixel in both the along-track direction and in height.

3.2 QuickBird Results

The same computational procedure as carried out in the Hobart testfield was followed with the QuickBird *Basic* stereo pair covering Melbourne. Table 3 lists the results obtained. Basically, the geopositioning accuracy achieved with QuickBird was the same as for IKONOS, though QuickBird produced in this case slightly lower accuracy in planimetry and slightly higher accuracy in height, no doubt as a consequence of the higher base-to-height ratio exhibited in the QuickBird stereo pair. What is seen with QuickBird, however, are stronger indications of residual systematic error which is not being modelled by the bias-compensated RPCs.

RPC Solution	No. of GCPs (Number of Checkpoints)	RMS of *l, s* image residuals (pixels)	RMS value of ground checkpoint discrepancies. Units are metres (and pixels)		
			Latitude (along track)	Longitude (across track)	Height
Spatial Intersection	None (81)	-	1.0 (1.3)	8.8 (12)	9.2 (12)
Shift: A_0, B_0	2 (79)	0.24	0.73 (1.0)	0.38 (0.5)	0.43 (0.6)
Drift: A_0, B_0, A_1, B_1	6 (75)	0.21	0.74 (1.0)	0.31 (0.4)	0.41 (0.6)
Affine: A_0 - B_2	9 (72)	0.19	0.74 (1.0)	0.34 (0.5)	0.36 (0.5)
Shift: A_0, B_0	*81 (sigma=2m)*	*0.24*	*0.70 (0.9)*	*0.36 (0.5)*	*0.37 (0.5)*

Table 3. Results of bias-compensated RPC bundle adjustments for the Melbourne QuickBird *Basic* stereo pair.

Shown in Fig. 2 is a plot of the image coordinate residuals arising from the RPC bundle adjustment with shift parameters (row 2 of Table 3) for one of the two images. The along-track alignment of the vectors is suggestive of perturbations in scan velocity, with the addition of a first-order scale effect. Thus, we would expect some of the error signal to be absorbed by the along-track drift parameter, A_1. The results listed in Table 3 for the RPC bundle adjustment with shift and drift parameters, however, show only a modest improvement in accuracy in the cross-track direction while there is no impact in along-track or height accuracy. Also, the full affine model produces no improvement in accuracy. Residual error patterns similar to those seen in Fig. 2 have been encountered with other QuickBird stereo pairs (eg Noguchi et al., 2004). As was the case with IKONOS, the achievement of sub-pixel geopositioning with QuickBird stereo imagery required only the provision of the APs A_0 and B_0. However, the nature of the image coordinate residuals obtained in the bundle adjustment with shift parameters suggest 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 30m in the QuickBird stereo images.

4. DSM GENERATION AND BUILDING EXTRACTION

The provision of a sensor orientation model that affords pixel level geopositioning is very important for downstream 3D spatial information generation from HRSI. Here, we mention just three such example applications. The first is digital surface model (DSM) generation through image matching. The merits of in-track stereo HRSI for image matching have been widely acknowledged, but of equal importance to high-accuracy automated surface modeling via least-squares matching, often incorporating geometric constraints, is a high-fidelity sensor orientation model such as bias-corrected RPCs. Shown in Fig. 3 is a DSM determined from the stereo pair of IKONOS *Geo* images of Hobart, with bias-corrected RPCs. The accuracy of the DSM, which was quantified through a comparison to LIDAR data, averaged just over 2m (RMS 1-sigma) for bare ground and reached 1m RMS at 110 GPS-surveyed checkpoints. The near-nadir IKONOS image from the Hobart triplet was orthorectified to this DSM, again via bias-corrected RPCs, and although a rigorous accuracy evaluation has not as yet been completed, it is apparent that the ortho-image generation was performed to about 1-pixel accuracy, or even a little better.

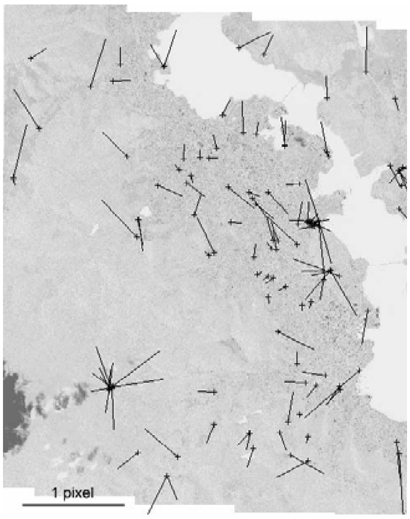

Figure 1: Image coordinate residuals, IKONOS *Geo* image, Hobart, RPC adjustment with APs A_0, B_0

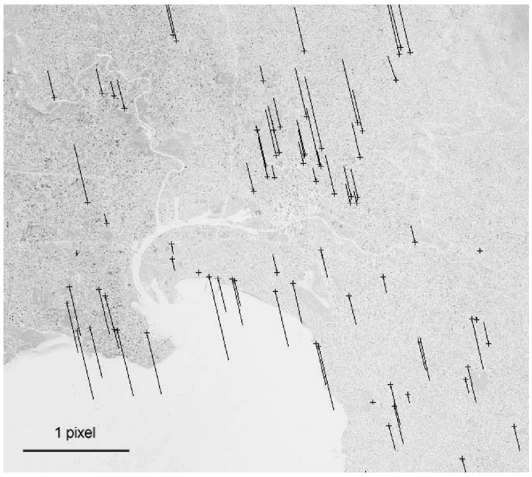

Figure 2: Image coordinate residuals, QuickBird *Basic* image, Melbourne, RPC adjustment with APs A_0, B_0.

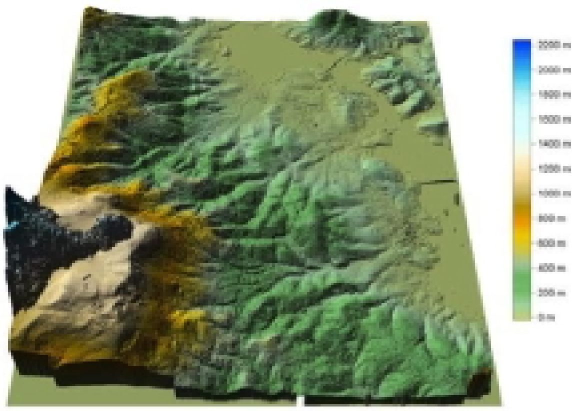

Figure 3: DSM generated from IKONOS *Geo* imagery of Hobart (dark area at left is cloud cover).

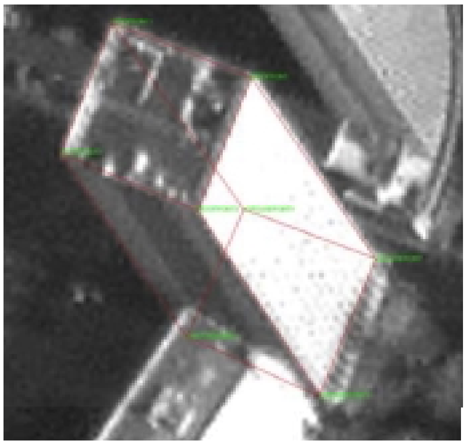

Figure 4: 3D Building 'frame' generated from single HRSI image with bias-compensated RPCs.

A further interesting application, which is still under metric evaluation, is the extraction of 3D building information from single, oblique satellite images. In this instance a DSM/DTM is required if absolute heights are desired, though relative height and other dimensional information can be extracted in the absence of an underlying terrain model. The method allows the collection of basic 3D wire frame models of buildings, from a simple digitizing of roof corner points and one or more ground points at the base of a vertical wall. A degree of automation is then available to complete the wire frame, as indicated in Fig. 4. This method allows a rapid and basic 3D building and city modeling from single HRSI images. The accuracy of the process depends upon a number of factors, but once again a prerequisite for highest absolute accuracy is an accurate sensor orientation model, as exemplified by bias-corrected RPCs.

5. 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 HRSI. Implicit in this conclusion is that the RPCs produced by Space Imaging and DigitalGlobe 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, not much difference is found 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 utilise sensor orientation models based on low-order empirical functions, such as the 3D affine model.

Finally, where one has the opportunity of utilising bias-compensated RPCs, they should do so with every confidence of achieving 1-pixel level accuracy. This sensor orientation model therefore facilitates geospatial information generation and large scale mapping tasks such as DSM generation, ortho-image production, feature extraction and 3D building modeling to optimal accuracy.

6. ACKNOWLEDGEMENTS

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