SENSOR ORIENTATION FOR HIGH-RESOLUTION SATELLITE IMAGERY: FURTHER INSIGHTS INTO BIAS-COMPENSATED RPCs

H.B. Hanley, C.S. Fraser

Department of Geomatics, University of Melbourne, Vic 3010, Australia
hanley@sunrise.sli.unimelb.edu.au, c.fraser@unimelb.edu.au

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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 notable recent innovations in sensor orientation modelling for HRSI has been bias compensated RPC bundle adjustment, which has shown that geopositioning to high accuracy can be achieved with minimal ground control; indeed, only one control point may be required. Bias-compensated RPCs and related issues are further examined in this paper, with attention being paid to the impact of terrain height variation and the issue of scanning mode. Image scanning characteristics can significantly influence metric performance, with the effect being more pronounced for HRSI sensors that dynamically vary their orientation during scene capture. Through experimental testing with IKONOS and QuickBird stereo imagery, the authors demonstrate that bias-corrected RPCs are capable of yielding sub-pixel geopositioning from base-level imagery products. Thus, bias-compensated RPCs are not only favourable in regard to optimising accuracy capability; they also offer cost advantages.

1. INTRODUCTION

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

As a sensor orientation model for stereo satellite image configurations, rational functions have a history of application spanning nearly two decades (Dowman & Doloff, 2000). However, it was not until the deployment of the IKONOS high-resolution imaging satellite in September, 1999 that widespread industry attention was paid to this 'replacement' model for sensor orientation and ground point determination. Indeed, the commercial photogrammetric industry had little option but to embrace RPC-based restitution, since this was the only means provided by Space Imaging for customers to extract accurate object space information from IKONOS imagery.

There was some early unease associated with the employment of rational functions, but it was soon apparent that the metric accuracy potential of IKONOS would not necessarily be compromised through use of Space Imaging produced RPCs. Indeed, Grodecki (2001) reported that the integrity of modelling the rigorous sensor orientation by RPCs was better than 0.05 pixels. Notwithstanding the very impressive results obtained with IKONOS image restitution via the bias-compensated RPC bundle adjustment approach, some uncertainties have persisted regarding the universal applicability of this sensor orientation approach. Some of this uncertainty can be attributed to the false association of vendor produced RPCs with those

empirically determined by users through the use of dense arrays of GCPs. More curious, however, have been suggestions that RPCs supplied with HRSI would somehow be influenced by variations in the terrain within the scene (eg Cheng et al., 2003).

One area of justifiable concern relates to the impact of sensor scanning mode upon the metric performance of RPCs. This effect is anticipated to be more pronounced with HRSI sensors in imaging modes where the look-orientation is varying significantly 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). Robertson (ibid.) has also observed that such levels of discrepancy would typically be dwarfed by other errors in any orthorectification process. From a practical standpoint, however, the distinction between agreement levels of 0.05 pixels and, say 0.2 pixels, seems rather academic, since theoretical expectations for maximum achievable geopositioning accuracy in practise are around 0.3-0.4 pixels in planimetry and 0.5-0.6 pixels in height.

This paper, which is a condensed version of Fraser & Hanley (2004), describes 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. It also illustrates, by way of a practical example,

that the nature of the terrain being imaged can be expected to have 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.

2. BIAS-COMPENSATED RPC BUNDLE ADJUSTMENT

2.1 The adjustment model

The RPC model provides a direct mapping from 3D object space coordinates (usually offset normalised latitude, longitude and height) to 2D image coordinates (usually offset normalised line and sample values). Here we give only a cursory account of this model in the form that provides bias-compensation. For a more comprehensive account of standard rational function models, as applied to HRSI, the reader is referred to Tao & Hu (2002), Di et al. (2003) and Grodecki & Dial (2003). For the present discussion we present the model in the form

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

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.
  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) and Grodecki & Dial (2003). The model of Eq. 1 has also been referred to as the adjustable RPC model (Ager, 2003).

2.2 Interpretation of orientation: relative and absolute

If we ignore the additional parameters for the moment, then in the same way as do collinearity equations, Eq. 1 describes an imaging ray from object to image space, which we will consider to belong to a 'bundle' of rays (not withstanding the lack of a true perspective centre). If one imagines that spatial intersections of all corresponding rays forming the two or more bundles involved are being determined, then the net outcome is equivalent to a photogrammetric 'relative orientation', which will also be equivalent to that derived via a rigorous model to the accuracy tolerance previously mentioned. The reason the orientation can be thought of as 'relative' as opposed to 'absolute' lies both in the inherent limitations in directly determining the true spatial orientation of every scan line, and in errors within the direct measurement of sensor orientation, especially attitude, but also position and velocity. Errors in sensor orientation within HRSI can, fortuitously, be modelled 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). In the simplest case, a small

systematic error in attitude determination is equivalent to a shift in image space coordinates. But, more than simple translation may be involved.

The case of shift parameters A_0, B_0 alone is one of where, effectively, there is 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. To effect this absolute orientation, only one GCP is required. More GCPs will of course enhance precision, but their number and location is not important. It is hard to see how this relative-to-absolute orientation process could be influenced by terrain height or ruggedness, and indeed we will demonstrate 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 sensors can give rise to both 'drift' effects in the image coordinates and an affine distortion of the image. More subtle, higher-order residual distortions, for example in gyro systems and in scan velocity, may also be present, but we will keep the error compensation model at first order. Thus, in the case of the full affine correction model (Case i) and the shift-and-drift model (Case ii), the relative-versus-absolute orientation situation is slightly different, at least when the parameter sets A_1 and B_1, or A_1, B_1, A_2 and B_2 are statistically significant. In these cases the absolute orientation process does imply a modification of the RPC relative orientation (Eq. 1 without the four APs with subscripts 1 and 2), especially since a non-conformal transformation of image coordinates ocurs. Here, the number and location of GCPs is important, with a practical minimum number being 4-6.

As will be seen, however, the parameters A_1, A_2, B_1 and B_2 are rarely significant with IKONOS Reverse scanned imagery. This means that with such imagery we need only worry about providing one GCP to compensate for the shifts A_0 and B_0. With QuickBird imagery on the otherhand, 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 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.

2.3 Regenerating RPCs corrected for bias

The ability to determine the bias parameters A_0 and B_0 is very useful, but of more utility is incorporation of a correction for the bias into the originally supplied RPCs. This allows bias-free application of RPC-positioning without reference to additional correction terms. This bias compensation 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:

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

Here, a_i, b_i, c_i and d_i are the RPC terms forming F_1, F_2, F_3 and F_4, respectively.

In cases where parameters beyond A_0, B_0, A_1 and B_2 are significant, the RPCs must be re-estimated, rather than simply corrected. This can be carried out using the accepted technique outlined in Grodecki (2001). A software system, *Barista*, has been developed to perform the necessary generation of bias-corrected RPCs. This system allows interactive measurement of selected image points and the necessary GCP(s). It also includes computation of the bias parameters for any number of images, from any number of object points, and it carries out the generation of corrected RPCs in a file format identical to that originally supplied with either IKONOS or QuickBird imagery. This file is thus suited to utilisation with standard photogrammetric workstations that support stereo restitution via RPCs, and it facilitates bias-free 3D ground point determination to metre-level accuracy.

3. EXPERIMENTAL TESTING

3.1 HRSI test ranges

Implicit in the assumption that high accuracy geopositioning can be achieved with bias-compensated RPC bundle adjustment is that RPCs do in fact constitute rigorous reparameterisations of the rigorous sensor orientation model. Thus, the APs $A_0 - B_2$ 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 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 that have been metrically evaluated by the authors, but they constitute two with GCP and image measurements of sufficient accuracy to highlight error signal in sensor orientation at the sub-pixel level.

The first testfield covers a 120 km^2 area of the city of Hobart along with its surroundings. A very prominent feature in the area, lying only 10km or so from the downtown area, is 1300m high Mount Wellington. The Hobart 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 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 Hanley & Fraser (2001) and Fraser et al. (2002), is 0.2 pixels.

The second testfield, for which there is both Ikonos and QuickBird stereo imagery, covers Melbourne. Here we consider only a stereo pair of QuickBird *Basic* images which exhibited a pixel size of 0.75m and a base-to-height ratio of 1. The imagery was recorded in July, 2003. 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.

3.2 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 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 30cm (RMS, 1-sigma) in longitude, and 70 cm in latitude and height are obtained with just 2 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 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 likely represents the effect of a bias of the adjusted position of the single GCP rather than any affine distortion in the relatively oriented 3-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 and also object space, these ranged from 0.1 to 4m for the three images of the *Geo* triplet.

The plots of image coordinate residuals shown in Fig. 1 provide an insight into the question of whether there may have been additional bias error signal in the RPCs, for example from time-dependent drift effects. The residuals for the left-hand stereo and near-nadir images displayed a quite random distribution, suggesting the absence of any further systematic error. Fig. 1a exemplifies this. However, the 'right-hand' stereo image, Fig. 1b, appeared to display residual systematic error in the along-track coordinate. It was found that while the use of drift terms, especially A_1, produced a reduction in the RMS value of image coordinate residuals for this image, from 0.32 to 0.25 pixels in the line coordinate direction, there was no increase in 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 50km. The results obtained in the Hobart testfield are consistent with this view, notwithstanding the small residual systematic error pattern seen in Fig. 1b.

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

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°, 75°, 69°)	110	Full scene; mountainous terrain
QuickBird, Melbourne	300 km^2 (17.5 x 17.5 km)	sea level to 50 m	Stereo pair (approx. 63° each)	81	Full scene, low relief area

Table 1. Characteristics of the Hobart and Melbourne testfields.

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 below ¼ pixel in the cross-track direction, and close to ½ pixel in both the along-track direction and in height.

The results for the stereo pair of *Geo* images alone, without the central image, match very closely those listed in Table 2. From RPC bundle adjustments carried out with the Hobart IKONOS imagery, as well as with other testfield imagery covering areas as large as 2000 km^2 (e.g. Hanley et al., 2002; Fraser & Hanley, 2003), we have ample evidence that sub-pixel geopositioning accuracy is quite achievable from IKONOS *Geo* stereo imagery. This can be expected to be the case irrespective of the nature of the terrain being imaged, the size of the scene, or the scanning mode of the satellite (Forward or Reverse). High quality GCPs and image coordinate measurement are of course prerequisites to the attainment of highest accuracy.

3.3 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. Whether any component of the minor accuracy discrepancy between the two stereo pairs resulted from either the degree to which the original RPCs described the rigorous sensor model, or the resolution and accuracy of the actual orientation sensors on the satellite is not known. What is seen with QuickBird, however, are stronger indications of residual systematic error which is not being modelled by the bias-compensated RPCs.

Shown in Figs. 2a and 2b are plots of the image coordinate residuals arising from the RPC bundle adjustment with shift parameters (row 2 of Table 3). 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).

| 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 RPC bundle adjustments with bias compensation for the IKONOS *Geo* stereo triplet covering Hobart.

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 RPC bundle adjustments with bias compensation for the Melbourne QuickBird *Basic* stereo pair.
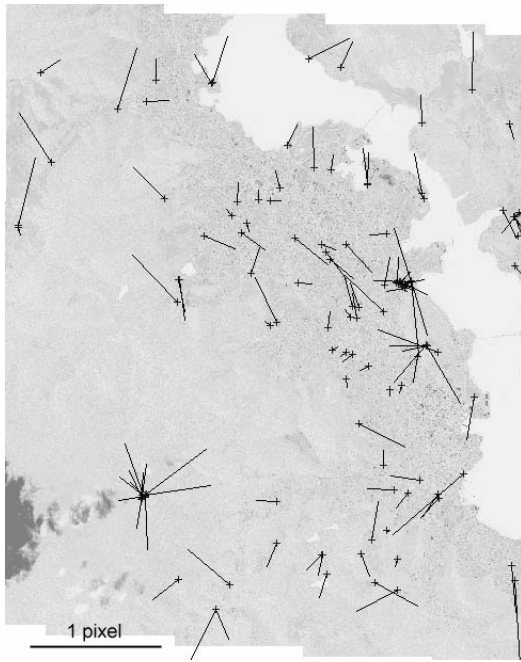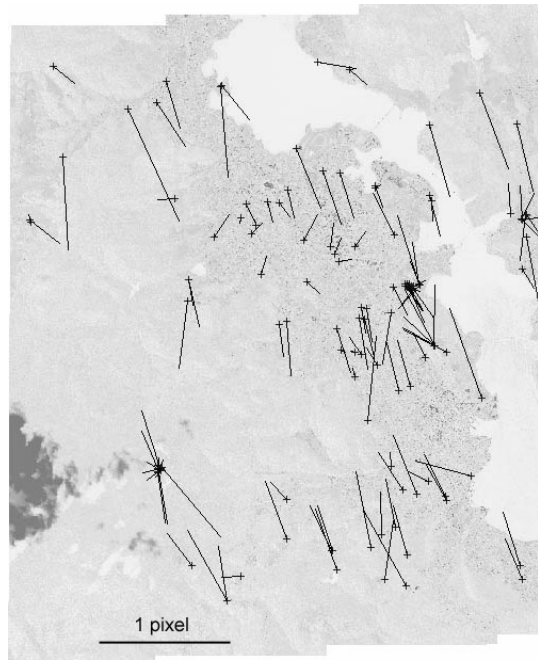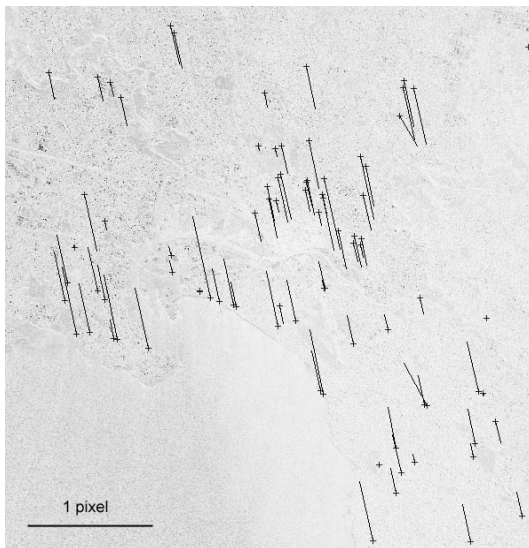
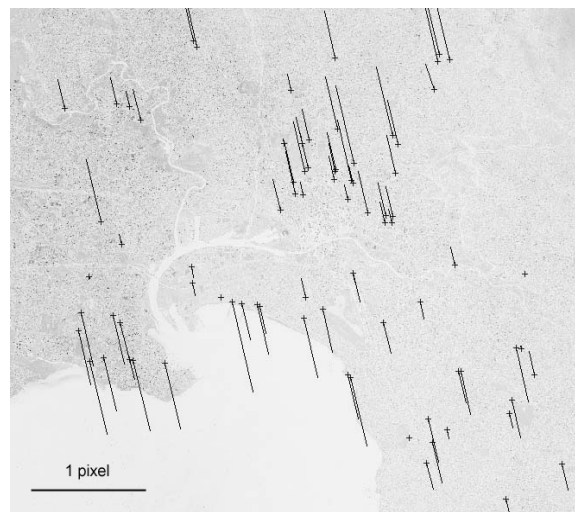a) Left stereo image, APs A_0, B_0 c) Right stereo image, APs A_0, B_0

Figure 1: Image coordinate residuals from RPC bundle adjustments of the IKONOS stereo triplet in the Hobart testfield.

a) Left stereo image, APs A_0, B_0 b) Right stereo image; APs A_0, B_0

Figure 2: Image coordinate residuals from RPC bundle adjustments of Melbourne QuickBird stereo imagery.

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 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 30m in the QuickBird stereo images.

4. 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, we find 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 utilise sensor orientation models based on low-order empirical functions, such as the 3D affine model.

Experience by the authors and others (e.g. Fraser & Yamakawa, 2003; 2004; Noguchi et al., 2004; Hanley et al., 2002) has shown that success with models such as 3D affine transformation is highly dependent on the absence of higher-order error 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 *Basic* stereo imagery suggests that standard low-order empirical models do not yield very impressive accuracy results. On the other hand, where one has the opportunity of utilising bias-compensated RPCs, they should do so with every confidence of achieving optimal accuracy.

5. ACKNOWLEDGEMENTS

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