PROSPECTS FOR MAPPING FROM HIGH-RESOLUTION SATELLITE IMAGERY

Clive S. Fraser
Professor, Department of Geomatics
University of Melbourne
Melbourne VIC 3010 Australia
Email: c.fraser@unimelb.edu.au

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ABSTRACT:

The new technology of high-resolution satellite imagery has demonstrated its metric potential for mapping. Both the Ikonos and Quickbird imaging systems offer ortho-image products meeting map accuracy specifications to scales as large as 1:10,000. The cost of acquiring such mapping products is, however, quite considerable and beyond the means of many prospective international users, especially in the developing world. Fortunately, there are methods available for users with photogrammetric capability to generate high-accuracy mapping from lowest-cost, Ikonos *Geo* and Quickbird *Basic* imagery, with the possibility of achieving savings of 60-70% over the cost of Ikonos *Pro* and Quickbird *Orthorectified Imagery* products. This paper summarises experiences gained with two such practical alternative approaches to metrically processing high-resolution satellite imagery, namely bias-correction for rational functions and affine projection models. These offer the prospects of much more affordable mapping from high-resolution satellite imagery.

1. INTRODUCTION

Shown in Table 1 is the high-resolution satellite imagery (HRSI) product range for Ikonos and Quickbird, offered by Space Imaging and DigitalGlobe, respectively. The products listed are all colour (i.e. pan-sharpened) and the prices are applicable globally in the case of Quickbird, and internationally (non-North America, outside specific international communications cones) in the case of Ikonos. The pricing information will be mainly used in this discussion in a relative sense, and readers seeking appropriate absolute pricing for Ikonos products in particular communications cones (eg Japan, Korea, Eurasia and the Middle East) are referred to Space Imaging's website (Space Imaging, 2002).

Let us assume that a user is seeking to generate ortho-image maps within a scale range of 1:10,000 to 1:25,000. In accordance with Table 1, the minimum level products required would be Ikonos *Pro* and Quickbird *Orthorectified Imagery* (here termed simply *Ortho*), each priced at approximately \$US 110 /km^2 (assume Quickbird *Ortho 1:25,000* since this is available internationally). Thus, in order to obtain ortho-imagery with an RMS accuracy of 5-7m, the user needs to pay some 3.5 times the price of the base products of Ikonos *Geo* and Quickbird *Basic*. Expressed in absolute terms, the ortho-imagery over a 200km^2 area would cost approximately \$US 16,000 more than basic image coverage, though the costs of producing the ortho-imagery from the *Geo* or *Basic* products would reduce this price difference somewhat. Even so, by the standards of aerial mapping, HRSI orthorectified products are quite expensive. One way of reducing the cost burden would of course be to provide the means for users to generate 5m-accurate ortho-imagery from *Geo* and *Basic* imagery. The cost advantages of such a prospect are immediately obvious, but what of practical approaches to make this possible?

Utilisation of Ikonos *Geo* imagery for higher-accuracy geopositioning and mapping has been somewhat constrained by the decision of Space Imaging to withhold the camera model (sensor calibration data). This has left two prospects for users to metrically exploit *Geo* imagery, namely vendor-supplied rational functions (here termed RPCs) and alternative models which do not explicitly require camera model data but do need ground control points (GCPs). In the case of RPCs, these are supplied at a cost premium, with the *Geo Ortho Kit* product. Nevertheless, the cost of the *Pro* product is still 2.3 times the *Geo Ortho Kit* price.

The situation with Quickbird products is a little more straightforward, since DigitalGlobe will make available the required camera model data and also provide RPCs with the *Basic* product. It is noteworthy at this point to mention that due to a level of terrain-dependent geometric correction of the imagery, the *Standard* product is generally not a suitable candidate for metric enhancement beyond its stated accuracy, though a measure of improvement in the 14m geopositioning accuracy is certainly possible in scenes with moderately flat terrain (DigitalGlobe, 2002).

As a result of nearly three year's operational experience with Ikonos imagery and close to one year's experience with Quickbird data, a number of alternative geometric processing approaches have been formulated and tested for metric enhancement of *Geo* and *Basic* imagery. These include a 'rigorous' model approach (Toutin et al., 2001), different forms of affine projection (Fraser et al, 2001,2002a; Yamakawa et al., 2002), and a bias-correction procedure for RPCs which is effectively a bundle adjustment when multiple overlapping images are involved (Fraser & Hanley, 2002; Fraser et al., 2002b, Hanley et al., 2002). These three approaches require modest levels of ground control (a single GCP for RPC correction) and are equally suited to the case of a single image with a DTM, or to stereo image configurations. Two further alternative geopositioning models are terrain-dependent rational functions (Hu & Tao, 2001) and the Direct Linear Transformation (DLT) (Fraser et al, 2001). The first of these is acknowledged to be a 'dangerous' approach for photogrammetric applications, and provision of extensive ground control is required. The situation with the DLT is less problematic, but the author's experience with HRSI has been that the DLT yields similar accuracies to the affine model, but requires more ground control and is less numerically robust.

Table 1. Accuracy specifications and cost of 1m pan-sharpened HRSI products from Ikonos and Quickbird imagery. Prices are 'international' for Ikonos and were current at 23 September, 2002.

HRSI Product	RMS Positional Accuracy	Meets Map Scale Accuracy for:	Price per sq. km ($US)
Ikonos			
Geo	25m	1:100,000	28
Geo Ortho Kit	25m	1:100,000	46
Reference	12m	1:50,000	68
Reference (stereo)	12m	1:50,000	141
Pro	5m	1:10,000	108
Precision	2m	1:5,000	150
Precision (stereo)	2m	1:5,000	275
Quickbird			
Basic	14m	1:50,000	30 [1]
Standard	14m	1:50,000	30 [2]
Ortho, 1:25,000	7.5m	1:25,000	117
Ortho, 1:10,000	6.1m	1:10,000	65 [3]

[1] Based on full scene cost. [2] Limited potential for metric enhancement. [3] Available only in the US.

In this paper it will be demonstrated that users of Ikonos *Geo* and Quickbird *Basic* imagery can generate mapping products with specifications akin to the *Pro* and *Ortho 1:25,000* products through the utilisation of two quite straightforward and practical modelling approaches. One is a bias-correction procedure for RPCs, which requires a minimum of only a single GCP, but does of course require RPCs. The other is an affine model that requires a minimum of four GCPs per scene, though six as a practical minimum would be recommended. For stereo scenes, this is all that is required for high-accuracy ortho-image generation from HRSI, though for single-images a DTM is also needed, except in areas of very low relief variation. For the international user of Ikonos and Quickbird imagery, these approaches, along with equivalent alternatives (eg Toutin et al., 2001) may constitute the only affordable means of exploiting the exciting new technology of 1m satellite imagery.

Of the two methods, it can be said that bias-corrected RPCs constitute a 'rigorous' approach, whereas the affine approach is in large part empirical. Consequently, there are some potential limitations with the affine model which are still being investigated, these assuming practical significance for longer strips of imagery (greater than a nominal scene size), and with some specific object space coordinate systems, e.g. latitude, longitude and height. Nevertheless, as will be shown, the affine approach can yield very high-accuracy results. With a modest amount of further investigation the full merits and shortcomings of the model will be better understood. Testing with the methods described has thus far been conducted over three multi-image

Ikonos 'blocks' covering ground areas of 7 X 7km to 50 X 60 km, and over a single Quickbird Basic scene. As a consequence of the more comprehensive analysis conducted to date with Ikonos imagery, the following discussion of experimental testing will be confined to the metric enhancement of *Geo* imagery.

2. BIAS-CORRECTED RPCs

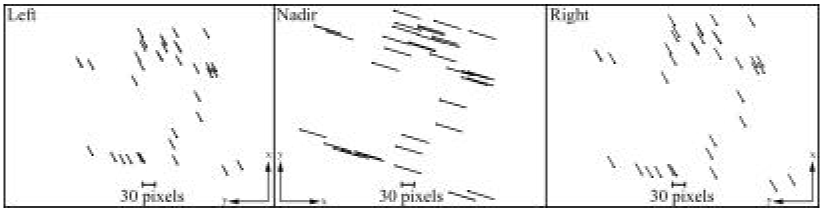
In discussing rational functions, only the RPCs that are provided by the imagery vendor (Spacing Imaging or DigitalGlobe) will be considered. These describe the object-to-image space transformation via an 80-parameter model which constitutes an accurate reparameterisation of the rigorously modelled sensor orientation (Grodecki, 2001):

$$l_n = \frac{Num_L(U,V,W)}{Den_L(U,V,W)} \qquad s_n = \frac{Num_S(U,V,W)}{Den_S(U,V,W)} \tag{1}$$

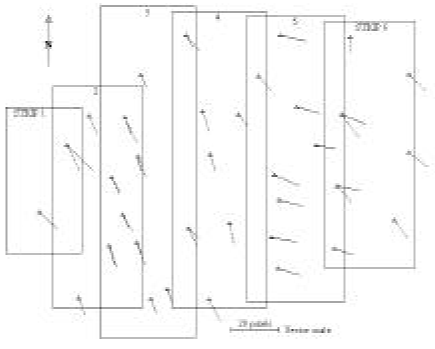
where $Num_L(U,V,W)_j = a_1 + a_2V + a_3U + a_4W + a_5VU + a_6VW + a_7UW + a_8V^2 + a_9U^2 + a_{10}W^2 + a_{11}UVW + a_{12}V^3$
$+ a_{13}VU^2 + a_{14}VW^2 + a_{15}V^2U + a_{16}U^3 + a_{17}UW^2 + a_{18}V^2W + a_{19}U^2W + a_{20}W^3$

and the expressions for $Den_L(U,V,W)$, $Num_S(U,V,W)$ and $Den_S(U,V,W)$ are similarly constructed with coefficients b_i, c_i and d_i, respectively. Also, l_n, s_n are the normalised (offset and scaled) line, sample image coordinates and U, V, W are the corresponding object point coordinates, which refer to normalised latitude, longitude and height.

In order to perform an image-to-object point transformation, either stereo image coverage or known height in the case of a single image is required. In stereo networks, ground coordinates can be obtained from the RPCs via an indirect least-squares spatial intersection model (eg Fraser et al., 2002a,b). Unfortunately, RPCs generated from recorded sensor exterior orientation, without reference to ground control, can be expected to display biases, which can reach 50m and more on the ground for *Geo* imagery (Fraser et al., 2001). For example, shown in Fig.1 are the biases in image space found for three different sets of Ikonos *Geo* imagery, an image triplet comprising a stereo pair and a nadir image over Melbourne (Fig.1a), a 25km strip over San Diego (Fig. 1b), and 6 strips of overlapping imagery over Mississippi (Fig. 1c). The vectors show the familiar near strip-invariant difference between measured image points and the corresponding positions obtained by projecting the GCP position into the image via Eq. 1. Although the magnitude of the bias vectors varies between just a few pixels and 70 pixels, the standard errors for all images are well under one pixel, confirming the high degree of invariance of image point biases within an image.



(a) Melbourne 3-image network.



(b) San Diego, 1 strip, near nadir image. (c) Mississippi, left-hand stereo images only.

Figure 1. Plots of RPC image point biases for the Melbourne (a), San Diego (b) and Mississippi (c) Ikonos *Geo* blocks.

Under the assumption that RPC biases manifest themselves for all practical purposes as image coordinate shifts, a model for spatial intersection with bias compensation, which comprises one offset parameter per image coordinate, can be derived as follows (Fraser & Hanley, 2002; Fraser et al., 2002a,b; Dial & Grodecki, 2002):

$$\begin{pmatrix} v_l \\ v_s \end{pmatrix}_{ij} = \begin{pmatrix} \frac{\partial F_1}{\partial f} & \frac{\partial F_1}{\partial l} & \frac{\partial F_1}{\partial h} & 1 & 0 \\ \frac{\partial F_2}{\partial f} & \frac{\partial F_2}{\partial l} & \frac{\partial F_2}{\partial h} & 0 & 1 \end{pmatrix}_{ij} \begin{pmatrix} df_j \\ dl_j \\ dh_j \\ A_{0i} \\ B_{0i} \end{pmatrix} + \begin{pmatrix} l^o - l \\ s^o - s \end{pmatrix}_{ij} \tag{2}$$

where v_l and v_s are observational residuals in pixels; , , h are corrections to approximate values for the object point coordinates in latitude, longitude and ellipsoidal height; l^0, s^0 are the image coordinates corresponding to the approximate object coordinates (obtained via Eq. 1); F_1 and F_2 are the two expressions forming Eq.1, and A_{0i} and B_{0i} are image coordinate biases that are common to image *i*. Within the least squares solution it is necessary to use *l, s*, and *h* instead of their normalized counterparts to account for different scales and offsets between images. In a 'bundle adjustment' of a stereo strip or block via Eq. 2, only one GCP is necessary for absolute geopositioning. The spatial intersection model is also applicable to multi-image triangulation using the Ikonos RPCs for images that exhibit very different bias characteristics, and the bias-correction model can be expanded to accommodate drift effects in the along- and cross-track directions (Hanley et al., 2002; Dial & Grodecki, 2002).

The ability to determine the bias parameters A_0 and B_0 is very useful, but of more utility is the incorporation of the bias compensation into the originally supplied RPCs. This allows bias-free application of RPC-positioning without any reference to additional correction terms. Fortunately, it turns out that this bias compensation is a very straightforward matter, as shown in Fraser & Hanley (2002) and Fraser et al. (2002b). 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 the Ikonos imagery. This file is thus suited to utilisation with standard photogrammetric workstations that support stereo restitution via Ikonos RPCs, and it will facilitate bias-free 3D ground point determination to metre-level accuracy.

3. THE AFFINE MODEL

Rational functions with vendor-supplied RPCs offer an effective alternative to collinearity-based sensor orientation models, but as mentioned, with Ikonos *Geo* imagery there is a significant financial cost involved. Also, in some markets, for example Japan, RPCs are not available at all with Ikonos imagery. There is therefore a considerable incentive to develop a practical sensor orientation model that has no requirement whatsoever for camera or exterior orientation parameters, but does need some GCPs. The author's research group have investigated a number of such models, notably the well-known DLT, an affine projection model and an affine-projective model (affine in line direction and projective in sample direction). Studies with *Geo* imagery from the smaller Melbourne 'block' (eg Fraser et al., 2001, 2002a; Yamakawa et al., 2002) suggest that of these alternative orientation models, the affine model shows the most promise. Although the affine model can be justified in terms of the narrow view angle of the Ikonos sensor, the model is nevertheless a special case of the rational function model. Thus, the following equations for the affine model are given in RPC terms as follows:

$$\begin{aligned} l_n &= \frac{Num_L(U,V,W)}{Den_L(U,V,W)} \\ s_n &= \frac{Num_S(U,V,W)}{Den_S(U,V,W)} \end{aligned} \tag{3}$$

where

$$Num_L\left(U,V,W\right)_j = a_1 + a_2 V + a_3 U + a_4 W$$

$$Den_L\left(U,V,W\right)_j = 1$$

$$Num_S\left(U,V,W\right)_j = c_1 + c_2 V + c_3 U + c_4 W$$

$$Den_S\left(U,V,W\right)_j = 1$$

Once again, the image line and sample coordinates are offset-normalised, as are the object space coordinates. Although the offsetting and normalisation is not required, we have chosen to be consistent with RPC terminology because there is then the potential that the affine coefficients can be provided in a format the same as 'standard RPCs' and so can be directly employed with a photogrammetric workstation. There is one difficulty associated with this idea, however, especially in the case of long image strips, where it may not be advisable to have the *(U,V,W)* coordinates representing normalised *(, h)* if highest accuracy is sought. Even with two additional parameters comprising quadratic correction terms, the affine model cannot always adequately account for the non-linear nature of the geographical coordinates.

To a much lesser extent the same is true for Cartesian coordinates in the case of strips of around 50km in length and the author's experience is that a standard 8-parameter affine model yields the best results when the chosen object space coordinate system is UTM. If a local Cartesian system is adopted, the affine model benefits from the inclusion of two additional parameters, namely a V^2 term in both the line and sample expressions. Here, only the results achieved with a model of eight parameters per strip and normalised UTM GCP coordinates with ellipsoidal heights are considered. Investigations into the full potential and limitations of the affine model are still being conducted. These take into account variables such as strip length, sensor orientation, ground coordinate system, and terrain elevation range. In the implementation of the affine projection model for *Geo* image orientation, all affine parameters are recovered simultaneously along with *U,V,W* ground coordinates in a process analogous to bundle adjustment.

4. APPLICATION OF ORIENTATION/TRIANGULATION MODELS

4.1 Test Data

The bias-corrected RPC ground point determination method, along with the affine model, have thus far been evaluated using three multi-image Ikonos *Geo* test data sets. The first of these was a 3-image triplet comprising a stereo pair and nadir image, the second a block of three overlapping strips comprising seven images, and the third a block of six overlapping strips of stereo images.

The Melbourne Ikonos Testfield formed the first data set. This covers a 7 x 7 km area of the city of Melbourne and currently comprises over 40 GPS-surveyed ground GCPs, 32 of which are road roundabouts. The remaining points are corners and other distinct features conducive to high precision measurement in both the imagery and on the ground. This array of ground points has been imaged with three-fold Ikonos *Geo* coverage comprising a stereo pair of panchromatic images and a near-nadir scene of panchromatic and multispectral imagery. The nadir image was recorded several months prior to the stereo images. In order to ensure high-accuracy GCPs and image coordinate data, multiple GPS and image measurements were made to 0.1-0.2 pixel accuracy for each feature point, with the centroids of roundabouts being determined by computing a best-fitting ellipse to six or more edge points around the circumference of the feature, in both object and image space (see Hanley & Fraser, 2001).

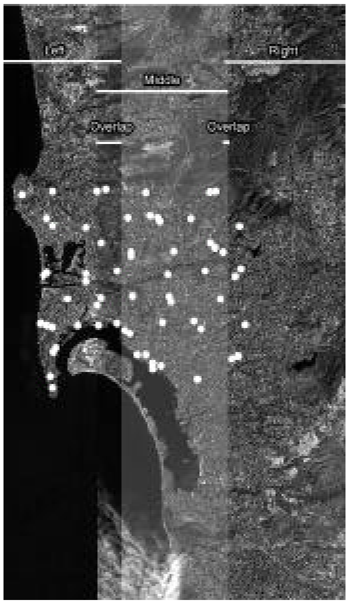


Figure 2. San Diego block & GCPs.

The second block, shown in Fig. 2, comprised three overlapping strips of stereo *Geo* imagery and covered an area of 50x50 km, although the ground control array of 62 GCPs was confined to a 24 x 24km area of central San Diego. The present investigation is thus restricted to the 580km^2 area containing the GCPs, which displayed an elevation range of 220m. The left most image strip had three-fold coverage consisting of a forward/nadir/reverse triplet recorded in a single orbit, whereas the middle and right strips each comprised a forward/reverse stereo pair. The left and middle strips overlapped by about 2.5 km and shared eight common GCPs, while the middle and right strips overlapped by only 400m and had no common GCPs. The accuracy of the GCPs was nominally sub-metre.

Shown in Fig. 1c is the 6-strip *Geo* image configuration of the approximately 50 x 60km Mississippi block (see also Dial & Grodecki, 2002), which comprised 36 GCPs and 16 measured tie points. As distinct from the San Diego and Melbourne imagery, the author had access to the measured image and GCP coordinates, and to the RPCs for the 12 images, but not to the imagery. The analysis for the block was therefore confined to this ground point data set alone. An advantage of the Mississippi block was that is allowed an investigation of the merits and shortcomings of alternative orientation models over a large area of 2800 km^2. A disadvantage was that there was no quantitative estimate of accuracy for either the GCPs or the supplied image coordinate observations.

4.2 RPC Bundle Adjustment Results

Table 2 provides a summary of the results of the RPC bias compensation 'bundle adjustments' of the three blocks of Ikonos *Geo* imagery, for a number of GCP configurations. The resulting RMS values of image space residuals ranged from about 0.2-0.4 pixels. It is noteworthy that positioning accuracy (RMS 1-sigma) in planimetry of better than 1 pixel was obtained in all cases, with height accuracy being between 0.6 and 1.5 pixels. The smaller Melbourne block, which had the most precisely surveyed GCPs and the most accurate image coordinate observations, produced the highest ground point accuracy. Given that the author does not have an estimate of either precision of the measured GCPs in the San Diego and Mississippi blocks, or the accuracy of image coordinate observations in the latter, results at the 1-metre accuracy level are seen as quite satisfactory, and certainly good enough to demonstrate the effectiveness of the RPC bias compensation approach in block sizes exceeding 1000km^2.

The role of the GCPs is to effect an image coordinate translation and thus their location within the scene is of no real consequence; addition of further GCPs makes no contribution to the geometric strength of the triangulation process per se. Instead the extra control points simply provide more information from which to evaluate an appropriate 'average' image coordinate correction. It can be seen in Table 2 that there is no clear link between the accuracy level attained and the location or number of GCPs. Nevertheless, with the use of redundant control points one can be more confident about the reliability of the geopositioning process.

Table 2. Ground Point Accuracy from Bias-Compensated Bundle Adjustments

Block & GCP config.	*RMS, chkpt resids.*	
	S_{XY}	S_Z (m)
Melbourne(3 images)		
1 (centre)	0.42	0.62
2	0.45	0.70
4 (corners)	0.42	0.71
6 (corners + 2 middle)	0.41	0.64
San Diego (7 images)		
1 (lower left)	0.72	1.29
1 (upper right)	1.02	1.26
4 (corners)	0.70	1.46
6 (corners + 2 middle)	0.63	1.23
Mississippi(12 images)		
1 (lower left)	0.90	1.57
1 (upper right)	0.89	1.26
4 (corners)	0.94	1.26
6 (corners + 2 middle)	0.95	1.17

Table 3. Ground Point Accuracy from Bundle Adjustments via Affine Model.

Block & GCP config.	*RMS, chkpt resids.*	
(GCPs in UTM)	S_{XY}	S_Z (m)
Melbourne (3 images)		
(4 GCPS, 40 Chk pts.)	0.43	0.58
(6 GCPS, 40 Chk pts.)	0.39	0.54
San Diego (5 images)		
(9 GCPs, 47 Chk pts.)	0.76	1.03
Mississippi (8 images)		
(15 GCPs, 25 Chk pts.)	0.79	1.13

4.3 Results from the Affine Model

The normal scenario for block formation with Ikonos imagery is to have a small overlap between strips, for example 10%. This geometric configuration unfortunately offers the prospect of adding via tie points additional signal to model affine distortion only in the along-track direction. Thus, it is generally warranted to provide the necessary minimum of 4 GCPs for each strip in the affine block adjustment computation. The GCP configurations selected for the testing within the San Diego and Mississippi blocks reflected this requirement, and strips contained from four to six GCPs. The single-strip Melbourne image triplet utilised four and six GCPs.

In the case of Melbourne and San Diego, the GCPs were real GPS-surveyed ground points and thus the affine triangulation allowed an assessment of absolute accuracy. In the Mississippi block, however, some of the selected GCPs were actually points that were measured only in the imagery, their ground coordinates having been determined through the RPC bias-compensated block adjustment procedure. This was unavoidable given the number of ground points available (recall that the imagery was not provided) and it meant that the results in the Mississippi block indicated accuracy with respect to the RPC triangulation, which effectively corresponded to the optimal possible solution.

Table 3 summarises the ground point determination results obtained using the affine model approach. Because of the relatively few control/checkpoints in the right-hand strip of the San Diego imagery, the affine model was applied only to the block comprising the left-hand and central strips. Similarly, in the case of Mississippi only four strips were included because of a shortage of checkpoints in the outer two strips. The results in the table show that the affine model applied to single- and multi-strip block configurations can produce object point positioning accuracy to the same level as achieved with bias-corrected RPCs, namely sub-pixel accuracy in planimetry and close to 1-pixel accuracy in height.

The attainment of accuracy equivalent to the bias-corrected RPC model is an important outcome of the investigation into the affine approach, because it demonstrates that long strips (greater than the nominal 11km Ikonos scene length) can be accommodated without loss of model fidelity. As has been stated on the occasion of the success of the affine model within the Melbourne testfield (Fraser et al., 2002a), the finding that such a straightforward 8-parameter linear model can produce geopositioning accuracy on a par with that from the 80-parameter RPC model (after bias removal) is very encouraging for the practitioner. Within the 50 km^2 Melbourne block, the adoption of object space units of latitude, longitude and height or local Cartesian (X,Y,Z) in Eq. 3 had no impact on the accuracy obtained. However, use of local Cartesian instead of UTM GCP coordinates degraded the results to S_{XY} = 1.0m and S_Z = 1.9m in the Mississippi block. The corresponding values in the San Diego block were S_{XY} = 0.7m and S_Z = 1.3m, which demonstrates the adverse influence of longer strip length when Cartesian coordinates are employed. A similar degradation is found when geographic coordinates are employed with only an 8-parameter model.

5. CONCLUSIONS

Users of Ikonos *Geo* imagery who seek to perform highest-accuracy geopositioning or processing such as orthoimage generation or DTM extraction can be very encouraged with the equivalence of the results obtained by the bias-corrected RPC and affine models. The question as to whether one should employ the empirical affine sensor orientation model or RPCs might well reduce to a matter of economics. The affine model requires more ground control (let's say 6-8 points per strip would be advisable), but *Geo* RPCs come at a price premium that could well exceed the cost of establishing and measuring the GCPs and carrying out the affine model computation. The answer to the question is left to the user, who of course would need the facilities to handle both approaches, for example via a software system such as the mentioned *Barista* system. One issue is clear, namely that both approaches yield accuracy results equivalent to the much more expensive *Pro* and *Precision* range of Ikonos products. Of practical significance is the fact that both HRSI orientation/triangulation models can be made readily compatible with the requirements of photogrammetric workstations which accommodate the RPC approach to stereo satellite image restitution.

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