

Georeferencing Accuracy of GeoEye-1

With bias-corrected RPCs and a single GCP, the RMS georeferencing accuracy of GeoEye-1 stereo imagery reaches the unprecedented level of 0.10m (0.2 pixel) in planimetry and 0.25m (0.5 pixel) in height.

INTRODUCTION

GeoEye-1, launched in September 2008, is the latest in a series of commercial high-resolution Earth observation satellites. With its ground sample distance (GSD) of 0.41m for the panchromatic band, GeoEye-1 offers the highest resolution yet available to the spatial information industry. However, for commercial users, image products are down-sampled to 0.5m GSD. Specifications for GeoEye-1 quote an accuracy in geolocation of better than 3m without ground control, specifically 2m and 2.5m Circular Error 90% (CE90) in planimetry for stereo and mono, respectively, and 3m Linear Error 90% (LE90) in height for stereo coverage (GeoEye, 2009). GeoEye-1 will thus constitute a suitable source of imagery for large scale topographic mapping, to scales of 1:5,000 and possibly larger.

Following a 5-month commissioned phase, commercial operations with GeoEye-1 commenced in February 2009. Not surprisingly, one of the first issues of interest within the photogrammetric community has centered upon the system's potential metric accuracy for precise geopositioning and subsequent generation of Digital Elevation Models (DEMs) and orthoimages. Based on nearly a decade of experience with imagery from Ikonos and other High-Resolution Satellite Imaging (HRSI) systems, one could infer that geopositioning accuracy to around 0.5 to 0.7 pixels in planimetry and 0.7 to 1 pixel in height would be readily achievable from the GeoEye-1 imagery. This assumes the use of vendor supplied Rational Function Coefficients (RFCs), with sensor orientation biases having been compensated through RPC-bias correction (Fraser and Hanley, 2003; Grodecki and Dial, 2003) via a modest number of high quality ground control points (GCPs), one being the minimum required. Also assumed is an image mensuration accuracy of better than 0.5 pixels, via manual measurement or image matching. For GeoEye-1, which has basically the same orbit height (~680km) as Ikonos and a 13m focal length camera (10m in Ikonos), these findings suggest an expected 3D georeferencing accuracy from stereo imagery of around 0.25-0.3m in planimetry and 0.4m in height.

In mid-February, the authors were provided with a stereopair of GeoEye-1 images covering the Hobart HRSI test field (Fraser and Hanley, 2005) in Hobart, Tasmania, Australia. This article will briefly report on the process undertaken to quantify the geopositioning accuracy of GeoEye-1, perhaps for the first time, within the Hobart test field. The account of this experimental assessment concentrates on practical aspects. As will be seen, GeoEye-1 can yield geopositioning accuracy (RMS 1-sigma) of close to 0.10m (0.2 pixels) in planimetry and 0.25m (0.5 pixels) in height through the use of a single GCP, which exceeds expectations based on the experience with Ikonos.

IMAGE DATA AND TEST FIELD

GeoEye-1 Stereo Pair

The GeoEye-1 stereo image pair was captured in reverse scan mode on February 5, 2009, with the panchromatic band and all four multispectral bands being recorded. The scene covered an area of 13.5km in the E-W direction by 15.8km N-S (the nominal scene width of GeoEye-1 is 15.2km), as shown in Figure 1. The forward looking image had a collection azimuth of 53.4° and an elevation of 63.9°, while the corresponding values for the backward looking image were 139.7° and 70.1°. The scan azimuth in each case was 270° or east-to-west, and the resulting Base/Height ratio was 0.6. For the accuracy analysis described here, only the panchromatic images have been considered, these having been processed to standard geometrically corrected level, as well as bundle-adjusted without reference to GCPs prior to the generation of the RPCs.

GeoEye-1 Imagery

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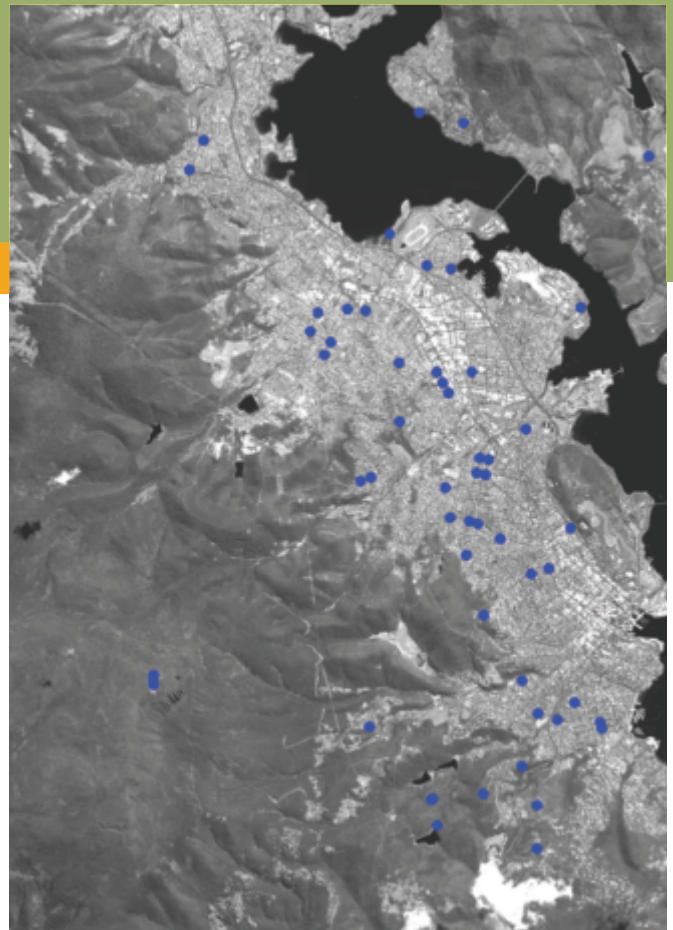
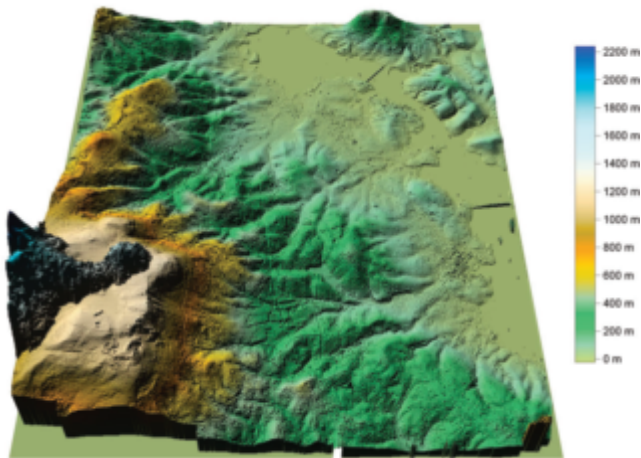


Figure 1. Hobart HRSI Test Field. (L) Ikonos-derived DEM (dark area in lower left is a cloud). (R) GeoEye-1 scene showing final 55 GCPs.

Test field

The Hobart HRSI test field covers an approximately 120km² area with topography varying from undulating terrain near sea-level to a mountain top at over 1,200m elevation. Land cover varies from forest to suburbia, to the central business district of Hobart. Figure 1 shows both the GCP/Checkpoint layout and a DEM for the test field. In the context of high-precision georeferencing from HRSI, a unique feature of the Hobart test field is that the majority of GCPs are road roundabouts, samples of which are shown in Figure 2. The positions of the roundabouts were determined to an accuracy of about 5cm by surveying a dozen or so points around their circumference with GPS and then applying a best-fitting ellipse to compute the center point. The same procedure was employed for measuring the corresponding image points.

It had been six years since the GCPs of the Hobart test field were measured by GPS. Thus, the first stage of the accuracy evaluation process was to ascertain which GCPs still constituted good control. Initially, all GCPs were back projected into the stereo images using the *Barista* software system for HRSI data processing (Barista, 2009) and a visual assessment was undertaken. It immediately became clear that many of the 100 or so original GCPs that fell within the GeoEye-1 scene area would not be usable. Some points had “moved”, for example markings on sports fields and tennis courts, hedge intersections and even some road detail; whereas others, while being sufficiently definable for Ikonos purposes, were insufficiently so for the 50cm resolution of GeoEye-1. Examples of “moved” points, both subtle

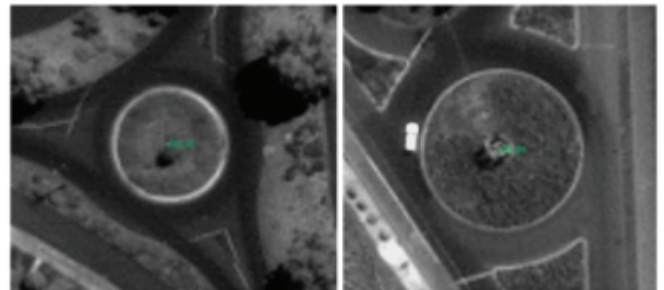


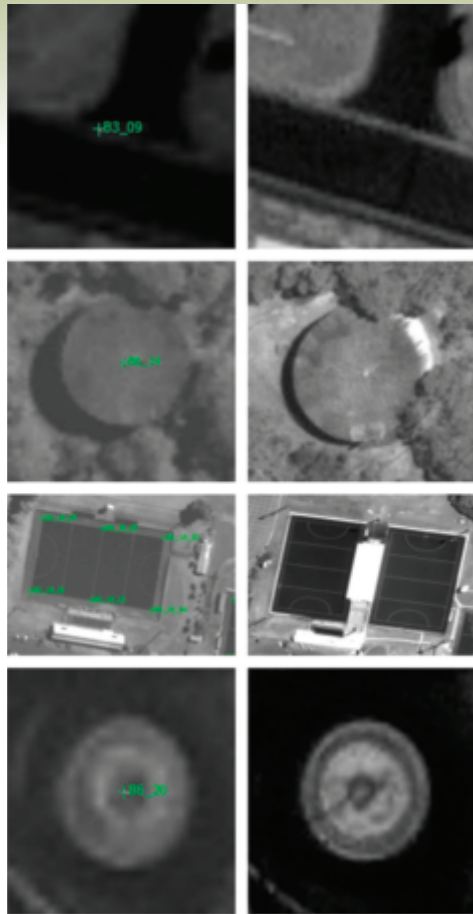
Figure 2. Sample road roundabout GCPs.

and obvious, are shown in Figure 3. As a result, the final number of GCPs adopted for the investigation was 55, including three at 1,260m elevation on the top of Mt. Wellington, even though these arguably fell a little short of the quality required. All but a half dozen of the GCPs were road roundabouts or circular tanks.

Image Measurement

The image measurements were carried out via monoscopic digitization within *Barista*, with two independent data sets being obtained. At least 10 points were digitized on the circumference of each roundabout, with the computed standard deviation of the center point in the best-fitting ellipse computation being in the range of 0.04 to 0.08 pixels. In order to avoid the possibility of back-projected points biasing the image measurement process, the RPCs were manually altered such that existing GCPs, which served as guide points, were projected 10m below (south of) their true positions in the images. Smaller biases were present in the RPCs as well, which is a subject that we will now turn to.

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(a) Ikonos (b) GeoEye-1
Figure 3. Examples of GCPs that had either "moved" or were otherwise deemed unsuitable.

IMPACT OF RPC BIASES

Initial Determination via Monoplotting

Biases in HRSI RPCs generated from sensor orientation, which are generally attributed to small systematic errors in gyro and star tracker recordings, have been shown to be adequately modeled by zero-order shifts in image space. For moderately flat terrain and near nadir imagery, these biases can be quite easily quantified by simply computing planimetric coordinates in object space via the RPCs and comparing these to known ground coordinates. In the case of oblique imagery over mountainous terrain, however, the concept of monoplotting needs to be adopted in order to achieve pixel-level accuracy for bias error determination.

The *Barista* system incorporates monoplotting functions, monoplotting being the familiar photogrammetric procedure that enables 3D feature extraction from single, oriented images when there is an underlying DEM. In the case of Hobart, an Ikonos-derived DEM was available. The height accuracy of this had been shown to be around 3m for the road roundabouts. A dozen GCPs were monoplotted in order to gain an initial estimate of the planimetric geopositioning biases. The resulting values for Easting and Northing coordinates were 1.1m and 3.1m (2.2; 6.2 pixels) for the forward-looking image, and -0.6m and -2.2m (-1.2; -4.4 pixels) for the backward-looking image. The standard deviation of each estimate was very close to 0.25m or 0.5 pixels.

3D Biases from Space Intersection

Biases within the RPCs also have a direct impact on 3D geopositioning from a stereo image pair. For the Hobart GeoEye-1 stereo pair, geolocation was performed via space intersection using the supplied RPCs. Systematic errors in object point coordinates of -2.1m in Easting, 0.5m in Northing and -7.6m in height resulted. (The vertical bias was reduced in a subsequent reprocessing of this early sample data by GeoEye.) It is noteworthy that modest biases of a few pixels in each image can be manifest as much more significant errors in height determination. One very encouraging feature of the initial 3D ground point determination was that the standard deviation for the resulting coordinate errors in object space was 0.12m in planimetry and 0.25m in height, which suggested the capability of bias-free geopositioning to an accuracy of 0.25 pixels in the horizontal and 0.5 pixels in the vertical.

The monoplotting and RPC spatial intersection determinations of biases were illustrative of two aspects that had previously become familiar with other HRSI systems, namely that although relative positional accuracy at the sub-pixel level can be readily achieved in the absence of ground control, absolute geolocation to 1-pixel or better accuracy cannot be assured without the provision of GCPs. While it might be tempting to compare the geopositioning errors found in Hobart to the geolocation accuracy quoted for GeoEye-1, this is not really valid. Implicit in the specified 2-2.5m CE90 and 3m LE90 values for GeoEye-1 is the assumption that a sizable random sample of data is available. In this context, however, the sample size of the 50+ ground points in the Hobart Testfield is only 1, since the same systematic error applies to all measured coordinates. We now turn our attention to the accuracy potential of GeoEye-1 in the case where such positional bias errors can be readily compensated.

BIAS-CORRECTED GEOREFERENCING

Bias-Compensation Model

A practical means of modeling and subsequently compensating for the biases inherent in RPCs is through a block-adjustment approach introduced, independently, by Grodecki and Dial (2003) and Fraser and Hanley (2003). In this approach, the standard rational function equations that express scaled and normalized line and sample image coordinates (l, s) as ratios of 3rd order polynomials in scaled and normalized object latitude, longitude and height (U, V, W) are supplemented with additional parameters, as indicated in Equation 1.

$$l + A_0 + A_1 l + A_2 s = \frac{Num_l(U, V, W)}{Den_l(U, V, W)} L_s + L_0 \quad (1)$$

$$s + B_0 + B_1 l + B_2 s = \frac{Num_s(U, V, W)}{Den_s(U, V, W)} S_s + S_0$$

Here, the parameters A_i, B_i describe an affine distortion of the image. Three likely choices for additional parameter sets for bias compensation are:

- i) $A_0, A_1, \dots, B_2$, which describes an affine transformation,
- ii) A_0, A_1, B_0, B_1 , which models shift and drift for a N-S scan, or A_0, A_2, B_0, B_2 , which models shift and drift for an E-W scan; and
- iii) A_0, B_0 , which represent image coordinate translations.

Practical experience with Ikonos imagery has indicated that of the terms comprising the general additional parameter model, the only two of significance in stereo pair orientation, even for high accuracy applications, are the shift terms A_0 and B_0 . This suggests that within the few seconds needed to capture an image, the time-dependent errors in sensor orientation remain constant.

An additional benefit of restricting the image correction model to shift terms alone is that the estimated parameters A_0 and B_0 can be directly applied to correct the original RPCs, thus providing a very effective means of bias-compensation (Fraser and Hanley, 2003; 2005). Alternatives such as utilizing the full affine image correction model or modeling the orientation biases in object space lead to the necessity of regenerating the RPCs, which is a less straightforward option than simple correction. Moreover, as soon as drift and affine coefficients are included in the bias compensation model, the geometric distribution and number of GCPs becomes a factor of significance, whereas for compensation by shift-terms alone only a single GCP is needed and its location within the scene has little bearing on the bias-compensation process.

Equation 1 can be formulated into a linear indirect model for bias-compensated object point determination. Since the process involves a least-squares adjustment of image coordinate observations and the estimation of exterior orientation, albeit indirectly, it has been termed a “bundle adjustment”, or indeed a block adjustment in cases where a number of images are included.

Results for Four GCP Configurations

As mentioned, for bias-compensation via the two shift terms alone, only one GCP is necessary. For the Hobart GeoEye-1 stereo pair, a number of 1-, 2- and 4-GCP configurations were tested. In the first 1-GCP case, the control point was near the middle of the test field at an elevation close to sea-level, and in the second, one of the three points on Mt. Wellington at an elevation of 1260m was selected. Both these GCPs were then employed in a 2-GCP adjustment, and we also report here on the results of a case of 4 GCPs. Tables 1 and 2 summarize the results.

The values shown for the line and sample bias terms are representative for all four cases, since the respective estimates of A_0 and B_0 varied by 0.1 pixel or less in each adjustment. The computed standard deviations for these shift parameters ranged from 0.15 pixels for the case of one GCP at sea level, to 0.1 pixel for the shift in the line coordinate for the single GCP on the mountain top. Similarly, the RMS values of image coordinates are representative for each adjustment since these were all in agreement to within 0.02 pixels.

Table 1. Image coordinate residuals and biases (shift parameters) in image space.

Image		Line (pixels)	Sample (pixels)
Forward-looking	RMS of image residuals	0.07	0.22
	Line/sample bias	6.7	-1.9
Backward-looking	RMS of image residuals	0.07	0.19
	Line/sample bias	-4.2	1.2

The most striking result presented in Table 2 is the very high accuracy achieved in geopositioning. The RMSE of the 50+ checkpoints is at the unprecedented level of 0.1m or 0.2 pixels in planimetry, and 0.25m or 0.5 pixels in height. This surpasses the results previously reported for Ikonos or QuickBird by a significant amount and takes HRSI accuracy performance to a new level, at least in the authors' experience. Whereas the anticipated discrepancy between RMS values of line and sample image coordinates is present, the line coordinates lying close to within the epipolar plane, the familiar difference between accuracy achieved in Northing versus Easting, which is normally associated with a N-S scanning direction, is no longer present, the scan here being E-W. Another feature of Table 2 is that the checkpoint RMSE values are considerably smaller than is suggested by the corresponding coordinate standard errors, at least for Easting and height.

In order to ascertain whether the drift or affine correction terms in Equation 1 would assume significance, additional bias-compensation block adjustments were computed. The extension of the additional parameter model to both shift and drift parameters (A_0 , A_2 , B_0 and B_2), and the full affine model (all A_i and B_i) did not alter the RMS value of image coordinate residuals by more than 0.02 pixels, or the RMSE values for object point coordinates by more than 0.02m. These parameters were thus shown to have no significance on the georeferencing process.

Results of “Free-Net” Solution

Free-net bundle adjustment is generally taken to mean the computation of relative orientation free of any shape constraints imposed by ground control. This can be approximated in RPC block adjustment by utilizing GCPs with low *a priori* weights, which are sufficient to remove, at least numerically, the singularity arising from the datum not being “fixed”. This approach offers the advantage of producing a best-fit to ground control of the relatively oriented network of images. Or, expressed another way, the adjustment will yield a solution which minimizes the overall checkpoint RMSE value (the checkpoints here are GCPs with low weight). In order to achieve a “free-net” solution for the Hobart GeoEye-1 bundle adjustment, all GCPs were assigned *a priori* standard errors of 5m (i.e. 10 pixels) and the shift terms alone were again adopted in the adjustment, the results of which are shown in Table 3.

For all practical purposes, the RMSE values listed in Table 3 match those of the 1- to 4-GCP cases of Table 1, even though the RMSE in height improves to 0.18m, which is equivalent to 0.4 pixels. Note also that no individual coordinate error in the georeferencing exceeds the

Table 2. Results of block adjustment with 1, 2 and 4 GCPs.

GCP configuration	RMSE against 55 Checkpoints (m)			Mean Object Point Standard Error (m)		
	s_E	s_N	s_H	σ_E	σ_N	σ_H
Case A: 1 GCP at sea level	0.13	0.10	0.25	0.18	0.13	0.43
Case B: 1 GCP at 1260m elev.	0.11	0.10	0.28	0.19	0.13	0.45
2 GCPs from Case A & B	0.11	0.10	0.24	0.16	0.11	0.38
4 GCPs	0.11	0.10	0.24	0.15	0.10	0.34

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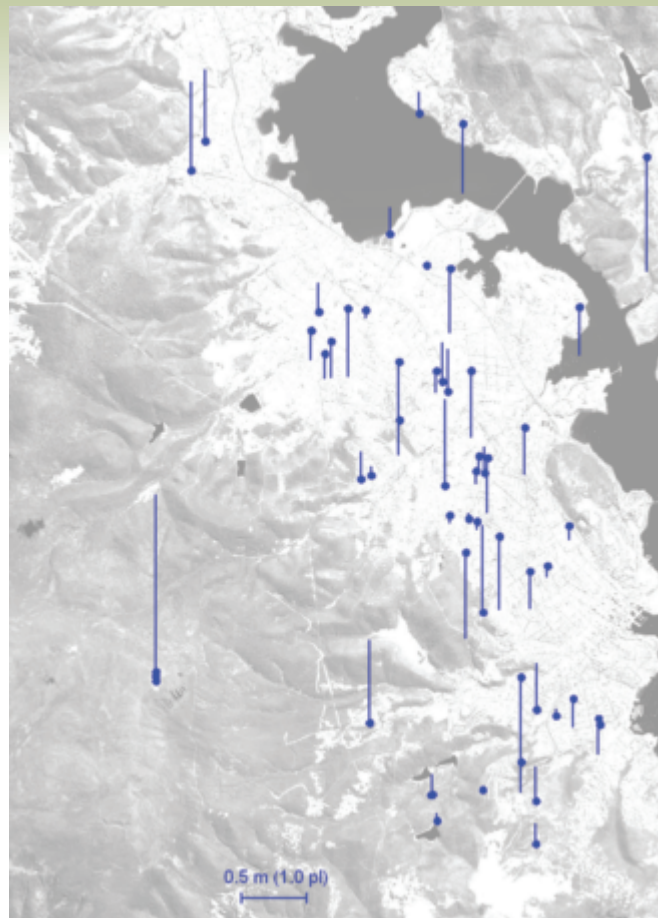
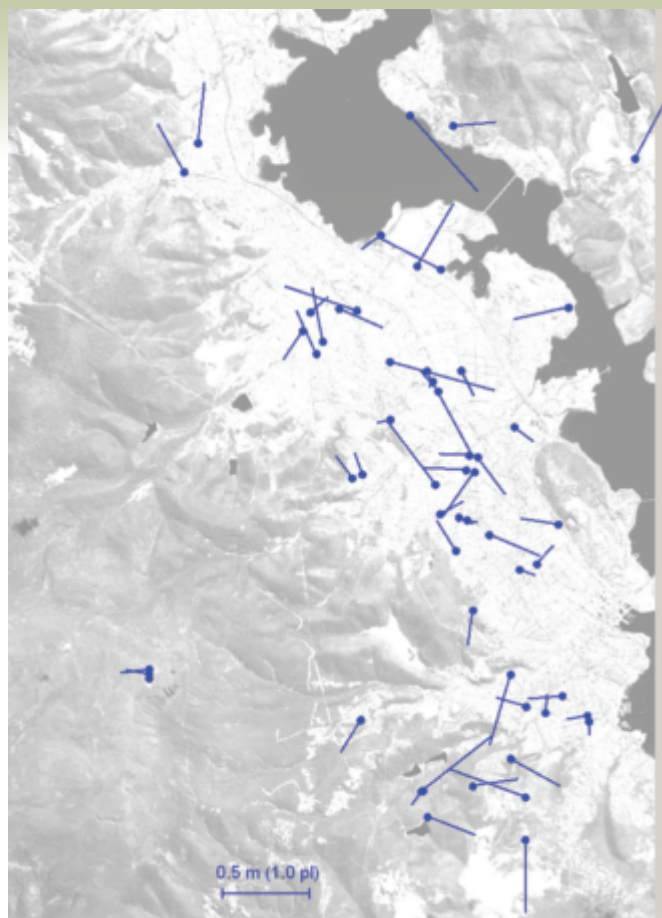


Figure 4. (L) Planimetry, (R) Height. Check point discrepancies for the free-net block adjustment solution.

Table 3. Results of 55-point free-net block adjustment.

	Easting	Northing	Height
RMSE, 55 Chkpts	0.10 m (0.2 pixels)	0.10 m (0.2 pixels)	0.18 m (0.4 pixels)
Range of coord. errors	-0.21 to 0.30m	-0.18 to 0.25m	-0.39 to 0.41m

50cm GSD of GeoEye-1. Shown in Figure 4 is a plot of the residuals in planimetry and height from the free-net bias-compensation adjustment.

CONCLUDING REMARKS

This first investigation into the metric potential of GeoEye-1 stereo imagery has demonstrated that this new 0.5m resolution satellite imaging system is capable of producing unprecedented levels of ground point determination accuracy. With bias-compensation adjustment of the supplied RPCs, using an additional parameter model comprising two shift parameters only, geopositioning accuracy of 0.1m (0.2 pixels) in planimetry and 0.25m (0.5 pixel) in height can be attained with a single GCP, though the use of redundant control is always recommended. This level of metric performance surpasses both the design expectations of the system and those inferred from experience with Ikonos, and it augurs well for the generation of both digital surface models to around 1-2m height accuracy and 0.25m GSD orthoimagery to sub-metre accuracy.

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