APPLICABILITY OF THE AFFINE MODEL FOR IKONOS IMAGE ORIENTATION OVER MOUNTAINOUS TERRAIN

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ABSTRACT:

The 3D affine transformation model has obvious attributes for sensor orientation of high-resolution satellite imagery. It is a straightforward linear model, comprising only eight parameters, which has demonstrated sub-pixel geopositioning accuracy when applied to Ikonos stereo imagery. This paper provides further insight into the affine model in order to understand why it performs as well as it does in mountainous terrain. The results of application of the affine sensor orientation model in a multi-image Ikonos testfield configuration exhibiting a ground elevation range of 1280m are presented. These illustrate the very high geopositioning accuracy attainable with the affine model, and illustrate that even though the model can be influenced to a modest extent by terrain variation, it constitutes a robust, accurate and practical sensor orientation/triangulation model. In order to highlight the accuracy potential of the affine model in comparison to a rigorous sensor model, the results obtained via rational functions with bias compensation are also presented.

1. INTRODUCTION

With the comprehensive camera models for commercial high-resolution satellite imagery (HRSI) generally not being accessible to the user community, it has been necessary to turn to alternative sensor orientation and geopositioning models for metric applications of Ikonos and Quickbird imagery. Contrary to initial concerns that alternative models may not yield optimal model fidelity, and therefore produce less than optimal geopositional accuracy, it has been demonstrated in a number of recent studies that such models can produce accuracies at a level corresponding to more rigorous collinearity-based approaches (eg Hanley et al., 2002; Grodecki & Dial, 2003; Jacobsen & Passini, 2003; Fraser & Yamakawa, 2003; Cheng et al., 2003). Undoubtedly, the most popular alternative model is the rational function model, where the coefficients (RPCs) are derived from the rigorously determined sensor orientation by the imagery provider. It has been shown by Grodecki (2001) that for Ikonos imagery the RPCs model the 'rigorous' object-to-image space transformation to within 0.05 pixel accuracy. Thus, although classed as an alternative model, RPC-based sensor orientation can be viewed as a standard against which other empirical models can be compared.

A second alternative model, which has also produced impressively high geopositioning accuracy with both Ikonos and Quickbird imagery is an empirical model based on affine projection. This quite straightforward, 8-parameter model is by no means rigorous, though it can be formulated in a 'rigorous' form as will be shown in a following section. In spite of a number of reported applications of the affine model to stereo- and multi-image geopositioning from Ikonos imagery, over a range of scene sizes and terrain types (Hanley et al., 2002; Fraser & Yamakawa, 2003, Jacobsen & Passini, 2003; Fraser et al., 2003), some scepticism persists regarding the utility of the approach. The main purpose of this paper is to demonstrate that the affine sensor orientation model can yield sub-pixel geopositioning accuracy, largely irrespective of the terrain characteristics within the scene. The paper will also offer an insight into why this might be the case. The principal concern with the model, and rightly so, is its ability to accommodate imagery over mountainous terrain, and this will be the area of focus of the following discussion.

In assessing the metric potential of the affine model for 3D ground point determination from HRSI, two criteria are useful. The first is absolute accuracy, as assessed via independently surveyed checkpoints, and the second is the accuracy attained relative to a rigorous model. The rigorous model adopted in this investigation, which describes an experiment with an Ikonos *Geo* stereopair, is RPC-based 'bundle adjustment' with bias-compensation, as described in Fraser & Hanley (2003) and Grodecki & Dial (2003). Limited coverage will be given to this model, though the reader should note the following: The RPC bundle adjustment is essentially an absolute orientation process, with the provided ground control points (GCPs) - one being the minimum - affording a removal of biases in exterior orientation via two translation parameters in image space. (Additional drift parameters, which can be appropriate for long image strips, are not considered in this paper.) Thus, shape invariance for the network can generally be assumed, irrespective of the number of GCPs involved, or their location. This is quite important, for it means that contrary to assertions seen in the literature, eg Cheng et al. (2003), the nature of the scene topography is of no consequence for bias-corrected RPCs. The method is just as rigorous in high relief areas as in flat areas, a characteristic that will be demonstrated in the experimental tests to be reported.

In the following sections we will first briefly overview the model for RPC bundle adjustment with bias compensation, since sensor orientation via this approach will be adopted as the benchmark against which the affine model is assessed. Both the standard and 'rigorous' forms of the affine model will then be reviewed, with the purpose being to shed light on why the standard model might perform so well when it is formulated as a bundle adjustment model for multi-image orientation and triangulation. Two further factors influencing the affine model, namely the choice of object space coordinate system and the impact of different scanning modes, are then briefly touched upon, after which an experimental evaluation of the model in both its forms is reported. The test site for the evaluation is a 120km^2 area of the city of Hobart, Tasmania in which the terrain height variation is 1280m.

2. RPC BUNDLE ADJUSTMENT

As detailed in Fraser & Hanley (2003) and Grodecki & Dial (2003), the basic model of the RPC bundle adjustment with bias compensation can be given as

$$\begin{pmatrix} v_x \\ v_y \end{pmatrix}_{ij} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & 1 & 0 \\ a_{21} & a_{22} & a_{23} & 0 & 1 \end{pmatrix}_{ij} \begin{pmatrix} \delta X_j \\ \delta Y_j \\ \delta Z_j \\ \Delta x_i \\ \Delta y_i \end{pmatrix} + \begin{pmatrix} x^o - x \\ y^o - y \end{pmatrix}_i \qquad (1)$$

Here, x, y are the normalised (offset and scaled) image coordinates (line, sample) for a point j on image i; v_x, v_y are image coordinate residuals; δX, δY, δZ are corrections to approximate values for the object point coordinates, which for Ikonos and Quickbird RPCs refer to latitude, longitude and height; x^0, y^0 are the image coordinates corresponding to approximate object coordinates; a_{ij} are elements of the matrix of partial derivatives of the rational functions; and Δx_i and Δy_i are image coordinate perturbations (biases) common to image i.

An immediate question that arises regarding Eq. 1 is how might this be a bundle adjustment since it is formulated as a spatial intersection with two additional shift parameters in image space. The answer is that the image coordinate bias terms effect a correction to sensor exterior orientation, thus yielding an estimation process in which both object space coordinates and sensor exterior orientation elements are treated as unknowns. As such, the basic model of Eq. 1 can accommodate any number of images and object points. There is no 'first order polynomial adjustment to the data' here (Cheng et al, 2003); the model can be expected to maintain the rigorous relative orientation embodied in the original RPCs, in spite of the shift in image space coordinates. As mentioned, a single GCP is needed for accurate absolute geopositioning, with its planimetric location and height being of no consequence. Naturally, multiple GCPs will provide a solution less prone to the influence of positional errors in single GCPs, but it is useful to recall that the geometric strength of the RPC bundle adjustment (again with shift-terms only) is not influenced by the number of GCPs, unlike other alternative models. As illustrated in Hanley et al. (2002), the RPC bundle adjustment has yielded sub-pixel absolute accuracies in multi-strip Ikonos stereo image blocks covering areas as large as 2000 km^2.

3. THE AFFINE MODEL

3.1 Standard Formulation

The model describing an affine transformation from 3D object space (X, Y, Z) to 2D image space (x, y) for a given point j within an image is given as

$$\begin{aligned} x_j &= A_1 X_j + A_2 Y_j + A_3 Z_j + A_4 \\ y_j &= A_5 X_j + A_6 Y_j + A_7 Z_j + A_8 \end{aligned} \qquad (2)$$

with the eight parameters accounting for translation (two), rotation (three), and non-uniform scaling and skew distortion within image space (three). It has been found in practical tests that the best results are obtained with the affine model when the chosen object coordinates are in a UTM projection system rather than in geographic coordinates or a Cartesian reference frame. Strictly speaking, the imaging operation of a satellite pushbroom scanner can be described as central perspective in the line of the linear array and parallel in the along-track direction. But with imaging systems such as Ikonos and Quickbird, with very narrow fields of view of 0.93^o and 2.1^o, respectively, the assumption that the projection is parallel and amenable to characterisation with an affine model has been shown to stand up quite well in practical tests (eg Fraser et al., 2002; Hanley et al., 2002). For the present multi-image application of the affine projection model, all model parameters are recovered simultaneously along with triangulated ground point coordinates in a process analogous to photogrammetric bundle adjustment.

Having introduced the arguably 'non-rigorous' affine model for HRSI sensor orientation, we examine links between the model of Eq. 2 and a 'rigorous' counterpart, also based on affine projection, as this will provide insight into both why the simple 8-parameter model might perform as well as it does, and why there might be limitations with the model for 3D geopositioning in mountainous terrain.

3.2 A Rigorous Affine Model

Both Okamoto (1996, 1998) and Zhang & Zhang (2002) have proposed affine orientation models for HRSI. Both take the form shown in Eq. 3, where y is assumed to be the image axis in line with the linear array:

$$\begin{aligned} x_i &= B_1 X_i + B_2 Y_i + B_3 Z_i + B_4 \\ y_i &= c_{Z_i} (B_5 X_i + B_6 Y_i + B_7 Z_i + B_8) \end{aligned} \qquad (3)$$

The height-dependent correction to the y-coordinate is given by

$$c_{Z_i} = \frac{f - y_i \tan\alpha}{f - \frac{Z_i}{m \cos\alpha}} = \frac{1 - \frac{y_i}{f} \tan\alpha}{1 - \frac{Z_i}{H \cos\alpha}} \qquad (4)$$

where f is the focal length, α the off-nadir viewing angle, H the satellite altitude and m the scale number of the imagery. This model is termed 'strict' by Zhang and Zhang and as one incorporating a 'central perspective to affine image conversion' by Okamoto. Regardless of the name, the two are equivalent. Given that for HRSI, $y << f$ and $Z << H$, it is clear that c_Z will have a value very close to unity. An account of how to implement this model in practise is given by Zhang & Zhang (2002), who also provide experimental results of the affine-based orientation approach for Ikonos and SPOT imagery. Application of the height-corrected model to SPOT and MOMS imagery has also been reported by Okamoto and colleagues (Okamoto et al., 1998, Hattori et al., 2000). As with the affine model of Eq. 2, only four control points are required for stereo restitution via this approach.

The two-stage correction approach implicit in Okamoto's perspective-to-affine image conversion is useful as it allows the correction to a measured y-image coordinate to be viewed as comprising two steps:

$$y_a^o = \frac{1}{(1 - \frac{y}{f} \tan\alpha)} \, y \qquad (5a)$$

and

$$y_a = (1 - \frac{Z}{H \cos\alpha}) \, y_a^o \qquad (5b)$$

Here, y is the measured sample coordinate of the point in the CCD line array (nominally with origin at the optical centre), y_a^o the corrected 'affine' coordinate on a plane of constant elevation and y_a the final affine coordinate after height correction. It can thus be seen that for a near-nadir image, Eq. 5b might apply but Eq. 5a will not, whereas for an oblique image of near level terrain, Eq. 5a will apply but Eq. 5b would simply introduce a common scale factor which is otherwise modelled within the affine transformation of Eq. 2. Further explanation of Eqs. 5a and 5b is provided in Fraser & Yamakawa (2003).

A further matter that must be addressed in relation to the correction factor c_Z is the impact of an initial image rectification to a given reference plane, as occurs, for example with Ikonos *Geo* imagery. It can be shown that for terrain of low relief there is a linear relationship between the y-coordinate of the *Geo* image and that of the affine image, y_a. Thus, the correction of Eq. 5a is implicit within the generation of the *Geo* image product, requiring application of Eq. 5b only in the *Geo*-to-affine conversion $y_a = y^{geo}/c_Z$. The resulting coordinate can then be substituted directly into Eq. 1.

Recent research into high-accuracy (sub-pixel) HRSI orientation/triangulation by the authors and others, especially involving Ikonos *Geo* imagery, has indicated that the affine model generally performs equally well with or without the correction factor c_Z (eg Fraser et al, 2002; Fraser & Yamakawa, 2003). In order for Eqs. 2 & 3 to be equivalent, it is necessary for c_Z to remain effectively invariant for any given image. Its degree of invariance is of more importance than its closeness to unity, as the correction factor then becomes effectively constant for all points in the image. It can be shown that for scenes with little variation in elevation, the correction factor c_Z maps as a quadratic function of the sample coordinate y, and is in fact effectively a linear function when it is considered that at the nominal edge of an Ikonos scene, with a sensor collection elevation angle of 70^o, the correction reaches only 15 pixels. This coordinate variation is thus projectively absorbed for most practical purposes within the eight parameters of the standard affine model, and for *Geo* imagery it can be expected to be fully absorbed.

Terrain height variations within the scene give rise to associated variations in the magnitude of the correction factor c_Z in accordance with Eq. 5b. Moreover, it would be expected that such non-linear corrections might not be fully absorbed by the eight parameters in Eq. 2. The question to be addressed, however, is to what extent c_Z is likely to depart from a constant value in the presence of hilly or mountainous terrain. If we again consider an off-nadir viewing angle of 20^o and a y-coordinate value of 6000 pixels (approximate edge of an Ikonos scene), then the height correction value, Δy_a, becomes about 5 pixels for ΔZ = 500m and only 2 pixels for 200m (values are 1.5 times higher for Quickbird). Expressed another way, for an Ikonos scene with a total height variation of 400m, the effective maximum error range in y coordinate values that will arise if Eq. 5b is ignored is 4 pixels.

In practical applications of the standard affine model to HRSI orientation/triangulation of object arrays with height variations of, say, 500m or less, it could therefore be expected that the results will be little influenced by whether or not the perspective-to-affine image conversion has been employed. For high-accuracy geopositioning in mountainous terrain, on the other hand, the affine correction may be warranted.

4. OBJECT SPACE COORDINATE SYSTEM AND SCANNING MODE

The authors have found that in the application of the affine model to 3D geopositioning, the attainable accuracy with geographic or Cartesian coordinates falls off as the area of coverage increases. For example, in a case involving overlapping strips of stereo Ikonos imagery, and covering a $2000km^2$ area, the geopositioning accuracy fell from 0.8m and 1.1m in planimetry and height when UTM coordinates were employed, to 1.0m and 1.9m when Cartesian coordinates were used, and to 2.8m and 3m when latitude, longitude and height were employed (Hanley et al, 2002). In regard to geographic coordinates, it should be anticipated that a linear object-to-image space transformation will not fully account for departures from rectilinearity. With a Cartesian coordinate system, on the other hand, the principal point of concern is the curved nature of the satellite trajectory, since relative to a rectangular reference coordinate system the imaging rays do not remain parallel when the sensor pointing angle remains constant.

The UTM projection is formed by wrapping a cylinder around a meridian of the earth, the axis of the cylinder being within the equatorial plane. Ground points are then projected onto the cylinder from a single point of projection and the cylindrical surface is unwrapped into a plane. To a first approximation, the satellite image could also be thought of as being formed upon a cylindrical surface (assuming a circular orbit). Noting also that for HRSI the projection is parallel in the along-track and perspective in the cross track direction, it is easy to imagine a near-orthogonal projection from the UTM 'surface' to the image 'plane'. Moreover, relative to the UTM projection plane, the satellite could be considered to be flying in a straight line at constant velocity, assuming a constant sensor pointing angle, which is consistent with a true affine projection. In the following discussion of experimental testing of the affine model, only the UTM coordinate system is employed.

Another issue of relevance to the likely applicability of the affine transformation from image to object space concerns the scanning mode of the sensor. As mentioned, the standard affine model assumes both a constant pointing direction during scene recording and a constant velocity, straight-line trajectory for the satellite. This requirement is generally satisfied with one of the scanning modes of Ikonos, namely the so-called Reverse mode where the scan and orbital velocity vectors are approximately aligned and there is very little rate of change of the sensor elevation angle. However, in the 'Forward' scanning mode the scan is in the opposite direction to the satellite trajectory and the sensor elevation angle is changing at roughly 1^o/sec. Such an arrangement is not fully consistent with the affine model assumptions, and is more prone to the introduction of non-linearities in the along-track axis. Nevertheless, the affine model can still be applied to Forward scanned images, though a mild accuracy degradation might be anticipated. This issue is also relevant to Quickbird, where the sensor elevation angle is dynamically changing in both scanning modes.

In the Ikonos tesfield considered here, the near-nadir image of the stereo triplet was scanned in Forward mode, and an initial affine object-to-image space transformation based on 112 GCPs revealed that this image displayed large image coordinate residuals in comparison to the two Reverse-scanned stereo images, namely greater than 1.2 pixels versus about 0.4 pixels. This indicated that the Forward-scanned image contained non-linearities in the along-track direction, which can have an adverse effect on the linear affine model. This error source had not been seen in previous analyses of Forward-scanned Ikonos imagery. As a consequence, and since the focus of this discussion is upon the influence of scene topography alone, subsequent analysis was restricted to the stereopair of images. Moreover, this better reflects what would be the normal case in practise.

5. EXPERIMENTAL TESTING

The experimental testing aimed to verify that for practical purposes the standard form of the affine model, coupled with UTM ground coordinates, would suffice for high precision sensor orientation and geopositioning in mountainous terrain. It should be noted that the metric potential of the affine model applied to HRSI has already been demonstrated (eg Fraser et al., 2002; 2003; Hanley et al., 2002), though not in a scene involving height differences of several hundreds of metres. The aim in relation to the height correction factor c_Z was to both quantify its metric impact and assess whether application of the correction is generally warranted.

5.1 The Hobart Testfield

The authors had to wait some time before a suitable HRSI testfield with mountainous terrain could be established in Australia. Not only is the country relatively flat, but mountainous areas tend to be away from cities, where the best prospects exist for finding suitable image-identifiable GCPs. With the Hobart Testfield, however, we were fortunate enough to have a 1280m elevation range and feature rich Ikonos *Geo* Stereo imagery with an abundance of suitable, specially surveyed GCPs. The full-scene testfield covers a 120 km^2 area of the city of Hobart and it surroundings, a very prominent features of which is Mount Wellington. Of the images in the Ikonos *Geo* triplet, the two stereo images (elevation angles of 69^o) were scanned in Reverse mode while the central image (elevation angle of 75^o) was acquired in Forward mode. As mentioned above, only the stereo images will be considered here.

A total of 112 precisely measured ground feature points (mainly road roundabouts) were available to serve as GCPs and checkpoints. The majority of these were 'circular' features which were surveyed and measured in the imagery to 0.2 pixel accuracy using a procedure described by Fraser et al. (2002). The layout of the GCPs is shown in Fig. 1, where it should be noted that the point indicated on Mount Wellington is actually a cluster of 11 points. Four sample GCP image chips are shown in Fig. 2.

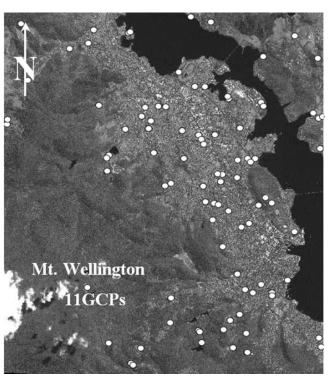

Figure 1: Hobart Testfield showing GCP locations.

Figure 2: Sample image chips of GCPs.

5.2 RPC Bundle Adjustment Results

The geopositioning results corresponding to a rigorous sensor orientation/triangulation provide the accuracy standard against which the affine model results can be compared. These rigorous results where obtained with the RPC bundle adjustment with bias compensation, generally with just two GCPs being employed. All bundle adjustment runs, RPC and affine, along with all image data processing and measurement operations, were performed with the BARISTA software package. This software system has been developed specifically to provide a practical data processing environment for HRSI sensor orientation and geopositioning, along with ortho-image generation and DTM extraction.

Shown in Table 1 are the RMS values of ground checkpoint residuals from geopositioning within the Hobart testfield via RPC bundle adjustment with different GCP arrangements.

Table 1. Geopositioning accuracy from the RPC bundle adjustment. (RMS of image coord. residuals = 0.18 pixels).

Geometric control configuration	RMS discrepancies at 110 checkpoints (m)		
	S_ϕ *(along track)*	S_λ *(cross track)*	S_h
All points as GCPs (loosely weighted at σ_{XYZ} = 3m)	0.65	0.26	0.62
Set 1: 2 GCPs on Mt Wellington	0.73	0.26	0.71
Set 2: 2 GCPs on Mt Wellington	0.78	0.32	0.71
Set 3: 2 GCPs at sea level	0.80	0.30	0.71
Set 4: 2 GCPs at sea level	0.66	0.26	0.82

Accuracy at sub-pixel level is obtained in planimetry and height, with the most impressive results being, as anticipated, within the cross-track direction where the RMS value of checkpoint residuals was close to 30cm. In the context of the present discussion, there is a primary point to be made regarding the results, which have been arrived at through the use of 110 checkpoints in each case. There is no relationship between GCP elevation and accuracy. Similar absolute accuracies are attained whether the GCPs are at 1280m only, at sea level only or at both elevations. The variations in RMS coordinate discrepancies result from residual biases in the 'mean GCP position'. One can easily show through 3D similarity transformation that the relative accuracy, as expressed by shape invariance of the network, is unchanged for different GCP configurations.

5.3 Results of Affine Bundle Adjustments

Listed in Table 2 are the RMS values of checkpoint residuals obtained in 3D geopositioning via affine bundle adjustment. Results are shown for both the standard model (Eq. 2) and the height-corrected 'strict' model (Eq. 3). The reason that only one listing of residuals is present for both the northing and height coordinates is that the values determined here from each model agreed to within a centimetre or so. Since the c_Z correction is applied to the cross-track *y*-coordinate, it is not surprising that the influence of this correction is seen in the easting direction.

In absolute terms, the standard affine model produces quite impressive results, with sub-pixel accuracy in planimetry and 1-pixel accuracy in height. The height correction factor c_Z improves accuracy by 20-30cm in the cross-track direction, though considering that accuracy is already better than 1m it might be argued that the improvement is of limited practical consequence. Overall, the affine model produces similar planimetric accuracy to the RPC approach, but slightly poorer heighting accuracy. One feature, which is unexpected – and unexplained – is that the affine model produces better accuracy in the along-track direction than the RPC bundle adjustment.

On the subject of whether the affine model can accommodate significant height variations within the scene, the results of the last-listed 9-GCP arrangement are noteworthy. Here, the maximum GCP elevation was at 400m. Thus, points on the mountain top were computed by extrapolating the affine model some 900m in elevation beyond the volume contained by the GCPs. This is by no means a recommended procedure, but it is nevertheless interesting that it produced an absolute positioning bias at 1280m elevation of only 2m in planimetry (in the cross-track direction) and 4m in height for the standard model. When height correction is applied, the bias in planimetry drops to about 0.5m while the height bias remains at 4m.

6. CONCLUSIONS

As more experience is gained with alternative sensor orientation models, so appreciation is gained of the merits and disadvantages of RPCs and the affine model. Other than issues of availability (RPCs are not available to some international Ikonos users) and cost (Space Imaging charge a premium for RPCs, which is now modest in most markets), there are very few disadvantages that spring to mind for RPCs that have been generated to a given accuracy specification from the rigorous sensor orientation, by the image provider. The extensive checkpoint array in the Hobart Testfield afforded a further conclusive verification of the sub-pixel geopositioning accuracy potential of Ikonos RPCs, irrespective of terrain characteristics. A similar test in a mountainous area is yet to be conducted with Quickbird imagery, though in a stereopair of *Basic* images over another testfield the RPC bundle adjustment has also yielded accuracies at the sub-pixel level.

With the affine model it is perhaps still too early to attempt to draw universally applicable conclusions regarding geopositioning accuracy from HRSI. However, what can be said is that the assertion that the straightforward 8-parameter affine model can yield pixel-level and even sub-pixel level accuracy is yet to be experimentally contradicted. Even in the case of the Hobart Testfield, where the height correction c_Z led to an accuracy improvement of 0.2m in the easting (cross-track) coordinate, accuracies of better than 1m in planimetry and 1.3m in height were obtained irrespective of the chosen GCP configuration, at least for sets of 6, 9 and 12 GCPs. One can only be encouraged by such results, especially in circumstances where an accurate sensor orientation model is sought and RPCs are, for whatever reason, unavailable. Also, if the desired downstream processing, for example for othoimage or DTM generation, requires RPCs, it is possible to compute a set of rational function coefficients corresponding (exactly) to the derived affine model, with the object space reference system being geographic coordinates.

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Table 2. Geopositioning accuracy from the affine model with UTM coordinates, with results from both the standard and height-corrected formulations being given for the cross-track (easting) coordinate.

Geometric control configuration	Number of ground checkpoints	RMS value of *xy* residuals (pixels)	RMS discrepancies at checkpoints (m)			
			s_E Std.	s_E *Height Corrected*	s_N	s_h
All points as GCPs (loosely weighted at σ_{XYZ} = 3m)	112	0.16	0.73	*0.42*	0.31	0.56
6 GCPs	106	0.16	0.79	*0.57*	0.45	0.93
9 GCPs	103	0.17	0.80	*0.58*	0.36	1.04
12 GCPs	100	0.18	0.81	*0.57*	0.42	0.97
14 GCPs	98	0.19	0.82	*0.59*	0.40	1.00
9 GCPs (none on Mt Wellington)	103	0.16	0.91	*0.57*	0.40	1.30

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