SINGLE-IMAGE HIGH-RESOLUTION SATELLITE DATA FOR 3D INFORMATION EXTRACTION

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ABSTRACT:

The demand for accurate and up-to-date spatial information is increasing and its availability is becoming more important for a variety of tasks. Today's commercial high-resolution satellite imagery (HRSI) offers the potential to extract useful and accurate spatial information for a wide variety of mapping and GIS applications. The extraction of metric information from images is possible due to suitable sensor orientation models, which describe the relationship between two-dimensional image coordinates and three-dimensional object points. With IKONOS and QuickBird imagery, camera replacement models such as rational polynomial coefficients (RPCs) or alternative models such as the affine projection model are used to describe the relationship between image space and object space. With the sensor orientation determined, accurate metric 3D information can be extracted from HRSI through multi-image processing as well as from single images via monoplotting. Monoplotting is a well-known photogrammetric technique for extracting 3D spatial information from single aerial imagery of terrain described by a digital elevation model (DEM). The method also offers potential for single-image analysis of high-resolution satellite imagery (HRSI). This paper describes the implementation and application of monoplotting functions in the photogrammetric software package *Barista* and investigates the prospects of single IKONOS and QuickBird images for 3D feature point collection and the generation of 3D building models. The experimental determination of the accuracy of monoplotting from IKONOS and QuickBird imagery is also reported.

1. INTRODUCTION

The high potential of today's commercial high-resolution satellite imagery (HRSI) allows the extraction of useful and accurate spatial information for a wide variety of mapping and GIS applications. For the extraction of metric information from images, suitable sensor orientation models are necessary to describe the relationship between 2D image coordinates and 3D object points. With IKONOS and QuickBird imagery, camera replacement models such as rational polynomial coefficients (RPCs) or alternative models such as the affine projection model are used to describe the relationship between image space and object space. The parameters of the sensor model are either supplied by the image provider, as is the case with RPCs, or can be determined in an orientation procedure requiring ground control points (GCPs) and corresponding image coordinate measurements. When employing either the RPC or affine models, it is possible to obtain metric information to metre-level accuracy and better (Fraser *et al.*, 2002; Hanley *et al.*, 2002; Fraser and Yamakawa, 2004).

As soon as the sensor orientation is determined, accurate geometric information from HRSI can be obtained through both multi-image processing and single image feature extraction via monoplotting. Monoplotting is a photogrammetric procedure which enables 3D feature extraction of objects from single images where an underlying digital elevation model (DEM) representing the bare earth exclusive of vegetation and buildings is available (Makarovic, 1973; Masry and McLaren, 1979; Mikhail *et al.*, 2001). Satellite image data from IKONOS and QuickBird can thus be used for mapping in monoplotting mode, so long as a DEM covering the area of interest is provided. To obtain the three-dimensional position of a ground point, the ray defined by a measured image point, is intersected with the underlying DEM. All monoplotting measurement modes require a comprehensive modelling of the sensor orientation data to derive reliable results. Monoplotting allows the measurement of points and linear features which lie on the terrain surface described by the DEM. In the case of buildings, if it is assumed that the planimetric positions of ground and roof points are identical (i.e. vertical walls), then it is also possible to extract 3D building models from single images.

The software package *Barista* developed at both the Department of Geomatics at the University of Melbourne, and within the Cooperative Research Centre for Spatial Information, supports the photogrammetric processing of HRSI data and has recently been extended to include monoplotting functions. The purpose of this paper is to describe these monoplotting functions and to assess their usefulness and accuracy for 3D feature extraction from IKONOS and QuickBird image data. The extraction of spatial information from HRSI via monoplotting has considerable practical potential in application fields as diverse as municipal planning, telecommunications, GIS revision and updating, real estate, environmental management, forestry and defence. The accuracy potential of single image analysis has been assessed for both IKONOS and Quickbird images by comparing the results obtained via monoplotting with those achieved through stereo and multi image processing, again using the *Barista* software.

2. APPLIED SENSOR MODELS

The two crucial factors to the accuracy of monoplotting results derived from HRSI are the quality of the DEM and the accuracy of the sensor orientation model. As a necessary first step in the monoplotting process, the image-to-ground coordinate transformation function must be determined to a sufficient level of precision. For this investigation, the techniques of bias-compensated RPCs and 3D affine transformation were adopted as sensor orientation models.

2.1 RPC Model and Bias Compensation

The RPC replacement sensor model for HRSI, which expresses the transformation from object space to image space, is comprehensively described in (Grodecki and Dial, 2001) and (Tao and Hu, 2002). It has been demonstrated, however, that RPCs which are solely produced from on-board GPS receivers, gyros and star trackers inherit systematic biases, primarily in attitude determination. These must be considered in order to exploit the full metric accuracy potential of HRSI (eg Fraser *et al.*, 2002; Hanley *et al.*, 2002). Consequently, an extended RPC bundle adjustment was developed to model these effects and compensate for existing biases (Fraser and Hanley, 2003; Grodecki and Dial, 2003). For the purpose of enabling the bias correction of the RPC parameters, GCPs provided in geographic coordinates along with corresponding image coordinate measurements must be made available. The image measurements can be performed in *Barista*, as described further in (Fraser and Hanley, 2003).

To exploit the full accuracy potential provided by HRSI in the context of monoplotting applications, it is important to be able to perform the bias correction procedure for a single image. *Barista* supports such a determination, and depending upon the choice of the bias correction model (image coordinate shift, shift and drift or full affine transformation), between one and four 3D GCPs are necessary to effect a bias correction. Once the bias parameters are determined, a set of bias-corrected RPCs is regenerated. Therefore, a bias-free application of RPC parameters for monoplotting becomes possible without using additional correction terms (Hanley and Fraser, 2004).

2.2 Affine Sensor Model

The affine projection model, which is fully described in (Fraser and Yamakawa, 2004), does not explicitly utilise camera or exterior orientation parameters. Instead, the use of an empirical model based on parallel projection is justified due to the very narrow fields of view for commercial high-resolution satellites, namely 0.98° for IKONOS and 2.1° for QuickBird. As the field of view of the linear array sensor becomes small, high correlations develop between the exterior orientation parameters and the bundle of rays effectively approaches a skew parallel projection (Yamakawa and Fraser 2004). The optimal reference coordinate system for the affine sensor orientation model and its assumption of a parallel imaging plane is thus the UTM projection. The affine model requires a minimum of four GCPs to solve for 3D object space coordinates and despite greatly differing from the RPC based approach, can produce similar levels of geopositioning accuracy (Fraser and Yamakawa, 2004).

3. SINGLE IMAGE PROCESSING WITH *BARISTA*

With the sensor orientation model in place, the monoplotting operation determines the object point corresponding to the measured image point via an iterative process of intersecting the imaging ray with the underlying DEM surface. The monoplotting function was implemented in *Barista* for both the affine and the RPC sensor models and supports monoplotting in geographical, UTM or any other arbitrary coordinate system. The monoplotter solves the planimetric position via least-squares estimation, with the final height being determined via interpolation from the DEM. Monoplotting measurement functions implemented in *Barista* include point, line and height determination or building modes.

3.1 Measurement of Points

To calculate the 3D position of a point, an initial height value (e.g. the average of the maximum and minimum heights occurring in the DEM) is required to determine a preliminary planimetric position. From this position, a new height value is interpolated from the DEM. The iterations terminate when the variation in the computed 3D position is below a certain convergence limit. Accounts of the principle of the point iteration process in monoplotting, as shown in Figure 1, are provided in (Makarovic, 1973; Masry and McLaren, 1979; Mikhail *et al.*, 2001), albeit for aerial photography.

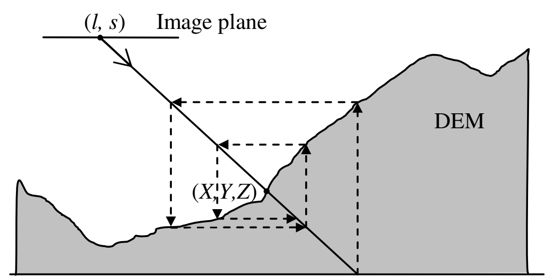

Figure 1. 3D point positioning from single image and DEM

Within *Barista*, monoplotting on an image becomes possible after choosing a sensor orientation model (RPCs or affine) and loading a suitable DEM. While the monoplotting function is active, a dialog box with the data of the current point is shown, which also enables a list of labelled 3D points to be displayed. The dialog box also displays the current coordinate system, along with a switch to display the point coordinates in different coordinate reference systems.

For the current implementation of monoplotting in *Barista*, the required DEM must be gridded and its coordinate system must match the parameters of the sensor orientation model, namely geographic coordinates for RPCs and either geographic, UTM or local Cartesian for the affine model. If required, a coordinate transformation to a different reference system can also be carried out in *Barista* for the monoplotted object points.

3.2 Measurement of Linear Features

Besides the measurement of single points the extraction of linear features is also important for mapping applications. In order to map roads, boundaries or linear features, a monoplotting mode to collect line data has been implemented within *Barista*. A line consists of a list of points which are connected and the line feature can be completed as an open or closed polygon. The line is displayed in image space by reprojecting the monoplotted 3D coordinates. Figure 2 shows the interface of *Barista* in monoplotting mode.

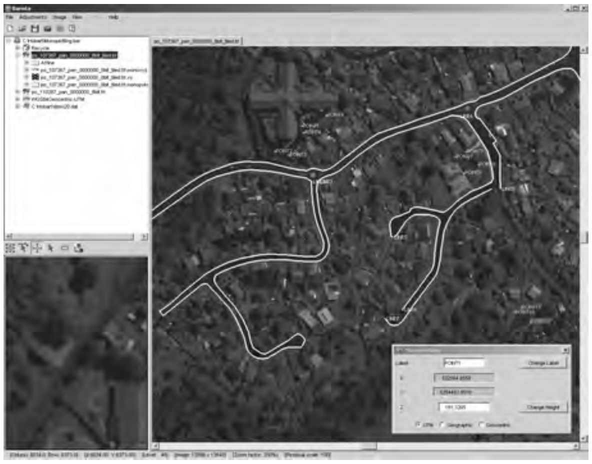

Figure 2. Monoplotting with *Barista*, user interface

3.3 Measurement of Buildings

Under certain conditions it is even possible to measure height differences and buildings with monoplotting. As an extension to the monoplotting function, a method to derive object height differences from single images has been incorporated into *Barista*. As illustrated in Figure 3, with the assumption of equal planimetric position, height difference information can be obtained by measuring the ground point in regular monoplotting mode and then measuring a feature point which is vertically above the initial point. For example, the operator might measure the base position of a corner of a building and then measure the same corner at the top of the building, thus determining its height. A least squares estimation process is employed to calculate the height value from the 3D position of the ground point and the image coordinates of the roof point.

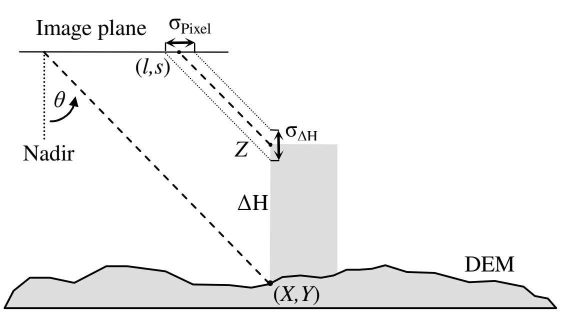

Figure 3. Measurement of height differences

The general object-to-image transformation can be formulated with $(l,s) = F(X,Y,Z)$, where F describes the sensor model employed. For the height determination of a roof point the XY-position of the ground point and the measured image coordinates of the roof point are the observations to derive the Z-value. Both sensor models describe the object-to-image transformation F in two separate functions, F_1 and F_2, leading to the following equation:

$$\begin{pmatrix} \frac{\partial F_1}{\partial Z} \\ \frac{\partial F_2}{\partial Z} \end{pmatrix} \delta Z + \begin{pmatrix} \frac{\partial F_1}{\partial X} & \frac{\partial F_1}{\partial Y} & \frac{\partial F_1}{\partial l} & \frac{\partial F_1}{\partial s} \\ \frac{\partial F_2}{\partial X} & \frac{\partial F_2}{\partial Y} & \frac{\partial F_2}{\partial l} & \frac{\partial F_2}{\partial s} \end{pmatrix} \begin{pmatrix} X \\ Y \\ l \\ s \end{pmatrix} + \begin{pmatrix} F_1 \\ F_2 \end{pmatrix} = 0 \qquad (1)$$

Quite clearly, a prerequisite for building height measurements within a single IKONOS or QuickBird image is an off-nadir orientation where the ground point and the vertically displaced position on the building are both clearly distinguishable.

It is relatively straightforward to extend the height difference determination to a more complete wireframe modelling of buildings. This capability, which is illustrated in Figure 4, has been implemented within *Barista*. The measurement of buildings from a single HRSI image is possible under the following conditions:

- at least one building point at ground level is visible and can be measured in regular monoplotting mode;
- the image coordinates of the corresponding roof point can also be measured;
- it is assumed that roof corner points are at the same height, though more complex multi-height buildings can be accommodated; and
- every roof point is assumed to have a corresponding ground point which is automatically determined via DEM intersection.

The wireframe of the building is displayed in image space by reprojecting the 3D points with their connecting lines. A building may consist of an arbitrary number of points.

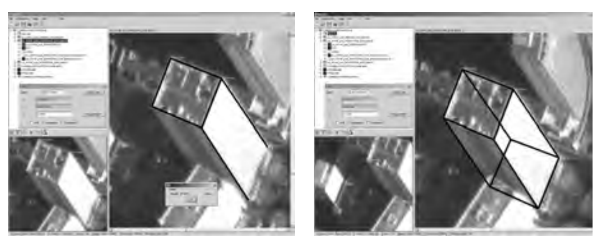

Figure 4. Monoplotting of buildings with *Barista*

3.4 3D Data Export and Visualization

It is important that the mapped 3D information can easily be transferred and made available for further processing with other systems. To enable the use of the collected 3D data for further processing and integration into a GIS, export in an appropriate file format needs to be provided. At this stage, the data export within *Barista* is realised in the widely used VRML format. The collected 3D information is stored in an ASCII file, which can be viewed in any VRML browser. Figure 5 shows a sample of mapped buildings and the visualization of the corresponding 3D wireframe data in a VRML viewer.

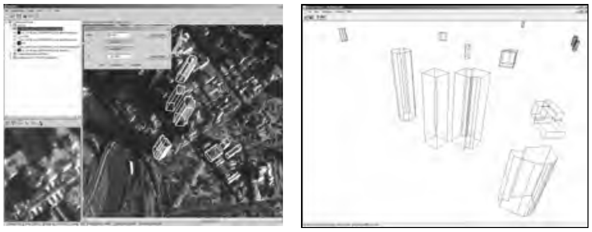

Figure 5. *Barista*, display of mapped buildings and 3D visualization of buildings in a VRML-viewer

4. EXPERIMENTAL ACCURACY ASSESSMENT

An important component of the overall evaluation of the new monoplotting functions within *Barista* has been an assessment of the accuracy of 3D feature point determination and, especially, a determination of the accuracy of the extraction of building model wireframes. An experimental test program was thus set up within the Melbourne HRSI testfield, which is an approximate 200 km^2 area of the city of Melbourne comprising over 100 accurately measured, image identifiable GCPs. This array of ground points, for which there is a precise underlying DEM of better than 0.5 m accuracy (RMS 1-sigma), has been imaged in stereo by both IKONOS and QuickBird. Further details of the Melbourne testfield are provided in (Fraser *et al.*, 2002) and (Fraser and Hanley, 2003). While central Melbourne is a relatively flat region with its surface terrain peaking at only 60 m or so above sea level, many tall buildings in the central business district exceed 100 m in height, which affords a good assessment potential for the building height determination.

The Melbourne IKONOS testfield comprises a panchromatic near-nadir and a stereopair of IKONOS *Geo* imagery covering a 50 km^2 area of central Melbourne, inclusive of Port Phillip Bay and the inner suburbs surrounding the central business district. The near-nadir image was acquired in March 2000 and the stereopair four months later at satellite collection elevation angles of 83° and 61°, respectively. Entirely overlapping the IKONOS scene, the Melbourne QuickBird coverage includes a stereopair of imagery encompassing a 17.5 x 17.5 km area. The in-track QuickBird stereo image pair was collected in July 2003 at satellite elevation angles of 60° and 58° for the forward- and backward-looking images, respectively. Additional details of this data set are provided in (Yamakawa and Fraser, 2004).

The DEM used in the analysis was originally referenced within the Australian Height Datum (AHD), however a datum transformation was applied to bring the elevation model into the WGS84 geodetic reference system and so ensure consistency with the GPS-surveyed GCPs and the HRSI RPCs which related to ellipsoidal heights on the WGS84 ellipsoid. To assess the accuracy of the height-translated DEM, elevation comparisons were computed between 44 GPS-surveyed GCPs and those interpolated from the DEM. This resulted in an RMS height discrepancy of just under 0.4 m, which was deemed sufficiently consistent for the purposes of evaluating the monoplotting functions in *Barista*.

Single image point positions and building heights were measured using both the RPC and affine sensor orientation models, for the three IKONOS and two QuickBird images. Therefore, bias-corrected RPCs and affine parameters were initially computed to ensure the imagery was orientated to 1-pixel accuracy. Indeed, sub-pixel geopositioning accuracy was achieved for both sensor orientation models (Hanley *et al.*, 2002; Hanley and Fraser, 2004; Fraser and Yamakawa, 2004).

4.1 Heighting Accuracy and Error Analysis

While the accuracy of regular monoplotting is mainly dependent upon the quality of the DEM, the sensor orientation model and the image measurement precision, the accuracy of the single-image height measurement technique is affected significantly by the off-nadir angle θ of the satellite image. A discussion of the main error sources from single image measurements can be found in (Croitoru *et al.*, 2004) and (Xu, 2004); here we concern ourselves only with the impact of the off-nadir angle. Assuming one-pixel image measurement accuracy, the height error Δh can be determined as

$$\Delta h = \tan^{-1}\theta \text{ pixels} \tag{2}$$

for single image measurements. The standard error $\sigma_{\Delta h}$ of height difference determination between measured roof and ground points of buildings is thus determined as

$$\sigma_{\Delta h} = \sqrt{2}\cdot\tan^{-1}\theta\cdot\sigma_{pixels} \tag{3}$$

The resulting precision of height difference determination anticipated for the five individual HRSI images covering the Melbourne testfield is listed in Table 1.

Satellite image	Nominal collection elevation (degrees)	$\sigma_{\Delta h}$ (m) for 1-pixel image measurement standard error
IKONOS, nadir	83.4	12.3
IKONOS, forward	60.7	2.5
IKONOS, backward	61.4	2.6
QuickBird, forward	59.7	1.7
QuickBird, backward	57.6	1.6

Table 1. Standard error of height difference determination for single image measurements within the Melbourne HRSI testfield

4.2 Results from IKONOS Imagery

To evaluate the accuracy of monoplotting within *Barista*, the measured 3D coordinates of 40-50 ground checkpoints (CKPs), which constituted principally road roundabouts and footpath intersections, were compared to measured GPS coordinates. The results are listed in Table 2, where the corresponding results for an RPC bundle adjustment of the three IKONOS images are also listed for comparison. As anticipated, the image triplet produces sub-pixel geopositioning accuracy when using either RPCs or the affine model. What was less anticipated was that the accuracy of 3D feature point determination via monoplotting was also at sub-pixel level.

While the accuracy attained in absolute point positioning via monoplotting for the IKONOS images was very encouraging, the building height extraction accuracy turned out to be even more impressive when compared to the theoretical expectations indicated in Table 1. Although the authors do not have a comprehensive account of why the affine model yields better results in planimetry, as indicated in Table 2, one reason could well be that the model in this case is derived for the local area of interest, whereas the RPC model applies to the entire scene. While building height determination via monoplotting is clearly not always applicable to buildings with roof overhangs, fortunately such structures are not common for multi-storey buildings in downtown areas of cities, where this method is most useful in practise. Shown in Table 3 are the RMS discrepancies between heights measured via monoplotting and those determined via 3-image spatial intersection, the accuracy of the latter being nominally 0.9m.

Sensor orientation model	No. of images	No. of CKPs	RMS discrepancy at CKPs (m)		
			Easting	Northing	Height
RPCs	*3, Triplet*	*44*	*0.32*	*0.53*	*0.87*
RPCs	1, nadir	46	0.60	0.70	0.70
RPCs	1, backward	41	0.98	0.59	0.70
RPCs	1, foreward	40	0.79	0.85	0.59
Affine	*3, Triplet*	*44*	*0.38*	*0.36*	*0.92*
Affine	1, nadir	47	0.36	0.46	0.77
Affine	1, backward	41	0.79	0.52	0.65
Affine	1, foreward	41	0.49	0.59	0.63

Table 2. Accuracy of monoplotted point positions from IKONOS imagery

Table 3 shows that the implied building height determination accuracy of close to 1m for single 29° off-nadir images is both better than the precision predicted via Equation 3 and effectively equivalent to measurements from a conventional multi-image spatial intersection.

Sensor orientation model	Height RMS discrepancy at CKPs (m)		
	Nadir (θ = 7°)	Forward (θ = 29°)	Backward (θ = 29°)
RPCs	6.59	1.08	1.31
No. of CKPs	*20*	*23*	*22*
Affine	3.05	0.69	0.76
No. of CKPs	*20*	*24*	*22*

Table 3. Accuracy of monoplotted building heights from IKONOS imagery

For the near-nadir image, lower height accuracies of approximately 6m for RPCs and 3m for the affine model were achieved. While the difference in accuracy for the IKONOS images is attributed primarily to the different satellite elevation angles, a DEM with denser post-spacing might have improved results even further. Nevertheless, it has been demonstrated that monoplotting from IKONOS imagery with the RPC and affine models is an efficient and effective method of producing 3D information to 1m accuracy level.

4.3 Results from QuickBird Imagery

A similar procedure to that described for the analysis of the IKONOS imagery was carried out for the two QuickBird images. Coordinate measurements derived from both monoplotting and stereo restitution were again compared to GPS observations for single 3D CKPs. For the case of QuickBird imagery, pixel level accuracy was obtained in planimetry and height when RPCs were employed with a single image, as indicated in Table 4. These results were more consistent than those from the standard 8-parameter 3D affine model, however, which produced poorer accuracy in planimetry, most noticeably in the easting or cross-track direction. This is likely a consequence of QuickBird's dynamic imaging geometry, which is characterised by a continuously varying pointing direction. Such perturbations can be modelled with an extended affine model with time-variant affine parameters and additional parameters (Yamakawa and Fraser, 2004), though this aspect has yet to be investigated in the context of monoplotting. In the meantime, it would appear prudent to consider only the RPC model for higher accuracy QuickBird sensor orientation.

Sensor orientation model	No. of images	No. of CKPs	RMS discrepancy at CKPs (m)		
			Easting	Northing	Height
RPCs	*2, Stereo*	*80*	*0.15*	*0.34*	*0.46*
RPCs	1, backward	32	0.54	1.53	0.71
RPCs	1, foreward	33	0.46	2.33	0.73
Affine	*2, Stereo*	*80*	*6.22*	*2.24*	*5.65*
Affine	1, backward	32	11.60	2.87	0.83
Affine	1, foreward	33	3.81	3.11	0.79

Table 4. Accuracy of monoplotted point positions from QuickBird imagery.

In spite of the lower than anticipated planimetric accuracy obtained in monoplotting with the affine sensor orientation model, the building heights derived monoscopically from QuickBird imagery produced 1m accuracy when compared to stereoscopic measurements for both the RPC and affine models, as indicated in Table 5.

Sensor orientation model	Height RMS discrepancy at CKPs (m)	
	Forward (θ = 30°)	Backward (θ = 32°)
RPCs	1.01	1.03
No. of CKPs	*30*	*30*
Affine	1.34	1.33
No. of CKPs	*29*	*29*

Table 5. Accuracy of monoplotted building heights from QuickBird imagery

The modest degradation in accuracy for the affine model is partly attributed to planimetric differences for the points where height comparisons were made, which affected the DEM height interpolation by extruding or truncating the building height. As with the IKONOS results, the height determination accuracy attained with single QuickBird images exceeded expectations. While it is true that the heighting precision listed in Table 1 is based on an image measurement standard error of 1 pixel, there was nothing to suggest that such a measurement precision was unrepresentative for the building feature points utilised in the investigation.

5. CONCLUSIONS

Monoplotting enables the extraction of 3D information from single HRSI, when an accurate DEM, a modest number of good quality GCPs and an appropriate sensor orientation model is provided. Under ideal conditions of off-nadir image acquisition, 1-pixel level point positioning and building height determination accuracy can be achieved. This paper shows that the monoplotting functions incorporated into the *Barista* software package provide a practical and efficient means for accurate 3D point positioning and building model extraction from single IKONOS and QuickBird image data. However, it has to be mentioned that with QuickBird imagery it is recommended to use the sensor orientation model of bias-corrected RPCs rather than the 3D affine model.

With the described monoplotting functions the *Barista* software now offers the option of 3D feature collection from single images, a capability which is very useful for map revision and image-based updating of spatial databases. In the case where an existing database contains geometric data limited to planimetric building footprints, single image analysis can be an appropriate method to collect the missing height information on an *ad hoc* basis. Moreover, the building footprint data can be projected into the image when the sensor model is known and DEM data for the area of interest is available. Starting from the footprint, the height of a building can be determined by image measurements. The footprint data are extruded by the height information and are then available for export in the same data format as the initial input data. However, problems which may be encountered using this approach are geometric discrepancies between the footprint data and the image contents, caused by either inaccurate footprint data or imprecise parameters of the sensor orientation model. Investigations into these issues are continuing, with the aim of enhancing the usability and utility of the monoplotting functions within *Barista*.

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