ACCURACY EVALUATION OF TERRAIN MODELLING FROM IKONOS STEREO IMAGERY

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ABSTRACT: An investigation of the accuracy of terrain model extraction from IKONOS stereo high-resolution satellite imagery is reported, in which digital surface model (DSM) data generated photogrammetrically was compared to height data acquired via LIDAR. In order to ensure generation of DSMs of optimal accuracy, the technique of bias-compensated RPCs was first employed to yield 1-pixel level sensor orientation and geopositioning accuracy. Two photogrammetric approaches were then employed to produce DSM data. The first was an intensity matching approach embodied in a commercial digital photogrammetric workstation from Z/I Imaging, and the second was a multi-photo, geometrically constrained (MPGC) image matching procedure incorporating point, edge and feature matching algorithms, developed at the Institute of Geodesy and Photogrammetry (IGP) of ETH Zurich. The resulting photogrammetrically generated DSMs were evaluated against LIDAR determined height data at several hundred thousand points over an area of 16 km^2. The accuracy assessment took into account varying terrain conditions, with heighting accuracy determinations being carried out for 10 different rural and urban land cover classes. The results indicate that DSMs can be generated from stereo IKONOS *Geo* imagery to an accuracy of 1.7m to 4.5m (RMS, 1-sigma) depending upon terrain and land cover conditions, with the best accuracies being produced by the MPGC image matching approach, which yielded an overall heighting accuracy at 750,000 checkpoints of 2.7m.

1. INTRODUCTION

History demonstrates that as new technology is introduced into a community, the community drives fresh requirements for more effective and efficient means of gathering knowledge. Take the introduction of civilian access to high-resolution satellite imagery (HRSI), for example. This has provided us with greater insights into earth information and has been exploited in a diverse range of practices such as topographic mapping, spatial and temporal change detection, feature extraction and visualisation. Among these, surface modelling is a common thread and core that underpins these applications, thereby propelling demands for increased detail and accuracy in digital surface models (DSMs).

There are several existing options for acquiring DSMs. Airborne laser ranging (LIDAR) and interferometric synthetic aperture RADAR (InSAR) produce metrically accurate models (Sties et al., 2000; Reutebuch et al., 2003; Alharthy et al., 2004), although for a large coverage area ideal for mapping applications, these methods lack the cost effectiveness of stereo restitution from spaceborne imagery. The advantage of HRSI for DSM generation is that the orbital path taken by the satellite allows consistent imaging, which when coupled with stereo capability is conducive to image matching. Additionally, many commercial software packages allow even the inexperienced user the opportunity to extract their own DSMs.

Evaluation of IKONOS imagery for metric purposes has been dominated by testing sensor orientation models for geometric point positioning (Gruen, 2000; Fraser, 2002; Toutin and Cheng, 2002) and its potential use in mapping and GIS products currently lies at medium scales (Zhang et al., 2002; Grodecki and Dial, 2003; Jacobsen, 2004; Passini and Jacobsen, 2004; Li and Gruen, 2004; Eisenbeiss et al., 2004). While DSM generation via stereo photogrammetric restitution is by no means new, there have been relatively few thorough accuracy evaluations of HRSI DSMs reported to date (see Poli et al., 2004; Gruen et. al., 2005).

This paper gives a detailed accuracy evaluation of a DSM generated with an IKONOS *Geo* stereopair, derived firstly using an intensity based matching method embedded in commercial software and, secondly, via a hybrid image matching algorithm. The accuracy assessment, which is based on comparisons against a first pulse laser DSM, encompasses diverse land cover types from urban high-rise buildings to rural forest areas.

2. IKONOS *GEO* IMAGERY

The DSMs evaluated were generated from an IKONOS *Geo* stereopair recorded in summer over Hobart, Australia. The 11 x 11 km images cover a variety of landforms, including mountainous forest areas, peaking at an elevation of 1280 m at Mount Wellington, and hilly neighbourhoods, parks and office blocks overlooking the Derwent River. In reverse scan mode, the images were collected at a sensor elevation of 69° and azimuths of 329° and 236° with a corresponding base-to-height ratio of 0.8. The testfield is also described in Fraser and Hanley (2005).

One of the challenges in using IKONOS imagery for photogrammetric image processing is that the product is delivered without physical camera model data. Rather, the object-to-image geometry is described by rational polynomial coefficients (RPCs) based on information derived from satellite ephemeris and star trackers. The absence of ground control information results in geopositioning biases. These biases are seen in the *Geo* product in particular, which offers a planimetric geopositioning accuracy of 15m CE90 (Space Imaging, 2005). However, the biases can be significantly reduced and for all practical purposes removed by incorporating additional parameters into an RPC bundle adjustment and then regenerating bias-corrected RPCs to facilitate 1-pixel level positioning in object space (Fraser and Hanley, 2003; 2005; Grodecki and Dial, 2003). For this investigation, 111 precisely measured ground control points (GCPs) were used to create bias-corrected RPC files, which were then incorporated into the image matching strategies adopted to ensure optimal image orientation during DSM generation.

3. ACCURACY EVALUATION

Accuracy assessment is commonly performed on the basis of a selection of several well-defined and precisely measured checkpoints. While these comparisons are valid, they only feign a realistic evaluation as check points are often characterised by highly contrasted features in locally flat areas of the test field, while areas of variable relief and diverse landcover are frequently misrepresented. Therefore, a precise LIDAR DSM acquired over a subset of the IKONOS scene, consisting of densely spaced points at an estimated heighting standard error of 0.25 m (AAMHatch, 2004), was used as control data. Figure 1 shows the location of the LIDAR strip within the IKONOS scene. As we are evaluating the surface, first pulse returns spaced at an average of 1.25 m were used to generate a 2 m reference grid for comparison with the actual matched points in the generated DSMs, allowing interpolation to be carried out in the higher quality data set to minimise effects of modelling errors.

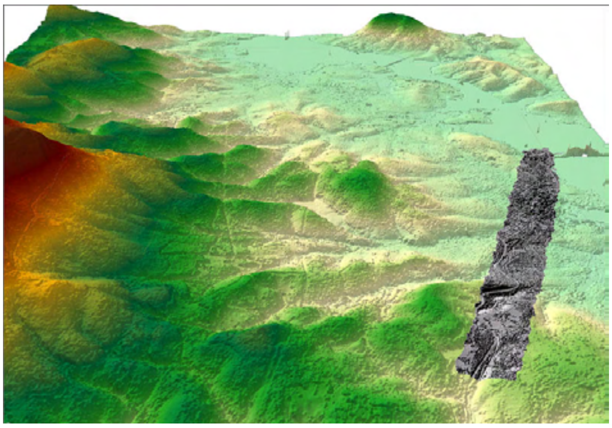

Figure 1. IKONOS scene highlighting LIDAR strip.

The surface content of the 16 km^2 LIDAR strip typified the IKONOS scene, since it included urban and rural areas in both undulating and flat terrain, as illustrated in Figure 2. The assessment region was classed into sections reflective of their landcover type to ensure that their accuracy could be evaluated independently; each class is expected to behave differently in the DSM generation process based on the imaging conditions. Broad categories of urban and rural regions were further subdivided into areas of the central business district (CBD), residential areas, the university, sports centres, parks, gardens, forest and bare ground areas as listed in Table 1 and shown graphically in Figure 3.

The benefit of testing within landcover classes is that some applications of height data, such as topographic mapping, specify different vertical accuracy requirements for various terrain conditions. Therefore, by subdividing terrain types, a more valuable assessment of the potential accuracy of each surface can be inferred.

Figure 2. LIDAR test field.

Class	*Description*
URBAN	
CBD	Tall buildings and asphalt car parks
Residential	Suburban housing
University	University campus consisting of elongated buildings mixed sporadically amongst parkland
Building	A large arched roof sports centre
Sporting fields	Sporting fields encompassing flat tennis courts and grassed ovals
Park	Parkland bordered by trees
Gardens	The botanical gardens comprising scattered Government buildings and trees surrounded by grass cover
RURAL	
Bare ground	Bare ground
Sporting fields	Sporting fields encompassing flat tennis courts and grassed ovals
Forest	Forest with moderately dense trees

Table 1. Land cover classes.

Two DSMs were generated for evaluation from the IKONOS imagery. Firstly, an intensity-based image matching procedure in Image Station Automatic Elevations (ISAE) from Z/I Imaging Corporation's commercially available ImageStation Photogrammetry Suite 4.3 was employed. Secondly, an integration of point, feature and grid matching algorithms with a modified multi-photo geometrically constrained matching procedure (MPGC, see Li and Gruen, 2004) was applied.

3.1 Evaluation of ISAE DSM

ISAE's method of automatic height generation uses image and feature pyramids to match homologous points in a hierarchical structure. Matches are deemed reliable when assessed by correlation coefficient and interest value similarity measures. The differences in parallax are expressed by bilinear finite elements and the high degree of automation in ISAE's DSM generation restricts the user to specifying only parallax bound and epipolar line distance parameters. A more detailed discussion of the ISAE mathematical model can be found in Z/I Imaging Corporation (2004).

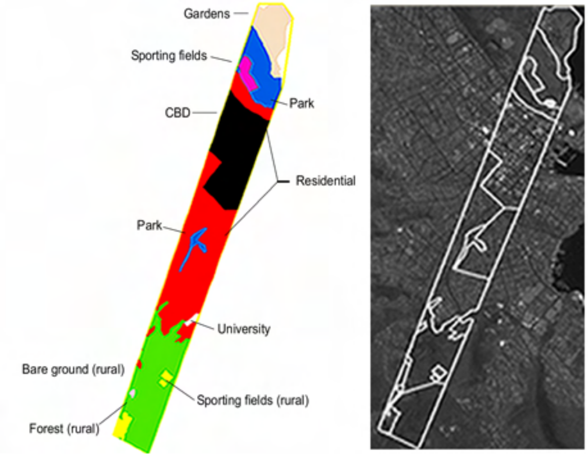

Figure 3. Classification of LIDAR test field.

The ISAE process generated 580,965 raw heights which were compared to derived heights that had been bilinearly interpolated from the LIDAR DSM. Overall, the RMS discrepancy (RMSE) was 4.0 m and the regions with the greatest error were, not surprisingly, in areas of large topographic variability, namely the CBD and forest regions with RMSE values of 4.3 and 4.5 m, respectively, as outlined in Table 2. The attainable accuracy was improved, however, in areas where imaging conditions were conducive to higher precision image matching, such as the bare ground in the rural category where accuracy increased to better than 3 pixels.

Class	*No. of points*	*Height Discrepancy at Checkpoints (m)*		
		RMSE	*Mean*	*Abs Max*
Overall	580 965	4.0	0.3	49
URBAN				
CBD	124 157	4.5	1.0	49
Residential	230 149	3.1	0.6	23.0
University	499	3.3	-0.3	15.1
Building	626	4.0	2.7	15.3
Sporting fields	12 105	3.6	0.3	24.0
Park	54 545	3.8	-0.7	36.8
Gardens	59 905	3.7	-0.6	36.8
RURAL				
Bare ground	271	2.8	-0.5	16.9
Sporting fields	19 732	3.8	0.1	31.2
Forest	78 976	4.3	-0.6	34.8

Table 2. Evaluation of ISAE DSM.

3.2 Evaluation of MPGC DSM

The second image matching approach involves extracting feature points using the Foerstner interest operator (Foerstner and Guelch, 1987) and matching candidates with a geometrically constrained cross-correlation method (Gruen, 1985). The Canny operator (Canny, 1986) is used to detect edge segments and the success of their corresponding matches is evaluated by intensity, relaxation and shape matching measures. Weak candidates for grid points are similarly eliminated by assessment of a relaxation technique based on Prazdny's coherence principle method (Prazdny, 1985). All successfully matched features are then refined with a modified MPGC allowing subpixel accuracy in image and object space. A more complete description of the process can be found in Li and Gruen (2004).

The hybrid image matching DSM procedure produced a total of 756,073 grid, edge and feature matched heights with an overall RMSE of 2.7 m. This evaluation tells us that the generated DSM is indeed a good representation of the actual terrain. The accuracy for each individual land cover class is summarised in Table 3, which shows that in general areas inclusive of low rise buildings and sparse vegetation were modelled to an accuracy of 1.7 – 2.2 m. A difference map is illustrated in Figure 4, showing the height discrepancies between the generated and reference DSMs.

Class	*No. of points*	*Height Discrepancy at Checkpoints (m)*		
		RMSE	*Mean*	*Abs Max*
Overall	756 073	2.7	0.2	32.7
URBAN				
CBD	147 908	3.4	1.1	27.2
Residential	291 923	2.0	0.4	25.0
University	736	2.2	0.04	10.1
Building	1 252	2.5	1.3	16.1
Sporting fields	14 156	2.2	0.1	19.0
Park	73 807	2.9	-0.6	30.4
Gardens	65 217	2.7	-0.5	31.7
RURAL				
Bare ground	763	1.7	0.4	9.8
Sporting fields	23 551	2.4	0.1	30.2
Forest	136 760	3.2	-0.5	32.7

Table 3. Evaluation of MPGC DSM.

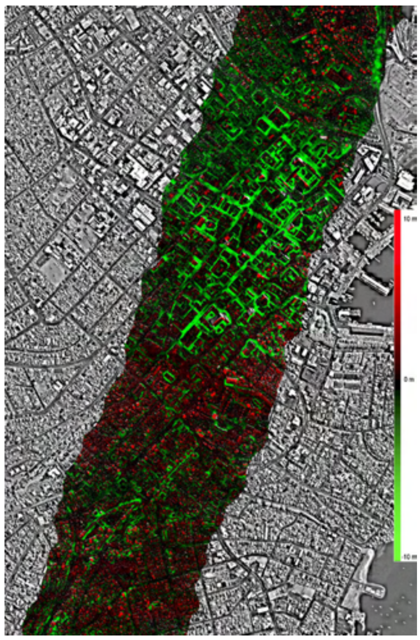

Figure 4. Difference map between the ISAE and MPGC generated DSMs.

3.3 Comparison of DSM generation approaches

Both DSMs generated had greatest discrepancies against the reference DSM in areas of mixed topography, for example in forests where irregular trees are modelled and in urban areas where buildings protrude from the surface. The forest area in particular was susceptible to poor image matching due to the low image contrast and occlusions. Occluded areas are also inherent in the urban areas where buildings cast shadows; in addition, moving vehicles on the roads may have produced blunders and false matches contributing to a higher RMSE.

The evaluation of the generated DSMs unrealistically assumes that errors are solely attributable to the image matching. There are also errors to consider in the LIDAR reference DSM, such as weaknesses in the returned laser signals over less reflective surfaces and misinterpretation of vertical profile strikes as representing a horizontal surface.

In all land cover classes, the MPGC matching produced considerably better results than the commercial automatic DSM generation method. Notably, the MPGC approach had a significantly greater number of successful matches. A comparison between the ISAE and MPGC DSMs showed that there was an RMS height discrepancy of 3.5 m, although the majority of the height differences were within 1 m, as indicated by Figure 5. Visual inspection showed that although reasonable results were achieved in the ISAE DSM, there were fewer successfully matched points over objects such as trees and small buildings, which may be attributed to insufficient edge matching and the lack of detail preservation in the adopted matching algorithm. Other errors may originate from incorrect surface modelling or interpolation inadequacy. Generally, 2.5D surface modelling should be replaced by a truly 3D approach, and is especially imperative in cases of strong surface discontinuities, steep terrain and man-made objects.

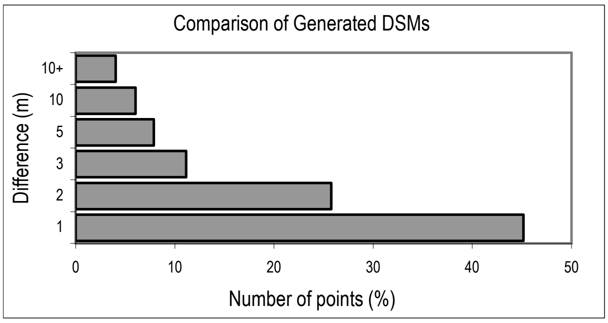

Figure 5. Comparison of ISAE and MPGC DSMs.

4. CONCLUDING REMARKS

DSM quality is largely dependent upon image resolution, land cover type and the adopted image matching algorithm. Here, it has been demonstrated that 1 m IKONOS HRSI is an effective source for accurate DSM generation. Moreover, this investigation has provided an insight into accuracy variability associated with areas of differing land cover. While automatic DSM extraction from the ISAE commercial software yielded an accuracy of approximately 4 pixels, use of the multi-stage MPGC process produced a heighting accuracy of better than 3 pixels over topographically diverse areas. This was further improved in ideal matching situations of feature-rich and relatively flat terrain where surface modelling to an accuracy of a little over one and a half pixels was attained.

The IKONOS results have reinforced the performance of IGP's Hybrid Matcher; similarly encouraging results have been achieved with SPOT data (Poli et al., 2004). As a further task, it is necessary to separate matching and modelling errors. This problem can be undertaken by replacing the traditional 2.5D modelling of terrain surfaces by a strict 3D modelling procedure.

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