

# HIGH-RESOLUTION SATELLITE IMAGING FOR DIGITAL SURFACE MODELS

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**ABSTRACT:** Elevation information is an important component of any geospatial database. It is imperative for applications such as topographic mapping, spatial and temporal change detection, feature extraction and visualisation. Although elevation data may in cases be purchasable from government agencies, the availability of alternative sources of data, such as space imagery, coupled with increased user confidence in technology, it is now viable for consumers to produce their own spatial datasets. With commercial-off-the-shelf (COTS) software, operators with limited expertise can easily create their own application specific project. This paper will provide a detailed study on the accuracy and performance of elevation extraction from COTS software, with emphasis on digital surface models (DSMs) generated from high-resolution satellite imagery. The evaluation is important due to the high cost investment associated with these systems. In checkpoints favourable to image matching, accuracy to a few pixels in height can be achieved from COTS DSMs; however the isolated points are unlikely to be representative of the entire testfield. Therefore, we look to alternative sources of control, such as the newly available DLR- and NASA-generated SRTM DEMs. A comparison to X-band SRTM DEMs showed that height RMSE values range from 4 – 9 metres, though most of this uncertainty is attributed to the SRTM data.

## 1. INTRODUCTION

One of the most significant, long term challenges faced in image processing is the problem of achieving highly accurate and automated image matching. Subject to significant research in both academia and industry, continuous improvements in image matching methods presently allow smarter algorithms to be implemented into digital photogrammetric workstations. The integration of modules such as automated terrain extraction based on image matching algorithms into commercial-off-the-shelf-systems (COTS) provide a viable option for consumers with limited expertise to create their own application specific spatial information.

COTS systems for stereoscopic terrain extraction may have similarities in workflow, but range widely in production environment and operational procedures. The high cost investment of such systems which promise greater efficiency and less labour cost with minimal human intervention stresses the importance of performance evaluation. This paper reports on the results of an investigation into the accuracy and performance of DSM extraction from high-resolution satellite imagery (HRSI) using COTS photogrammetric workstation software.

Conditions conducive to automatic image matching, such as HRSI acquired in along-track stereoscopic mode coupled with accurate geopositioning enhance the prospects for generating accurate terrain data from space images (Eisenbeiss et al., 2004; Fraser and Hanley, 2005). Although there have been quality assessments of DSM generation from optical imagery, many of these originate from sources of independent matching algorithms (Büyüksalih et al., 2004; Gruen et al., 2005; Poon et al., 2005) and although reports of COTS generated products from aerial imagery exist (Baltsavias & Käser, 1998;

Büyüksalih and Zhang, 2003), there are few accounts involving space imagery (Al-Rousan and Petrie, 1998; Biard et al., 2004).

There are numerous COTS systems which contain an automated terrain extraction capacity. Here we concern ourselves with three systems which were accessible to the authors: the Softcopy Exploitation Tool (SOCET SET) Automatic Terrain Extraction (ATE) version 5.2, Z/I Imaging's ImageStation Automatic Elevation (ISAE) version 4.4 and ERDAS' Imagine OrthoBASE Pro version 8.6 (BAE Systems, 2005; Intergraph Corporation, 2005; Leica Geosystems, 2002).

## 2. IKONOS IMAGERY

Traditional bundle adjustments cannot be applied to pushbroom scanner IKONOS imagery due to each line of imagery being independently acquired, coupled with the omission of camera model and satellite positional and ephemeris data. However, the image-to-object geometry can be reconstructed with alternative sensor orientation models. For the case of IKONOS imagery, rational polynomial coefficients (RPCs) originating from satellite ephemeris and star tracker observations can be used to describe the object-to-image space transformation. Consequential of excluding ground control in the derivation of RPCs, biases inherent in the polynomials must be removed in order to facilitate 1-pixel level geopositioning (Fraser and Hanley, 2005; Grodecki and Dial, 2003). For this investigation, four precisely measured GCPs of 10 – 15 cm accuracy were used to create bias-corrected RPC files, which were then input into the COTS systems.

The test field consists of an IKONOS Geo stereopair, recorded over Hobart, Australia in February 2003. The images were collected in reverse scan mode at a sensor elevation of 69° and azimuths of 329° and 236° with a corresponding base-to-height

ratio of 0.8. Within the 120 km<sup>2</sup> coverage, there is a variety of landforms, including mountainous forest areas to office blocks overlooking the Derwent River. Shown in Figure 1 is a perspective view of the test area, obtained by draping an ortho-corrected IKONOS image over the extracted terrain model. The test field is also described in Fraser and Hanley (2005). The test field was subdivided into 5 classes, detailed in table 1 and shown in figure 2. The division of the land cover classes was determined by monoplotted using bias-corrected RPCs to allow boundaries to pixel level accuracy (Willneff et al., 2005).

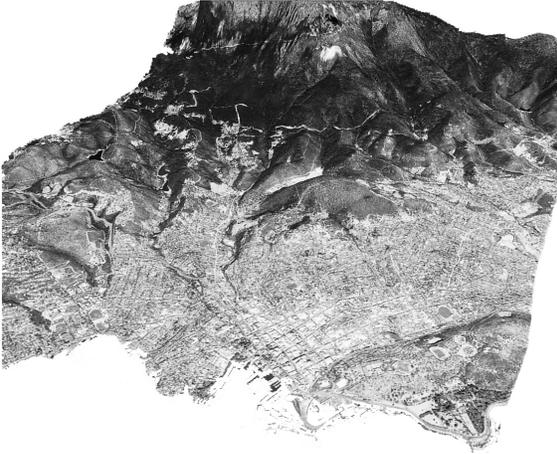


Figure 1. Perspective view of test field

<i>Class</i>	<i>Description</i>
Bare ground	Bare ground
Urban	Suburban housing and multistorey office blocks
Rural	Suburban – rural fringe consisting of mixed land use
Forest	Forest
Water	Water bodies inclusive of agricultural dams and Derwent River

Table 1. Land cover classes

### 3. SRTM INSAR REFERENCE

Although there were 138 available CKPs, these isolated, distinct features are unlikely to be representative of the entire test region. Therefore, we looked to alternative sources of terrain surface control, such as the newly available DEMs extracted from the Shuttle Radar Terrain Mission (SRTM) by both NASA and the German Aerospace Centre (DLR).

The advantage of SRTM data is that the InSAR can capture elevation independent of time and seasonality affects such as light and weather inconsistencies. The InSAR data was collected by two antenna pairs, a 12 m steerable antenna transmitting and receiving C-band microwave pulses with a 5.6 m wavelength, and a 60 m baseline mast supporting X-band InSAR at a wavelength of 3.1 m. The processing of the X-band data has been conducted by DLR, as detailed in Knöpfle et al. (1998). Provided in WGS84 geographic coordinates, the DEMs are accurate to +/- 16m absolute vertical and +/- 6m relative vertical accuracy (Rabus et al., 2003). In this paper, the DLR-supplied high energy X-band DEM, which represents the

surface of the terrain and is effectively a DSM, will be used as a reference source for purposes of comparison with the HRSI DSMs.

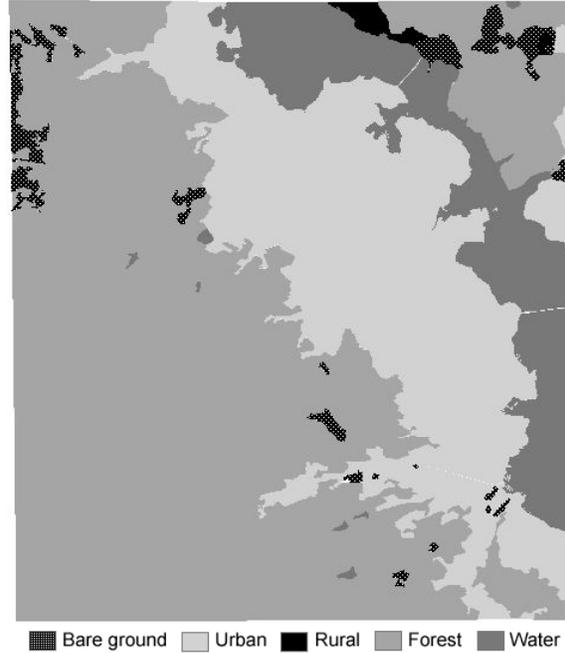


Figure 2. Hobart IKONOS test field land cover

As outlined in table 2, a comparison between bilinearly interpolated heights from a 23 m post spacing SRTM grid against 138 CKPs showed that there was an RMSE height discrepancy of 3.8 m. SRTM heights at the CKPs are generally modelled below the true surface, although there were no trends to suggest systematic biases over any particular area – even the peak of Mt Wellington was reasonably modelled with an RMSE height discrepancy of 2.9 m. If we take the InSAR derived heights to be ‘true’, then we have the advantage of a larger reference surface to aid in a more complete evaluation of whole scene DSMs, and additionally observe the differences between optical and radar derived terrain models.

<i>System</i>	<i>No of valid CKPs</i>	<i>Height Discrepancy at CKPs (m)</i>		
		<i>RMSE</i>	<i>Mean</i>	<i>Abs Max</i>
SRTM DEM	138	3.75	-1.91	9.48

Table 2. Height discrepancy of SRTM DEM at GPS CKPs

### 4. COTS EVALUATION

The accuracy of the terrain model generated within a particular COTS system will be influenced by the adopted image matching strategy. Each system allows a number of alternatives for parameters such as search size, parallax bound, correlation coefficient threshold, terrain type and options for smoothing. In this investigation, six strategies were trialled in OrthoBASE Pro and SOCET SET ATE, while four were tested in Z/I Imaging’s ISAE. All automated terrain extraction algorithms were based on a coarse to fine pyramid structure to determine elevation,

using image matching and calculations of cross correlation coefficients to identify corresponding image points (ERDAS LLC, 2002; BAE Systems National Security Solutions Inc,

2004; Z/I Imaging Corporation, 2004). Tables 3-5 summarise RMSE height discrepancies of COTS generated DSMs compared to the InSAR reference.

<i>OrthoBASE Pro</i> <i>Landcover Class</i>	<i>RMSE Height Discrepancy with InSAR reference (m)</i>					
	<i>High Urban</i>	<i>High Urban Adaptive</i>	<i>Forest</i>	<i>Forest Adaptive</i>	<i>Open</i>	<i>Open Adaptive</i>
No of valid CKPs	657,284	657,632	666,741	670,315	671,367	670,330
Invalid CKPs	0.8%	0.9%	1.1%	1.2%	1.1%	1.2%
Bareground	6.11	6.08	6.08	6.04	6.10	6.06
Urban	5.25	5.23	5.17	5.15	5.20	5.18
Rural	5.56	5.52	5.49	5.45	5.52	5.50
Forest	8.58	8.43	8.51	8.49	8.54	8.45
Water	7.40	7.28	7.40	7.26	7.43	7.23
Overall	6.20	6.12	6.15	6.09	6.18	6.12

Table 3. Height discrepancy between OrthoBASE Pro DSMs and InSAR reference

<i>SOCET SET ATE</i> <i>Landcover Class</i>	<i>RMSE Height Discrepancy at CKPs (m)</i>					
	<i>SPOT</i>	<i>SPOT smooth</i>	<i>Steep plus</i>	<i>Steep plus smooth</i>	<i>Adaptive</i>	<i>Adaptive smooth</i>
No of valid CKPs	6,174,545	6,197,821	6,697,456	6,727,359	6,652,028	6,686,003
Invalid CKPs	21.5%	21.2%	14.9%	14.5%	15.4%	15.0%
Bareground	6.48	6.42	6.42	6.45	6.47	6.42
Urban	5.64	5.45	5.45	5.45	5.59	5.42
Rural	6.27	6.12	6.11	6.10	6.25	6.09
Forest	10.85	10.74	10.74	10.59	10.69	10.62
Water	10.42	10.43	10.43	10.65	10.58	10.54
Overall	9.34	9.25	9.40	9.31	9.36	9.28

Table 4. Height discrepancy between SOCET SET ATE DSMs and InSAR reference

<i>Z/I Imaging ISAE</i> <i>Class</i>	<i>RMSE Height Discrepancy at CKPs (m)</i>							
	<i>S2R</i>	<i>S4R</i>	<i>S5R</i>	<i>S7R</i>	<i>S2Q</i>	<i>S4Q</i>	<i>S5Q</i>	<i>S7Q</i>
No of valid CKPs	16,830,242	16,517,942	16,360,359	16,570,762	1,638,270	1,615,273	1,633,648	1,634,425
Invalid CKPs	5.6%	11.1%	26.8%	10.9%	10.5%	11.7%	10.7%	10.7%
Ground	8.20	7.73	7.79	7.74	6.51	6.50	6.51	6.48
Urban	7.91	7.44	7.35	7.44	5.78	5.76	5.78	5.76
Rural	8.74	8.56	8.20	8.58	6.69	6.67	6.71	6.67
Forest	11.03	11.27	10.78	11.24	10.59	10.64	10.62	10.59
Water	10.37	9.55	9.97	9.50	12.04	11.96	11.78	12.03
Overall	9.37	9.26	8.97	9.26	9.50	9.49	9.48	9.49

Table 5. Height discrepancy between Z/I Imaging ISAE and InSAR reference

### 5. COMPARISON OF COTS

SOCET SET ISAE and OrthoBASE Pro have options for selecting predetermined strategies specific for a particular land cover type, for example forest, open or steep areas. It is noteworthy that for the Hobart IKONOS data the choice of a given unique strategy, such as the forest strategy, did not appear to improve modelling in the forest regions. In fact, accuracy was slightly degraded. Similarly, the open and urban areas were not improved with their corresponding strategies. This suggests that perhaps users should not overly rely on predetermined

settings. Overall, there was little variation between the strategies and their corresponding RMSE height discrepancy values for each COTS system.

Raw mass points could not be retrieved from the Z/I Imaging scratch files, with only a regular grid point output being obtained. The raw mass points are highly dense and the percentage of blunders ranged from 5 – 27% for the varying strategies, though after blunder elimination, similar RMSE values were evident across all the test strategies. For regularised grid DSMs, blunders were consistently 10% of the

total number of matched points (the fact that regular post spacing output from the Z/I Imaging system would be used, and not the raw mass point files, has been accounted for in the comparison between results from the three COTS systems, which employed regularly gridded DSMs). Although over 6 million elevation nodes were generated at a 5 m post spacing in the SOCET SET ATE DSM, visual representation of the terrain is better reflected in the Z/I Imaging ISAE DSM despite a 10 m post spacing. The SOCET SET ATE achieved similar accuracy levels to Z/I Imaging's ISAE, yet blunders accounted for 15 – 22 % of the data. Without blunder elimination, there were far too many errors in the SOCET SET ATE data.

It appears that from the RMSE values alone, the OrthoBASE Pro DSM is higher in accuracy. However, we should be mindful that there are fewer mass points in the OrthoBASE Pro DSM, which is therefore less susceptible to possible cumulative errors inherent in the interpolation and modelling. The best results overall from the COTS systems is detailed in Table 6.

It is important to note when evaluating the listed height discrepancies that the InSAR reference terrain model is also subject to error. Due to the larger grid spacing of the SRTM DEM in comparison to the COTS system DSMs, features would be effectively smoothed out in the InSAR reference. A degradation of accuracy in the SRTM DEM may result from spurious reflections and backscatter and hence fail to replicate the true physical surface, which also cannot be expected to correspond exactly with the HRSI derived surface. Disparities between the photogrammetrically and radar derived DSMs can mislead accuracy indicators. This was especially evident in the test field's south west where there was cloud cover in the satellite imagery. Matching may have failed in this area where the image quality is low, whereas the active InSAR sensor is able to penetrate cloud and would therefore produce more reliable ground surface heights.

Comparisons can also be made between the COTS generated DSMs to highlight differences in matching strategies. Each COTS DSM was used in turn as the reference source and terrain points in the DSMs were used to bilinearly interpolate a height from the reference grid. Table 7 indicates that although the greatest discrepancies are in the modelling of forest and water regions, interpolation is the dominant contributor to higher RMSE values. Where there are fewer CKPs, there are fewer interpolations and hence less errors propagating into the accuracy indicators. For a true comparison, the interpolation should be taken in the higher order reference set.

## 6. CONCLUDING REMARKS

This paper has demonstrated that readily available COTS systems can extract elevation information from HRSI to accuracies of 4 – 9m, overall. This accuracy figure must be seen as indicative, for it is derived from both comparisons between DSMs from a single IKONOS stereo pair generated by three COTS systems, and a comparison against an InSAR DEM of lower, but arguably more consistent accuracy across a large area of the Hobart test site.

As regards the different DSM generation strategies offered by commercial digital photogrammetric workstations, distinctions between the terrain extraction solutions from the different predetermined default parameter sets was not clearly apparent, suggesting that a degree of photogrammetric experience remains desirable when using these systems. As many errors in modelling can be accounted for in the interpolation process, further research into assessing the effect of interpolation errors in gridded DSMs would enhance the understanding of DSM generation from HRSI.

System	Reference	Class	No of valid CKPs	Height Discrepancy at CKPs (m)	
				RMSE	Mean
Z/I Imaging ISAE (S5Q)	InSAR	Bare ground	37,925	6.51	0.60
		Urban	475,190	5.78	2.16
		Rural	8,496	6.70	3.85
		Forest	852,921	10.63	1.94
		Water	154,878	11.78	-5.13
		Overall / Invalid	1,633,648 / 10.7%	9.48	0.34
SOCET SET ATE (SPOT smoothed)	InSAR	Bare ground	152,589	6.42	0.62
		Urban	1,908,037	5.45	2.12
		Rural	33,977	6.11	3.53
		Forest	2,960,847	10.74	-181.58
		Water	481,011	10.43	94.35
		Overall / Invalid	6,197,821 / 21.2%	9.25	0.55
OrthoBASE Pro (Forest adaptive)	InSAR	Bare ground	21,056	6.04	0.78
		Urban	460,025	5.15	1.95
		Rural	7,716	5.45	2.56
		Forest	133,151	8.49	-1.06
		Water	5,491	7.26	-0.74
		Overall / Invalid	670,315 / 1.2%	6.09	1.63

Table 6. Height discrepancies between COTS system DSMs and InSAR reference in land cover classes

System	Reference	Class	No of valid CKPs	Height Discrepancy at CKPs (m)	
				RMSE	Mean
Z/I Imaging ISAE	SOCET SET ATE	Bareground	37,744	1.71	-0.15
		Urban	475,895	2.15	-0.14
		Rural	8,802	2.24	0.47
		Forest	718,435	4.28	152.63
		Water	133,478	7.58	-88.48
		Overall / Invalid	1,523,665 / 20.1%	4.21	-0.34
SOCET SET ATE	Z/I Imaging ISAE	Bareground	150,995	2.34	-0.45
		Urban	1,903,858	2.25	-0.41
		Rural	35,147	2.13	0.13
		Forest	2,871,069	5.08	-153.61
		Water	533,340	7.53	88.55
		Overall / Invalid	6,085,103 / 18.0%	4.67	-0.49
Z/I Imaging ISAE	OrthoBASE Pro	Bareground	37,503	2.64	0.15
		Urban	472,561	2.47	0.33
		Rural	8,709	2.84	1.44
		Forest	526,112	8.67	20.64
		Water	183,356	9.99	-4.29
		Overall / Invalid	1,360,351 / 25.7%	7.09	0.32
OrthoBASE Pro	Z/I Imaging ISAE	Bareground	20,934	2.30	-0.68
		Urban	460,433	2.18	-0.61
		Rural	7,908	2.11	-0.65
		Forest	122,808	4.17	-1.53
		Water	5,679	3.28	-0.60
		Overall / Invalid	660,367 / 1.2%	2.83	-0.69
SOCET SET ATE	OrthoBASE Pro	Bareground	149,968	2.33	0.13
		Urban	1,890,409	1.70	0.26
		Rural	34,829	1.87	1.14
		Forest	2,090,710	8.34	-118.15
		Water	534,506	4.78	75.99
		Overall / Invalid	5,305,732 / 28.9%	6.03	0.76
OrthoBASE Pro	SOCET SET ATE	Bareground	20,938	1.51	-0.61
		Urban	460,441	1.48	-0.51
		Rural	7,908	1.39	-0.65
		Forest	122,289	3.28	6.72
		Water	5,683	1.91	-0.29
		Overall / Invalid	671,644 / 1.0%	2.03	-0.60

Table 7. Height discrepancies between COTS system DSMs for different land cover classes

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