

Next-Generation Automatic Terrain Extraction (NGATE)

Innovation in the cost-effective derivation
of elevation data from imagery

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Executive summary

Automatic determination of heights from imagery is a difficult problem. BAE Systems has offered the Automatic Terrain Extraction (ATE) and Interactive Terrain Editing (ITE) modules of SOCET SET® for many years and these represent a best-in-industry solution, though mistakes can occur in certain circumstances. Now BAE Systems has introduced Next-Generation Automatic Terrain Extraction (NGATE), a new approach to the problem. NGATE is easy to use and offers significant improvements in accuracy to ATE, resulting in a reduction in the amount of editing required in the ITE phase. Tests indicate that *this reduction is in excess of 30%*, which represents considerable progress in terms of productivity and cost savings sufficient to provide ample ROI on the cost of ownership of NGATE.

Introduction

The derivation of elevation data from imagery is a challenge with which photogrammetrists have grappled for half a century. The goal of fully automating the laborious task of measuring many thousands of points in every stereo overlap is overwhelmingly attractive, yet ultimately elusive. The problem is that the underlying image matching process may fail or give incorrect results, not because the algorithms are erroneous, but because the overlapping images are simply different. For example, a pitched roof may have both sloping sides dark on one image, but one of them much lighter on another. This is trivial for a human viewing the imagery, since it is straightforward to understand what is being viewed, but very difficult for an automated software process. A second problem is that, especially on large-scale imagery, automated algorithms often hit problems with trees and buildings, which simply look different in different overlapping images. The discontinuities at the edges of roofs of buildings are particularly difficult, added to the fact that often the side of a building appears in one image but not another.

The approach taken with the ATE and ITE modules in SOCET SET has been a reasoned solution to the practical problems. ATE has a long history, originating in work done in the 1980s on U.S. government programs. It is based on area-matching, i.e., a small window in one image is matched against a moving window in another image to find the best match using two-dimensional cross-correlation. This method is a refinement of possibly the most popular method of image matching. ATE includes certain special algorithms to increase its effectiveness, for example different strategies can be applied for different kinds of terrain, so that in the event of failed or very poor matching, for example, a slope constraint parameter ensures that the algorithm does not stray unrealistically far from the true terrain. The parameters for the different strategies can be specified by the user, but this demands a deeper knowledge of SOCET SET than should be expected of most users. Consequently, in 1997 Adaptive ATE was introduced, enabling the parameters to start in accordance with one of a limited range of strategies then vary according to the nature of the terrain. Development work has continued and the following examples illustrate the advances aimed at more reliable terrain from the automated process:

- Numerous improvements to the interactive editing functions and the speed of drawing terrain over the stereomodel; a “bare earth” filter to remove trees and buildings, i.e., change the digital surface model (DSM) derived from the image matching into a digital elevation model (DEM)
- Import existing terrain models or feature files to “seed” the ATE process, i.e., provide it with reasonable starting values to reduce computing time and increase the probability of the correlation algorithm finding the true optimum for each point
- Merge different DTMs into a single output, taking into account the precision of each component DTM and any biases (systematic vertical shifts) between them
- Increase compatibility in switching between grid and TIN (triangulated irregular network) representations of the terrain and the provision of equivalent functionality for both representations
- Multi-image matching, whereby the optimum stereo pair is selected for each area based on the nature of the terrain and the overall geometry of the sensor positions and orientations with respect to it
- Back-matching, whereby a fixed window in one image is correlated with a moving one in the other, then the process is reversed and any discrepancies between the results are evidence of an erroneous point, which can then be rejected — indeed, multi-image

matching can also reveal discrepancies and detect blunders, or the multi-image and back-matching approaches can be used in combination [more detail is provided in Zhang *et al.* (2006a)]

- Redesign the architecture of the underlying terrain database to accommodate the massive point clouds being acquired by the airborne LIDAR systems that are central in current mapping operations

These examples summarize the tremendous progress in ATE and ITE software, embodying many labor years of effort, resulting in a best-in-industry software product. Nevertheless, with technology, there is always room for improvement. In 2005, Dr. Bingcai Zhang began to work on some ground-breaking ideas for a new approach.

Principles of NGATE

The theory behind NGATE and the algorithms associated with it have been described in a series of published papers, for example Zhang *et al.* (2006b) and Zhang (2006).

The foundation of NGATE's algorithms is as follows:

- At the heart of the concept is the idea that earlier algorithms were all based on the principle that the terrain within the window being matched is level. This is clearly not the case and, indeed, elevation differences within the window reduce the correlation. Thus NGATE was built with the capability of allowing terrain variation within the window and the window size is related to the elevation difference.
- Most image matching algorithms perform correlation at specific points, usually spaced out according to the choice of the user. In ATE, for example, the user selects the point spacing as a function of the resolution of the imagery, i.e., some multiple of the ground sample distance (GSD) or pixel size of the imagery. In NGATE, however, matching takes place for every pixel. Previously, this approach was regarded as too slow owing to the daunting computational effort of matching at each of the hundreds of millions of pixels in a stereo overlap, but NGATE's innovative computational algorithms are so fast that this has ceased to be a stumbling-block.
- ATE and similar solutions use area-matching, usually based on a form of the two-dimensional cross-correlation function. The problem of discontinuities at the edges of roofs has already been highlighted. Furthermore, edges are lines rather than areas, so in this situation it is probably better to match edges rather than areas. Edge-matching is more robust for buildings: elevation discontinuities such as building edges usually generate image edges; and edge-matching "masks" out pixels that are not edge pixels, which likely have significant elevation differences. NGATE, therefore, uses both edge-matching and area-matching. Moreover, the algorithm enables the area-matching to be used to assist the edge-matching, and *vice versa*— an extremely powerful combination. NGATE is based on a hybrid approach: results from image correlation are used to guide and constrain edge-matching; results from edge-matching are used to guide and constrain image correlation; and the final results are the combined results from both area-matching and edge-matching with blunder detection and inconsistency checking.
- These principles are the basis of a complex body of algorithms and efficient software code, resulting in accurate, very dense terrain models. NGATE is designed not only to be robust and fast, but also to be easy to use, with rather few choices to be made by the user. It functions with all the sensor models and image types available in SOCET SET.

A comparison of NGATE and ATE is provided in Table 1.

Criterion	NGATE	ATE
Computation of image matching	Every pixel	Each post
Type of matching	Combines results optimally from area-matching and edge-matching	Uses only area-matching
Basis of accuracy and speed	RSET level at which to stop	Post spacing or number of posts
Back matching	On by default	User can turn on/off via GUI
Performance	Better with large-scale imagery in urban areas	
Editing time	Less, resulting from highly accurate DTMs	

Table 1: Comparison of NGATE and ATE

Using NGATE

NGATE is called from the top-level menu in SOCET SET, in the same way as ATE: **Extraction > Terrain > Next Generation Automatic Extraction** (Figure 1).

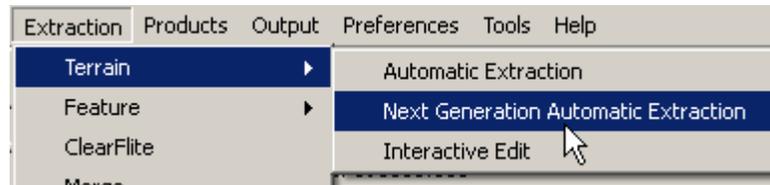


Figure 1: Calling NGATE from top-level menu in SOCET SET

When the NGATE window opens, typically the user will choose **Create DTM** (Figure 2).

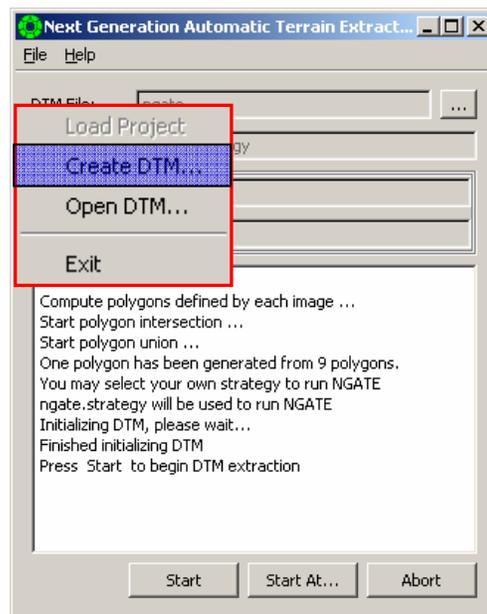


Figure 2: NGATE main window

The *Create DTM* window that appears is in the modern tabbed style (Figures 3 – 6). This is where the user names the DTM that is to be generated, using *Save* or *Save As*. The first tab is *Images*: the user selects the images to be used in the normal SOCET SET way (Figure 3).

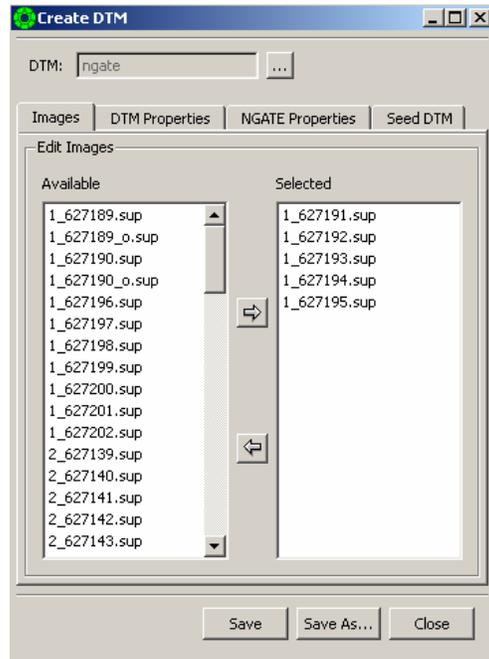


Figure 3: Selecting imagery for NGATE to use

The *DTM Properties* tab (Figure 4) enables the user to define the extent of the required DTM, using coordinates, a bounding polygon or image footprints, the representation of the output (grid or TIN), and the spacing (*X Spacing* and *Y Spacing*). In the case of a grid, spacing is a straightforward concept. In the case of a TIN, NGATE makes cells of the size specified in the spacing and puts points in the cells where good quality matches are achieved. This constitutes the raw data to be triangulated into the TIN. NGATE computes an elevation for every pixel. The user, however, may not want such a huge DTM. The spacing is used to resample the internal NGATE DTM to the desired density.

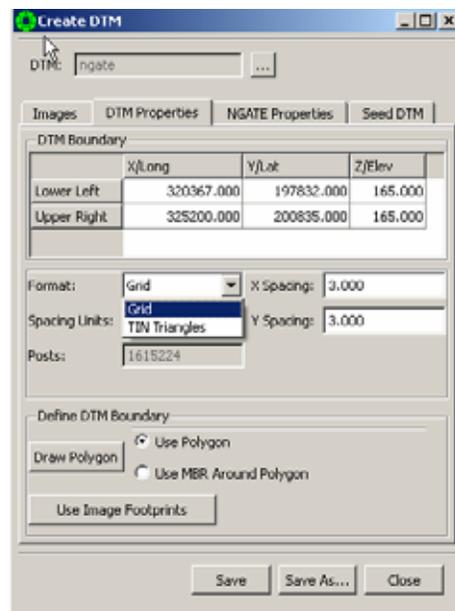


Figure 4: Defining the extent of the DTM NGATE is to create

The third tab, *NGATE Properties* (Figure 5), enables the user to make all of the important decisions about how NGATE will run. These options require more discussion:

1. Two *Strategies* are available: *ngate.strategy* for small to medium scale imagery, mostly natural terrain; and *ngate_urban.strategy* for larger scale imagery, as commonly acquired over urban areas. These strategies can be customized for difficult areas. The strategy files are in `<SS root>\internal_dbs\DTM_STRATEGY`.
2. The *Maximum Number Image Pairs Per Point* has a default value of one. If there is more than one image pair, a value of two to three is recommended. The *Number of Sections* has a default value of one. If your computer has more than one CPU and you have more than one NGATE license, then you can select a value greater than one, in which case more than one NGATE executes. Each NGATE generates a section of the whole DTM and, after completing all sections, NGATE merges them into one DTM.
3. The *Eliminate Trees/Buildings/Other* option determines whether NGATE generates a DEM or DSM. If you check this option box, specify two parameters: *Minimum Height* and *Maximum Width*. These parameters are expressed in the project elevation unit, i.e., meters or feet. Buildings or trees with heights above ground greater than the minimum height and width less than the maximum width are eliminated. We recommend that this option be turned on in flat areas. In other areas, it is convenient to use ITE to eliminate buildings and trees.
4. *Undo* and *Redo* in ITE enable the selection of the most appropriate values for the bare earth algorithm.
5. The *Precision/Speed* selection has a default value of high precision and low speed (*High/Slow*). If you want fast speed and precision is not critical, you can select low precision and fast speed (*Low/Fast*). When you select *High/Slow*, NGATE performs area- and edge-matching all the way to minification level 1:1 (*RSET1*). When you select *Medium/Medium*, NGATE stops at minification level 2:1 (*RSET2*). When you select *Low/Fast*, NGATE stops at minification level 4:1 (*RSET4*). The speed of NGATE does not depend on the post spacing. NGATE always performs matching on every image pixel regardless of the post spacing.
6. Finally, the TIN Masspoints selection enables the user to choose *No Thinning*, *Medium Thinning* or *Heavy Thinning*. The second and third of these create sparser TINs if required, thus reducing the data volume and the amount of detail in the DSM or DEM.

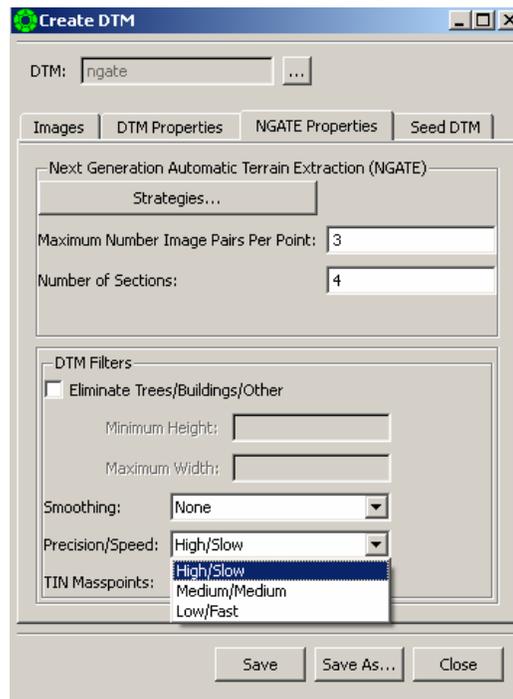


Figure 5: Selecting parameters to define how NGATE will run

Finally, the user switches to the fourth tab, *Seed DTM*, to provide NGATE with starting values (Figure 6). The *Seed Points* pull-down lets the user define the RSET, or minimification level at which NGATE will no longer hold the seed points fixed: if *RSET1* is chosen, therefore, the seed points will not change at all throughout the whole process. If *Automatic* is chosen, NGATE will determine when to let the seed points move, based on the "Relative LE" value in the seed header file (.dth). The remainder of this tab is devoted to the user's selection of the *Seed DTM Files* containing the seed points. A popular choice of seed data is Shuttle Radar Topography Mission (SRTM) data. These are available for download at <http://seamless.usgs.gov/> as 1 arc second GeoTIFF, which can be imported into SOCET SET using *Import>Terrain>GeoTIFF*. If SRTM seed data is available, the user should select *Automatic* from the *Seed Point* pull-down menu.

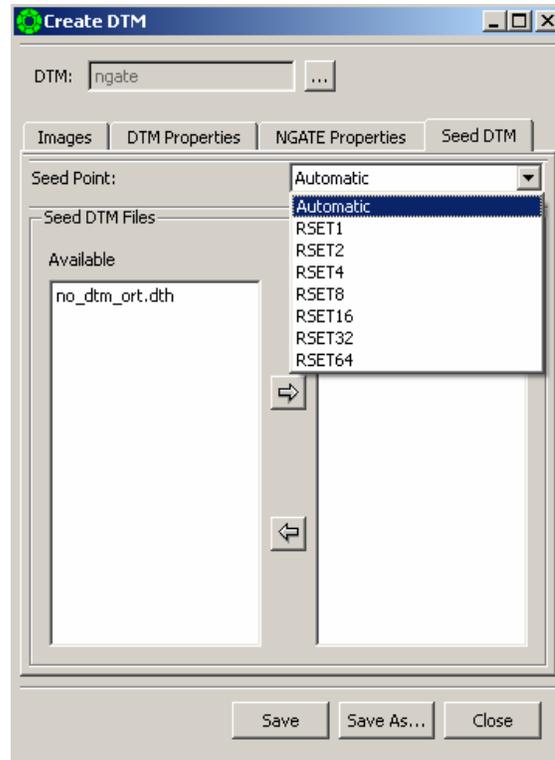


Figure 6: Seed points for NGATE

After all of these choices have been made, the user can *Save* and *Close* the *Create DTM* window, return to the main NGATE window and click *Start*.

Results from NGATE

Several case studies are presented to illustrate the performance of NGATE.

Case study 1

The first case study is summarized in Table 2 and Figure 7. This example is based on large-scale imagery of an urban area with 5 cm pixel size.

Location	San Diego, California
Type of terrain	Urban
Coordinate system	UTM
Imagery	Film, scanned at 12.5 μm
Image scale	Large
Spectral characteristics	Color, 3 bands, 8 bits per pixel per band
Number of images	21
GSD (m)	0.05
DTM representation	Grid
DTM spacing (m)	0.25 in both X and Y
Number of points	52,200,024
NGATE strategy	ngate_urban.strategy
Relative LE (m)	0.15

Table 2: Case study 1

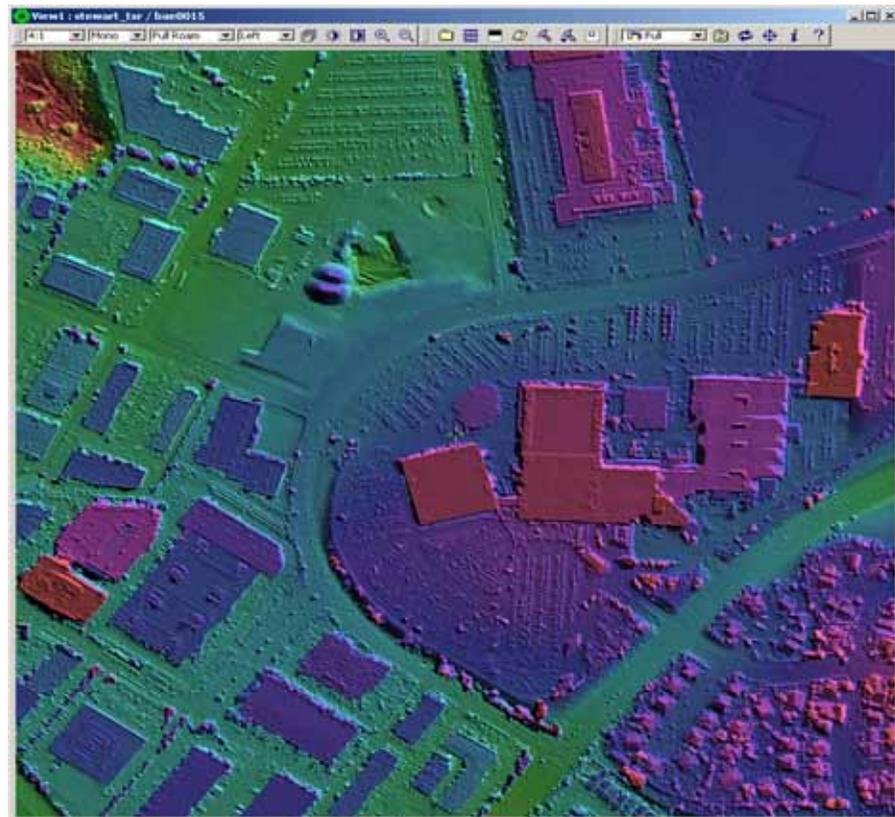


Figure 7: Case study 1 – terrain shaded relief

Whereas Figure 7 shows terrain shaded relief of an overview of the area, Figure 8 shows three selected sub-areas at a larger scale and the richness of detail captured by NGATE is apparent, for example the air-conditioning and elevator hardware on the tops of industrial buildings.

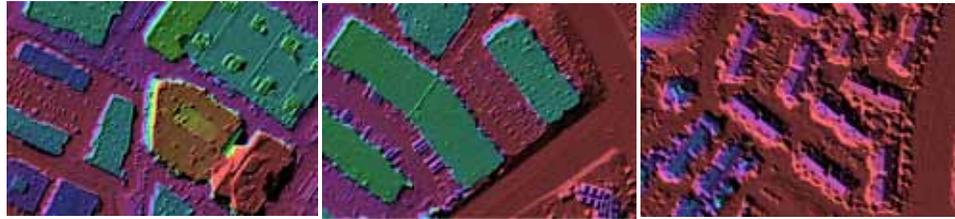


Figure 8: Case study 1 – terrain shaded relief of small areas

Tables 3 and 4 summarize test data from this case study. Table 3 shows statistics from 204 manually edited, regularly spaced grid points, measured twice by two engineers to ensure their accuracy. These points were used to estimate the accuracy of the DSM of 52 million points generated from NGATE. With no editing whatsoever, the Root Mean Square Error (RMSE) was 0.18 m, i.e., 3.5 pixels or 0.08‰ of the flying height. When only 1.5% of the points were removed by editing, these values dropped to 0.13 m, 2.5, and 0.05‰ respectively. Table 4 shows the results when ATE was used to generate the DSM. In this case the unedited values were RMSE 0.76 m, 15 pixels and 0.33‰. If 6.8% of the ATE sample points were edited, the quality of the results was similar to the unedited NGATE points. 6.8% of 52 million points is 3.5 million points! That is a significant reduction in time in terms of DTM editing. All biases were well below one pixel.

Points	% points removed	RMSE (m)	Bias (m)
204	0.0	0.18	-0.03
201	1.5	0.13	-0.04
195	4.6	0.11	-0.03
192	6.3	0.10	-0.03

Table 3: Case study 1 – comparison of NGATE DSM and ground truth

Points	% points removed	RMSE (m)	Bias (m)
204	0.0	0.76	0.03
197	3.6	0.33	-0.00
191	6.8	0.19	-0.03
188	8.5	0.16	-0.01

Table 4: Case study 1 – comparison of ATE DSM and ground truth

Let us examine this case study from a different point of view – the orthorectified imagery that can be generated from the NGATE TIN. Unless appropriate attention is paid to the elevation data, the positional error of orthorectified imagery can be 100 times greater than its ground sample distance (GSD), a poor indictment of the photogrammetric process. We used the imagery from case study 1 to demonstrate the positional errors due to elevation errors in the DEM. Two orthoimages were generated, the first using the DSM from NGATE, and the second, using a SRTM DEM from USGS. In Table 5, X_1 and Y_1 are the true XY coordinates measured from a stereo pair, X_2 and Y_2 are the XY coordinates measured from the orthoimage generated using the NGATE DEM, and X_3 and Y_3 are the XY coordinates measured from the orthoimage generated using SRTM. δX_2 and δY_2 , which are the differences between X_1 and X_2 , and Y_1 and Y_2 respectively, are positional errors in the orthoimage generated using NGATE. δX_3 and δY_3 , which are the differences between X_1 and X_3 , and Y_1 and Y_3 respectively, are positional errors in the orthoimage generated using SRTM. Table 5 indicates that the largest positional error in the orthoimage generated using the SRTM DEM was 5.35 m, 107 times the imagery GSD. The largest positional error in the orthoimage generated using the NGATE DEM was 0.40 m, 13 times more accurate. The RMSE of δX_2 was 0.17 m, the RMSE of δY_2 was 0.13 m and the RMSE of $\delta X_2 \delta Y_2$ was 0.21 m. The RMSE of δX_3 was 1.80 m, the

RMSE of δY_3 was 1.99 m and the RMSE of $\delta X_3 \delta Y_3$ was 2.68 m. In other words, the positional error measured by RMSE for the orthoimage generated using NGATE was 13 times more accurate.

ID	X ₁	Y ₁	X ₂	Y ₂	X ₃	Y ₃	δX_2	δY_2	δX_3	δY_3
1	49.227	15.413	49.304	15.394	47.604	14.844	-0.077	0.019	1.623	0.569
2	6.594	83.520	6.619	83.570	6.644	83.170	-0.025	-0.050	-0.050	0.350
3	55.931	30.423	55.944	30.320	56.444	31.620	-0.013	0.103	-0.513	-1.197
4	12.079	20.367	12.156	20.323	12.931	21.873	-0.077	0.044	-0.852	-1.505
5	30.705	48.186	30.594	48.261	28.519	46.022	0.111	-0.075	2.186	2.164
6	4.971	85.420	4.905	85.586	7.730	88.186	0.066	-0.166	-2.759	-2.766
7	21.707	58.428	21.971	58.545	24.946	60.345	-0.264	-0.117	-3.239	-1.917
8	93.766	57.208	93.832	57.128	93.357	56.953	-0.066	0.080	0.409	0.255
9	48.402	37.138	48.491	37.183	46.791	36.958	-0.089	-0.045	1.611	0.180
10	81.867	2.501	81.927	2.513	81.902	2.488	-0.060	-0.012	-0.035	0.013
11	85.887	80.671	85.917	80.651	85.192	80.701	-0.030	0.020	0.695	-0.030
12	73.885	24.948	73.987	24.921	73.862	25.021	-0.102	0.027	0.023	-0.073
13	84.659	74.749	84.785	74.698	82.960	75.923	-0.126	0.051	1.699	-1.174
14	52.819	18.478	52.884	18.499	50.959	20.249	-0.065	-0.021	1.860	-1.771
15	76.196	13.062	76.169	12.928	74.669	11.578	0.027	0.134	1.527	1.484
16	50.845	6.410	50.646	6.062	47.296	2.312	0.199	0.348	3.549	4.098
17	50.368	66.804	50.345	66.560	50.795	67.810	0.023	0.244	-0.427	-1.006
18	53.355	27.320	53.468	27.154	55.468	22.404	-0.113	0.166	-2.113	4.916
19	9.671	74.990	9.855	74.870	6.705	78.070	-0.184	0.120	2.966	-3.200
20	51.853	0.852	51.946	0.790	51.671	1.265	-0.093	0.062	0.182	-0.413

Table 5: Case study 1 – horizontal errors of orthoimages using NGATE and SRTM DEMs

Case study 2

The second case study is summarized in Table 6 and Figure 9.

Location	Santa Barbara, California
Type of terrain	Urban, rural, lakes, airport, mountains
Coordinate system	Geographic
Imagery	Film, scanned at 14 μ m
Image scale	Medium
Spectral characteristics	Color, 3 bands, 8 bits per pixel per band
Number of Images	90
GSD (m)	0.35
DTM representation	Grid
DTM spacing (m)	3 in both X and Y
Number of points	56,981,100
NGATE strategy	ngate_urban.strategy
Relative LE (m)	0.61

Table 6: Case study 2

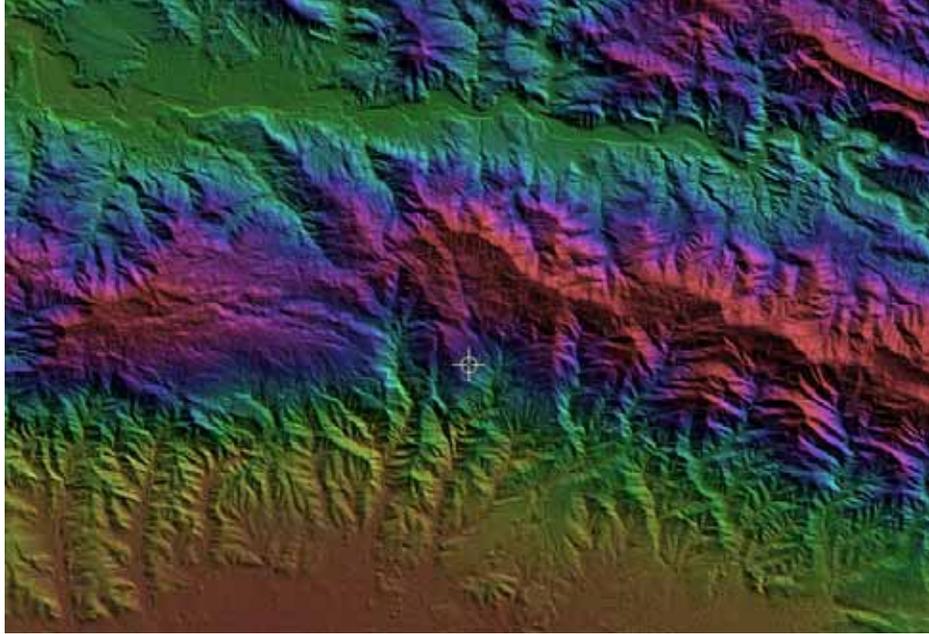


Figure 9: Case study 2 - terrain shaded relief

Tables 7 and 8 provide an analysis of accuracy. Table 7 shows statistics from 347 manually edited, regularly spaced grid points (edited twice by two engineers to ensure their accuracy), used to estimate the accuracy of the DSM of 57 million points generated from NGATE. With no editing, the RMSE was 1.12 m, 3 pixels or 0.29‰ of the flying height. Table 8 shows the results when ATE is used to generate the DSM. The unedited values were 1.83 m, 5 pixels or 0.48‰. When 4.8% of the ATE sample points were edited, the quality of the results was similar to the unedited NGATE points. 4.8% of 57 million points is 2.7 million points! That is a significant reduction in time in terms of DTM editing. Finally, a small test was performed over an airport in the area of the case study, which we would expect to present fewer challenges than the often mountainous and wooded terrain of the case study as a whole. 96 sample points in the airport area were measured manually in a stereo pair and compared with the NGATE results, giving an RMSE of 0.31 m, 0.9 pixels and 0.08‰ of the flying height.

Points	% points removed	RMSE (m)	Bias (m)
347	0.0	1.12	-0.28
344	0.9	1.06	-0.27

Table 7: Case study 2 – comparison of NGATE DSM and ground truth

Points	% points removed	RMSE (m)	Bias (m)
347	0.0	1.83	0.06
340	2.16	1.40	-0.06
336	3.3	1.32	-0.06
331	4.8	1.24	-0.12

Table 8: Case study 2 – comparison of ATE DSM and ground truth

Case study 3

The third case study is summarized in Table 9 and Figure 10.

Location	Sussex, UK
Type of terrain	Suburban and rural
Coordinate system	LSR
Imagery	Digital: Intergraph DMC
Image scale	Medium
Spectral characteristics	Color, 3 bands, 8 bits per pixel per band
Number of images	320
GSD (m)	0.25
DTM representation	Grid
DTM spacing (m)	1.5 in both X and Y
Number of points	55,823,460
NGATE strategy	ngate.strategy
Relative LE (m)	1.05

Table 9: Case study 3

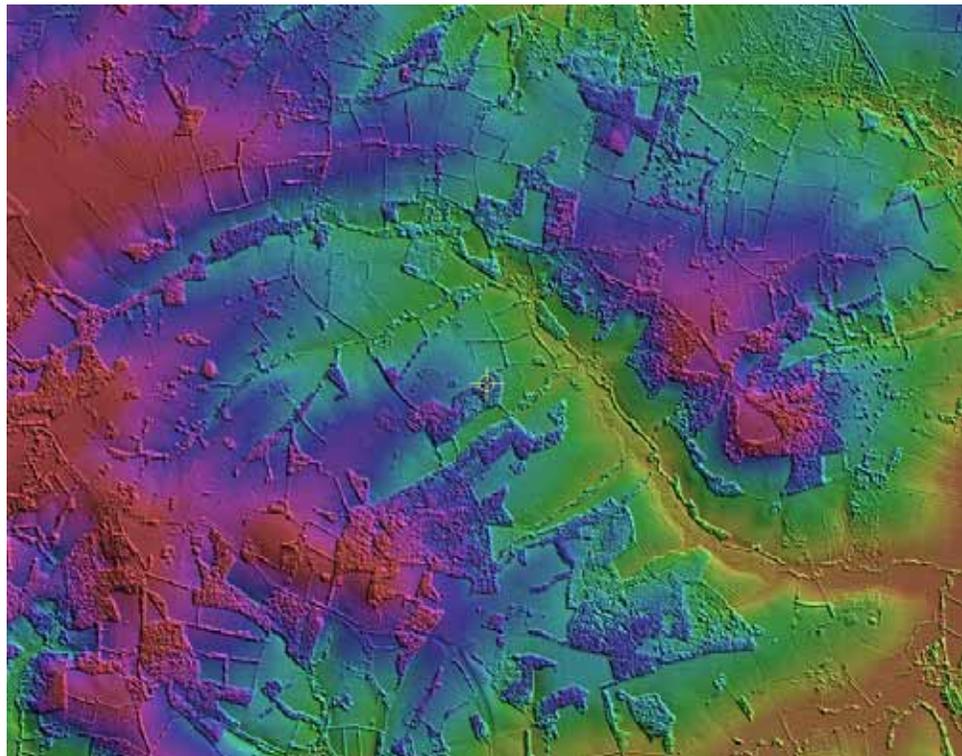


Figure 10: Case study 3 - terrain shaded relief

Once again, we present accuracy tests. Table 10 gives statistics from 522 manually edited, regularly spaced grid points (edited twice by two engineers to ensure their accuracy), used to estimate the accuracy of the DSM of 56 million points generated from NGATE. With no editing, the RMSE was 0.56 m, 2 pixels or 0.22% of the flying height. Substantial

improvements were available with some editing: 0.41 m, 1.6 pixels and 0.16‰ with 1.75% of points removed and 0.35 m, 1.4 and 0.14‰ with 4.2% removed. Table 11 shows the results when ATE was used to generate the DSM. The unedited values were 1.76 m, 7 pixels or 0.70‰. When 6.1% of the ATE sample points were edited, the quality of the results is similar to the unedited NGATE points. 6.1% of 56 million points is 3.4 million points! That is a significant reduction in time in terms of DTM editing.

Points	% points removed	RMSE (m)	Bias (m)
522	0.0	0.56	-0.24
513	1.8	0.41	-0.20
504	4.2	0.35	-0.17

Table 10: Case study 3 – comparison of NGATE DSM and ground truth

Points	% points removed	RMSE (m)	Bias (m)
522	0.0	1.76	0.07
508	2.8	0.89	-0.15
492	6.1	0.61	-0.23
479	9.0	0.50	-0.21

Table 11: Case study 3 – comparison of ATE DSM and ground truth

Case study 4

The fourth case study, summarized in Table 12 and Figure 11, also includes ground truth. The red dots in Figure 11 are points measured manually in SOCET SET using the same image support data referenced by NGATE. Table 13 is a comparison of the Z coordinates of the measured points and the values interpolated from the NGATE point cloud. A small number of blunders were then removed sequentially. It is seen that with no editing, NGATE gave an RMSE of 0.73 m, i.e. 5 pixels or 0.49‰ of the flying height. With only 1.7% of points edited these values improved to 0.35 m, 2 pixels and 0.23‰ respectively. Table 14 shows a variant of the information presented in Table 13: all points on trees were removed from the data set to give an estimate of what could be obtained if photogrammetrically derived heights were used in treeless areas only. With no editing, the Figures were 0.57 m, 4 pixels and 0.38‰ respectively. With only 1% of points edited, these values improved to be almost the same as those from the data set without trees removed and 1.7% edited. In all cases, biases were less than 0.4 pixel.

Location	Bournemouth, UK
Type of terrain	Urban
Coordinate system	LSR
Imagery	Digital: Intergraph DMC
Image scale	Large
Spectral characteristics	Panchromatic, 12 bits
Number of Images	12
GSD (m)	0.15
DTM representation	TIN
DTM spacing (m)	0.5 in X and Y
Number of points	34,933,605
NGATE strategy	ngate_urban
Relative LE (m)	0.52

Table 12: Case study 4



Figure 11: Case study 4 – sample image showing manually measured points

Points	% blunders removed	RMSE (m)	Bias (m)
121	0.0	0.73	-0.02
119	1.7	0.35	0.00
115	5.0	0.32	0.01
112	7.4	0.28	0.02

Table 13: Case study 4 – comparison of NGATE and ground truth

Points	% blunders removed	Rmse (m)	Bias (m)
104	0.0	0.57	-0.06
103	1.0	0.35	-0.01
101	2.9	0.29	0.02
99	4.8	0.25	0.04

Table 14: Case study 4 – comparison of NGATE and ground truth for treeless points

Case study 5

The fifth case study is summarized in Table 15 and Figure 12. Note that the units are feet. An analysis of the results against points manually measured in SOCET SET revealed that on natural terrain the NGATE DTM had RMSE of 0.4 feet (3 pixels, 0.25‰); on streets and parking lots, 0.3 feet (2, 0.19‰); on center points of flat roof buildings, 0.5 feet (4, 0.32‰); on corner points of flat roof buildings, 0.9 feet (6, 0.57‰; 94% of the building corners measured); on center points, edge points, corner points, and ground points of complex buildings, 0.9 feet (6, 0.57‰; 90% of these points had an RMSE of 0.4 feet). At first glance these results are not especially impressive, so they will be examined in greater detail. No editing whatsoever was carried out; many of the points were on buildings, and there were a number of trees in the scene as well as moving vehicles. As results of a process without human intervention, these are very acceptable.

Location	Philadelphia, Pennsylvania
Type of terrain	Urban
Coordinate system	Pa_s_83
Imagery	Microsoft UltraCam _o
Image scale	Large
Spectral characteristics	Color, 3 bands, 8 bits per pixel per band
Number of Images	66
GSD (feet)	0.14
DTM representation	TIN
DTM spacing (feet)	0.7
Number of points	21 million
NGATE strategy	ngate_urban.strategy
Relative LE (feet)	0.54

Table 15: Case study 5

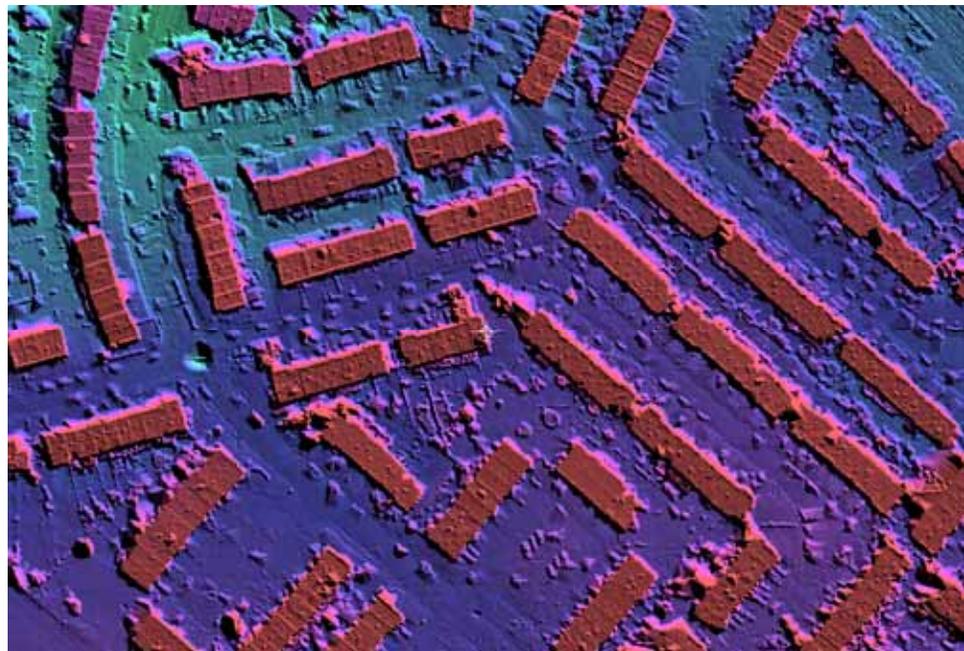


Figure 12: Case study 5 – terrain shaded relief showing apartment blocks

Case study 6

The sixth case study (Table 16 and Figures 13 – 14) completes the set of examples based on the market-leading airborne digital imaging systems in production photogrammetry.

Location	Stuttgart, Germany
Type of terrain	Urban
Coordinate system	Geographic
Imagery	Leica ADS40
Image scale	Large
Spectral characteristics	2-byte panchromatic
Number of images	3
GSD (m)	0.16
DTM representation	TIN
DTM spacing (m)	1.0
Number of points	18,898,230
NGATE strategy	ngate_urban.strategy
Relative LE (m)	0.57

Table 16: Case study 6



Figure 13: Case study 6 – 2 m contours overlaid on ADS40 panchromatic image

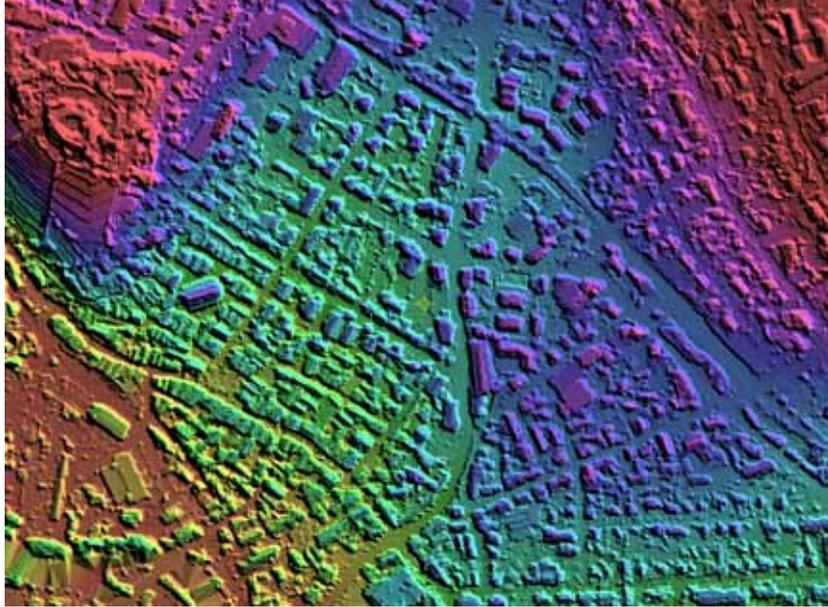


Figure 14: Case study 6 – terrain shaded relief

Case study 7

The seventh case study involves satellite rather than airborne imagery. It is summarized in Table 17 and Figure 15. The top row of illustrations in Figure 15 is overlaid with 3 m contours. Those in the top left illustration show how well the buildings are modeled, for example the corners shown by the arrows. The contours in the top center and top right illustrations show how well the DSM follows the surface, sloping down sharply from the decks of bridges and finding the ground in the narrow gap between the two bridges shown by the central arrow in the center illustration (the process has not been confused by the moving vehicles on the freeway). The contours follow the very steep slopes of the construction site closely, shown by the arrows in the top right illustration. The 5 m contours in red in the lower left illustration are from NGATE, whereas those in green are from ATE with back matching: the NGATE data needs no editing and the contours follow the terrain slightly better than those from ATE, for example in the ditch at the left center of the illustration. The red dots in the lower right illustration are the NGATE DSM: the water body is flat, with no spurious points, and an object on it has been correctly detected by NGATE.

Location	San Diego, California
Type of terrain	Urban, rural, highways, water bodies, construction sites, forest
Coordinate system	UTM
Imagery	GeoEye™ IKONOS®
Image scale	High-resolution satellite
Spectral characteristics	Panchromatic
Number of images	2
GSD (m)	1.0
DTM representation	Grid
DTM spacing (m)	5
Number of points	8,206,380
NGATE strategy	ngate.strategy
Relative LE (m)	1.99

Table 17: Case study 7

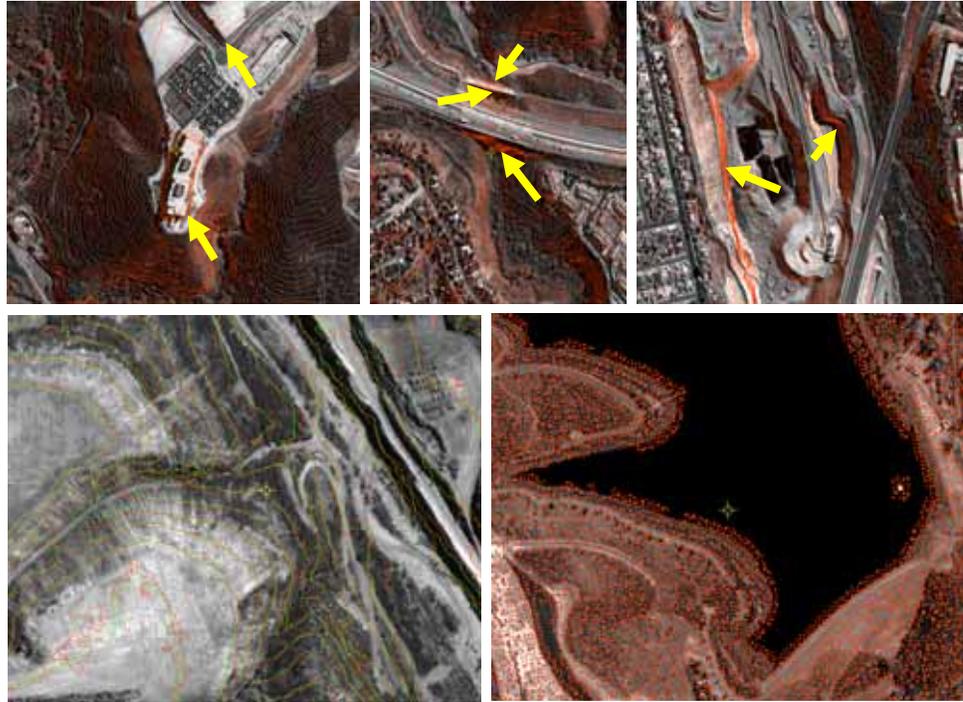


Figure 15: Case study 7 - IKONOS panchromatic 1m image with various overlays, as explained in the text

A sample of 221 check points was measured manually and compared to the NGATE DSM. The results were RMSE of 0.98 m (1 pixel) and bias of 0.11 m. These results were remarkably good and it was concluded that no editing was needed with NGATE, whereas minimal editing was needed with ATE.

Further case studies

As explained towards the end of this paper, several customers are involved in an ongoing program to evaluate NGATE. This has resulted in some interesting examples, which are illustrated here. Figure 16 shows a case of a lake and river, surrounded by heavily wooded terrain, on medium-scale airborne imagery with GSD 0.43 m. NGATE has discerned the water areas almost perfectly and there are no spurious points on the water surface. Figure 17 shows an urban area on medium-scale airborne imagery with GSD 0.25 m. The 1 m contours demonstrate that the corners, edges and roofs of the buildings have all been modeled well.

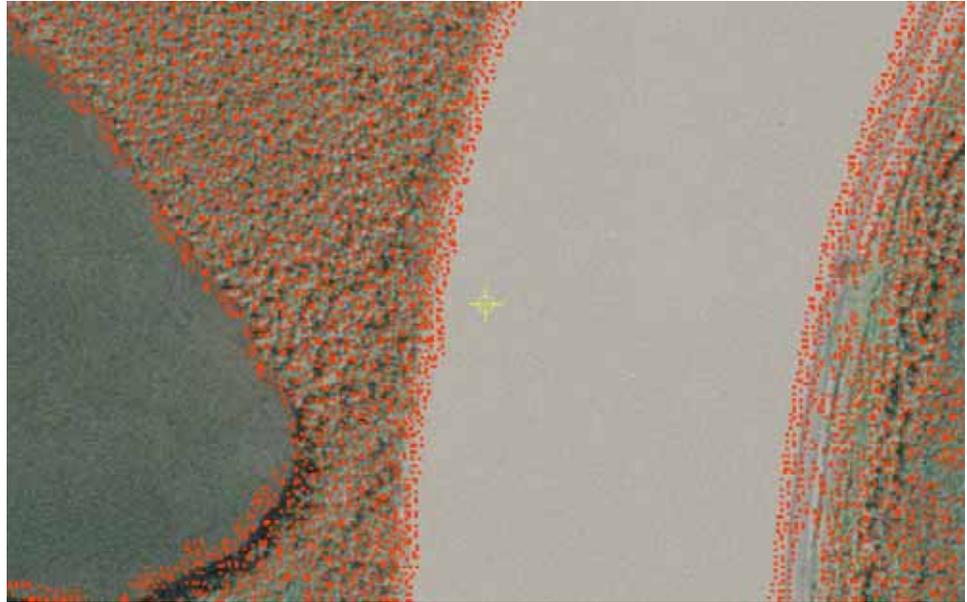


Figure 16: Customer example – medium-scale image of lake and river

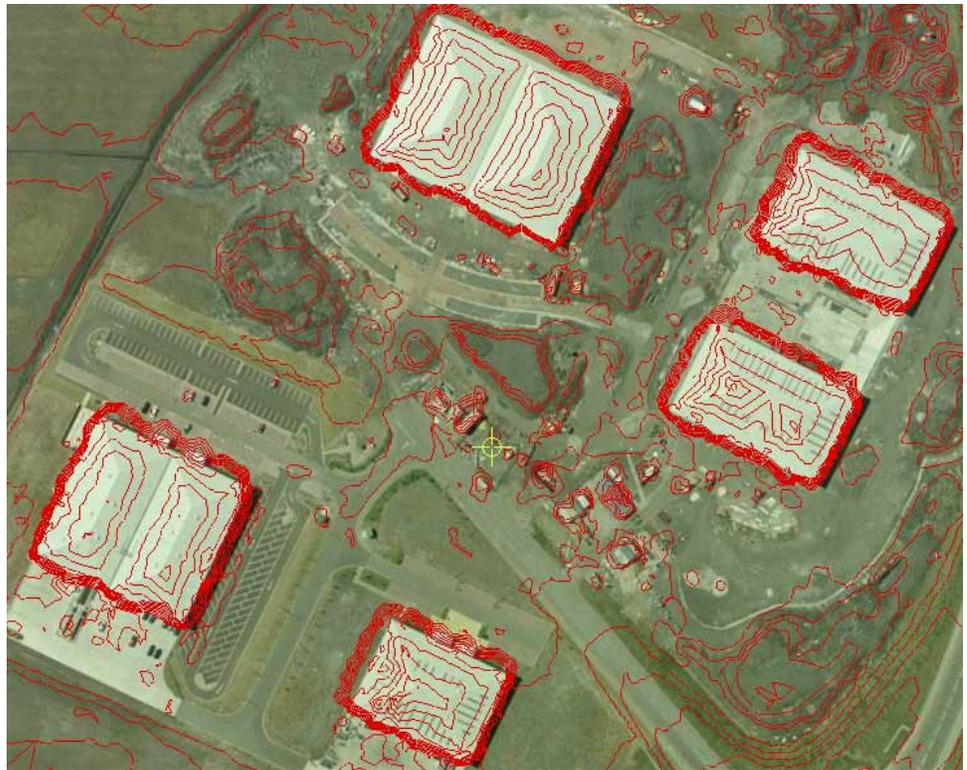


Figure 17: Customer example – medium-scale image of buildings

NGATE has also been tested with U.S. government classified imagery from various sources, which cannot be shown here, and once again was found to be more effective than ATE in terms of the quality and density of the resulting DTM and the reduction in the interactive editing required.

Experience in production

BAE Systems includes a business area called Geospatial Products and Services (GP&S), which operates as a commercial photogrammetric service company, competing in the private sector for both commercial and government business. GP&S began using NGATE in the autumn of 2006 and at the time of writing this paper had accumulated six months of experience with it, covering a wide range of image sources and scales and terrain types. *The conclusion from the GP&S production managers is that the editing time spent with the ITE module has been reduced 30%.* This is a tremendously important statistic and represents substantial cost savings. Given that GP&S started with a very early version of the production module of NGATE and that significant improvements have been made in the intervening time, it is reasonable to expect that this figure of 30% has now been exceeded.

Conclusions from the various results

Having acquired extensive experience and conducted a brace of tests, BAE Systems feels able to state the following with confidence with respect to NGATE:

- On small to medium scale imagery, DTM editing is minimal
- On large scale imagery in urban areas, DTM editing is significantly reduced
- On large scale imagery in natural terrain, DTM editing is minimal
- Building edges are preserved
- Water bodies are flattened
- Streets and featureless areas are precisely modeled
- The main cost of DTM generation is manual editing, which is significantly reduced, by more than 30%.

Availability of NGATE

NGATE was scheduled to be included with SOCET GXP® v3.0, the version of BAE Systems' new image processing product that will include full photogrammetric functionality and is scheduled for release in 2008. Owing to customer demand, however, a decision was made to bring forward the introduction of NGATE by including it with SOCET SET in 2007.

NGATE is an add-on module for SOCET SET and requires the Core module to run (and Advanced Sensor Models or DataThruWay® modules if sensor models other than those in Core are required). Upgrade Entitlement support is available for NGATE in the same way as for other modules.

NGATE will be available with SOCET SET v5.4.1, scheduled for release in Fall 2007. Customers who currently use ATE, however, and would like to try NGATE are welcome to do so; these customers should contact their local BAE Systems GXP sales office or distributor and request the special pre-release version of SOCET SET v5.4 with NGATE.

NGATE will also be included in SOCET GXP v3.0, scheduled for release in summer 2008.

Though NGATE is now part of the standard product, development is continuing. Work in progress includes the following improvements:

- Hough Transform to match edges that are parallel to epipolar lines and improve edge-matching for non-epipolar-parallel edges
- Two DTMs (DSM and bare earth DEM) from NGATE simultaneously
 - Expect much better bare earth DEM
 - Improve sharpness of DSM at building edges
 - Users will have three options: DSM; DEM; or both DSM and DEM
- Bare earth algorithm enhancement especially for hilly areas to remove trees
 - The current bare earth algorithm works reasonably well in relatively flat areas with dense DTM
 - Need enhancement to work with hilly areas, especially to remove trees from DSM
 - Current bare earth algorithm is rather slow
 - New bare earth algorithm should be fast and work well with all types of terrain
- Flatten water body for Grid format
 - Though NGATE typically generates no elevation points on water for TIN format, the Grid representation is not perfectly flat on water — this must be improved.

A note on LIDAR

Any discussion of high density, accurate elevation data prompts thoughts about LIDAR. SOCET SET handles point clouds regardless of origin. Its LIDAR import enables multiple returns and intensity values to be imported, in ASCII or the industry standard LAS format, in either grid or TIN format. The design of the terrain database enables more than two billion points to be accommodated. LIDAR data can be viewed on its own or with imagery, monoscopically or stereoscopically, using the same terrain representations that are available for photogrammetrically derived elevation data. The intensity values can be used to create an intensity image, which is in fact an orthophoto, on input. The functionality in the Ortho module of SOCET SET enables the user to create a stereomate and uses this, together with the intensity image, to extract features stereoscopically, a process sometimes known as "LIDARgrammetry." Monoscopic extraction from the intensity image is also possible — SOCET SET adds Z coordinates from the underlying LIDAR DTM — but the lack of stereoscopic visualization makes the interpretation of the scene more difficult. SOCET SET is a photogrammetric software package and is not designed for automatic classification of LIDAR point clouds. Nevertheless, the bare earth filter and the powerful range of ITE tools enable much to be done with this data in a very effective way. Finally, it is worth remembering SOCET SET's capabilities with terrain shaded relief; this is a very effective way of showing that LIDAR data can be viewed monoscopically, stereoscopically, or as perspective scenes, and may be exported in OpenFlight format to third-party visualization packages.

Extensive experience working with LIDAR and NGATE data sets at BAE Systems has led to the conclusion that a LIDAR DSM has advantages over an NGATE DSM in shadow areas, in narrow alleys between buildings, and in forest areas. Typically, an NGATE DSM has fewer blunders because of embedded blunder detection and removal. For natural terrain, photogrammetry and LIDAR DSMs have similar accuracy, though of course this depends on the relative flying heights of the image and LIDAR acquisition missions.

Since high-density photogrammetric DTMs and LIDAR data are so similar, certain operations can be applied equally to either data set, as noted above. Both data sets contain huge numbers of points that define the terrain surface but are not accompanied by attributes providing any qualitative information about that surface. Bare earth filtering is one way to divide the data sets into the "bald earth" surface and the buildings, trees and other structures and phenomena upon it. BAE Systems, however, has gone beyond that and is working on automatic extraction of buildings from point clouds, with straight edges that are accurate, appealing representations of reality. It is anticipated that this work will be incorporated into SOCET SET and SOCET GXP products in 2008.

Conclusions

NGATE is an innovative module for SOCET SET that can create terrain models automatically from imagery. The results are more accurate than those from the earlier ATE module and require significantly less human editing, resulting in remarkable cost savings. Furthermore, the terrain models generated by NGATE are denser and represent the terrain, including small features and details, better than those from ATE or SOCET SET's competitors. Using NGATE, together with rather modest interactive editing in the ITE module, the resultant photogrammetrically derived DTMs are first-rate deliverables on their own, or a superb basis from which to create orthorectified imagery and other products. Photogrammetry and LIDAR should be regarded as complementary rather than competing technologies with respect to the cost-effective acquisition of high-quality terrain elevation data.

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