PRODUCTION OF DSM/DTM IN URBAN AREAS:
ROLE AND INFLUENCE OF 3D VECTORS

C. Baillard

SIRADEL, 3 allée Adolphe Bobière CS24343, 35043 Rennes, FRANCE
cbaillard@siradel.com

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ABSTRACT:

Thanks to the evolution of new sensors and the development of efficient algorithms, the automatic production of DSM (Digital Surface Models) and DTM (Digital Terrain Models) in urban areas has become possible. At SIRADEL, we have been interested in a new approach using external 3D vectors and a pair of aerial stereo images. In this paper, our method for computing DSM and DTM is briefly presented. Then this approach is compared to the traditional manual process in term of production cost and accuracy. In particular, the role and the influence of 3D vector data is quantitatively assessed and analysed.

1. INTRODUCTION

1.1 Context

The use of 3D cartographic data has become very important for many applications related to urban areas: telecommunication, urbanism, estate agencies, communication, transport, tourism, air analysis, flooding risk, etc. There is an increasing need for accurate, realistic and affordable 3D digital data over cities. In particular, the availability of urban DTM (Digital Terrain Models) and DSM (Digital Surface Models) is a major concern for most users.

Thanks to the recent evolution of new sensors (digital camera, LIDAR data, high resolution satellites) and the development of efficient algorithms, the automatic production of urban DSMs including buildings and trees is now possible (Cord *et al*., 1999; Maas, 2001; Paparoditis and Maillet, 2001; Roux and Maître, 2001; Fraser *et al*., 2002; Zinger *et al.*, 2002). However the automatic computation of 3D vector data is much more difficult because of low-contrasted building contours, hidden areas and complex-shaped buildings (Jung and Paparoditis, 2003). A solution consists of using external 2D vector information (Jibrini *et al.*, 2002; Vosselman and Suveg, 2001). For most applications requiring high quality vector data, a manual or a semi-automatic intervention is necessary (Brenner, 2001; Flamanc, 2003).

1.2 Industrial production: manual vs semi-automatic

This study focuses on the industrial production of urban cartographic data. SIRADEL is a company that has produced digital 3D data over a large number of European cities. These data include reliable and accurate 3D vectors (buildings, water, vegetation, road network, terrain breaklines, etc) and raster data (DSM, DTM, land-use). Although initially dedicated to radio planning applications, they can be used within many sectors. The accuracy is below 1 meter, and the detail level is more than sufficient for most applications.

Two different production lines coexist at SIRADEL. The first one is based on manual photogrammetric capture. The benefits of this method are the accuracy and the reliability of the produced vectors, along with the availability and the low cost of the source imagery. However it implies a high production cost due to capture time. An alternative semi-automatic approach for computing DSM and DTM has recently been studied, which only requires a small set of 3D vectors. The input imagery is the same one as in the manual approach: acquisition costs do not increase and off-the-shelf image data can be used.

This paper presents a comparison of accuracy and production cost related to both processes.

2. MANUAL PROCESS

2.1 Principle

A detailed set of 3D vectors is manually produced by photogrammetric capture from stereo imagery. Raster data (DTM, DSM) are then entirely derived from the captured vectors (see Figure 1).
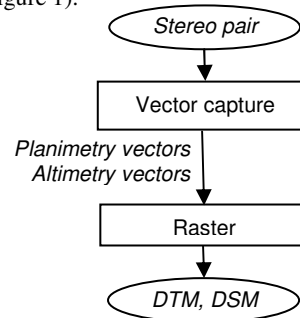

Figure 1: Manual process

2.2 Source imagery

Aerial imagery is available at a scale between 1:15000 and 1:25000 (focal length 157mm), scanned at 14μm. The pixel size is between 21 and 35cm. The stereo pairs have an overlap of 60% intra-band and 20% inter-band. The orientation of the images is performed with an analytical stereo plotter. Examples are given in Figures 8a, 8b and 8c.

2.3 Photogrammetric capture

Vectors can be of 3 types:
- Planimetry contours: 3D polygons describing buildings, vegetation, water, bridges;
- Altimetry points and breaklines: 3D points and lines describing the terrain and its orographic characteristics in a very precise way (more numerous when elevation varies); roads and railway connected at intersections (crossroads, etc).

These 3D vectors are captured according to specific rules depending on the type of object. For example, building contours are captured at the gutter elevation. The minimal area is 25m² and the minimal height above terrain is 2.5m. A building block is divided into independent contours if the difference in height between them exceeds 2m. This division also applies for roof superstructures, as long as area and height thresholds are valid. Each polygon is associated to a 3D point captured at the highest roof point (roof ridge or chimney). In addition, automatic analysis guarantees that planimetry objects have a consistent topology (closed contours, no intersection or self-intersection, connected adjacent polygons). An example is given in figure 2.

Figure 2: Example of captured vectors (Kerlaz)

2.4 Raster data computation: DTM and DSM

The DTM is computed by triangulation from altimetry vectors, including roads, railway, and water contours. Superimposing aboveground elevations (buildings, vegetation and bridges) with the DTM produces the DSM. Each polygon is associated to a single elevation value corresponding to the highest point.

3. SEMI-AUTOMATIC PROCESS
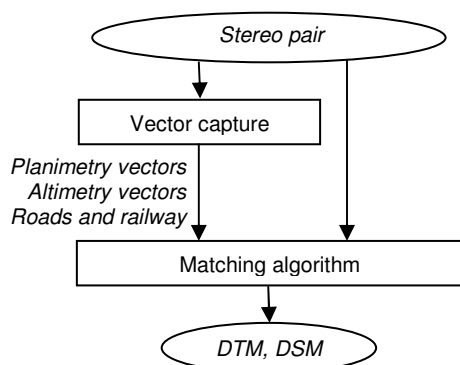
3.1 Principle

Figure 3: Semi-automatic process

The semi-automatic process is based on an automatic matching algorithm named AutoDEM that computes a DTM and a DSM

from two images and a few 3D vectors (see Figure 3). Input vectors (altimetry and planimetry) are manually captured then considered as external data by AutoDEM. Unlike the manual process, raster data are computed using both vectors and source images.

3.2 Matching algorithm AutoDEM

The matching algorithm consists of 4 steps (see Figure 4). It is briefly described in the followings subsections and more details can be found in (Baillard, 2003). It is characterized by the intensive use of vector information at each stage of the process:
- Definition of an input elevation map (step 1),
- Computation of local minimal and maximal z values (step 1),
- Definition of an adaptive correlation window (step 2),
- Prior information for filtering raw DSM (step 3),
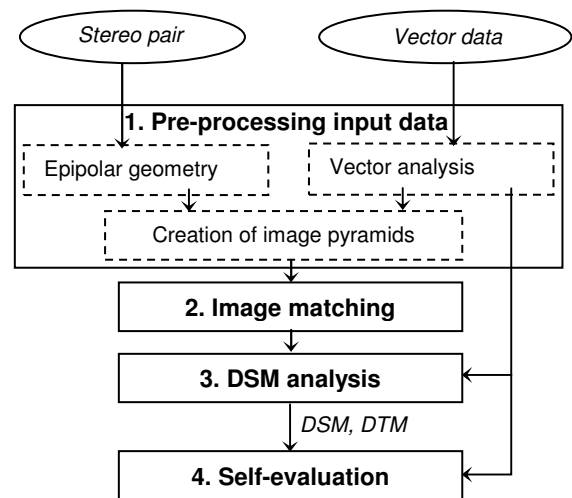- Reference data for quality control (step 4).

Figure 4: Automatic computation of DTM / DSM with AutoDEM

3.2.1 Pre-processing input data (images and vectors)
Each image pair is resampled into epipolar geometry. The vectors are analysed in order to produce a set of reference vectors (used for quality control) and a set of "input maps": input elevation map, building maps, minimal and maximal elevation maps. Finally source images and input maps are sub-sampled in order to create image pyramids.

3.2.2 Image matching: computation of a "raw" DSM
The matching algorithm uses dynamic programming within a multi-resolution scheme, which is particularly appropriate to dense urban scenes (Baillard, 2003). Input maps are taken into account as follows:
- The input elevation map constrains the research for an optimal path by defining input matched points,
- The minimal and maximal elevation maps define allowed and forbidden areas for the path,
- The building maps are used to weigh the correlation score between 2 pixels.

3.2.3 Analysis and filtering of "raw" DSM
A set of reliable ground points is first selected from the DSM by combining various criteria and filtering methods: Top hat morphological filtering, small height relative to neighbours, small slope, significant correlation score. These points are sampled and triangulated in order to produce a dense DTM.

Superimposing with this DTM all aboveground objects defined by external vectors then produces a "clean" DSM. Prior to superposition, the aboveground object elevations are preprocessed (noise filtering, interpolation) in order to produce dense data which exactly matches the external vectors. Finally, additional "significant" aboveground objects (trees, sheds, etc) can be detected and added in the DSM.

3.2.4 Self-evaluation

The DTM accuracy is assessed using reference vectors selected in the beginning of the process. The DSM accuracy is assessed using the input 3D points associated to each building polygon.

4. PERFORMANCE ANALYSIS

The accuracy of the DTM and the DSM produced with both manual and semi-automatic approaches has been assessed. In particular, we analysed the following aspects:

- Influence of the accuracy of input vectors,
- Influence of the detail level of input vectors,
- Influence of the number of input breaklines,
- Estimation of the capture cost.

4.1 Description of the test data set

Three test areas are presented, with various scales and significant height variations. Each area is approximately 2000x2000 pixels, with a content representative of urban areas (see Figure 8). Detailed characteristics are given in Table 1.

Name	Scale	Xyres (m)	Zres (m)	Zmin (m)	Zmax (m) ground	Zmax (m) build
Deauville	1:15000	0.21	0.36	0	33	46
Kerlaz	1:20000	0.28	0.53	0	47	54
Le Havre	1:25000	0.32	0.56	4	41	56

Table 1: characteristics of test areas

For each area, a set of 3D vectors was produced by photogrammetric capture, according to the rules mentioned in section 2. Various DTM and DSM were computed for each area, with both manual and semi-automatic approaches (see examples of semi-automatic DSM in Figures 9a, 9b, 9c).

Raster accuracy is assessed during the self-evaluation stage of AutoDEM (see section 3), but also using complementary independent vectors captured for this purpose: ground points (20m grid) and 3D points located anywhere on building roofs (one point per roof).

The accuracy is estimated with the average error (Avg), the error standard deviation (Std), the root mean square error (RMS), the maximal error (Emax), and finally the percentage of "reliable" points (%Pts+/-1), characterized by a measured error within [-1;1]. NbPtsRef is the number of reference points used for assessment. The production cost is estimated with the total number of captured points (NbPtsUsed); this estimation gives an indication about one particular stage of the process, but it can not be representative of the whole cost.

4.2 DTM Production

The DTM accuracy was assessed by varying the breakline number, complexity and accuracy:

- Random selection of 0% to 100% of available breaklines, or exclusive use of the main road network,
- Polyline simplification,
- Random perturbations on Z-values.

4.2.1 Influence of the number of breaklines

Manual approach. The accuracy of the "manual" DTM is presented in Table 2. By using all available breaklines, the RMS is always below 0.85cm, with 85% to 95% reliable points. The evolution of RMS with the number of breaklines shows that a small reduction does not significantly decrease accuracy (see Figure 5). However, by using only the road network (around 35% of the breaklines over test areas), the percentage of reliable points goes down to 75%, with a RMS between 1 and 1.70m (see Table 3).

Semi-automatic approach. It gives similar results to the manual approach when using all the breaklines (see Table 2). However, when using less breaklines, the semi-automatic approach generally improves accuracy (see Figure 6 for a comparison). It is particularly true with the road network only (see Table 3): it is then possible to get a RMS around 1m and a proportion of reliable points between 77 and 89%, for a capture cost of 65% less than for the traditional manual approach with all the breaklines.

AREA	Deauville		Kerlaz		Le Havre	
Cost (NptsUsed)	4027		9553		2884	
NptsRef	378		684		934	
DTM Accuracy	Man	Auto	Man	Auto	Man	Auto
Avg	0.39	0.42	0.20	0.21	0.48	0.51
Std	0.73	0.72	0.48	0.61	0.69	0.68
RMS	0.83	0.84	0.52	0.64	0.85	0.85
Emax	6.92	7.09	4.09	7.60	5.58	5.68
%Pts+/-1	85.98	86.24	96.05	96.35	84.80	83.68

Table 2: Cost and accuracy of DTM produced with all available breaklines (manual and semi-automatic process)

AREA	Deauville		Kerlaz		Le Havre	
Cost (NptsUsed)	1551		3199		972	
NptsRef	378		684		934	
DTM Accuracy	Man	Auto	Man	Auto	Man	Auto
Avg	0.17	0.41	-0.36	0.08	0.35	0.37
Std	1.00	0.89	1.65	0.86	1.09	0.99
RMS	1.01	0.98	1.69	0.86	1.15	1.06
Emax	5.06	6.80	10.93	7.50	6.13	6.96
%Pts+/-1	75.13	79.95	78.51	88.61	73.49	77.52

Table 3: Cost and accuracy of DTM produced with the main road network (manual and semi-automatic process)
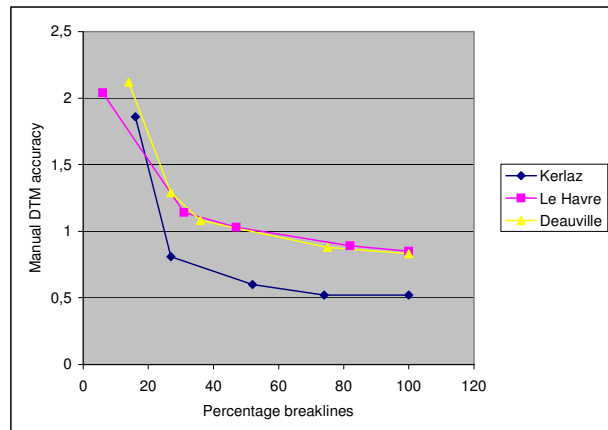

Figure 5: RMS of manual DTM for the 3 test areas, against the percentage of used breaklines
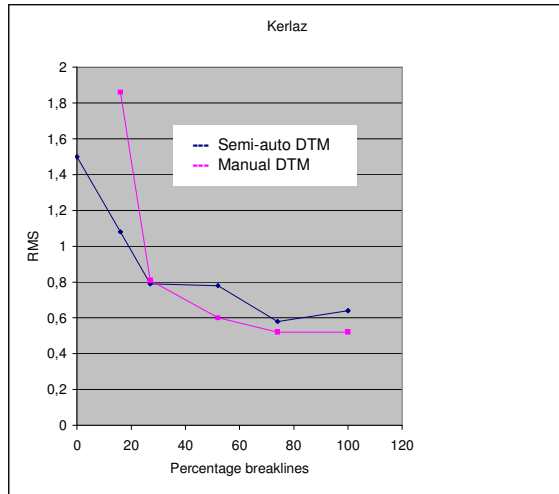
Figure 6. RMS of manual and semi-automatic DTM, against the percentage of used breaklines (Kerlaz)

4.2.2 Influence of the breakline accuracy

The input breaklines have been randomly modified: random displacement along z-values with a standart deviation of 1 or 2m, no segments shorter than 2 or 5m. Table 4 shows results on Kerlaz. For both the manual and the semi-automatic process:

- The polyline simplification does not significantly affect the DTM accuracy, but it has a drastic effect on the capture cost (35 to 40% reduction over test areas),
- The z-displacement introduces a significant error on the DTM, which is, however, less important within the semi-automatic process than within the manual process (loss of 0.65 to 0.95m instead of 1 to 1.2m).

Input Breaklines	Cost	Accuracy					
	NbPts Used	NbPts Ref	Avg	Std	Emq	Emax	%Pts +/-1
Manual DTM							
REF	7100	684	0.18	0.49	0.52	4.19	95.47
Dz1	-	684	0.27	0.97	1.01	4.67	64.91
Dz2	-	684	0.35	1.73	1.76	5.14	40.79
Spl2	4428	684	0.18	0.54	0.57	3.09	93.57
Spl5	4357	684	0.16	0.58	0.61	4.33	92.84
Semi-automatic DTM							
REF	7100	725	0.25	0.67	0.71	10.96	93.93
Dz1	-	718	0.30	1.01	1.06	10.37	80.22
Dz2	-	715	0.36	1.62	1.66	11.27	53.57
Spl2	4428	722	0.20	0.86	0.89	10.57	95.38
Spl5	4357	721	0.19	0.77	0.79	10.36	93.20

Table 4: DTM cost and accuracy when input breakline accuracy varies (Kerlaz)

4.2.3 DTM production: conclusion

The best accuracy is provided by the manual process (RMS below 85cm), but at an important cost. The semi-automatic process allows a significant productivity gain (65% capture time saved) for a small loss in accuracy (final RMS around 1m). If input vectors are not very accurate, then the semi-automatic approach is prefereable. In both cases, it is always worth simplifying the breakleables.

4.3 DEM production

4.3.1 Manual approach

Within the manual process, all the buildings are represented with a constant height (highest elevation, see Figure 7). The DEM accuracy is therefore naturally limited by this model. For highest precision, a very detailed vector description with frequent building block division is required (separation every 2m height in our process).
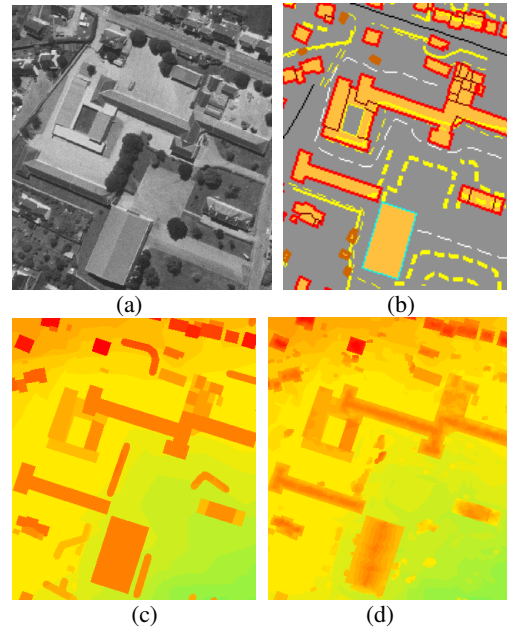

(a)　　　　　　　　(b)

(c)　　　　　　　　(d)

Figure 7: Extract from Kerlaz: left image (a), captured vectors (b), manual DEM (c) and semi-automatic DEM (d)

4.3.2 Semi-automatic approach

It provides a realistic representation of roof shapes and superstructures (see Figure 7d). In order to precisely assess the influence of input vectors, we have modified the nature and the accuracy of the input polygons:

- Ref: reference polygons as described in section 2: variable z values and block division every 2m;
- Zmed: polygons with constant z + division every 2m;
- Blocks: polygons with variable z but no division
- Dz: random displacement along z axis (standard deviation 1, 2 or 3m);
- Dxy: random displacement in the XY plane (standard deviation 1m);
- Spl: contour simplification (no segment shorter than 3m)

Results are given in Table 5.

The roof accuracy using reference polygons is around 1m, and the proportion of reliable points is above 75%; at least 93% of the checked roof points are less than 2m away from the reference point (column Pct+/-2 of Table 5). These figures show that the matching algorithm AutoDEM provides a roof description close to ground truth, with an accuracy appropriate to many applications.

The perturbations introduced on input polygons affect accuracy as follows:

- A constant z-value on polygons does not affect accuracy,
- Using whole building blocks instead of independent adjacent contours implies a small loss in accuracy (0

to 20cm RMS), whilst significantly reducing capture cost (30% reduction over test areas),

- A perturbation on z-values slightly degrades quality: a perturbation with a 2m standard deviation introduces a loss of 15 to 45cm in RMS,
- A perturbation on xy-values can introduce local gross errors,
- The contour simplification implies a 5 to 10cm loss in accuracy whilst reducing capture costs from 15 to 20% on examples.

Input Poly	Cost	Semi-automatic DSM accuracy						
	NPts Used	NPts Ref	Avg	Std	RMS	Emax	Pct +/-1	Pct +/-2
REF	6131	690	0.53	0.85	1.00	4.47	75.94	94.64
Zmed	6066	690	0.55	0.81	0.98	4.13	76.23	95.07
Blocks	4460	690	0.42	0.95	1.04	6.44	80.14	95.65
Dz1	6327	688	0.40	0.89	0.98	5.67	75.73	95.49
Dz2	6959	690	0.40	1.09	1.16	5.00	71.16	91.30
Dz3	7356	690	0.35	1.51	1.55	7.40	64.78	85.94
Dxy1	5146	688	0.30	1.25	1.29	15.47	75.00	92.59
Spl3	4991	688	0.58	0.94	1.10	4.85	73.26	91.86
Blocks + spl3	3464	692	0.26	1.15	1.18	6.54	78.03	92.49

Table 5: Semi-automatic DSM cost and accuracy, when input planimetry contours vary (Kerlaz)

4.3.3 DSM production: conclusion

The semi-automatic process provides DSM close to ground truth with an accuracy around 1m. It is reasonably robust to planimetric and altimetric variations. Capture costs can be significantly reduced. For example, using building blocks and simplified polygons can reduce capture costs by 40%, whilst providing a DSM with a RMS below 1.50m and more than 75% reliable points.

5. CONCLUSION

Two methods for producing urban DTM and DSM from aerial images have been compared:

- A traditional approach based on the manual capture of 3D vectors,
- A semi-automatic approach using automatic image matching.

Regarding DTM production, the manual approach provides a very good accuracy (better than 85cm) but at an important cost. The semi-automatic approach is a good alternative solution for reducing capture cost, whilst keeping a 1m accuracy.

As for building description, the data produced with the manual approach are good quality but limited by the single elevation roof model. The semi-automatic approach provides a representation closer to ground truth, including oblique roofs and superstructures, even when capture cost is significantly reduced. The roof accuracy then lies between 1m and 1.50m.

These two approaches are complementary and correspond to different needs. The manual approach is relevant when a full vector description and very accurate data are necessary. The semi-automatic approach is more appropriate when cost reduction is a priority, or when roof shape is required by the user.

This study finally shows it is possible to compute high quality DTM and DSM from 2 aerial images, as long as appropriate external data are available. The accuracy could be improved using multiple views, or pre-defined roof models. To fulfil this study, complementary tests should focus on the planimetric accuracy of the produced data and on the specific behaviour of vegetation.

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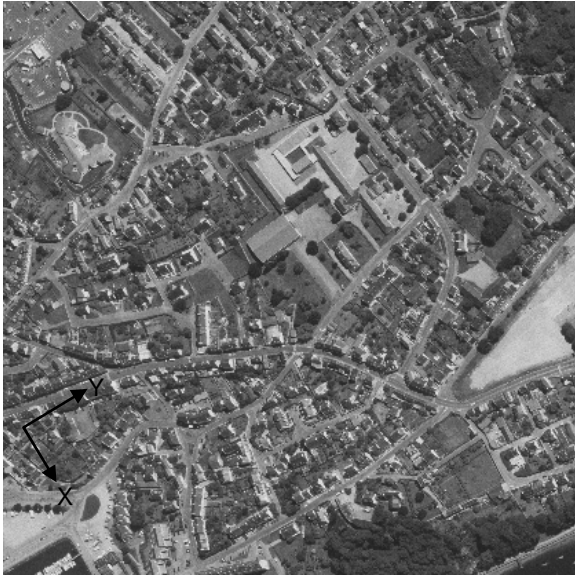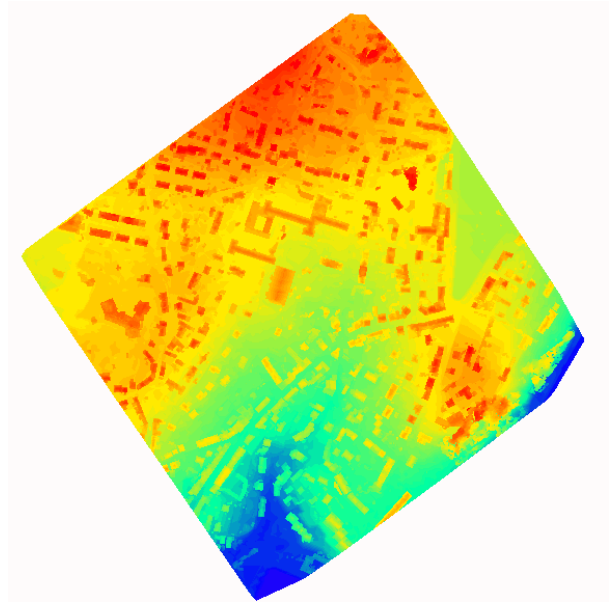
Figure 8a: Kerlaz, left image

Figure 9a: Kerlaz, semi-automatic DSM

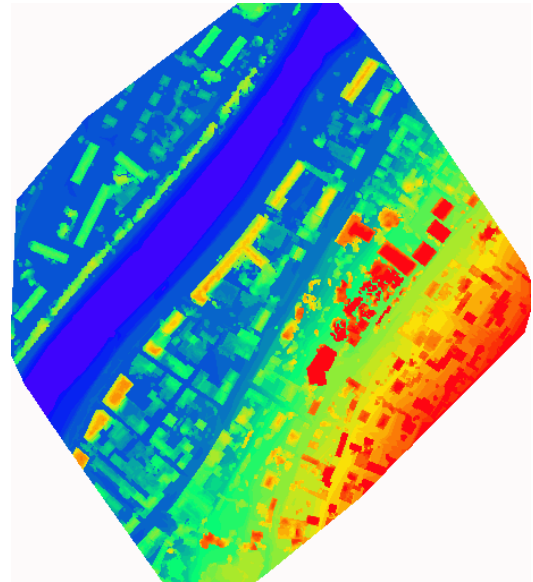Figure 8b: Deauville, left image

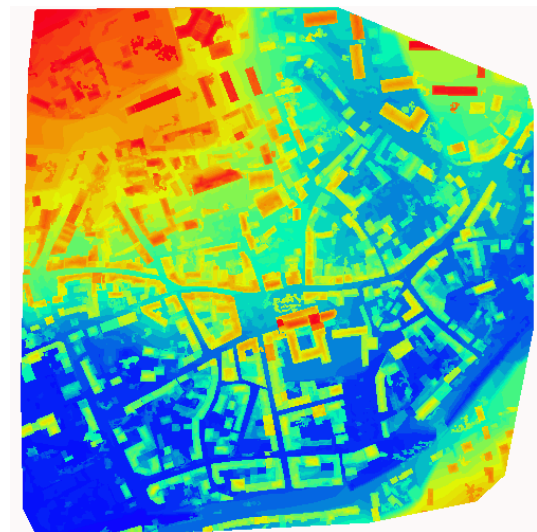Figure 9b: Deauville, semi-automatic DSM

Figure 8c: Le Havre, left image

Figure 9c: Le Havre, semi-automatic DSM