Pixel based matching of satellite stereo pairs for build up areas

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Abstract: The traditional area based matching is handling the object plane in the area covered by the matching window as a plane. In areas with sudden height changes this does not correspond to the reality, causing a smoothening of the objects, which can be seen especially at buildings. Semi Global Matching (SGM) belongs to the pixel based matching; SGM is able to handle sudden height changes, as appearing at buildings, in the correct manner. With images taken by IKONOS and GeoEye-1 3D city models have been generated by area based matching with Least Squares Matching (LSM) and SGM. As expected, LSM is flattening the objects, while SGM delivers the best result.

Especially the building shape is more precise based on SGM and SGM has not as much problems with areas of low contrast and shadows. Nevertheless with DSMs of both methods differential height models could be generated, showing very clear height changes of buildings caused by new, eliminated and enlarged buildings. Height changes of one floor, in the range of 2.7m, became obvious.

Ground control points (GCPs) for the bias corrected RPC-orientation of the satellite images have been determined in aerial images. Based on the GCPs a shift of the models against the direct sensor orientation for IKONOS in X and Y in the range of 7m and in Z of 0.3m and for GeoEye in X and Y below 1m and in Z 2.8m were determined

Key Words: satellite data, digital surface model, urban area, local and global matching, empirical comparison

1. Introduction

The extraction of the third dimension from stereoscopic image pairs is a well-known technique. Photogrammetry is one of the oldest methods, which has been used for 3D information generation, with developments already beginning around 1840 (Falkner, 1995).

One of the first application of satellite technologies was the military reconnaissance. Since 1962 stereoscopic coverage has been available (Konecny, 1998), but for civilian application use of satellite stereo pairs started with SPOT in 1986. The ground resolution and imaging at different instants limited the photogrammetric space application. In 1999 when the IKONOS satellite was launched in order to provide very high-resolution stereo imagery, a new era was opened with a competition to aerial images. Based on such images, high resolution DSMs can be generated.

DSMs got an increasing interest in recent years because of their significant role for many applications, e. g. telecommunication (Renouard and Lehmann, 1999), urban planning (Allam, M.M., 1978; Zhang, et al., 2002; Thomas, et al., 2003; Kux et al., 2006), map update and monitoring land-cover changes (Mas, 1999; Caetano and Santos, 2001 ; Brito et al.,2008). DSMs also have become an information source for generation of high resolution urban models (Fraser, et al.,2001; Flamanc, et al.,2005; Krauß, et al.,2008). In addition, DSM can be used as information layers in Geographic Information System (GIS) (Welch, R., 1990; Baltsavias and Stallmann,1992; Skidmore, 1997; Poli, et al., 2004).

The applications of DSMs led to intense research with the aim to generate DSMs from very high resolution stereo satellite images (HRSI) for large areas automatically.

In this paper, our investigation has been initiated for two primary reasons. The first reason relates to the use of high resolution satellite images for DSM generation instead of other sources such as aerial images or laser scanner data, which in many parts of the world are unavailable, expensive or classified. Stereo pairs from very high resolution satellites such as IKONOS and GeoEye-1 led the way into a new, not restricted era of generating DSMs.
The second reason is a recent revival of image matching (see e.g. (Haala, 2009)), and thus a renewed interest in the capabilities of recently developed algorithms with respect to traditional solutions. An automatic procedure for the generation of DSMs including building shapes based on image matching techniques is highly desirable.
In this paper we present an analysis and a comparison of two different matching methods for generating urban DSMs based on very high resolution satellite images:

- least squares matching (LSM; Förstner, 1982) in a region growing fashion (Otto, Chau, 1989; Heipke et al., 1996), a local area based method which compares the intensity values within a template to those in a search window;
- semiglobal matching (SGM; Hirschmüller, 2008), which computes conjugate points along multiple conjugate lines hierarchically by using mutual information instead of intensity value differences as dissimilarity measure.

The mentioned matching algorithms for automated DSM generation from high resolution satellite stereo image pairs are described in (Alobeid et al., 2010)

2. Used data and project areas

IKONOS and GeoEye-1 stereo pairs of urban area was used to generate DSMs in Riyadh, Saudi Arabia, the project areas are located in rolling terrain, including densely built up areas. Panchromatic IKONOS GEO stereo models with a ground sampling distance (GSD) of 1m was available, also a GeoEye-1 pair with 0.5m GSD. Some technical specification of the used GeoEye-1 and IKONOS stereo pairs are shown in table 1 and 2.

General Description	Acquisition date	Height-to-base h/b	Angle of convergence	Sun Elevation	Image quality
buildings, close together, separate building	2009/09/15	1.5	35.9°	62.9°	good

Table 1: Basic properties of Geo Eye-1 stereo pairs used for DSM generation

General Description	Acquisition date	Height-to-base h/b	Angle of convergence	Sun Elevation	Image quality
buildings, close together, separate buildings	2008/05/24	1.7	31.7°	74.7°	low contrast

Table 2: Basic characteristics of IKONOS stereo pairs used for DSM generation

3. Reference Data

In order to carry out a qualitative and statistical analysis of DSMs generated by the mentioned matching algorithms, accurate reference data have to be available. A DSM was generated by using aerial photos taken in May 2007 by an analogue aerial camera RC30. The aerial images were available at a scale 1/5500 (focal length =303.2 mm), scanned at 14 μm corresponding to a ground sampling distance (GSD) of 7 cm. The stereo pairs have 60% forward overlap and 20% side lap .The image quality of the scanned grainy analogue aerial images was improved by an average Filter (4×4 filter window), reducing the image noise. The DSMs are generated by LSM with image orientation given from a bundle block adjustment. LSM was used because of processing time and the very high resolution of 7 cm. The bundle block adjustment is with 2.7 μm σ_0 and mean square discrepancies at GCPs of 1.0 cm for X, 1.1 cm for Y and 4.4 cm in Z. The DSM has been used as reference to compare the geometric accuracy of DSMs generated by the used matching algorithms from IKONOS and GeoEye-1 images in the Riyadh test area.

4. Image Orientation

The relation between ground coordinates and its corresponding position in the image has be calculated by using the replacement model of Rational Polynomial Coefficients (RPC), details can be found in (Grodecki 2001; Jacobsen, et al 2005).
The absolute geo-reference for the Riyadh satellite stereo models are GCPs extracted from aerial images. By bias based RPC determination the shifts listed in table 3 of the direct sensor orientation were determined. The root mean square differences of the GCPs are slightly above 1 GSD, mainly caused by limited identification of the GCPs.

Test area	Number of GCPs	X-shift	Y-shift	Z-shift	RMSX	RMSY
Riyadh (IKONOS)	19	-4.98 m	+8.0 m	+ 0.3 m	1.26m	0.95m
Riyadh (GeoEye-1)	22	+1.04 m	+0.7 m	-2.5 m	0.61m	0.75m

Table 3: results of the bias corrected RPC orientation

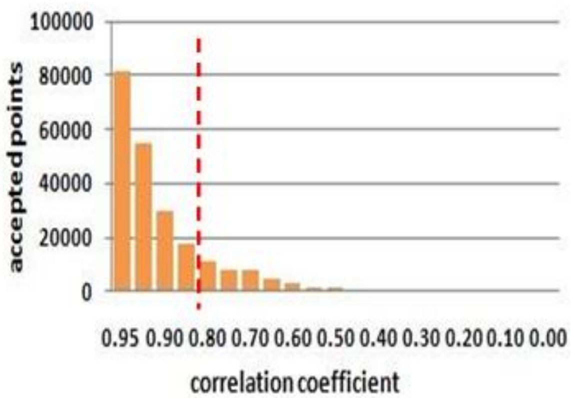
5. Analysis of DSM generated by LSM

The automatic extraction of DSMs in urban areas has been carried out with high-resolution satellite imagery, such as IKONOS and GeoEye-1 described in tables 1 and 2.
A good choice of the parameters is essential for the success of the algorithm. The parameters in automated DSM generation by LSM algorithm are: seed points, window size, matching step distance and threshold for correlation coefficient.
The image positions of seed points and some check points for the image matching have been measured manually using the Hannover program DPLX. Then Hannover program DPCOR, embedded in DPLX, has been used for automatic image matching. The used program for least squares image matching uses region growing. The core of this program was developed by (Heipke and Wegmann, 2002; see also Heipke, 1996). Matching in image space is independent from any orientation information. The number of required seed points depends on image similarity and decreases with a larger height-to-base (h/b) ratio corresponding to a smaller angle of convergence.
We found empirically that the optimal size of the matching window in the investigated areas was 10 by 10 pixels as usual. In particular for larger window sizes, adjacent buildings may be merged and appear as a common blob. A smaller template may circumvent this problem to a certain extent and thus yield more correct results near height discontinuities, but generally leads to a lower accuracy because of the reduced redundancy of the adjustment.
The step width of region growing should depend upon the roughness of the terrain. In images of urban areas, there is no significant difference in identifying the borders of the building when the matching step distance was changed from 1x1 pixel to 3×3 pixels (Alobeid, 2011). In order not to lose any information a point interval of 1 pixel was used in all investigations.

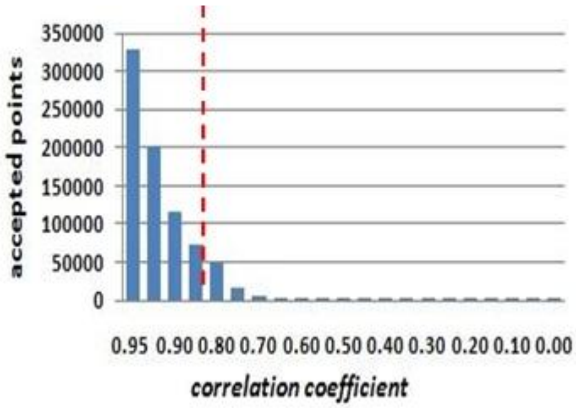
The threshold for the correlation coefficient plays an important role for the success of this algorithm. It can easily be determined empirically. The threshold of the correlation coefficient used for LSM was selected based on the histogram of the obtained correlation coefficients (figure 1). The image quality allowed a threshold of 0.8, what is high in relation to other areas. Table 4 shows the resulting matching success.

Test area	Riyadh, IKONOS	Riyadh, GeoEye-1
Percentage of accepted points	79%	78%

Table 4: matching success



Threshold of the correlation coefficient=0.8 , Riyadh test area, IKONOS



Threshold of the correlation coefficient=0.8, Riyadh test area, GeoEye-1

Fig.1: frequency distribution of correlation coefficients by LSM with used threshold

The IKONOS stereo pair over Riyadh city was used to generate a DSM by LSM. The images have limited contrast and a satisfying height-to-base ratio of 1.75. These characteristics make the matching algorithm particularly interesting for the generation of urban DSMs especially in an urban area with high sun brightness.

As demonstrated with figure 2, the LMS matching results based on IKONOS images are not very good. Especially building outlines are fuzzy and deformed into blobs. The DSM from LSM makes a determination of satisfying building shapes difficult. More problems occur in occluded areas and on homogenous roof tops and streets. Black areas as highlighted in figure 2 upper right corresponding to larger matching gaps, appearing where no contrast is available. Buildings close to each other are merged and appear as building blocks where hidden parts are not matched. On the other hand, due to the use of a fixed template size, the street level, building facades and roof tops are partially merged, and LSM leads to an averaged height. So the building outlines are smoothened. Few or no points are extracted in shadow areas close to the base of buildings. The matching in these areas may not be satisfying to model discontinuities such as caused by buildings.

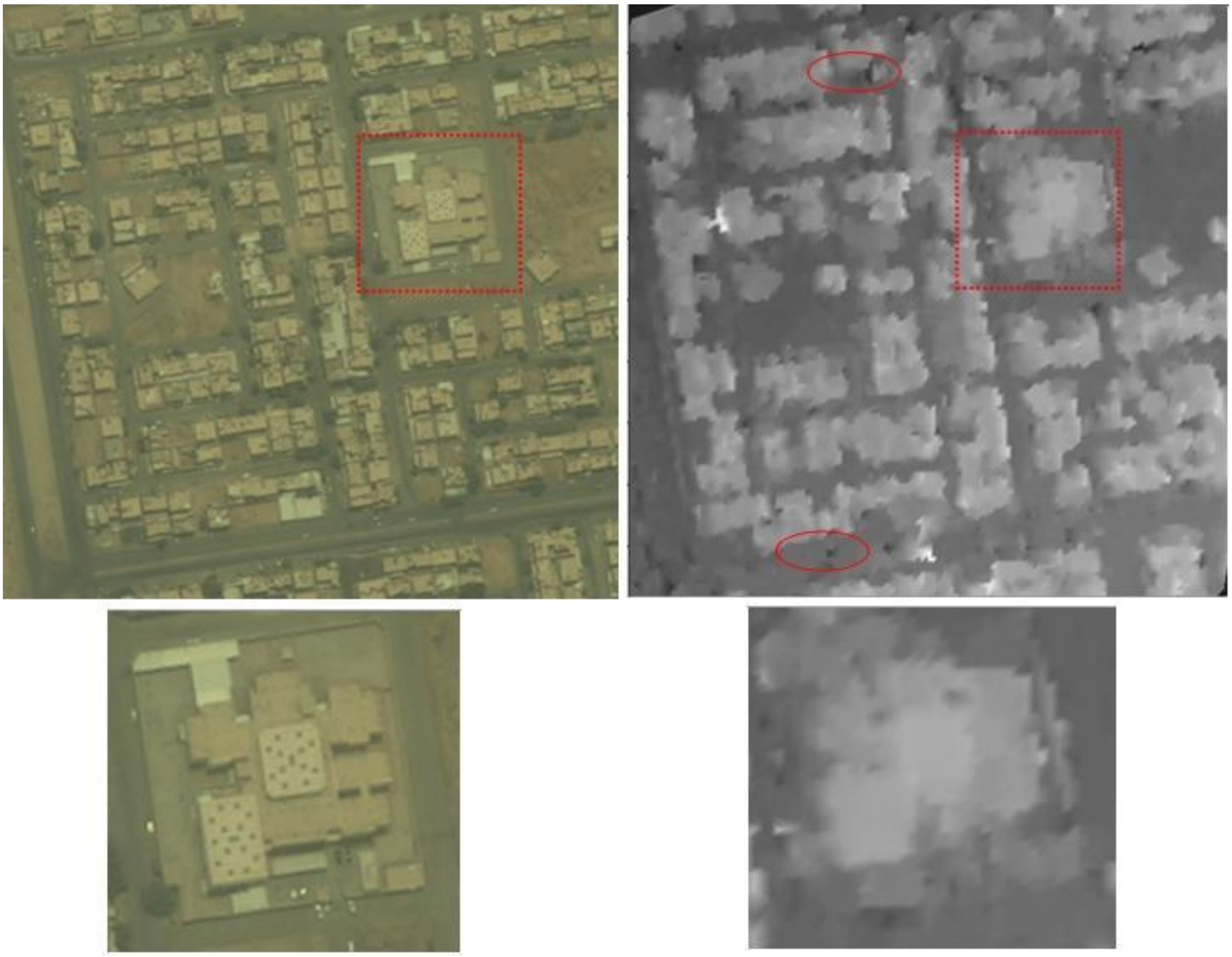


Fig.2: Left hand side: IKONOS image, grey value coded DSM generated by LSM algorithm on right hand side; lighter gray levels correspond to higher elevations

Matching with GeoEye-1 images was also done for the Riyadh test site. Of course the GeoEye-1 image with 0.50m GSD includes more details as the IKONOS image. The spatial resolution is better; because of the view direction, the shadow areas are disturbing more as in the used IKONOS stereo pair. With the higher resolution of GeoEye-1 of course the result is better as with IKONOS (see figure 3). The building shapes are clearer than those generated from the IKONOS stereo pair. As expected, with the area based LSM the building shape cannot be sharp as in the original form. Also some incorrect information on top of the buildings and close to facades remain unresolved.
The generated DSM has some interpolated blurry areas that correspond to shadow areas. The buildings close to each other are merged and appear as building blocks where the hidden parts are not matched. The border between the houses cannot be clearly distinguished. In addition, the building outlines are smoothened.

Summarizing it can be said that LSM generated visually acceptable results. However, DSMs are blurry and contain large interpolated areas. LSM still does not yield clear building shapes. The building footprints can be extracted from the generated DSM, but not with satisfying detail. LSM failed in extracting details of small and very small houses.
The used LSM program may require several seed points. The main source of mismatching was missing texture of some buildings. Some errors in the generated DSM correspond to moving objects on the streets and low contrast areas.

Fig.3: Left hand side: GeoEye-1 image, grey value coded DSM generated by LSM algorithm on right hand side; lighter gray levels correspond to higher elevations

6. Analysis of DSM generated by SGM

SGM has been proposed as an alternative solution to overcome drawbacks in LSM. SGM requires epipolar images. The algorithm was tested with the same high-resolution satellite imagery datasets as described before (tables 1 and 2).

A program written in Visual C++ was designed for automatic image matching by SGM. The parameters of SGM have been determined empirically based on visual inspection of the generated DSMs. The parameters in automated DSM generation by SGM algorithm are: number of accumulated path and penalty for changes in disparity of one pixel (P1) and penalty for changes in disparity more than one pixel (P2).

The number of paths should be at least 8 or16 for providing a good coverage of the 2D image. Sixteen paths have lead to better results than eight paths.

The investigations proved that the best results were achieved for ratio P2/P1 of approximately two. Up to 10% of all pixels changed their disparity values in the test area when P1 and P2 were increased above the used values. The building shapes were not affected too much by such an increase. Most of the changed values were on building outlines and lower buildings. The used values of P1 and P2 in the test area are P1=6 and P2=12.

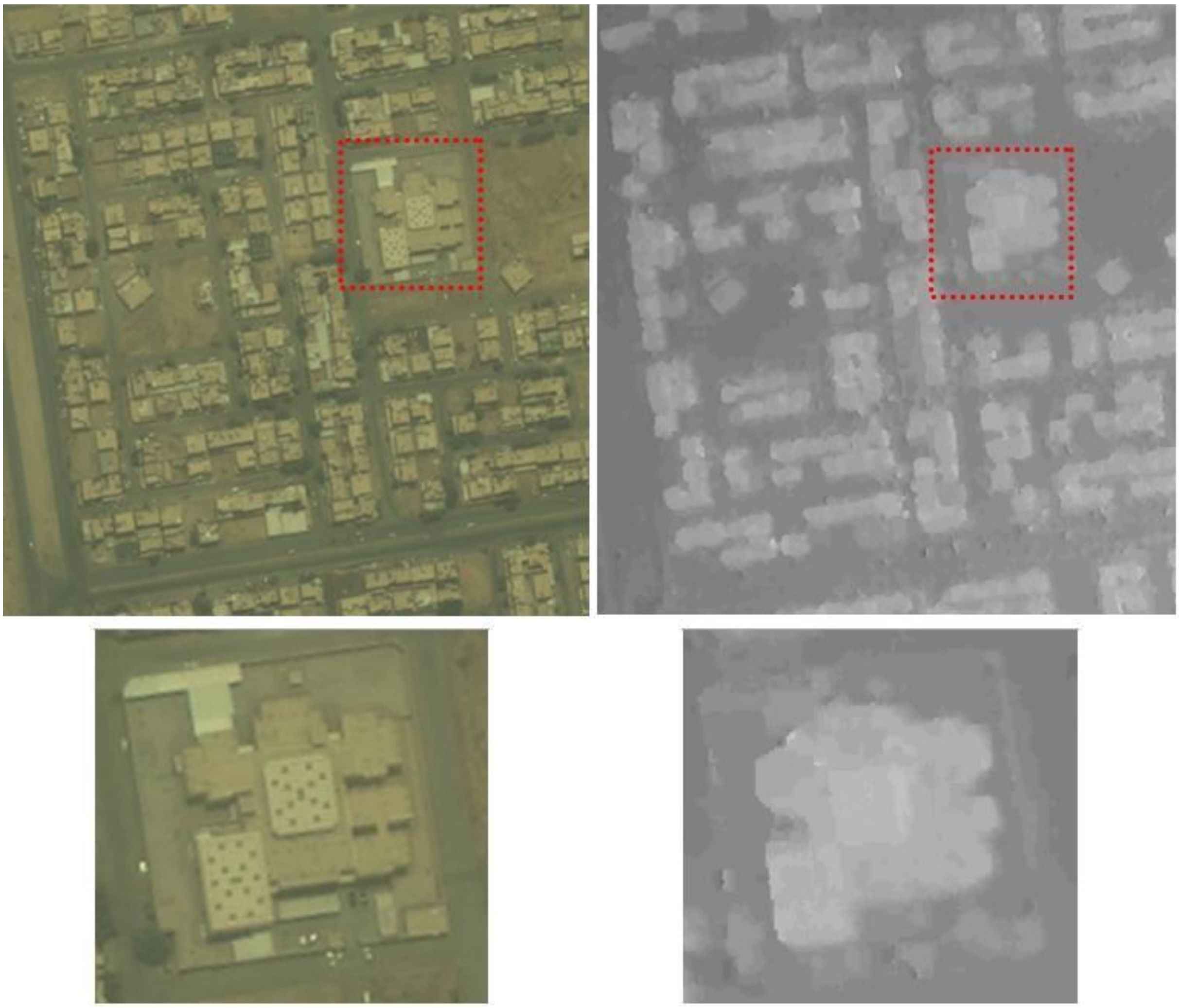


Fig. 4: Left hand side: IKONOS image, grey value coded DSM generated by SGM on right hand side; lighter gray levels correspond to higher elevations

The mentioned IKONOS stereo pair over Riyadh city has been used to generate a DSM by SGM with results as demonstrated in figure 4. Although the images have low contrast, a visual inspection shows that SGM is able to generate a DSM with more and clearer details as LSM. Most buildings are well represented. Building outlines seem to be sharp as in the original image, but some inaccurate points appeared especially around building edges due to shadows. However, trees around buildings may affect the extraction of the correct building shape. The borders between houses can clearly be distinguished. The DSM shows details similar to the original images, where the details of building roofs are clearly extracted (see figure 4, lower right).
Although the IKONOS stereo pair was taken with high sun elevation, the generated DSM is not affected because SGM is based on mutual information (MI). Matching cost and MI has been shown to be rather robust with respect to radiometric variations. A visual inspection shows that some errors correspond to moving objects on the streets.

The GeoEye-1 image pair of the Riyadh test site also has been used to generate a DSM by SGM; it is shown in figure 5. Also with these images DSMs based on SGM are clearly better as based on LSM. A visual inspection shows that most buildings are very well represented and building outlines seem to be sharp as in the original images. Trees around the buildings affect the extraction of the correct shape of some buildings. However, spaces between buildings could clearly be distinguished. Black areas appear where no contrast exists or moving objects disturbed the matching. Vertical walls are visible very well. SGM shows more details on building roofs and around buildings such as parked cars.

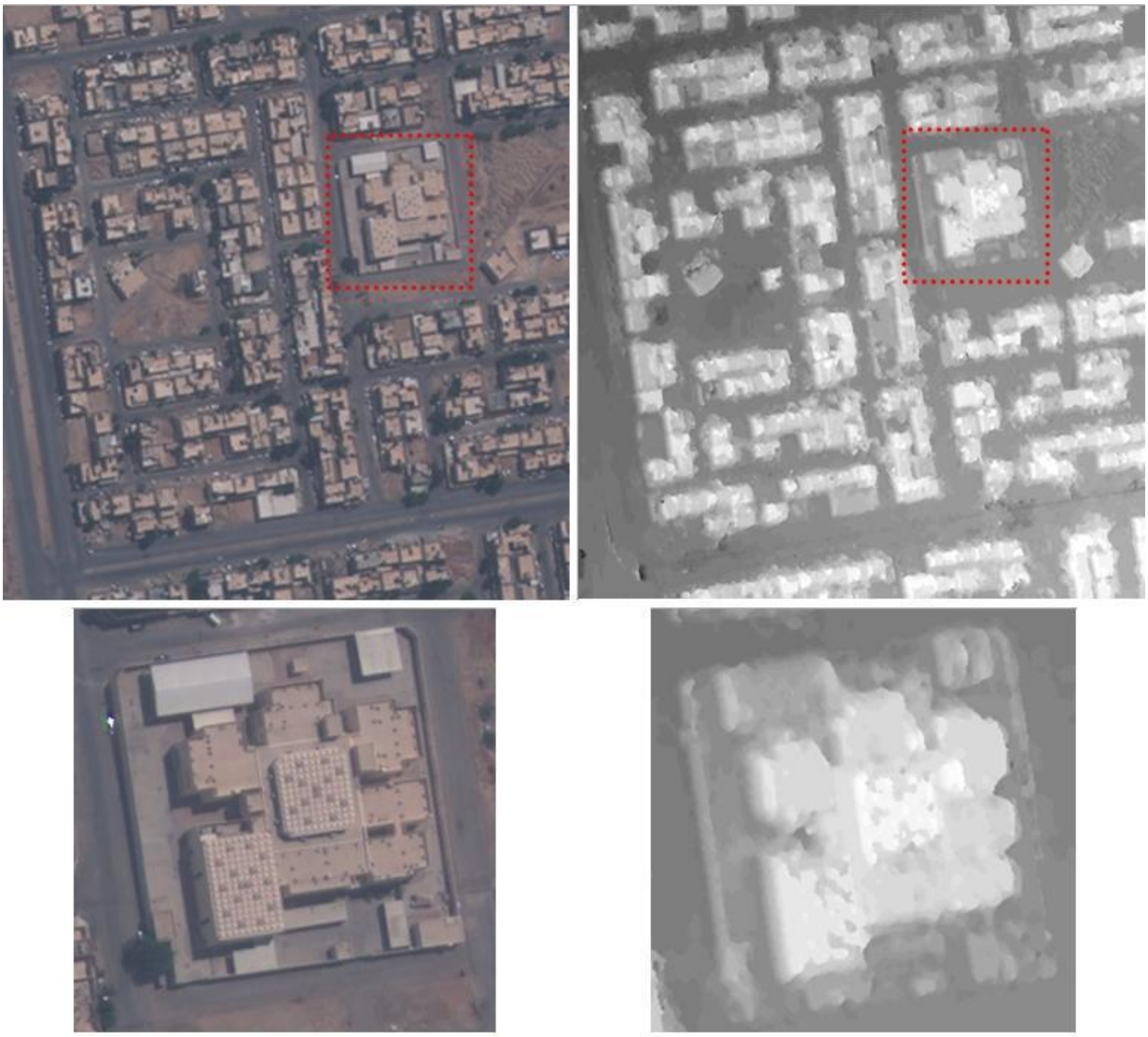


Fig.5: Left hand side: GeoEye-1 image, grey value coded DSM generated by SGM on right hand side; lighter gray levels correspond to higher elevations

Summarizing the results it can be said that SGM achieves visually very good results for most building shapes. The main drawback to the algorithm is caused by buildings without contrast, leading to limited results. Generally, it can clearly be seen that thanks to the pixel based matching and the combination of several 1D paths in the different directions, the SGM algorithm is able to produce an improved DSM compared to LSM. SGM is able to match complex roof shapes in some situations where LSM fails and shows positions with sudden height changes in the correct manner.

7. Qualitative and Quantitative analysis

A qualitative and visual evaluation assessment was made by comparing different aspects based by visual inspection. It is possible to draw the following summary of the qualitative analysis listed in table 5.

Object	LSM	SGM
Buildings outlines	Smooth	Sharp
Flat roofs	Smoothened shape	Correct shape
Gable and hip roofs	Acceptable shape	Good shape
Facades	Not vertical	Nearly vertical
Base of buildings	Wider as correct size	Similar to correct size
Details on roof	Not detected	Most details detected
Poor texture	Not matched	Acceptable match, interpolation
Densely located buildings	Merged and appear as building blocks	Merged and appear as building blocks
Borders between usual buildings	Often not distinguished	Clearly distinguished
Bridge over highway	Deformed	Clearly extracted
Bare area	Clearly extracted	Clearly extracted
Groups of trees	blurred	Extracted

Table 5: summary of qualitative analysis of the used matching algorithms

Building heights determined by matching are compared with reference heights from aerial images with 7cm GSD. Some of the buildings have been changed after aerial imaging and before imaging from space. The differences of the DSMs from IKONOS and GeoEye-1 minus the reference DSM based on the aerial images may be influenced by building changes. Only building heights existing in all data sets have been taken for comparison. The newly erected buildings (red circle in figure 6) have been avoided in the comparison with reference data as shown in figure 6. Furthermore, some gaps and shadow areas in the reference DSM also have been avoided. In order to derive building heights from the DSMs the heights of 4 points on the roof and close to the building corners have been averaged for each building. The height of the selected buildings ranges from 6 m to 18 m. In the Riyadh test area all buildings have flat roofs.

In order to quantify the performance of matching algorithms, the generated building heights from IKONOS by LSM, DP and SGM have been compared manually with corresponding heights from reference data.

For the independent check, 75 buildings have been selected. These buildings have a random location within the scene. The investigated building heights are average values of 4 points on the roof close to the building corners. The results of the analysis of the IKONOS building height are shown in table 6.

The RMS of height difference is slightly below 1m corresponding to 0.5 pixels for the x-parallax for LSM, and in the range of 0.8 m or 0.4 pixels for the x-parallax for SGM. The building outlines were not tracked perfectly by LSM. It was difficult to determine accurate elevations although supported by contour lines. The obtained results from SGM are considerably better that obtained by LSM.

Fig. 6: Upper left: part of GeoEye-1 image, Upper right: grey value coded reference DSM, lower left: grey value coded GeoEye-1 DSM, Lower right: grey value coded DSM differences

Riyadh (height/base=1.7) checked with 75 buildings		
	LSM	SGM
Standard deviation of reference heights	0.2 m	0.2 m
RMS of IKONOS height differences	0.9 m	0.8 m
SZ of IKONOS height differences	0.8 m	0.7 m
RMS of x-parallax	0.5 GSD	0.5 GSD

Table 6: Accuracy of IKONOS building heights

The frequency distribution of the height differences is shown in figure 7, with height intervals of 0.25 m together with the Gaussian distribution (red lines). The discrepancies between the real and normal distribution can be explained by the limited number of differences. Only the results based on LSM shows a small bias of 0.20 m.

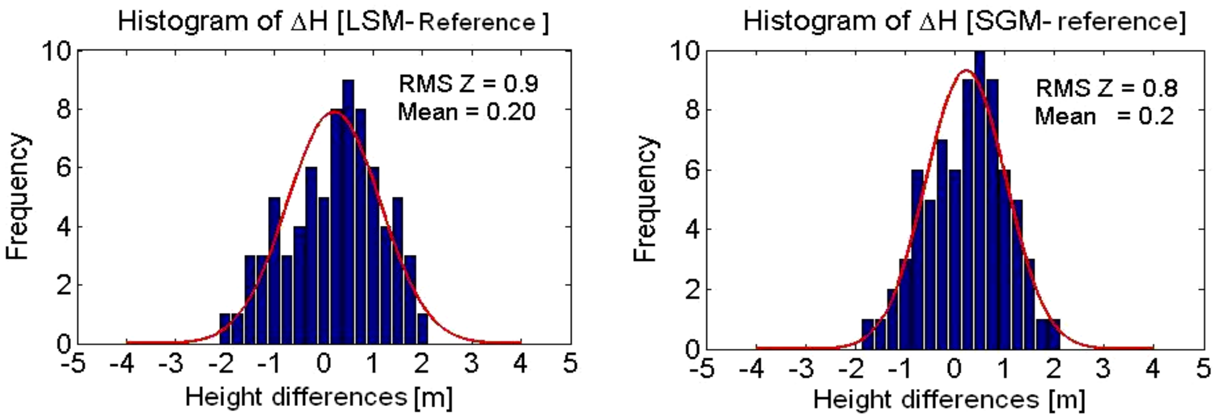


Fig 7: Histograms of the height differences, left: LSM, right: SGM

Riyadh (height/base=1.5) checked with 125 buildings		
	LSM	SGM
Standard deviation of reference heights	0.2	0.2
RMS of GeoEye-1 height differences	0.7	0.5
SZ of GeoEye-1 height differences	0.6	0.4
RMS of x-parallax	0.5	0.3

Table7: Accuracy of GeoEye-1 building heights

The vertical accuracies of the GeoEye-1 DHM are below 0.7 m corresponding to 0.4 pixels for the x-parallax for LSM, and in the range of 0.5 m or 0.3 pixels for the x-parallax for SGM. Figure 8 shows a satisfying normal distribution of the results. LSM results have a very small bias of +0.07 m and the SGM results 0.06m.

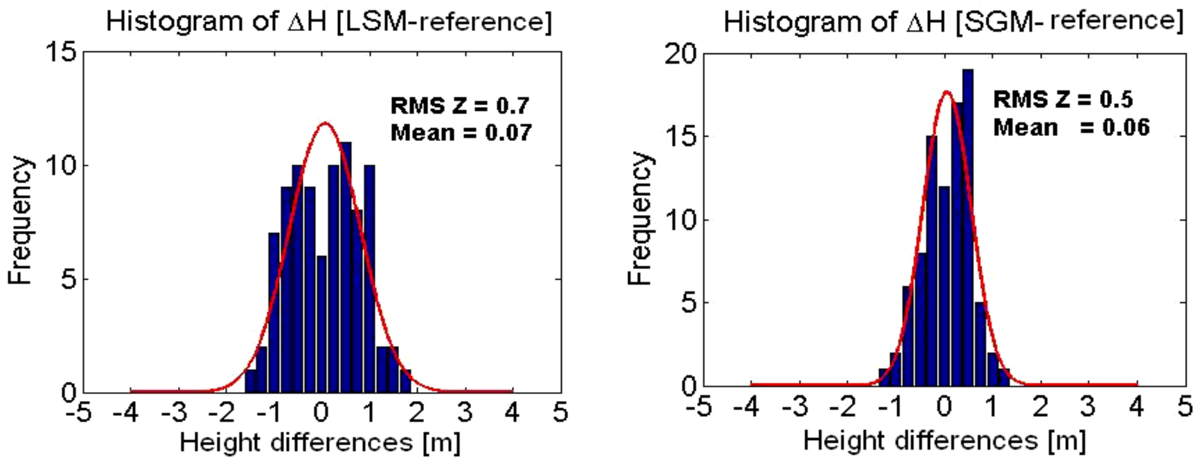


Fig.8: Histograms of the height differences, left: LSM, right: SGM

8. CONCLUSION

The generation of digital surface models in urban areas based on very high resolution stereo satellites pairs has reached a high level of accuracy. The area based least squares matching is not able to generate clear building outlines and is strongly influenced by occlusions. Semiglobal matching requires epipolar images. It leads to improved DSMs compared to LSM. In general it is possible to generate DSMs by automatic image matching in urban areas with a quality acceptable for a number of applications using very high resolution satellite images.

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