High-Accuracy Satellite Image Analysis and Rapid DSM Extraction for Urban Environment Evaluations (Tripoli-Libya)

Abdunaser Abduelmula, Maria Luisa M. Bastos, José A. Gonçalves

***Abstract*—**Modelling of the earth's surface and evaluation of urban environment, with 3D models, is an important research topic. New stereo capabilities of high resolution optical satellites images, such as the tri-stereo mode of Pleiades, combined with new image matching algorithms, are now available and can be applied in urban area analysis. In addition, photogrammetry software packages gained new, more efficient matching algorithms, such as SGM, as well as improved filters to deal with shadow areas, can achieve more dense and more precise results.

This paper describes a comparison between 3D data extracted from tri-stereo and dual stereo satellite images, combined with pixel based matching and Wallis filter. The aim was to improve the accuracy of 3D models especially in urban areas, in order to assess if satellite images are appropriate for a rapid evaluation of urban environments.

The results showed that 3D models achieved by Pleiades tri-stereo outperformed, both in terms of accuracy and detail, the result obtained from a Geo-eye pair. The assessment was made with reference digital surface models derived from high resolution aerial photography. This could mean that tri-stereo images can be successfully used for the proposed urban change analyses.

***Keywords*—**3D Models, Environment, Matching, Pleiades.

I. INTRODUCTION

REMOTE sensing became more and more important in developing countries for applications such as urban environment evaluation and mapping update. 3D models of the terrain surface can be achieved via LIDAR and digital aerial images, which became key technologies in the field of high-resolution 3D digital model extraction. Nevertheless, due to acquisition costs, logistic requirements, security or possibly prohibition, in many developing countries satellite imagery can be much more competitive [5].

Different space agencies and companies developed, in recent years, satellite configurations that could satisfy/meet the terms of accuracy of automatic extraction of 3D city model. Therefore, in the last two years, CNES has launched a new generation of satellites called Pleiades, with the ability of a multiple stereo coverage of the same location on the terrain surface from three points of view "Backwards", "Nadir" and "Forward", called tri-stereo images. Therefore, satellite tri-stereo images may become a natural choice to fulfill this demand for extracting of topographic data, for applications of monitoring and natural or disaster management, with lower cost in comparison with aerial imagery.

The automatic image matching becomes an essential task for 3D point collections in digital image processing and computer vision. Therefore, the goal of image matching is to automatically calculate the correspondences of 3D points on overlapping images, thus it is a critical technique in many applications, including digital surface model generation [2], [10].

A wide variety of approaches have been developed for DSM extraction and some packages are commercially available. On the other hand, a fully automatic, precise and reliable image matching method, capable to adapt for different images and scene contents does not yet exist. The difficulties in image matching were usually resulting from, for example, radiometric differences, geometric distortion and occlusion, repeated and lack of patterns [3], [8].

Hence, the recent research trends in image matching are towards hierarchical solutions with a combination of several algorithms and automatic control. In general, the 3D model extraction can be done in semi-automated or fully automated mode.

Additionally, most of photogrammetric workstations softwares have gained new, more efficient, stereo matching algorithms, such as the Semi Global Matching (SGM), as well as high accuracy 3D point's filter, namely Wallis filter. In addition to Wallis filter, that can improve the matching in shadow areas, the user can choose one of three image combinations that can avoid and/or reduce the shadow effects in the automatic stereo matching process [6].

The new data, such as the tri-stereo images, may open a new challenge in terms of improving the matching accuracy, especially in the shadow between buildings, in urban areas. This paper describes tests, carried with both satellite images, using pixel matching, combined with the Wallis filter, for automatic 3D model extraction. These models were analyzed with respect to a higher resolution 3D model of the area, derived from aerial photography, in order to determine if satellite images can be used in a fast evaluation of urban environmental changes especially in the developing countries.

An automatic processing chain for 3D model extraction based on Geo-eye stereo and Pleiades tri-stereo images has been implemented. In the meantime, several numbers of

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Ground Control Points (GCPs) were measured within the test field, in particular to assess the accuracy of image orientation and apply automatic stereo. Some building heights were also measured in order to assess the accuracy of the extracted 3D building models [4].

II. Used Data

Two image data sets were used in this study: a stereo-pair of Geo-Eye images, collected on January 2010 and a tri-stereo Pleiades data set collected on June 2012. Both images cover an area of about 100-150 km2 over the city of Tripoli, in Libya. Fig. 1 represents a scheme of the tri-stereo image acquisition, the occluded areas in For/ Back ward combinations. The main advantage is that there is less probability of occlusions, which is a common situation in the dense urban and wooded areas.

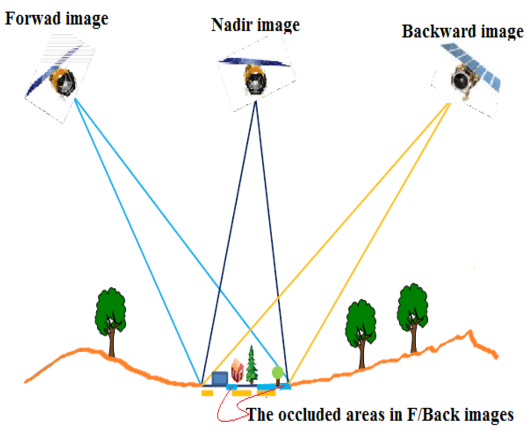

Fig. 1 The Pleiades tri-stereo imaging capability

The Geo-eye dataset was collected in its normal stereo mode, with a forward image, and the other one in “reverse” mode, with an off-nadir angle. The three Pleiades images acquired for the same area, one taken from a back nadir, the second one at the nadir, and the last image taken from off-nadir position in north to south triplet. Fig. 2 shows a subset of the study area, where (left) subset (375m× 565m) is from Geo-Eye image and (right) subset (596m× 881m) is from Pleiades Nadir image for Tripoli. Both images have the same Ground Sampling Distance (GSD) of 0.50 m. The base-height (B/H) ratio is equal to 0.70 for Geo-Eye, and in the case of Pleiades, both combinations Backwards, Nadir and Forward have B/H ratios of 0.5, the combination Backwards and Forward have a ratio of 1.0 [1].

There was also available a set of aerial photographs taken by a digital camera Vexcel Ultra-Cam, taken in September 2007, with a GSD of 10 cm, covering only a part of the city area. These data were also used to extract a digital surface model, which was used as a reference to assess the models derived from satellite images. Fig. 3 shows a subset (436m×621m) of the aerial images of the study area.

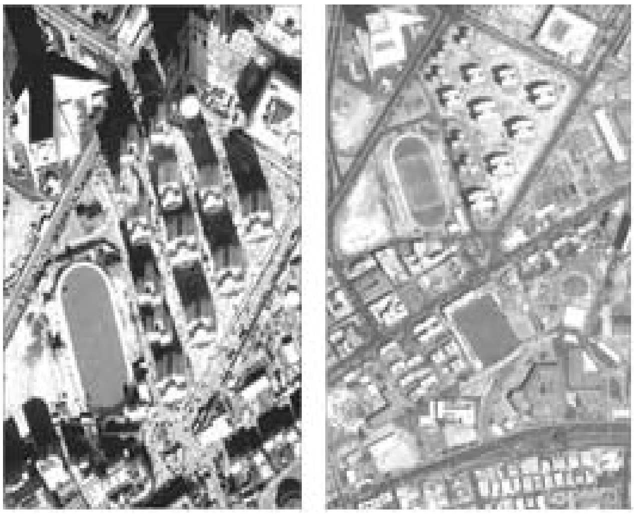

Fig. 2 Used satellite images of the study area

Fig. 3 A subset represents the used aerial images

III. Image Orientations

The purpose of image orientation is to determine a relation between the object and the image coordinates. This may be achieving based on direct sensor orientation, a combination of on-board GPS positioning and attitude sensors, where the relation between the image and the object is known at least approximately. For instance, image orientations of some remote sensing images may be achieved without GCPs in the level of pixel accuracy. On the other hand, this may not be precise for all the satellites. This is known as bias correction and has to be improved using GCPs, in particular to orient images to a planar surface and make their geometry epipolar, in general to establish the images in correct spatial location and orientation for subsequent quantitative analysis[3].

Several photogrammetric software packages are available for 3D data extraction, such as Inpho Match-T and Geomatica

PCI-2013. These packages include advanced matching algorithms that improve the accuracy of the extracted models. Unfortunately, Inpho Mach-T is not compatible with the Pleiades data format, at least in the version used (5.4), and so it was not possible to use the advanced dense matching algorithms provided by this software.

PCI Geomatica (version 2013) was the first commercial remote sensing software to accept the Pleiades image format and was used in this work. In addition, this software includes advanced matching algorithms and applies the Wallis filter technique that is a powerful method to improve contrast and matching completeness and accuracy in urban areas [9].

In order to optimize mathematical models both of the Pleiades image combinations and of the Geo-eye, different GCPs located in the study area (Tripoli, Libya) were surveyed by geodetic class Trimble GPS receivers, with mean horizontal and vertical accuracy in the range of 10cm. These GCPs were applied in a least squares adjustment of the image orientation mathematical models, which improved the geo-location accuracy, to the sub-pixel/ sub-meter accuracy. The RMS values were calculated based on the bias in across/along track (x/y), which refers to the optimized mathematical models.

Table I shows the RMS_x and RMS_y values for the residuals computed at first order transformation along x and y axes after the bundle adjustment of the GeoEye-1 stereo-pair and Pleiades image combinations. According to these results, the Geo-Eye image orientation worked slightly better, with residuals slightly smaller than the ones achieved for the Pleiades image combinations.

In general, both satellite images show residuals of around 0.70 meter and are thus acceptable. Figs. 4 (a)-(c) represent the residuals of the GCPs, in all used satellite image combinations considered.

TABLE I
IMAGE ORIENTATION ACCURACY AND THE RESULTS EXPRESSED IN METERS

Image Combinations	N. GCPs	RMSx (m)	RMSy (m)	
Pleiades	F/V	9	0.56	0.64
	F/B	9	0.82	0.51
	V/B	8	0.62	0.56
Geo-eye	F/B	8	0.35	0.41

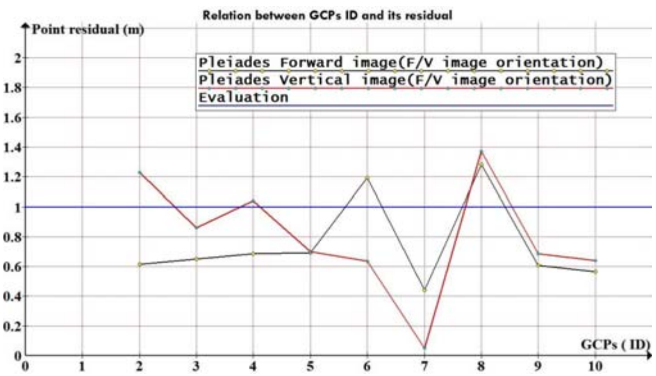

Fig. 4 (a) Absolute residuals error of used GCPs within Pleiades (F/V) orientation

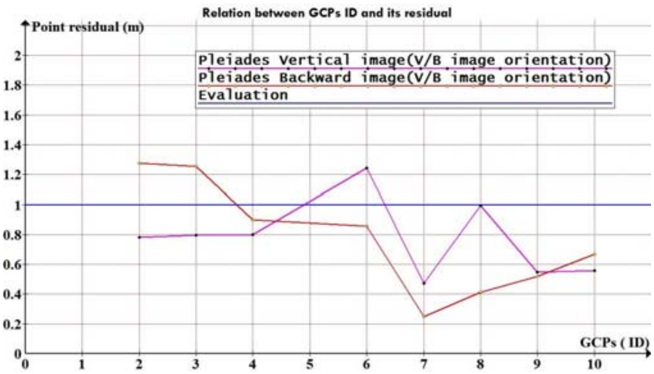

Fig. 4 (b) Absolute residuals error of used GCPs within Pleiades (V/B) orientation

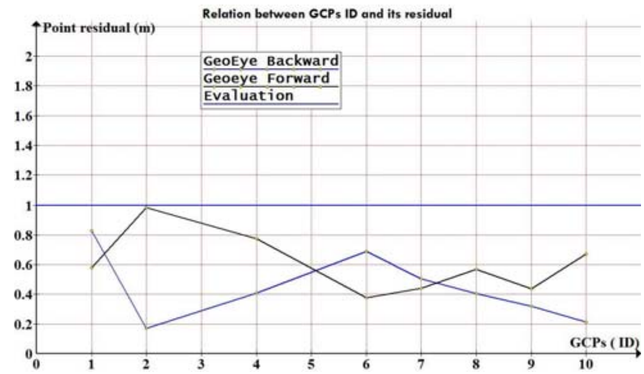

Fig. 4 (c) Absolute residuals error of used GCPs within Geo-eye s images orientation

IV. MODEL EXTRACTION

Regarding the semi-automated methods, this work tested a new generation of satellite images for rapid extractions of 3D models that may be useful for urban environments evaluations. Ortho-Engine from Geomatica PCI-2013 was the first commercial software package that accepts Pleiades images. Thus it was used for both sensor orientation and DSM extraction.

The automated image matching or image correlation technique was used to extract matching points on the two overlapping images from a search for pixels of corresponding contrast and brightness. This procedure is based on a mean normalized cross-correlation matching method with a multi-scale strategy to match the image using the statistics collected in the defined windows. Only a few parameters can be adjusted by the user in the Ortho-Engine DSM extraction module, such as the sampling interval and the level of detail. For every DSM, the epipolar images were generated with 0.50 m GSD (down sample factor of 1) [9]. Therefore a high detail DSM with 32 bits and a pixel sampling factor of 2 were selected in Ortho-Engine, DSMs with a resolution of 1.00 m were obtained.

The following different strategies were carried out for testing and extracting DSMs from Pleiades combinations and the GeoEye-1 stereo-pair images.

i) The first order transformation was considered, using 9 GCPs with heights above the ellipsoid, which are the ones considered in the orientation mathematical model. Later the DSM was converted to height above the geoid.

ii) Pleiades tri-stereo image combinations, pixel matching algorithms and Wallis filter have been tested for DSM extraction. Tri-stereo image combinations showed results indicating that accuracy of 3D points matching has been improved. For example, in terms of shadow, image combination Pleiades (N/B) has reached to the level of high accuracy in 3D models extractions in urban and suburban areas.

iii) The same strategy has been used for obtaining DSMs from GeoEye-1 stereo-pair that proved to be very sensitive to the gray values variation and shadow. In fact, the DSM of Geo-eye images shows the worst results and still poor extractions especially within the urban areas. In this case, height values which located principally in shadow areas, image matching algorithms did not work well and it made pointing errors that could produce a high error in models extractions. Fig. 5 shows the left DSM was extracted via Geo-eye stereo pair images and the right via Pleiades Nadir –Backwards image combination. These differences between DSMs models can be seen and appearing clearly.

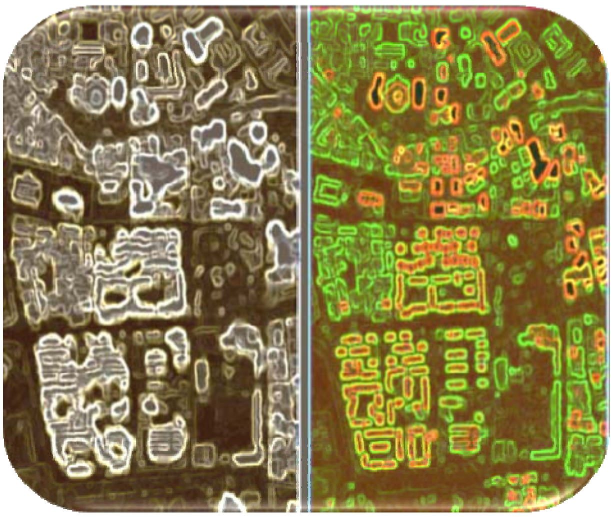

Fig. 5 The DSM extracted via Geo-eye in the left and the right via Pleiades (N/B) combination

V. DSM Geometric Analysis

Accuracy assessment of the extracted DSMs is critical for all further calculations and collection of 3D features. In order to assess the extracted models, city maps or high accuracy digital models should be available. However, in the developing countries, city databases are usually classified or not available at the time of the results analysis. Therefore, other data such as high accuracy 3D building models, field test of height measurements and GPS checkpoints need to be available, in order to achieve these assessments of model extraction [7].

In this work, reference databases of Tripoli, for the accuracy assessment of extracted models were not available. Therefore, in order to accomplish this assessment, a high accuracy 3D building model extracted from stereo-pairs of aerial images has been used as reference model, where a different set of points on the top of building roofs were measured and used for these assessments. Fig. 6 shows a profile of the detailed 3D reference model extracted by aerial images that was used for building height measurements. This model has also showed a great challenge in automatic matching for 3D gabled roofs extracted via aerial images. In addition, Fig. 7 represents the DSM for the main urban part of Tripoli, and includes different buildings roofs that were used for building height measurements in order to do the accuracy assessment.

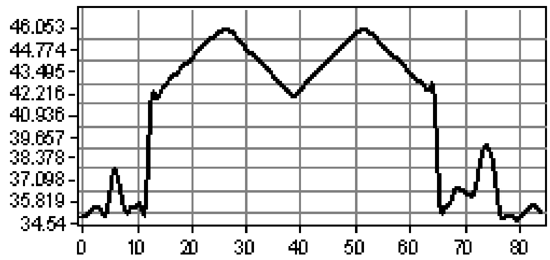

Fig. 6 Used reference models' profile

Fig. 7 Reference DSM

The height of these points was compared with the height of the projected points in both DSMs, which were extracted via

Geo-eye stereo-pair, Pleiades tri-stereo-pair satellites and the comparison has been achieved according to the following:

First: the comparison has been performed according to the visual inspections of shaded DSMs, which we showed in Fig. 5. In addition, Figs. 8 (a)-(c) show different profiles representing buildings that were measured, in particular to test whether tri-stereo image and Wallis filter based on auto-correlation pixel matching could improve the accuracy of the automatic extraction of 3D models.

Second: in order to achieve the quantitative analysis of absolute height values, different comparisons were made:

i) A reference 3D model extracted based on stereo-pairs of aerial images was used and certain points over building roofs were also measured. A total of 30 points were considered and measured as check points to assess the DSMs extracted via both satellite images. Height differences were calculated with respect to the aerial DSM, for these 30 points, as well as their statistics, which are given in Table II.

ii) In addition, the graphical representation of these errors was plotted showing that Geo-eye stereo-pair satellite images have still very large errors leading to poor 3D model generations. Moreover, tri-stereo satellite image is shown to be significantly better than stereo-pair images for 3D building extraction when compared against a reference automatic model extracted via aerial images.

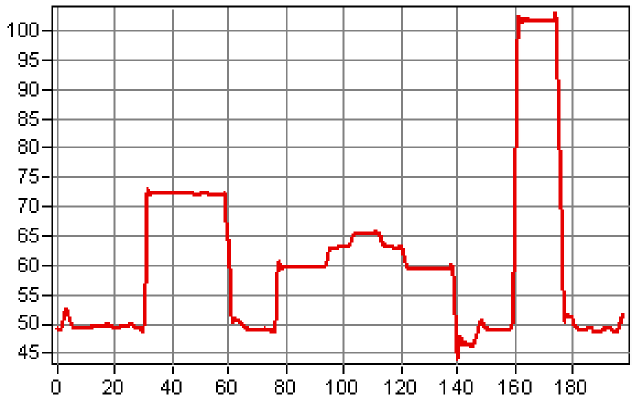

Fig. 8 (a) DSM profile extracted via aerial images

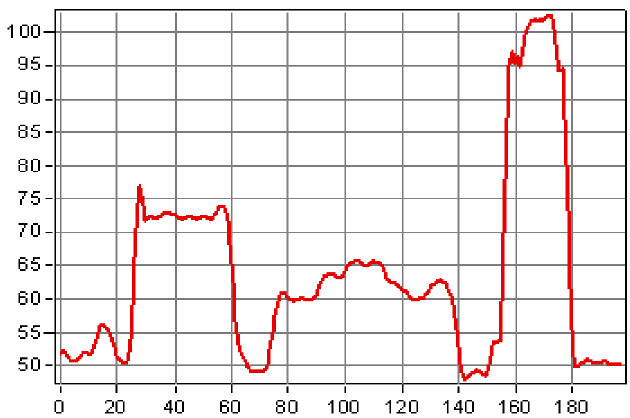

Fig. 8 (b) DSM profile extracted via Pleiades (V/B)

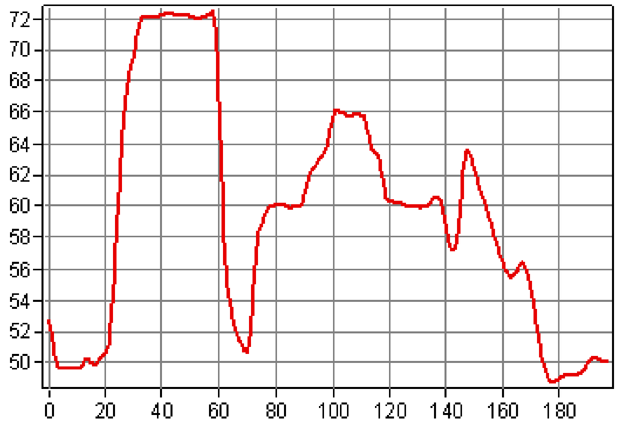

Fig. 8 (c) DSM profile extracted via Geo-eye

TABLE II
REPRESENTS THE HEIGHT ACCURACY OF DSM BASED ON 3D REFERENCE POINT OVER THE STUDY AREA

Satellite	Height difference accuracy between reference and extracted DSMs Models (m)			
	Geo-eye	Pleiades		
Diff.	$H_R - H_{Geo\text{-}eye}$	$H_R - H_{V/B}$	$H_R - H_{F/B}$	$H_R - H_{F/V}$
STD	2.64	0.60	0.89	0.79
RMS	2.65	0.60	1.33	0.92

The extracted models from Geo-eye stereo-pair gave poorer results with some buildings showing as belly shaped. Pleiades tri-stereo images produced much better quality building models in urban and sub-urban areas, which and are good for a rapid evaluation. Fig. 9 shows the relationship and the differences between the elevations of reference points and the elevations measured from DSM of tri-stereo and stereo-pair images.

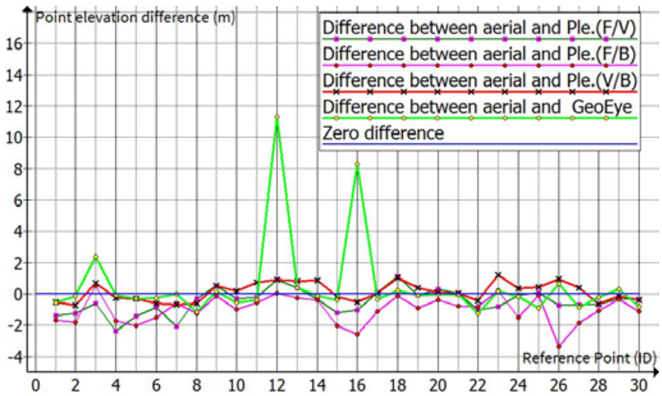

Fig. 9 The DSMs height differences analyses

iii) In order to assess the capability of Pleiades DSMs to detect and map differences in buildings, the extracted DSM (N/B) was subtracted from the DSM derived from the aerial photo DSM. There is between the two datasets a time difference of five years, during which several buildings were destroyed due to war. Fig. 10 shows a map of DSM difference (2012 minus 2007), with negative differences represented in gray. Large uniform areas correspond to destroyed buildings.

VI. Conclusion

According to the accuracy assessment of satellite image orientations, the Geo-eye stereo-pair achieved sub-pixel accuracy, whereas Pleiades tri-stereo image combinations had an accuracy of 0.70 of a meter. That, however, does not indicate that the Geo-eye stereo-pair achieves a better accuracy for DSM extraction.

The automatic extraction of 3D models was achieved in the images covering urban and suburban areas. Shadow effects caused the quality of the DSM extracted by Geo-eye stereo-pair images to be of lower quality, not being appropriate for the intended assessment in urban areas. Several combinations of tri-stereo images were tested and the result achieved via a Pleiades Nadir/ Back-nadir image combination outperformed in completeness and accuracy. In terms of detail it was possible to verify, by analyzing building profiles, that the Pleiades DSMs presented a good level of detail, even in areas of concentrated buildings with variable heights.

Based on the presented accuracy, we conclude that the percentage of correct details extracted from Pleiades tri-stereo images is higher than that from Geo-Eye stereo images and the results are more precise in terms of model details.

The aforementioned accuracy results and the agility of image and model extraction provide an evidence to use the Pleiades tri-stereo images as an alternative to aerial images in terms of improving the cost, time and related complications of image collection. In addition, the results showed in Fig. 10, Pleiades tri-stereo images can be used successfully for automatic 3D model extraction which can then be used for rapid evaluations of damage assessments in case of catastrophic events, such as earthquakes or war.

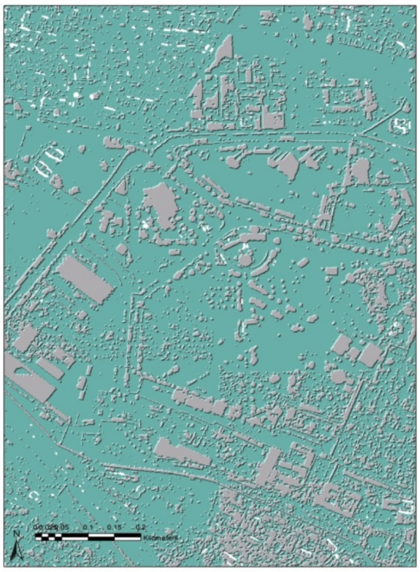

Fig. 10 The affected zones automatically extracted

Acknowledgment

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