International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 35 No. 2 Jan. 2022, pp. 268-281
© 2022 Innovative Space of Scientific Research Journals
http://www.ijias.issr-journals.org/

Building height estimation from high resolution satellite images

***Abdelatif Rajji*[1], *Abdessamad Najine*[1], *Amina Wafik*[2], *and Amroumoussa Benmoussa*[1]**

[1]Sultan Moulay Slimane University, Department of Earth Science, Faculty of Science and Techniques, Beni Mellal, Morocco

[2]Cadi Ayyad University, Department of Earth Science, Faculty of Science Semlalia, Marrakech, Morocco

Copyright © 2022 ISSR Journals. This is an open access article distributed under the ***Creative Commons Attribution License***, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

ABSTRACT: This paper presents a new automated method for the detection and determination of building heights using their cast shadows. The approach consists in applying image processing using PCA and segmentation for the detection and recognition of buildings and their shadows. The height of the buildings is deduced by knowing the length of their shadow projected on the ground, the position (azimuth and zenith) of the sun and the sensor at the time of acquisition. These shadow analyses were carried out on a free satellite image from Google Earth. The results of the height calculations are used for the three-dimensional modelling of the buildings.
The 3D models produced can be used for strategic decisions in the professional field and for urban monitoring and surveillance, as well as for various research studies on the relationship between building heights and natural and man-made phenomena: energy consumption and land subsidence. Our method, which requires a good precision of the geometric characteristics of the proposed remotely sensed data, has outperformed the majority of existing research as an automated approach to exploiting the shadows of several buildings in a single satellite image and their 3D reconstruction.

KEYWORDS: Buildings, remote sensing, urban planning, shadow, Google Earth, high resolution satellite image.

1 INTRODUCTION

In order to prevent and manage land instabilities linked to the presence of underground cavities, the assessment of the vulnerability of buildings to collapse due to these movements is of great importance. The method used to undertake this study is based on the identification of potential or actual causes of collapse taking into account several factors, among them the geometric shape and height of buildings.

Before examining the relationship between building form and collapse risk, information on building geometry and height must be obtained.

The data sources mentioned above in previous work in this direction include several types of sensors of which DTM (Digital Terrain Model), DSM (Digital Surface Model) were the most used. H.Sportouche employed DTM and SAR sensor system parameters and provided a method for estimating building heights based on likelihood criterion optimisation [1]. By automated generation of 3D building models from DTM and DS, F.Rottensteiner presented his new method [2]. 3d building dimension extraction from high resolution stereo images captured by the SAR sensor was performed by Simonettto et al [3].

In recent years and with the development of the field of remote sensing, researchers have directed their research to the calculation of heights by processing satellite images. Ding et al. based on the use of the roof size provided by Google Earth and the image coordinates of the four corners of the rectangular building facade, presented a method to obtain the building height from a single ground image based on the intrinsic parameters of the camera [4].

Another group of researchers focused on the connection between the actual height of the building and the length of its shadow. Shettigara and Sumerling estimated average building heights using shadows detected in the SPOT panchromatic band and multispectral images [5].

Shao et al, started with the development of an automated approach for estimating the shadow length and corresponding building height for very tall buildings, especially above 15 m [6]. Comber presented a method that complements existing approaches for extracting building heights using the detected shadow, width, solar elevation and solar azimuth at distance [7]. Adding the satellite position The height of buildings was deduced by Massalabi et al based on their shadow length, the position (azimuth and zenith) of the sun and the sensor [8]. Izadi deduced a new system of building height determination based on sine-cosine and using shadow length, solar altitude, satellite altitude and the difference between solar and satellite azimuth [9].

Determining the height of the building by the length of their shadow requires a remote sensing analysis that mostly considers the shadow as noise because of the change in its size. Several researches have been developed to correct and exploit the shadow of buildings and correct their negative effects [10], [11]. LOSCOS et al evaluated shadows in a scene using global lighting algorithms [12]. Chen et al present a method for studying shadows and retrieving information from the area covered by shadows in very high resolution images [11]. Zhou et al. proposed three methods for applying an object-based classification procedure to solve shadow-related problems in remote sensing image analysis [14]. [14]. Shettigara et al and Hartel et al have made attempts to determine building heights by their shadows but using Spot panchromatic images [11], [15].

This paper describes a new automated extraction-based method applied to a high-resolution satellite image from (Google Earth) to simultaneously determine the heights of a group of buildings by their shadows. Shao et al, started with the development of an automated approach for estimating the shadow length and corresponding building height for very tall buildings, especially above 15 m [6]. Comber presented a method that completes Adding the satellite position The height of buildings was deduced by Massalabi et al based on their shadow length, the position (azimuth and zenith) of the sun and the sensor [8]. Izadi deduced a new system of building height determination based on sine-cosine and using shadow length, solar altitude, satellite altitude and the difference between solar and satellite azimuth [9].

Determining the height of the building by the length of their shadow requires a remote sensing analysis that mostly considers the shadow as noise because of the change in its size. Several researches have been developed to correct and exploit the shadow of buildings and correct their negative effects [10], [11]. LOSCOS et al evaluated shadows in a scene using global lighting algorithms [12]. Chen et al present a method for studying shadows and retrieving information from the area covered by shadows in very high resolution images [11]. Zhou et al. proposed three methods for applying an object-based classification procedure to solve shadow-related problems in remote sensing image analysis [14]. [14]. Shettigara et al and Hartel et al have made attempts to determine building heights by their shadows but using Spot panchromatic images [11], [15].

This paper describes a new automated extraction-based method applied to a high-resolution satellite image from Google Earth) to simultaneously determine the heights of a group of buildings by their shadows. The image processing first involves the detection and highlighting of buildings and their associated shadows. The height of the buildings is then automatically deduced by calculating the lengths of their projected shadows after applying a sequence of vector algorithms and existing data from the sun's position and the satellite sensors. Thus the 3D reconstruction of buildings will be practically easy by combining the deduced vector database and the vector file of the detected buildings.

2 METHODOLOGY

Figure 1 shows the general methodology of the study. It represents three main steps for the 3D reconstruction of buildings from the length of their shadows. This process starts with the detection and extraction of buildings and their shadows by applying PCA and segmentation algorithms on a high spatial resolution monoscopic satellite image from Google Earth. Then, the extracted data is vectorized in order to calculate the lengths of the building shadows. The next step is a phase of determining the principle of calculating building heights from their shadows based on fundamental trigonometric parameters. The last step is the most important component in this work, which is the integration of the processed database of building lengths into their vector database in order to model the site in 3D.

2.1 PROCESSING AND DETECTION OF SHADOWS AND BUILDINGS TO DETERMINE THE LENGTH OF CAST SHADOWS

Shadows occur when buildings totally or partially block the direct light projected by a light source (the sun). In practice, the detection of buildings and their shadows is a rather complex operation and has always been a source of difficulty, especially in urban areas, because of the modification of the dimensions of the shadows according to several parameters: the shape of the building, the orientation and the solar and satellite azimuth. A precise identification of buildings and their shadows is therefore a requirement for a correct calculation of building heights.

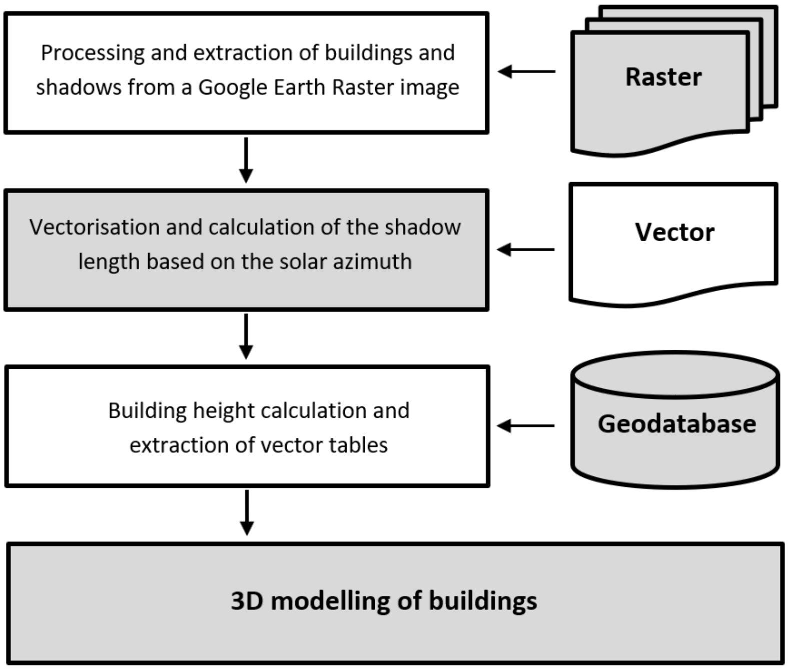

Fig. 1. Proposed system for 3d reconstruction of buildings

2.2 Criteria For Choosing The High Resolution Google Earth Image:

Google Earth is a free virtual globe, map and geographic information platform originally called Earth Viewer 3D created by Keyhole, Inc. It maps the Earth by overlaying images obtained from satellite imagery, aerial photography and the Geographic Information System (GIS) on a 3D globe.

To ensure correct and accurate detection of buildings and their projected shadows, the satellite image used for dimensional estimation of buildings must meet the following criteria:

- The shadow must be clear to avoid ambiguity;
- Good object distinction to differentiate buildings and shadows;
- The angle at which the satellite image is taken must be greater than 70°;
- The time of the image acquisition should be between 10 and 15 hours;
- Avoid images where the shadow of one building is cast on another;
- The dimensions of the selected image are less than 6x6 km.

Another condition is that the solar elevation and solar azimuth of each point in the same image must be very close or equal. The RGB satellite images provided by Google Earth generally meet this condition [20]. All spatial changes of the image source are reported on the platform.

After retrieving the solar azimuth from Google Earth. The solar elevation can be obtained by an open source software "Sunearthtool". It allows to investigate the solar position. Taking into account the time period of taking the image.

2.3 Extraction Of Buildings And Their Shadows

The first phase of the proposed methodology consists in extracting buildings and their projected shadows, in order to construct the variables "building" / " no-building" and "shadow" / "no-shadow". These variables will allow us to disaggregate the spatial information of the image, and thus to delimit our areas of interest.

To extract the buildings and shadows, we use two different approaches; supervised classification of the 3 PCA colour composite of the satellite image and object-oriented classification (Figure 2).

In order to integrate the data into the local reference system (Lambert Maroc Z1 projected coordinate system), geometric corrections and radiometric processing were performed on the different data. In the same context, a "majority" filter was applied in order to clean up the variability of isolated pixels.

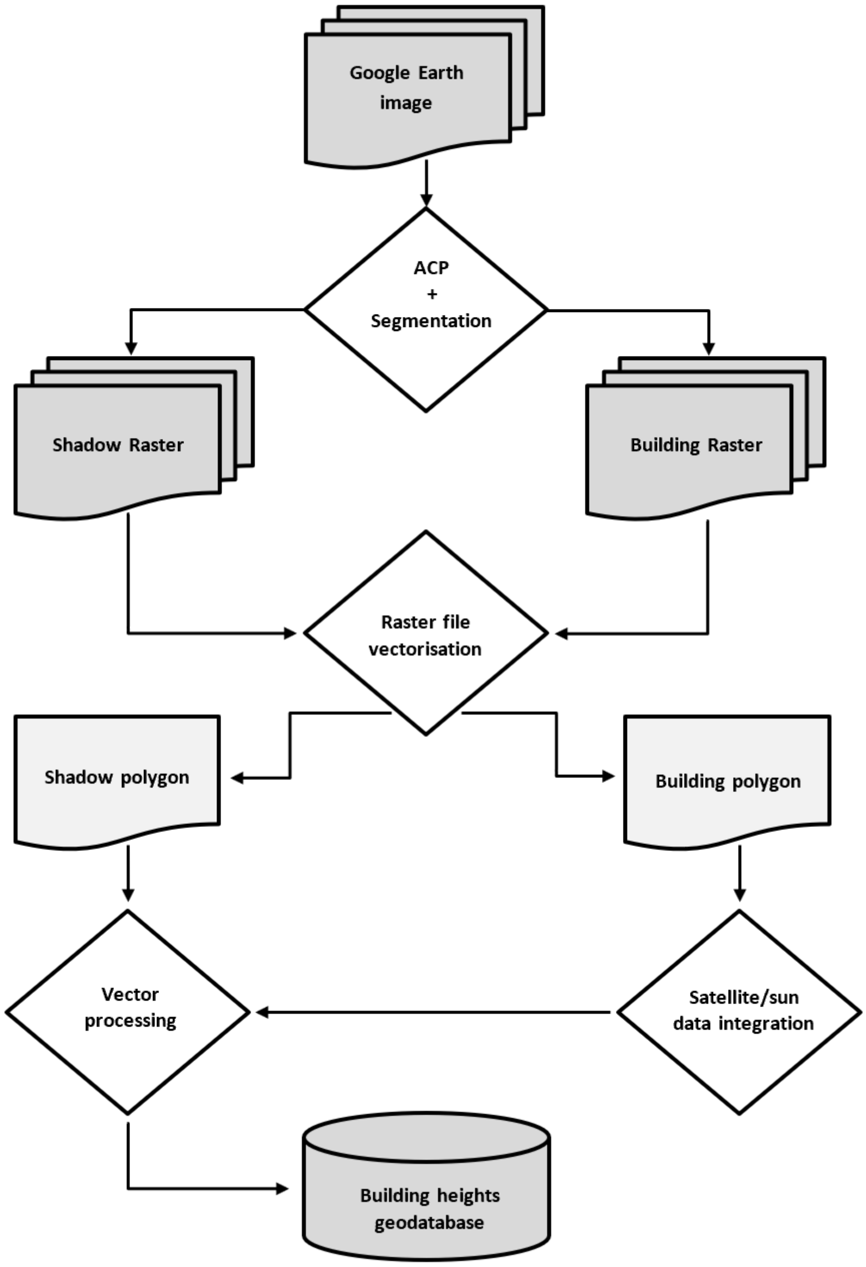

Fig. 2. The flowchart for extracting shadows and buildings and calculating height

2.3.1 SHADOW DETECTION AND EXTRACTION

Shadows have always been a source of problems in the processing of high resolution images in urban areas, due to the concealment of the information they produce. However, the proposed methodology takes advantage of their presence for the automatic estimation of building heights [21].

To extract the shadows from the image, we first performed a principal component (PC) analysis of the three RGB bands of the image. Then, using the first PC1 component, which carries 97.7% of the total variance of the data, we identified the intensity value that most effectively isolates shadows by means of a threshold. To do this, pixels belonging to areas with shadows on the one hand, and pixels without shadows on the other hand, are selected. The values of both groups are used to draw their histograms, which are used to determine the intensity value by which the shadows will be isolated (Figure 3).

2.3.2 Detection And Extraction Of Buildings

For the identification of buildings, we have chosen a classification based on the object-oriented approach. This approach is widely used for the processing of high spatial resolution satellite images.

The adopted treatment process generally consists of 3 steps:

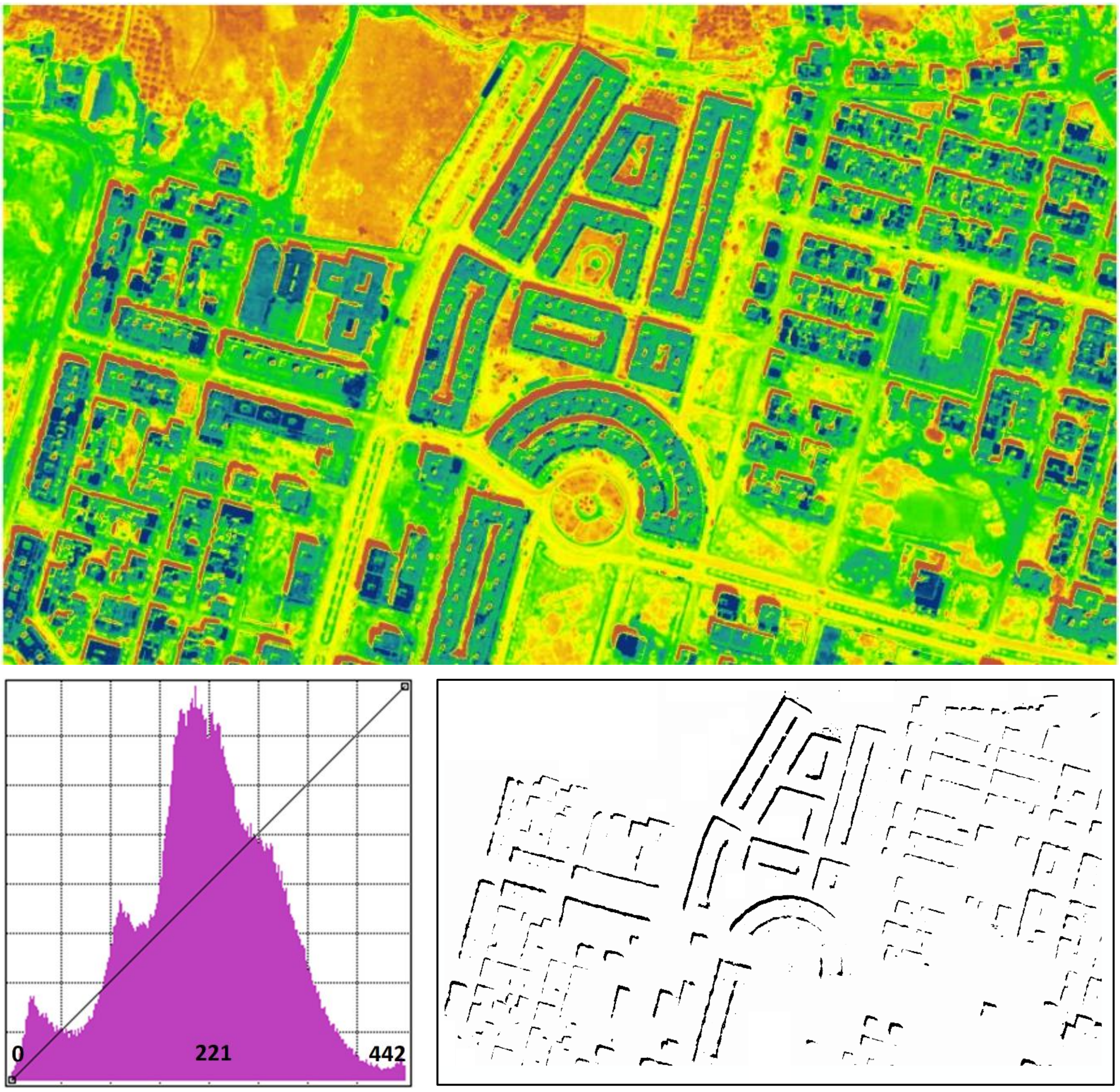

Fig. 3. a= PCA1; b = Histograms of shaded and unshaded pixels and threshold value used; c= shade

- Segmentation: Image segmentation consists of merging pixels into homogeneous regions, These regions are then considered as "objects" independent of each other. These regions are then considered as independent "objects". This allows the implementation of a classification based on objects instead of individual pixels [21]. The segmentation algorithm used is multi-resolution. It is a region-based growth technique that starts by considering objects of a pixel. The principle consists of grouping pixels according to their attributes without taking into account their location within the image. This makes it possible to construct classes of pixels; adjacent pixels belonging to the same class then form regions.
- Characterisation of regions: this stage consists of determining the recognition rules by researching their spectral, topological and contextual properties. Thus, in a first step, we can identify the buildings by their colour and size; in a second step, we can extract the buildings by the morphological attributes of the segmented objects. This is related to the two main

tasks required to understand the images [24]. The colour criterion would allow us to retrieve the different surfaces of a roof, which may vary in colour depending on the sunlight. The size criterion would allow us to identify buildings with different surfaces.

- Classification: Once the segmentation levels have been determined, the classification is based on the feature regions previously defined for the different classes. These regions are developed on the basis of selected test areas (nearest neighbour classifier) or created by fuzzy logic functions. In the first case, objects are automatically assigned to a class and in the second case, the user himself presents the characteristics and threshold values of a class membership.
- For the creation of the knowledge base, the nearest neighbour classification (Edit Standard NN) is used. It allows to use the selection of example segments that several features in the classification process can include. Initially, the classes and features to be used for each class are specified. Subsequently, sample objects for the individual classes are defined.

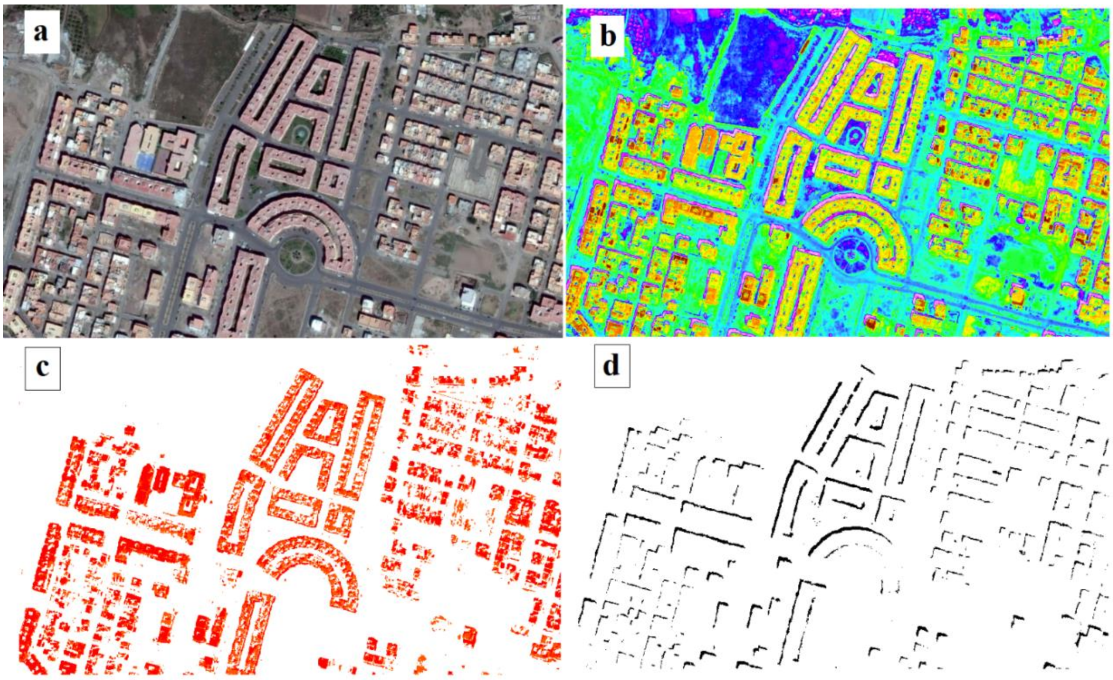

Fig. 4. Extraction process of buildings and their shadows: a: High spatial resolution satellite image taken by Google Earth, b: Processed and classified image, c: Raster buildings, d: Raster shadows

Thus, the segmented and classified satellite image obtained allows to distinguish accurately buildings and other unwanted elements (vegetation, roads, soil and shadows). Figure 4 shows the results of image processing by segmentation.

2.4 VECTORISATION OF SHADOW AND BUILDING IMAGES

The objective of vectorising the building and shadow raster images extracted from the resulting high resolution satellite image (VHRS) is to create a file in vector format. The vector file can then be interpreted by GIS software and perform spatial processing.

There are different ways to convert a file from raster to vector format. The first is to manually draw polygons on top of the Raster image and assign a category to each one (building, shadow...). The second technique is automatic vectorisation using the "Raster to Polygon" algorithm of the Arcgis software, which is able to distinguish areas according to their attribute values. This method allows the creation of a shapefile and the individualisation of each building or shadow element in the image into a polygon which contains a definition of its geometric aspect in the form of a series of points delimiting the limits of each element (figure 5).

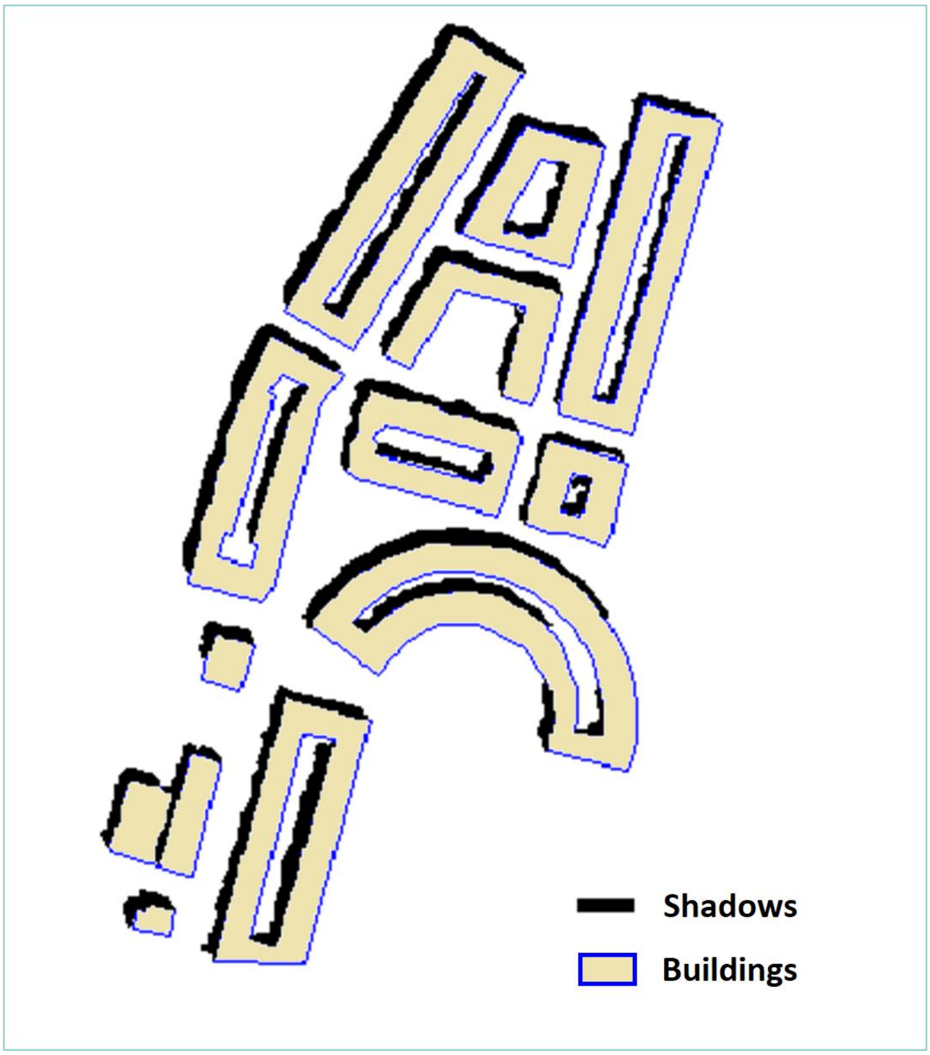

Fig. 5. Vectorisation results of detected buildings and their shadows

2.5 Calculation Of The Theoretical Shadow Length Of A Building

After the identification and precise vectorisation of building and shadow areas. The length of the shadow is calculated using the azimuth angle of the sun and the building and shadow polygons.

Based on the Arcgis software, in each polygon that represents a building a centroid point is automatically made using the tool "Calculate geometry /Coordinate of Centroide" in the table of the "Building" Shapefile database. (X1, Y1) is the starting point of a line oriented in the direction of the sun's azimuth and which ends with a second point having coordinates (X2, Y2) calculated according to the following formula:

$$X2 = X1 + \sqrt{S} + n, Y2 = Y1 + \sqrt{S} + n \ (1)$$

$$n = L\ max + 1, dont\ Lmax = \frac{\mathrm{Hmax}}{\mathrm{tn\ (h)}}$$

Where S is the building area, Lmax is the maximum shadow length in the site, Hmax is the maximum height of the buildings and h is the height of the sun (Figure 6).

After inserting the shadow polygons, the shadow length of each building is calculated by the intersection of the previously created lines and the shadow polygons using the "itersect" algorithm of the "Overlay" tool proposed by Arcgis. As a result of this step, a shapefile of "shadow_length" polylines is obtained, which represent the lengths of the shadows associated with the buildings. Finally, we associate the table of calculated shadow lengths with the table of buildings. This will allow us to have in Output a single shapefile of buildings including in its attribute table the shadow lengths for each building unit. By using the field calculator tool we can then automatically calculate the building heights through the application of the formulas detailed in the next chapter.

3 Principe For Building Height Estimation From Shadows

The determination of the height of buildings from the length of their cast shadow is based on these basic parameters:

- **The sun's elevation:** the position of the sun at the time of imaging is directly related to the length of the cast shadow.
- **Sun azimuth:** determines the orientation of the sides of the shadow.
- **Satellite azimuth:** The position of the sensor determines the building and shadow components seen by the sensor. If the sensor is in a position perpendicular to the earth's surface, the components captured by the sensor will have the correct dimensions and geometric shapes. However, if the sensor forms an angle α with the perpendicular to the earth's surface, corrections will be required.

The parameters listed above are retrieved directly or indirectly from the satellite image (VHRS).

3.1 Solar Declination

Solar declination is defined as the angle between the sun's rays and the Earth's equatorial plane. Several approaches have been developed in the form of regular and high precision algorithms [18-19] for the calculation of solar declination. Coper and Bourges [16-17] calculated the solar declination based on regular algorithms. According to C.X. Du [23] the error of the regular algorithms is greater than 0.02° and that of the high precision algorithms is equal or less than 0.01°. However the application of the latter is very complicated, they are often used for modelling solar energy automation systems. To easily calculate the solar declination of a day n of the year at noon, we used the algorithm proposed by Bourges [17] as shown in equations (3) and (4).

$$\delta = 0.3723 + 23.2567sin(w) + 0.1149sin(2w) - 0.1712sin(3w) - 0.7580cos(w) + 0.3656cos(2w) + 0.0201cos(3w) \quad (3)$$

$$Where\ W = \frac{360\ (n - n0 - 0.05)}{365.2422} \quad (4)$$

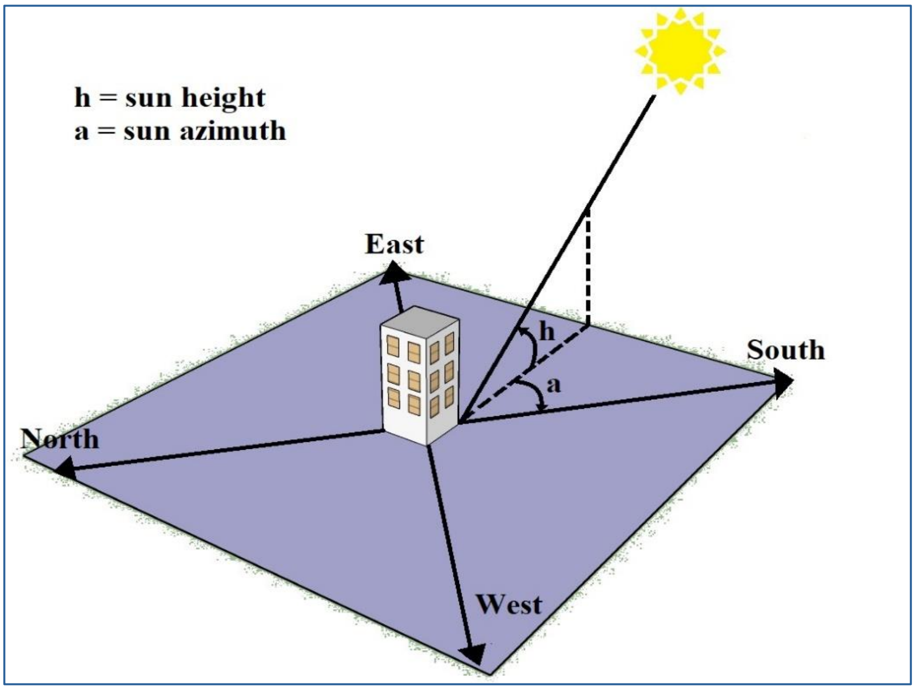

Fig. 6. Solar basic parameters

3.2 THE SOLAR HOUR ANGLE:

To calculate the solar hour angle one must first identify the relationships between the different solar parameters such as solar elevation, solar azimuth, solar declination and latitude. These relationships are expressed in equations (5), (6) and (7):

$$sin(hs) = sin(\phi)sin(\delta) + cos(\varphi)cos(\delta)\cos(\Omega) \quad (5)$$

$$ta\,n(\alpha s) = cos(\delta)sin(\Omega)cos(hs) \ (6)$$

$$cos(\alpha s) = \frac{sin(hs)sin(\phi) - sin(\delta)}{cos(hs)(\phi)} \ (7)$$

Where hs: solar elevation; αs: solar azimuth; ϕ: latitude; δ: solar declination; Ω: solar hour angle

The solar hour angle is thus calculated by the following relationship:

$$\Omega = \begin{cases} \min\left(arccos\left(\frac{-b+\sqrt{b^2-4ac}}{2a}\right) arccos\left(\frac{-b-\sqrt{b^2-4ac}}{2a}\right)\right) in\ the\ morning \\ -\min\left(arccos\left(\frac{-b+\sqrt{b^2-4ac}}{2a}\right) arccos\left(\frac{-b-\sqrt{b^2-4ac}}{2a}\right)\right) in\ the\ afternoon \end{cases} \quad (8)$$

Where :

$$a = \tan^2\alpha_s \sin^2\phi + 1 \ (9)$$

$$b = -\sin 2\,\phi \tan\delta\ \tan^2\alpha_s \ (10)$$

$$\mathrm{c} = \tan^2\alpha_s \cos^2\phi\ \tan^2\delta - 1 \ (11)$$

3.3 SOLAR ELEVATION

The solar elevation is defined by equation (12) and is calculated based on equation (5) after identifying the other solar parameters:

$$Hs = Arcsin\ (sin(\phi)sin(\delta) + cos(\varphi)cos(\delta)\cos\ (\Omega)) \ (12)$$

3.4 PRINCIPE FOR BUILDING HEIGHT CALCULATIONS

After determining the solar elevation and the shadow length, it can now inform about the building height. In this article the process is done automatically in the attribute table of the shapefile "Building" using the algorithms "calculate geometry" and "field calculator" proposed by Arcgis.

The principle of this section is based on the use of the shadow lengths of each building to estimate its height. However, the use of the shadow to estimate the height of the buildings requires in addition the knowledge of the following parameters: the solar elevation, the solar azimuth and the position of the satellite at the time of the image acquisition.

If the sensor is in a vertical position and perpendicular to the earth's surface, then only the position of the sun is taken into consideration. The position of the satellite sensor is negligible.

(Figure 6) shows the triangular relationship between the solar elevation angle, the height of the building and the length of the shadow. In (Figure 6), hs is the sun's elevation angle, αs is the solar azimuth angle, H is the height of a building, and S is the length of the building's shadow:

$$\begin{gathered} tan(hs) = \frac{H}{s} \\ so\ H = s.\tan\ (hs) \end{gathered} \quad (13)$$

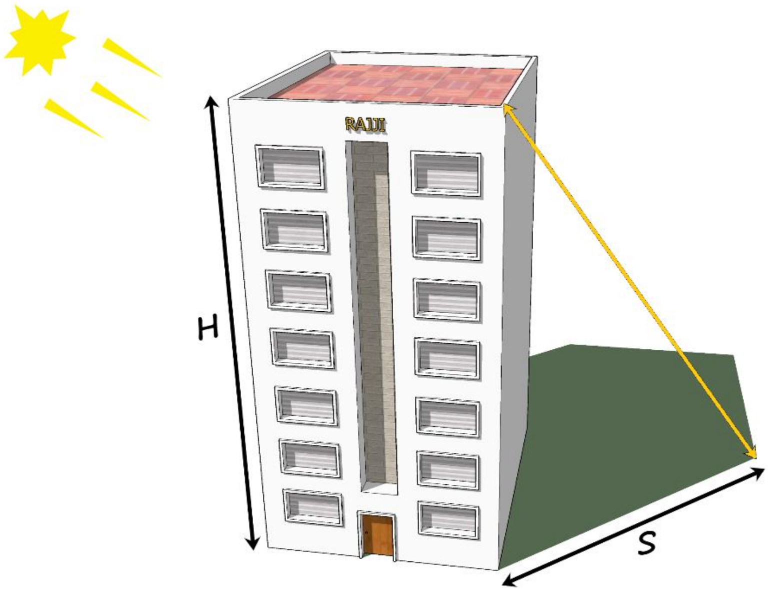

Fig. 7. Spatial relationship between the building and its shadow

In the case where the satellite is positioned with a view not perpendicular to the earth's surface at the time of imaging, equation (15) proposed by [shetigara et al 1998] is used, this equation takes into consideration the azimuth and zenith parameters of the satellite sensor [11]:

$$H = \frac{s}{\{[\cos(\phi sun + 90° - \phi wall)\,/\tan\ (\theta sun)\,] - [\cos(\phi sun + 90° - \phi wall)\,/\tan\ (\theta sat)\,]\}} \quad (14)$$

Where:

- H: the height of the building;
- s: measured length of the shadow seen in the wall normal direction
- Φ Sun: Azimuth of the sun; θ sun: sun zenith
- Φ Sat: Azimuth of satellite; θ sat: satellite zenith
- Φ Wall + 90°: Normal building wall

3.5 D Building Modelling

Our new proposed approach is mainly aimed at improving the techniques of 3D modelling and presentation of the detected buildings by proposing easy-to-use tools on GIS or CAD platforms.

The third level of analysis consists of the application of an algorithm that consists of a series of the aforementioned equations for calculating building heights using the necessary data to deduce the height of each building in an automated manner and the presentation of these buildings in 3D. The automatic reconstruction of these buildings in 3D is considered the most important component of this paper.

Based on the estimated heights, the buildings will be presented as a 3D model using a GIS information system that transforms the height data into a representative model.

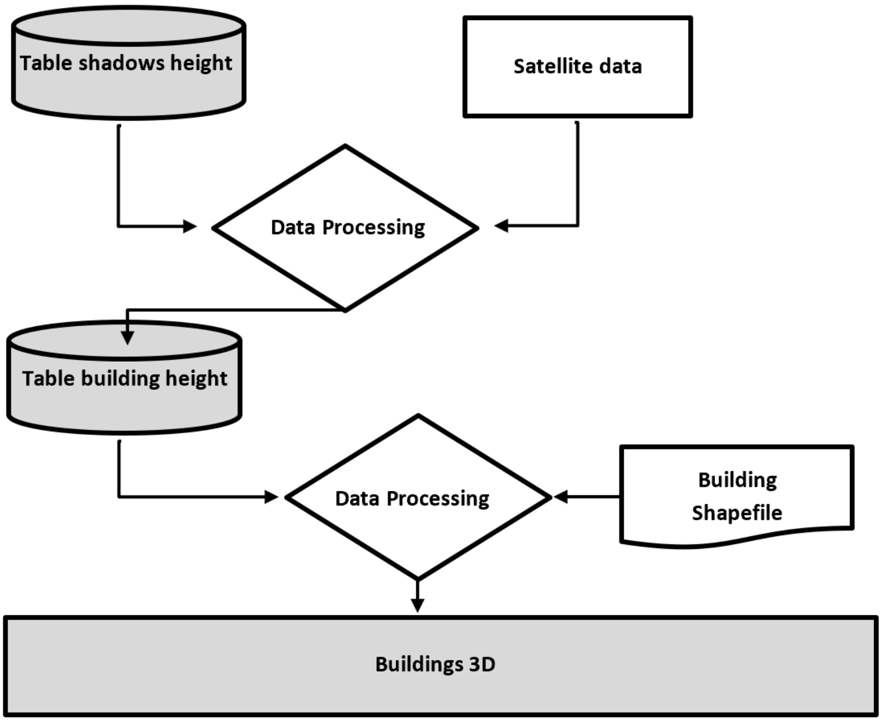

Fig. 8. 3d building modelling process

4 Results And Discussion

The results of this work are of two kinds: those related to the development of the methods of extraction of buildings and shadows on the one hand, and on the other hand their application to the calculation of the heights of these buildings and to carry out the 3D modelling. We illustrate the detection results of the proposed approach in Chapter 2.

The detection and extraction of buildings and their associated shadows by processing a Google Earth satellite image through PCA and segmentation allows a good dimensional characterisation. This characterisation was used to calculate the length of the shadow and then to estimate the heights of these buildings and their 3D reconstruction.

The high spatial resolution satellite image was first tested and ensured that it presents at least a clear and sharp presence of shadows and buildings to allow an accurate estimation of the length of the shadows. The original image in figure (8-a) is processed to give the areas of shadows and buildings 8-b.

In high spatial resolution satellite images, segmentation is of great importance for image analysis and interpretation. An approach based on PCA and object-oriented segmentation analysis has proven to be effective for the detection of buildings and shadows.

To evaluate the performance and efficiency of the system proposed in this paper, Table 1 presents the results of the height calculation of 14 buildings using our approach and two other existing methods [1] and [5]. 14 shadow lengths were calculated automatically and at the same time. The analysis of the difference between the calculated heights and those measured in the field varies between 17cm and 78cm. While the application of the approaches proposed by [1] and [5] shows deviations that vary between (45 cm and 130 cm) and (112 and 170 cm) respectively. It can be clearly seen that the proposed method has a better accuracy compared to the main existing approaches.

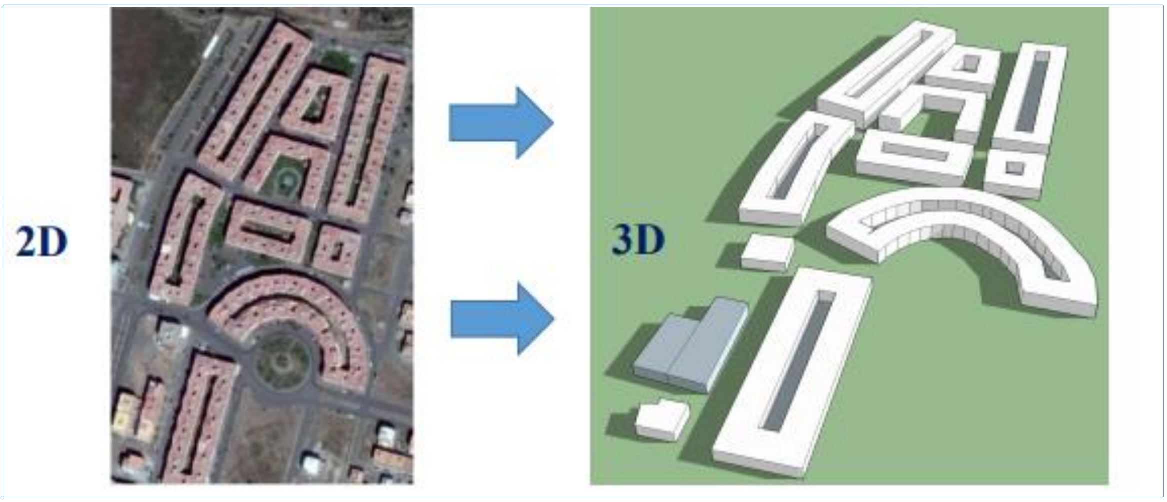

Fig. 9. a: satellite image selected and validated to perform the extraction of shadows and buildings b: 3D reconstruction results of the buildings

Table 1. Comparison table of the height measurements of the buildings studied

Building	Height (m)	Height (m) [1]	Height (m) [5]	Height (m) [our approach]
Building 1	15.23	15.90	16.55	15.4
Building 2	14.18	15.11	15.87	14.41
Building 3	14.86	14.41	15.98	15.05
Building 4	11.45	10.90	12.62	12.06
Building 5	11.63	12.21	13.04	12.03
Building 6	14.31	15.03	15.64	15.09
Building 7	15.10	15.74	13.93	15.6
Building 8	15.25	15.90	16.95	14.86
Building 9	18.85	20.00	20.08	18.24
Building 10	13.86	14.66	15.47	14.17
Building 11	14.97	15.5	16.54	15.71
Building 12	13.88	14.39	15.18	14.1
Building 13	19.74	21.04	21.29	20.11
Building 14	11.87	12.40	13.26	12.24

The results of the proposed approach present evidence of a highly developed and robust approach and that the detected buildings and their shadows are quite convincing and representative given the good distinction between buildings and shadows. As shown in the final results (Figure 8.b), the buildings are successfully represented in three dimensions.

5 Conclusion

The main contribution of this paper is that we propose a simple but automated method to simultaneously and accurately estimate the heights of several buildings from a simple monoscopic satellite image. This study presents a method for calculating the height of buildings based on the processing and information acquisition tools provided by Google Earth. For the evaluation of the accuracy of the method, the calculated and measured heights of 14 buildings are compared.

The final model obtained went through the recovery of satellite images, the detection of shadows and buildings and the estimation of the length of the shadow, the recovery of the necessary information using the Arcgis tool for the calculation of heights and the three-dimensional presentation of the buildings.

It is concluded that the method has three advantages: an original, simple and automated method of calculating the heights of several buildings in a single image; secondly, a greater precision of the results obtained. And finally the availability of the most important information: the sun and satellite parameters and the google Earth satellite image which can be used with full freedom. This method gives a tool and a source available free of charge to acquire the information of size of existing buildings to reuse it for practical purposes of civil, monitoring or surveillance of many levels of regulations related to the allowed height of buildings and structures, as well as for studies to visualize the impacts of building heights on some phenomena without moving to the field and manually calculate the various sizes of buildings to be studied.

ACKNOWLEDGMENT

We would like to thank the entire team of the GEOPLATINUM and HYDROSEPT engineering office for accompanying us during the execution of this work.

REFERENCES

[1] H. Sportouche, F. Tupin, L. Denise, Building detection by fusion of optical and SAR features in metric resolution data, in: Geoscience and Remote Sensing Symposium, 2009, IEEE International, IGARSS 2009. IEEE, 2009, 4: IV-769–IV-772, 2016.

[2] F. Rottensteiner, C. Briese, A new method for building extraction in urban areas from high-resolution LIDAR data, International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences 34 (3/A) (2002) 295–301.

[3] E. Simonetto, H. Oriot, R. Garello, Rectangular building extraction from stereoscopic airborne radar images, IEEE Trans. Geosci. Remote Sens. 43 (10) (2005) 2386–2395. Pour estimer la hauteur des bâtiments à toit plat Wegner a basé son travail sur l'utilisation une paire d'images InSAR (radar à synthèse d'ouverture) interférométrique et un orthophoto.

[4] F. Ding, Interactive 3d city modeling using google earth and ground images, Image and Graphics, in: Fourth International Conference on ICIG 2007, IEEE, 2007, pp. 849–854.

[5] SHETTIGARA V.K. and SUMERLING G. M., 1998. Height determination of extended objects using shadows in spot Images. Photogrammetric Engineering & Remote Sensing, 64: 35-44.

[6] Y. Shao, G.N. Taff, S.J. Walsh, Shadow detection and building-height estimation using IKONOS data, Int. J. Remote Sens. 32 (22) (2011) 6929–6944.

[7] A. Comber, M. Umezaki, R. Zhou, Y.M. Ding, Y. Li, H. Fu, H.W. Jiang, A. Tewkesbury, Using shadows in high-resolution imagery to determine building height, Remote Sens. Lett. 3 (7) (2012) 551–556.

[8] D.C. Massalabi, G.B. Bénié, E. Beaudry, Detecting information under and from shadow in panchromatic Ikonos images of the city of Sherbrooke, in: Geoscience and Remote Sensing Symposium, Proceedings IGARSS 2004, IEEE International, 3: 2000–2003, 2004.

[9] M. Izadi, P. Saeedi, Three-dimensional polygonal building model estimation from single satellite images, IEEE Trans. Geosci. Remote Sens. 50 (6) (2012) 2254–2272.

[10] Nakajima Takashi, Tao, G., Yasuoka, Y., (2002), simulated recovery of information in shadow areas on Ikonos image by combing ALS data. Gis develppement proceedings www.gisdevelopment.net/aars/acrs/2002/vhr/index.shtml (mai 2003).

[11] Shettigara V.K. and Sumerling G. M. (1998), Height determination of extended objects using shadows in spot Images, Photogrammetric Engineering & Remote Sensing, Vol. 64. N°1, pp. 35-44.

[12] , [LOSCOS et al 98] Loscos C., Drettakis G., Robert L., Interactive Modification of Real and Virtual Lights for Augmented Reality, Technical Sketch, SIGGRAPH'98, Orlando (FL), juillet 1998.

[13] CHEN, Y., WEN, D., JING, L. and SHI, P., 2007. Shadow information recovery in urban areas from very high resolution satellite imagery. International Journal of Remote Sensing, 28: 3249–3254.

[14] ZHOU, W., HUANG, G., TROY, A. and CADENASSO, M.L., 2009. Object-based land cover classification of shaded areas in high spatial resolution imagery of urban areas: A comparison study. Remote Sensing of Environment 113: 1769– 1777.

[15] Hartel. Ph et F. Cheng (1995), Délimiter la hauteur des bâtiments dans une ville de l'ombre sur une image SPOT panchromatique: Partie 2: Test d'une image complète ville. Journal international de télédétection. Vol 16, N ° 15, pp 2829-2842.

[16] P.I. Cooper, The absorption of radiation in solar stills, Solar Energy 12 (3) (1969) 333–346.

[17] B. Bourges, Improvement in solar declination computation, Solar Energy 35 (4) (1985) 367–369. [18] R. Walraven, Calculating the position of the sun, Solar Energy 20 (5) (1978) 393–397.

[18] I. Reda, A. Andreas, Solar position algorithm for solar radiation applications, Solar Energy 76 (5) (2004) 577–589.

[19] F. Qi, Y.X. Wang, A new calculation method for shape coefficient of residential building using Google Earth, Energy Build. 76 (2014) 72–80.

[20] Madhavan, B.B., Tachibana, K., Sasagawa, T., Okada, H., Shimozuma, Y., 2004. Automatic Extraction of Shadow Regions in High-resolution Ads40p. En: XX ISPRS Congress, Istambul.
[21] WENG Q., 2010, Remote sensing and GIS integration Theories, methods and application,.
[22] Mc Graw Hill: 397 p.
[23] C.X. Du, P. Wang, C.F. Ma, A high accuracy algorithm for the calculation of solar position, Energy Eng. 4 (2) (2010) 1–44.
[24] Matsuyama T., Hwang V.SS. (1990) Experimental Results and Performance Evaluation. In: SIGMA. Advances in Computer Vision and Machine Intelligence. Springer, Boston.