ASSESSMENT OF PRECISION IN DEMS GENERATED USING AUTOMATIC CORRELATION

ENRIQUE PEREZ-MARTÍN (enrique.perez@upm.es),
TOMAS RAMÓN HERRERO-TEJEDOR (tomas.herrero.tejedor@upm.es),
MIGUEL ÁNGEL GÓMEZ-ELVIRA GONZÁLEZ (miguelangel.gomezelvira@upm.es)
Universidad Politécnica de Madrid

JOSÉ IGNACIO ROJAS-SOLA (jirojas@ujaen.es)
Universidad de Jaén

Abstract

This study shows an experiment in the generation of DEMs (Digital Elevation Models) from automatic correlation algorithms from a Digital Photogrammetry Workstation (DPW), as well as an evaluation of the precision obtained based on the data available and the methodology used. This study is applied to "Calderico" hill in Consuegra (Toledo, Spain), site of the famous windmills found in Don Quixote. Here there are three different zones, characterized mainly by different slopes. After creating the different DEMs for each slope, we carry out a statistical analysis which will help us to make a quantitative assessment of both the models and the orthoimages which we obtain. The results indicate a greater disparity in the accuracy of the equivalent points identified in each DEM for the areas with steeper slopes, and less disparity in areas with more shallow slopes. In addition, a high level of accuracy was found in points controlled using differential GPS.

KEYWORDS: Digital Photogrammetry, DEM, Accuracy, Stereoscopic, Correlation, Slope Variability

INTRODUCTION

Aimé Laussedat, considered as the founder of photogrammetry, developed in 1849 photogrammetic methods and apparatus, using photos of terrain to map the earth's surface (Li, 2005).

The evolution of photogrammetry cannot be separated from the evolution of its instruments and equipment. There has been a progression from mechanical optical equipment, through analogical equipment, to the digital world, in which digital photogrammetry stations are replacing older ones (Molina, 1999). The advantages of this evolution have been the substitution of the optical, mechanical and electronic components for software, and the possibility of using automatic processes in the identification of homologous points in consecutive images, which will lead to the generation of digital models using the application of image correlation techniques (Ackermann, 1996).

In recent years, the use of digital cartography as a basic document in land ordering and planning has meant that geographical databases must be updated, and that other digital applications should be used in order to give swift and effective responses. In this context, the generation and application of DEM gives a three-dimensional representation of the surface under study. Therefore, in general, digital photography presents a series of advantages over other systems. (Heipke, 1999; Saleh, 1996)

In the field of photogrammetry the term "*Matching*" is used to express the correlation between different sets of data, so enabling the study of internal orientation, relative orientation, aerotriangulation, absolute orientation, the generation of digital elevation models, etc.

This article attempts a photogrammetric analysis of an area home to the famous windmills of Don Quixote. Different sources are used to generate DEMs and verify the quality of each one. The area under study is "Cerro Calderico", near the town of Consuegra in the province of Toledo (Spain).

BACKGROUND

A DEM is defined as "a digital representation of the continuous variation of terrain over space" (Burrough and McDonnell, 1998). Since the mid 1990s the use of the LIDAR (LIight Detection And Ranging) system has offered a high level of accuracy and rapid data collection at a low cost, because it is possible to capture points in atmospheric conditions in which conventional aerial photography cannot, such as reduced visibility or night acquisition (Fowler, 2001). DEMs are the initial data used in GIS analyses, as terrain models, mapping or hydrological or erosion maps, etc.

The definition of the Earth's surface using DEM is necessary for land planning and management in fields such as civil engineering, agricultural engineering, environmental actions, archaeology, civil protection and telecommunications (Kaufmann and Sulzer, 1997; Konecny, 2000).

Obtaining a DEM is a process of automatic employment of the stereoscopic model. It is based on the automatic identification of homologous points in both photos, so that when the orientation parameters are known, the Z coordinate can be calculated digitally on the terrain. The accuracy of DEMs depends on several factors, including the horizontal resolution and vertical precision at which the elevation data are represented, and the source of the elevation data. There are studies which propose methods for improving the aspects relating to elevations in automatic photogrammetric processes (Felicísimo et al., 2004).

For the obtaining of the MDE it is suitable to digitize manually the breaklines and structure as a previous phase, since it helps to the automatic process of identification of aerial photographs.

The next stage is the automatic process, in which using ABM (Area Based Matching) or FBM (Feature Based Matching) techniques, a detail of the original image is selected and is identified in a homologous photograph once the coordinates have been obtained in the photogrammetric system. Using co-linear equations, the beams are intercepted and finally Z is obtained on the terrain. Table I shows the image identification methods.

TABLE I. Image identification methods

Matching method	*Similarity measure*	*Matching entities*
Area Based Matching ABM	LSM Correlation	pixel window/ greyscale
Feature Based Matching FBM	Cost function	Entities: Points /axes /areas
Symbolic Based Matching	Cost function	Topological properties

The precision of the DEM is represented by “spatial resolution” and by “height precision” (Tankagi, 1998). This article analyses the quality of precision of a DEM in different ambit. It is necessary to relate the quality of the DEM with the optimization of the project to be carried out, bearing in mind that digital photogrammetry, using satellite images or lidar can obtain levels of precision close to 1 cm and even smaller; therefore, we should carry out a prior study of the desired cartography, as well as of the quality of the DEM, taking into account the spatial resolution, data collection and the time spent. Examples for global DTM accuracy measures can be found in Li (1993), and there are also studies of methods to estimate the accuracy at a high level of detail, at best for every interpolated DEM point (Kraus, 2006).

Orthophotography is the final product of digital photogrammetry, and it is obtained by following a series of necessary steps, taking the elevation of each point from the DEM (Krupnik, 2003).

Some previous studies analyse the quality of the DEM by comparing a model created by contour lines (topographic map) with another model taken from digital images and the correlation model (Hohle and Potuckova, 2005). Toutin (2004), in a project analyzing the natural resources of Canada, assesses the precision of a

DEM created from Ikonos stereo digital images compared with a lidar elevation data model, in different types of terrain (mountain, town, lakes, flat plains, etc.). Based on this type of analysis, this paper studies a unique area characterized by the presence of the Don Quixote's famous windmills, where there are three different ambits: a flat area, an urban area and a hilly area; the quality of the DEM will be tested in each area.

The correlation stereo explains the process of automatic identification of homologous points in digital images (Ackermann, 1984). There are studies which relate the error in the process of automatic correlation with certain areas, (Heipke, 1995; Gooch and Chandler, 2001), very monotonous surfaces with similar land cover and areas with steep slopes.

Below we describe two typical methods of direct computational calculation. Given that no one method is 100% accurate, two or more methods are used together in order to compare results and reduce errors in the definition of homologous points.

Covariance Function Method

The relationship between images can be expressed using covariance equations. The values of the covariance function of two groups of data are calculated, and the higher covariance is taken as the correlation position.

The value x_i represents the digital value in position i in the first group of data, and y_i represents the second group of data. The average values of each group are:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (1)$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \qquad (2)$$

The covariance σ_{xy} of the two groups is:

$$\sigma_{xy} = \frac{1}{n}\sum_{i=1}^{n}\left(x_i y_i - \bar{x}\bar{y}\right) \qquad (3)$$

Correlation Coefficient Method

The correlation between two groups of data can be represented using a coefficient ρ or using its square c^2.

$$c = \frac{\sigma_{xy}}{\sqrt{\sigma_{xx}\sigma_{yy}}} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left(x_{ij}-\bar{x}\right)\left(y_{ij}-\bar{y}\right)}{\sqrt{\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\left(x_{ij}-\bar{x}\right)^2\right)\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\left(y_{ij}-\bar{y}\right)^2\right)}} \tag{4}$$

The value of the correlation coefficient is between +1 and -1. A value of 1 shows the strongest correlation between two objects, and a value of 0 shows that the two objects do not correspond to each other.

LOCATION AND STUDY AREA

Consuegra is located in the province of Toledo (Castilla-La Mancha, Spain), on nº 712 – Los Carrascales, of the National Topographical Map. The area under study is located in Cerro Calderico (Fig. 1), to the south of Consuegra (39º26' – 39º27' latitude north and 3º35' – 3º37' longitude west) and has an area of around 504 hectares (10.35 % of developed and 89.65 % of undeveloped rural land). The altitude varies between 700 and 830 m.

FIG. 1. Location map and area of study.
The map shows the urban area, "Calderico" hill (more than 9º slope) and the flat area (0 – 9º slope)

METHODOLOGY

The following methodology was used to obtain the DEMs of the points found using automatic correlation and the model of DEMs derived from photogrammetric surface points manually collected in a DPW:

Photogrammetric flight. Model taken from a photogrammetric flight made in 2005. Taking the delimitation of the area under study on a digital map, a photogrammetric flight was made with a scale of 1/8.000 with a longitudinal coverage of 60 %, using a RMK TOP 15 camera with a wide angle lens with a 6-inch focal length. The film used was Kodak high definition aerocolor 2444, with an emulsion capable of recording perceptible details between 2 and 3 microns. The final result is four stereo pairs to cover the test area.

Scanning of aerial photographs. Using a Digital Scanning Workstation (Leica DSW700), the negatives of the photographs were scanned, with the following characteristics: resolution 1,200 ppp (21 microns), 24 bit color, image size ~ 11,000 x 11,000 pixels (.TIF file, 350 MB).

Data Compilation

Taking as a basis studies comparing DEM (Büyüksalih et al., 2004), the zoning of the area under study was carried out as follows: an urban area, limited by the end of the built-up area, a flat area, with a slope from 0 – 9º, and hilly rural terrain, with slopes in excess of 9º. The source data was taken from four information sources:

SOURCE 1 (MODEL 1). Reference model. A base DEM derived from photogrammetric surface points manually collected in a DPW. Using a stereoscopic model, the points were digitized manually in each stereo pair, obtaining 1564 points in the 4 stereo pairs selected which cover the test area (Fig. 2a). Using stereoscopic vision, the operator captured the points on the terrain. A 40 meter grid was used in the flat area, owing to lack of variation in the slope. In the urban area, points were captured at the intersections of the streets, and in the hilly area (slopes of more than 9º) sufficient points were captured in order to produce a detailed representation of the terrain.

The photogrammetric process was carried out with a high precision PhoTopol DPW, with both internal and external orientation. The external orientation was done with a simultaneous adjustment of beams using as terrain information a series of control points. The software was developed by Photopol Atlas (DPW) Software Ltd. Prague, Czech Republic.

The DEM was generated from the points obtained by manual digitalization, and the result was the surface shown in figure 2b.

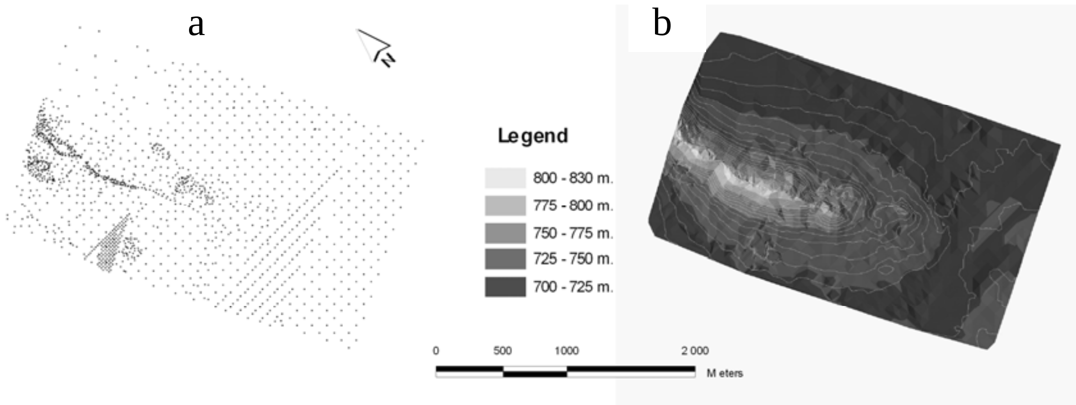

FIG. 2a & 2b. Points obtained using photogrammetric restitution and DEMs. The figure shows the grid created in the flat area and the density of points in the sloping area in order to fit the DEM better.

SOURCE 2 (MODEL 2). A DEM developed using a mathematical correlation operation. The selected software (TopoL Software) generates a block of points with their true heights above the terrain in all the stereo pairs selected. This generation is based on the comparison of the areas in the two photographs, using a digital stereo correlation algorithm which is capable of finding homologous points in the left and right photographs of the stereo pair. A 40x40m grid was established, obtaining 2,747 points using automatic correlation in the 4 stereo pairs which cover the studied area. As a quality filter, it has been supposed that the correlation coefficient (ρ) is greater than 0.35 and that the minimum distance between beams is less than 1.0 (Fig. 3a) (Takagi, 2002). This size of grid was enough in the flat area to construct a DEM of sufficient quality. In the hilly area different grid sizes were analysed (20m and 10m), but the same errors in the correlation algorithm were found.

The DEM was generated from the points obtained by automatic correlation, and the result was the surface shown in figure 3b.

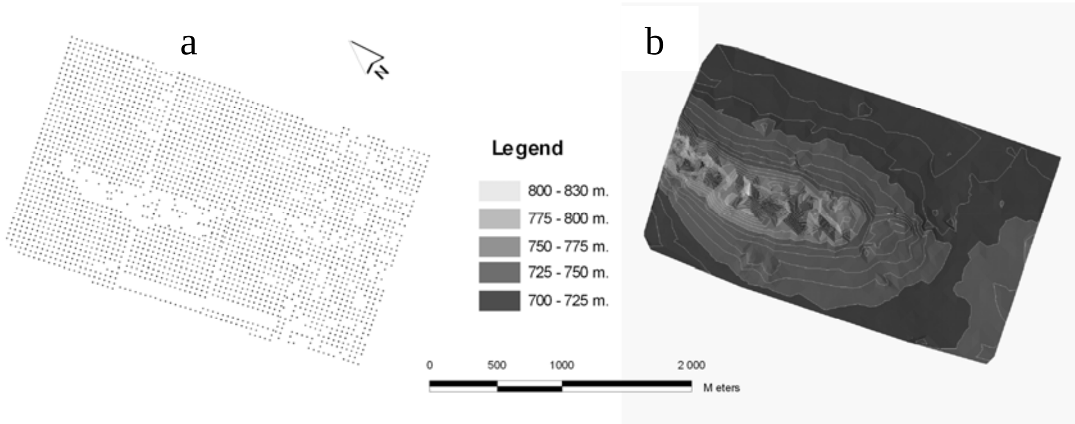

FIG. 3a & 3b. Points obtained using automatic correlation and DEM. The figures show that the area with the greatest slope is the most problematic when carrying out automatic correlation

Subsequently, all the points generated by the automatic correlation algorithm were checked one by one. This check, carried out using stereoscopic vision, showed that 71.6% of all the points obtained by automatic correlation were correctly situated, and 2.9% of the points were incorrect and were not on the terrain. The areas where the system had to move homologous points, and these did not exist, corresponded to 13.5 % of the total points. Table II shows the results obtained from the process of automatic correlation.

TABLE II: Results of the automatic correlation process

Epipolar Pair	*Points*	*In terrain*	*%*	*Error*	*%*	*Not Correlated*	*%*	*Urban area*	*%*
432433	890	463	52.0	12	1.3	103	11.6	312	35.1
433434	650	491	75.5	41	6.3	103	15.9	15	2.3
434435	553	454	82.1	14	2.5	83	15.0	2	0.4
435436	654	559	85.5	13	2.0	82	12.5	0	0.0
Total	2747	1967	71.6	80	2.9	371	13.5	329	12.0

SOURCE 3 (MODEL 3). As in other studies (Büyüksalih et al., 2004), automatic correlation model checked and rectified using breaklines, revision, contour lines, etc.

The revision detected errors in the DEM in the inclusion of the heights of natural or manmade surfaces (trees, houses, etc.); errors made in automatic correlation and defined as blunder (Maas, 1996), which may be due to the poor geometric stability of a non-calibrated scanner, or because the automatic correlation process has not been able to correct ambiguities in a specific point (Fig. 4). Once the breaklines had been incorporated into the model, a check was carried out using stereoscopic vision of each incorrect point of Model 2 (table II). When a point was on a building, it was edited and situated on the terrain as near as possible. There are studies which examine the application of filters or automatic processes in order to detect blunder-type errors and subsequently eliminate them, (Hohle and Potuckova, 2005; Sithole and Vosselman, 2004). Studies on the quality of elevation data obtained using lidar advise the use of this technique based on laser technology for the generation of points in urban areas (Shan and Sampath, 2005).

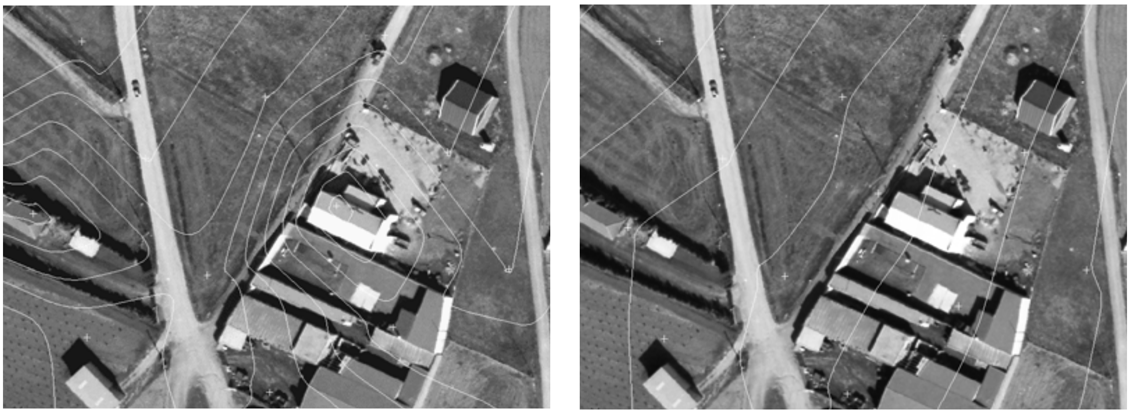

FIG. 4. Points obtained using automatic correlation and rectification. An example of blunder in points obtained using automatic correlation in built-up areas.

SOURCE 4 (MODEL 4). A DEM generated from the National Topographic Map of Spain, 1:25000 scale. Map nº 712 – II Madridejos, with contour lines at 10 m intervals, height points and breaklines. This map was also compiled by photogrammetry in an analytical plotter Wild BC3. This is a map in common use, covering the whole of Spain, and easy to obtain.

In addition to the assessment of the quality of the four models generated, we carried out another experiment using GPS techniques in order to validate and contrast the quality of the DEMs. Using as a basis the geodesic vertex of the ROI "La Cuesta", map 712 of the National Topographic Map, located in Cerro Calderico (Consuegra), we observed 10 control points using GPS techniques, calculating their coordinates to accuracies of centimetres, in order to analyse the precision of the Z coordinate in the different DEMs. The calculations were made in the WGS-84 reference system for subsequent transformation to the Local Geodesic Reference System (UTM ED-50). The points taken in the field using GPS techniques are well spread over the test area and correspond to details that can be identified in the aerial photography. The GPS points were then identified on model 1 (z1), and databases were used to calculate the different heights in the other DEMs (z2, z3, z4).

ANALYSIS OF RESULTS

A database was compiled from this process (table III) with the following structure: point number, x coordinate (x), y coordinate (y), and z coordinate of the different models being assessed (z1, z2, z3, z4). We added to the structure a new field (*type*) to indicate the ambit to which each point belonged.

TABLE III. Structure of the generated database

Point	*x*	*Y*	*z1*	*z2*	*z3*	*z4*	*Type*
1	447309.621	4366893.221	721.872	723.087	723.042	720.469	Flat
2	448703.412	4367210.714	714.023	714.989	714.743	713.995	Urban
3	447456.055	4366440.704	724.004	724.088	723.834	721.731	Flat
4	448928.208	4366740.852	715.415	715.595	715.696	715.404	Flat
5	449246.571	4366186.270	713.899	714.008	714.017	716.362	Flat
6	447815.631	4367688.072	790.564	718.543	787.921	788.750	Hill
7	447738.346	4367684.271	802.366	734.181	791.056	790.000	Hill
8	447898.889	4367762.813	762.095	762.350	762.350	759.167	Hill
9	447978.845	4367762.776	737.344	739.126	737.986	737.917	Hill
10	447260.533	4367289.196	720.257	717.772	717.772	716.544	Flat
11	447340.808	4367298.473	721.455	720.243	720.710	719.134	Flat
12	447725.816	4366710.725	738.063	744.884	745.483	744.375	Hill
13	447339.368	4367362.278	722.856	720.137	720.137	718.482	Flat
14	447259.423	4367362.575	713.398	716.015	716.152	715.625	Flat
15	447179.368	4367362.278	711.368	712.595	712.775	712.824	Urban
...							
1564	448028.221	4365328.757	720.844	724.233	724.233	721.105	Flat

In this article, in the same as in other studies of the quality of DEM, we relate topographic characteristics (slope and orientation) with vertical differences between different DEM (Racoviteanu et al., 2006; Hsing-Chung, 2004). To interpret the data obtained, we have used the ArcGIS 9.1 software and the 3D Analyst extension to develop the maps of height differences between the different DEM (Fig. 5).

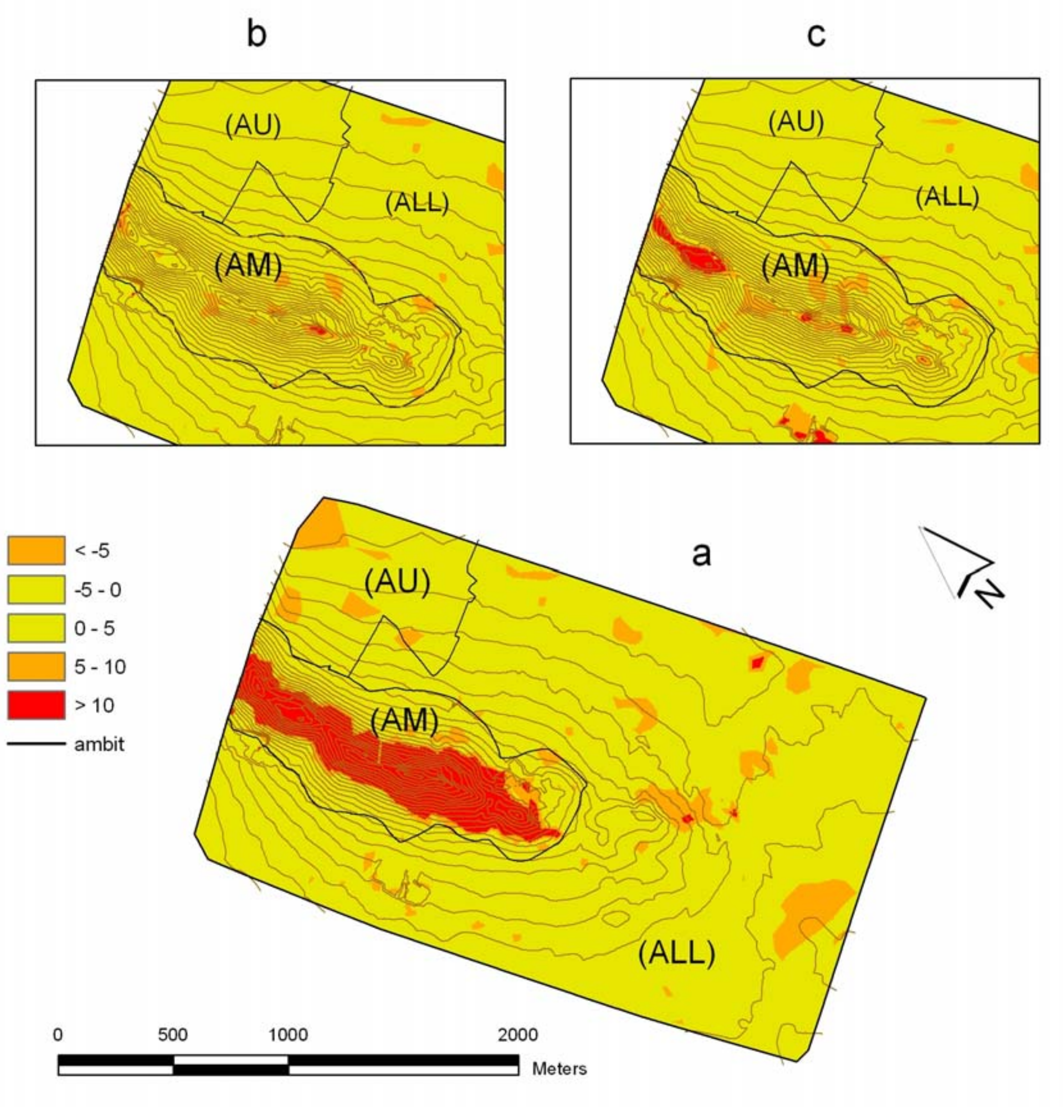

FIG. 5. Map showing height differences between models (in metres). Equidistance = 5 meters. a) Base model compared to automatic correlation model. b) Base model compared to revised and rectified correlation model. c) Base model compared to the official map of the Instituto Geográfico Nacional (IGN) (1:25,000 scale)
AM: Hill - AU: Urban - ALL: Flat

Figure 5a shows how more than 80 % of the differences between the manual model (MODEL 1) and the model using automatic correlation (MODEL 2) have errors between -5.0 and +5.0, highlighting the largest errors in correlation with slope (Heipke, 1995). These results are in line with other research which relates slope and topographic complexity. (Lane et al., 2000).

Lane et al. (2000) describes how changes in the parameters of the slope depend on spatial resolution. They therefore advise taking into account various factors when planning a project: the values of spatial resolution, the resolution of the scanner, the scale of the photograph, the complexity of the surface to be represented, the efficiency in terms of time and space, and the future application of the points.

The hilly rural terrain area is where the operator should concentrate in order to carry out the necessary supervision and edition of the model; the result would be MODEL 3 (Fig. 5b). In addition, there are studies which analyse the differences between DEM (Büyüksalih et al., 2004), which concludes that precision depends mainly on the structure of the surface and the slope of the land. The map of height differences (Fig. 5c) between the base model (MODEL 1) and the model generated from the official map (MODEL 4) shows how the hilly area has the highest concentration of the largest errors.

The source of the National Topographic Map of Spain (1:25000), is compiled by photogrammetry, but with a different scale of flight from that of model 1, and therefore the level of quality is lower than that of model 1. This map was compared because it covers the whole of Spain and it is easily available.

The modelling process depends on the characteristics of the area studied; therefore, in areas with greater variation in terrain, such as the hilly area, it is more likely that larger errors will be found, in comparison with flat areas.

The urban area is treated differently; in the model using automatic correlation (MODEL 2) there is a high percentage of points that have been identified in the roofs of buildings. Since this project is not concerned with points obtained on buildings (Fig. 6a), but rather with a DEM solely of the terrain, these points have to be rectified. The process used has been to disregard all the points generated by automatic correlation (MODEL 2) and to digitize manually a number of homogeneous points located in the intersections of the streets. The result is the surface shown in figure 6b.

FIG. 6a & 6b. Treatment of points in the urban area. Figure 6a is a surface with existing buildings and 6b is the same surface without blunder-type errors.

Similarly to studies on the precision of DEM generated by RADARSAT which relate the causes of error with slope and orientation (Toutin, 2002; Hodgson et al., 2005), it is clear that in our study the accuracy of the DEM shows a direct correlation with the slope, as the greater the slope the greater the error.

In this study the statistical error used is mean quadratic error (MQE) (Li, 1988; Yang and Hodler, 2000). This error is used to describe the vertical accuracy of a DEM, including the "random errors" and the "systematic errors" introduced during the production of the data.

MQE is defined as:

$$MQE = \sqrt{\frac{\sum (Zi - Zt)^2}{n}} \qquad (5)$$

where:

Zi = Interpolated value of the DEM elevations at the test point
Zt = "True" elevation value of the test point.

MODEL 1, the reference model, was analysed statistically with 1,564 points digitized manually. The statistical values analysed in the three areas are shown in table IV.

The highest MQE (3.7 m) is found in comparing the height differences between MODEL 1 and MODEL 2 in the hilly area (table V). All the indices between these two models are lower when MODEL 2 is revised and rectified. The differences are less obvious in the flat area, as automatic correlation obtains better results in flat surfaces.

TABLE IV: Statistical values for Model 1

Type	*Points*	*Average*	*Dev*	*Min*	*Max*
URBAN	25	716.2	6.8	707.7	732.6
HILL	610	754.8	12.7	731.0	818.2
FLAT	929	727.5	8.9	706.9	753.5

TABLE V: MQE value with the other models

Type	*Points*	*MQE value (m)*		
		Mod 1 - 2	*Mod 1 - 3*	*Mod 1 - 4*
URBAN	25	2.6	0.0	1.3
HILL	610	3.7	3.0	3.7
FLAT	929	2.1	1.9	3.2

The corrected and rectified DEM show the best ratio between precision and time spent, along with a higher number of generated points.

Table VI shows the coordinates of the control points taken using GPS techniques in differential mode with transformation to the Local Geodesic Reference System (UTM ED-50) for the quality control of the DEM analysed and the corresponding increment of coordinate z for each model.

TABLE VI. Comparison with GPS techniques

Point Comparison with GPS techniques	*x*	*y*	*GPS*	*Δ1*	*Δ2*	*Δ3*	*Δ4*
1	448735.115	4367593.981	711.063	0.723	-1.794	0.723	-1.884
2	448034.503	4367649.044	732.749	0.196	-2.940	0.196	2.262
3	447309.621	4366893.221	721.344	-0.528	-1.743	-1.698	0.875
4	447885.405	4367015.008	817.506	-0.709	3.958	0.942	-2.494
5	447821.675	4367393.298	801.849	-0.541	1.313	-0.001	-4.401
6	448703.412	4367210.714	714.987	0.964	-0.002	0.244	0.992
7	447456.055	4366440.704	723.879	-0.125	-0.209	0.045	2.148
8	448928.208	4366740.852	715.817	0.402	0.222	0.121	0.413
9	449246.571	4366186.270	714.558	0.659	0.550	0.541	-1.804
10	448028.974	4365331.289	723.184	0.795	-1.049	-0.887	2.196

The MQE index is again used to analyse the quality of the different DEM analysed; the results are shown in table VII. The values nearest to the points taken as references (GPS points) are the points digitized manually from MODEL 1 (0.6 m), as they are points which correspond to details which can be identified in the aerial image.

Figure 7 shows how the z coordinate obtained from MODEL 1 of the control points has an error of no more than 1.0 m. The z coordinates of the GPS points on MODEL 3 range between 0.0 m and 1.5 m.

TABLE VII. Statistical index to analyse the quality of the DEM

Points	*MQE value (m)*			
	Mod GPS - 1	Mod GPS - 2	Mod GPS - 3	Mod GPS - 4
10	0.6	1.8	0.7	2.2

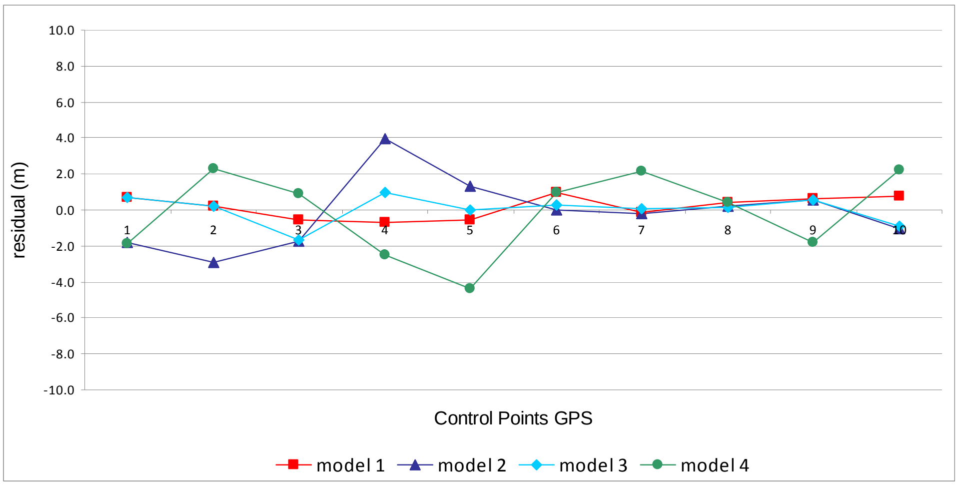

FIG. 7: Precision of obtained results. The differences with model 1 are the most accurate, comparing them with those obtained using GPS.

Figure 8 shows a digital orthophotograph of the DEM of the area studied.

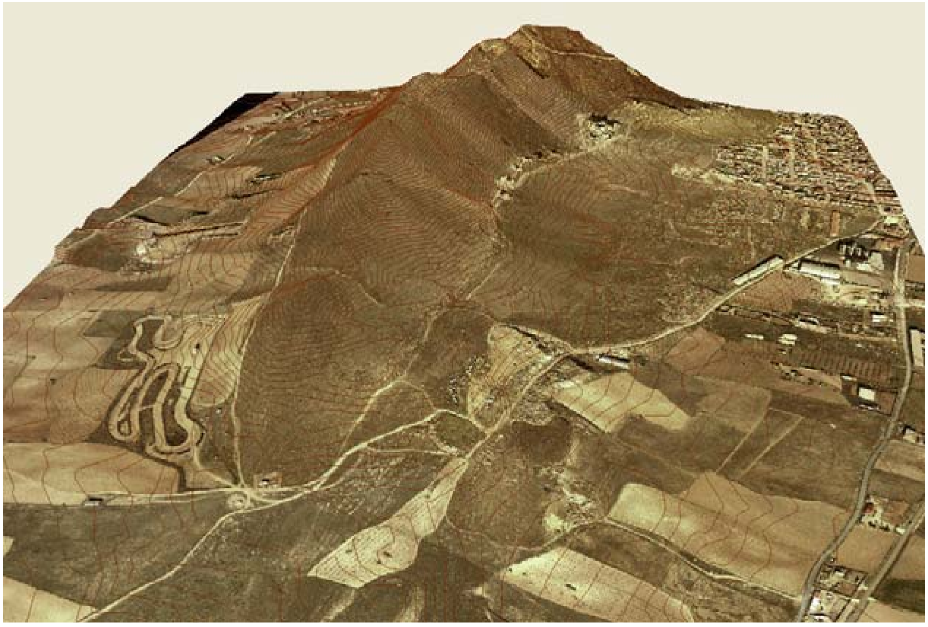

FIG. 8: Digital orthophotograph on DEM of the area studied. This can be used to help future environmental projects dealing with the heritage of the area.

CONCLUSIONS

The accuracy of the DEM depends on the scale of map used and the accuracy of the methods used to obtain the digitalization of the contour lines: scanning and digitalization, or manual digitalization of the contour lines.

The DEMs developed using automatic correlation generate an added time of analysis and correction of the points which are not on the terrain. The rectification of models with different land cover, such as wooded areas, urban areas and areas with sloped of more than 9º implies up to five times more time. We have observed that in a check carried out using a stereo pair, the time used in the automatic correlation of the model was 10 minutes and the rectification process of the model took 50 minutes. This is because many of the points found using automatic correlation are not on the terrain and have to be re-situated.

The greatest errors of DEMs developed using automatic correlation are found in urban areas. This is due to sharp changes of tone and height differences of buildings, which make it impossible to identify correctly the homologous points in both photographs.

The precision of DEM has a direct correlation with the slope, as the steeper the slope, the larger the error. The work of Krupnik (2003) is related to this conclusion. This author analyses the quality of orthophotographs according to the slope and the distance from the centre of the aerial photography.

We can deduce that the generation of DEM is more efficient using direct stereoscopic vision, provided that the photogrammetric operator has some experience.

Orthophotographs such as that in figure 8 have certain geometric and topological links that may be used in subsequent studies and inventories linked to rural heritage sites.

For a study such as this one, we can conclude that the number of GPS points used is relatively low (table VII), as the possible extrapolation of results is limited.

ACKNOWLEDGEMENTS

This study has been carried out in the framework of Research Project (HUM2006-00377) of the National Research, Development and Innovation Plan, subsidized by the Spanish Ministry of Education and Science.

The authors thank the aid of Manuel Mateos Hernández for their experience as the photogrammetric user, Miguel Ángel Conejo Martin and Fernando Mauleón Torres for their know-how in the use and application of the programs of Topol and Atlas.

REFERENCES

ACKERMANN, F., 1984. Digital image correlation: Perfomance and potencial application in Photogrammetry, *Photogrammetric Record*, 11 (645):429-439.

ACKERMANN, F., 1996. Digital Photogrammetry: Challenge and Potential. *Photogrammetric Engineering & Remote Sensing*, 59(11): 679.

BURROUGH, P.A. AND R.A. MCDONNELL, 1998. Principles of Geographic Information Systems, Oxford University Press, New York, 333 pp.

BÜYÜKSALIH, G. ET AL., 2004. Accuracy analysis, dem generation and validation using russian tk-350 stereo-images. *Photogrammetric Record*, 19(107): 200-218.

FELICÍSIMO, A.M.; CUARTERO, A. AND ARIZA, F.J. 2004 A method for the improvement elevation data generated from automated photogrammetric methods into SIS. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, 35(4), pp. 255-260.

FOWLER, R., 2001. Topographic Lidar, *Digital Elevation Model Technologies and Applications: The DEM Users Manual* (D.F. Maune, editor), The America Society for Photogrammetry and Remote Sensing, Bethesda, MD, pp. 207-236.

GOOCH, M.J. AND J.H. CHANDLER, 2001. Failure prediction in automatically generated digital elevation models, *Computers & Geosciences,* 27(8):913-920.

HEIPKE, C., 1995. State-of-the-art of digital photogrammetric workstations for topographic applications, *Photogrammetric Engineering and Remote Sensing,* 61(1):49-56.

HEIPKE, C., 1999. Digital photogrammetry workstations, *GIM International*, 1(13):81.

HODGSON, M. E.; JENSEN, J.; RABER, G.; TULLIS, J.; DAVIS, B. A.; THOMPSON, G., AND SCHUCKMAN, K., 2005. An Evaluation of Lidar-Derived Elevation and Terrain Slope in Leaf-Off Conditions, *Photogrammetric Engineering and Remote Sensing*, 71(7):817-823.

HOHLE, J. K. AND POTUCKOVA, M., 2005. Automated Quality Control for OrthoImages and Dem. *Photogrammetric Engineering and Remote Sensing*, 71(1):81-87.

HSING-CHUNG, C., 2004. Validation of DEM Derived from Radar Interferometry, Airborne Laser Scanning and Photogrammetry by Using GPS-RTK, *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 20–24 September, Anchorage, Alaska, pp. 2815-2818.

KAUFMANN, V., AND W. SULZER, 1997. Über die Nutzungsmöglichkeit hochauflösender amerikanischer Spionage-Satellitenbilder (1960 – 1972), *Vermessung und Geoinformation*, Heft 3/97:166 – 173.

KONECNY, G., 2000. *Mapping from Space, Remote Sensing for Environmental Data in Albania: A Strategy for Integrated Management*, Tirana, Albania (M.F. Buchroithner, editor), NATO Science Series, Vol. 72, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 41-58.

KRAUS, K. ET AL., (2006). Local accuracy measures for digital terrain models. *Photogrammetric Record,* 21 (116): 342-354.

KRUPNIK, A., 2003. Accuracy prediction for ortho-image generation, *Photogrammetric Record,* 18 (101): 41-58.

LANE, S. N., T. D. JAMES, AND M. CROWELL. (2000). Application of digital photogrammetry to complex topography for geomorphological research, *Photogrammetric Record*, 16(95): 793-821.

LI, Z., 1988. On the measure of digital terrain accuracy, *Photogrammetric Record,* 12 (72):873-877.

LI, Z., 1993. Theoretical models of the accuracy of digital terrain models: an evaluation and some observations. *Photogrammetric Record,* 14 (82):651-660.

LI, Z., 2005. *Digital terrain modeling: principles and methodology*. CRC Press, New York. 323 pages.

MAAS, H.G., 1996. Automatic DEM generation by multi-image feature based matching, *IAPRS Journal of Photogrammetry & Remote Sensing,* 31:484-489.

MOLINA, A., 1999. Flujo de trabajo en Fotogrametría Digital, *Mapping*, 53:53-62

RACOVITEANU, A.; MANLEY, W.F. ; ARNAUD, Y. AND WILLIAMS, M., 2006. Evaluating digital elevation models for glaciologic applications: An example from Nevado Coropuna, Peruvian Andes. *Global and Planetary Change*, 59(1-4):110-125.

SALEH, R.A., 1996. Photogrammetry and the quest for digitisation, *Photogrammetric Engineering and Remote Sensing,* 62 (6):675-678.

SHAN, J. AND A. SAMPATH, 2005. Urban Dem Generation From Raw Lidar Data: a Labeling Algorithm and Its Performance, *Photogrammetric Engineering and Remote Sensing*, 71(2):217-226.

SITHOLE, G. AND VOSSELMAN, G., 2004. Experimental comparison of filter algorithms for base-earth extraction from airborne laser scanning point clouds. *ISPRS Journal of Photogrammetry & Remote Sensing,* 59(1/2):85-101.

TANKAGI, M., 1998. *Accuracy of Digital Elevation Model According to Spatial Resolution*. ISPRS Commission IV Symposium on GIS – Between Visions and Applications Stuttgart, Germany, Vol. 32, No. 4.

TAKAGI, M., ASANO, H. AND KIKUCHI, Y. 2002. *Optimum Spatial Resolution of Digital Elevation Model for Topographical Analysis*, Proceedings of the Joint International Symposium on Geospatial Theory, Processing and Applications.

TOUTIN, TH., 2002. Impact of terrain slope and aspect on radargrammetric DEM accuracy, *Journal of Photogrammetry & Remote Sensing,* 57:228-240.

TOUTIN, TH., 2004. Dtm Generation From Ikonos in-Track Stereo Images Using a 3d Physical Model, *Photogrammetric Engineering and Remote Sensing*, 70(6):695-702.

YANG, X., AND T. HODLER, 2000. Visual and statistical comparisons of surface modelling techniques for point-based environmental data, *Cartography and Geographic Information Science,* 27 (2): 165 – 175.

Résumé

Cet article montre une expérimentation dans la génération de MNE (Modéles Numériques d'Elévations) à partir d'algorithmes de corrélation automatique propres à une Station de Photogramétrie Numérique (SPN), ainsi qu' une évaluation de la précision obtenue en fonction des données disponibles et de la métodologie employée.

Cet article est appliqué à l'espace particulier nommé "Calderico", une colline à Consuegra (Toledo, Espagne) site des célèbres moulins de vent décrits dans "Don Quixote". Dans cette colline se trouvent trois secteurs bien différenciés par leur inclinaison.

Une fois créés les différents MNE pour les aires décrites, une analyse statistique a été effectuée. Cette analyse servira à faire une évaluation quantitatif des modèles ainsi que des orthoimages obtenues.

Les résultats apportés indiquent une plus grande disparité dans la précision des points homologues identifiés dans chaque MNE pour les zones de décalage plus pronnoncé et moins important pour celles d'une inclinaison moins abrupte. Aussi, il est intéressant de noter la bonne qualité des points contrôllés par GPS différentiel.

Resumen

En este trabajo se muestra una experiencia en la generación de Modelos Digitales de Elevaciones (MDE) a partir de algoritmos de correlación automática propios de una Estación de Fotogrametría Digital (EFD), así como una evaluación sobre la precisión obtenida en función de los datos disponibles y de la metodología empleada.

Este estudio se aplica a un espacio singular denominado cerro "Calderico" en el que se ubican los famosos molinos de viento de Don Quijote en Consuegra (Toledo, España), donde se diferencian tres zonas, caracterizadas principalmente por su distinta pendiente.

Una vez creados los diferentes MDE para los ámbitos descritos se efectúa un análisis estadístico que nos servirá para hacer una valoración cuantitativa tanto de los modelos como de las ortoimágenes que se obtengan.

Los resultados que se aportan indican mayor disparidad en la precisión de los puntos homólogos identificados en cada MDE para las zonas de más desnivel y menor en las zonas con pendiente más suave. Es interesante observar la buena calidad de los puntos controlados mediante GPS diferencial.