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DEM extraction from archive aerial photos: accuracy assessment in areas of complex topography

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Abstract
The aim of this study is to analyze the accuracy of a Digital Elevation Model (DEM) created with photogrammetric techniques from stereoscopic pairs of aerial photos in areas with complex geomorphologic characteristics. The evaluation of DEM and derived geomorphometric parameters was conducted by comparison with other standard DEM products (i.e. TINITALY/01 and ASTER GDEM-V2) and by accuracy assessment based on Check Points (CPs). The validation process includes the comparison of elevation profiles, the calculation of DEM accuracies, and the evaluation of the effect of slope and aspect on the DEM accuracy.
The produced DEM accurately represent complex terrain (RMSE = 4.90 m), thus providing information suitable for local-scale geomorphometric analysis. The obtained accuracy resulted slightly worse than TINITALY/01 (RMSE = 2.53 m), but significantly better than ASTER GDEM (RMSE = 12.95 m). These results confirm that photo-based DEM extraction can be a very competitive and precise methodology if other expensive high-resolution data are not accessible.
Keywords: DEM, aerial photos, aerial triangulation, accuracy assessment.

Introduction
Nowadays, the Digital Elevation Model (DEM), which is a 3D digital representation of an elevation surface over a specified area, is one of the most fundamental requirements for a large variety of spatial analysis and modeling problems in environmental sciences. It is used in analyses in ecology, hydrology, agriculture, geology, pedology, geomorphology and many others, as a means both of explaining processes and of predicting them through modeling [Schumann et al., 2008; Christoph et al., 2009; Marzolff and Poesen, 2009]. Our capacity to understand and model these processes depends on the quality of the topographic data that are available [Jarvis et al., 2004].
DEMs are also a necessary input parameters for: determining the extent of a watershed

and extracting a drainage network [Tucker et al., 2001], determining the slope and aspect associated with a geographic region [Kuhni and Pfiffner, 2001], modeling and planning for telecommunications [Sawada et al., 2006], orthorectification [Toutin, 2004], preparing 3D simulations, 3D perspectives and flight simulations [Lisle, 2006], agricultural applications [Pilesjö et al., 2006], studies of landscape dynamics [Mitasova et al., 2005] and morphometric characterization of volcanoes [Grosse et al., 2012]. As with any other geospatial dataset, DEMs are produced at a number of spatial scales each of which has its own cost-effective techniques for data acquisition [Oksanen and Sarjakoski, 2006]. With the advent of satellite imagery covering the globe, various global datasets of topography have been produced, of increasingly better resolution. The possible sources of these elevation data can be Interferometric Synthetic Aperture Radar (InSAR), photogrammetric methods with space and aerial images, laser scanning using airborne Light Detection and Ranging (LiDAR) and classical ground survey [Nelson et al., 2009; Hirt et al., 2010]. Each of these methods have advantages and disadvantages.

The classical field survey is economic only for small areas (e.g. geoarchaeology). Aerial laser scanning is detailed and accurate but very expensive, requiring specifically designed flights and intensive elaboration of the raw data [Grosse et al., 2012]. Satellite photogrammetry is also weather depending and still quite expensive as the very high resolution satellites are mainly operating in a single image mode. In fact, stereo pairs are frequently collected on demand. Radar interferometry is weather independent (rainfall may cause some problems), but time-consuming and quite complex to elaborate [Panagiotis et al., 2008].

Aerial photogrammetry is an accurate and powerful tool in surface model generation, extracting high resolution DEMs by means of automated image matching procedures [Fabris and Pesci, 2005]. Very high-resolution aerial imagery are currently available for modeling more detailed earth surface processes [Jarvis et al., 2004; Marzolff and Poesen, 2009; Prokešová et al., 2010], especially in fields such as hydrology, pedology, landslide dynamics or geomorphology. In particular, historical aerial photos collected in Italian archives over the past 60 years [Fabris and Pesci, 2005; Fabris et al., 2011], as well as in other countries, represent an extensive source of data that support environmental studies, and in general for planning.

The performance of automated DEM generation were re-evaluated through the use of professional photogrammetric workstations [Hohle, 2009], that allow important advantages, for example, faster processing and low processing costs. The methodology of automatic DEM extraction and orthophoto generation from digital stereo imagery is well established and extensively described [e.g. Rivera et al., 2005; Pieczonka et al., 2011]. However, an accuracy assessment of these elevation data is necessary. Inadequate and inaccurate representations can lead to poor decisions that can negatively impact our environment and the associated human, cultural, and physical landscape. This is particularly true in classification or other cartographic modeling applications where elevation, slope and aspect are derived from DEMs and used with other spatial data [Bolstad and Stowe, 1994]. Still, only a limited number of studies have addressed the issue of accuracy evaluation of DEM produced by photogrammetric methods from archive aerial photographs and derived geomorphometric features in areas with complex topography. The purpose of this paper is to investigate the quality of DEM created with photogrammetric methods using stereo aerial photos in areas of complex topography, and its potential use for geomorphometic analysis at local scale.

Specifically, the objective of this case study was to answer the following questions:

I) What is the accuracy of the DEM created from archive aerial photos in comparison with two other DEMs generated with different methodologies?

II) How do slope and aspect influence DEM accuracy?

Material and methods

Study area

The study area is located about 30 km south of Cagliari, in southern Sardinia, Italy, around 38º 59' north latitude and 8º 54' west longitude, and covers an area of 10 km x 5 km. The elevations range from 4 m up to over 860 m a.s.l., the average slope is 22° and most of the reliefs are facing south-east. Land cover consists mainly of a mixture of coniferous forest and mediterranean maquis, with patches of pastures and agricultural areas. The site is dominated by *Quercus ilex* L., *Quercus suber* L., *Arbutus unedo* L. and *Phillyrea* L. sp. with a maximum height of 3 m. Paleozoic Granites (*Complesso Granitoide del Sulcis-Arburese*) constitute the bedrock. They are deeply altered and friable, showing the typical arenization at the surface. Limited Pleistocene and Holocene sediment covers are present in the lower valley areas. This region is characterized by hilly and undulating terrain which extends to the coastline, and represent a specific landscape characterized by steep ridges, high peaks, deep valleys and gorges. Figure 1 depicts the study area and the locations of the CPs collected from a topographic map with a scale of 1:10.000.

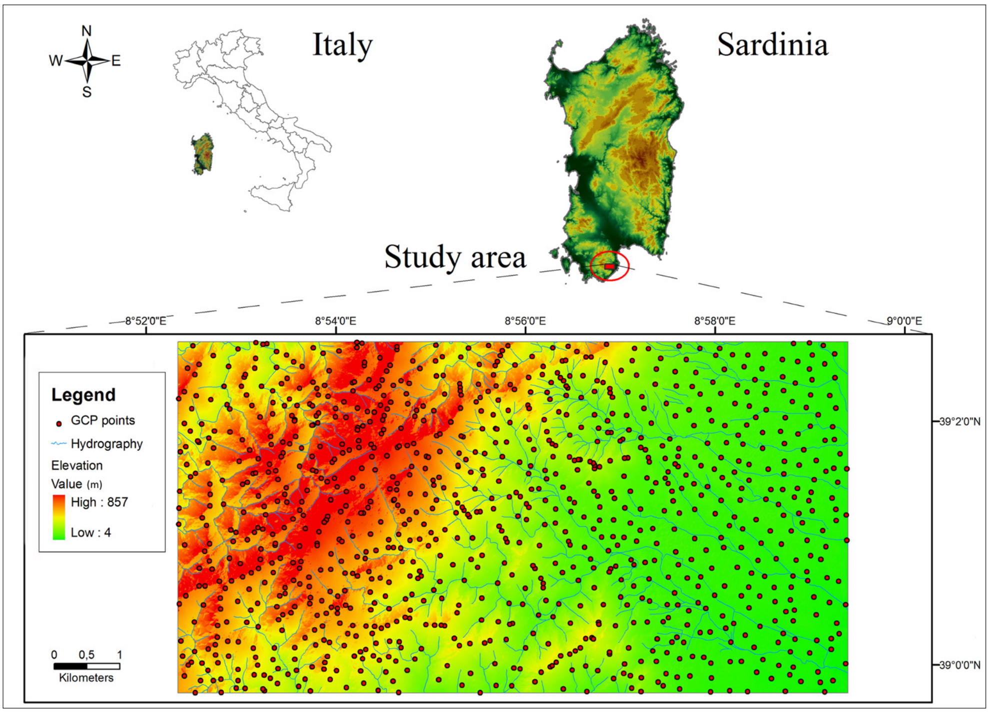

Figure 1 – Location of the study site and the distributions of CPs.

DEM generation from airphoto stereo pairs

The Digital Elevation Model, called DEM95, is a digital elevation model which we have developed from 12 archive aerial photos along 2 strips at a mean scale of 1:34.000. The flight was performed on July 29, 1995 (Tab. 1). The black-and-white photo frames, obtained from the Italian Military Geographical Institute (IGM), were scanned using Wehrli Raster Master RM2 photogrammetric scanner at 1200 dpi resolution, resulting in a ground pixel resolution of 0.7 m. Each frame has associated information relating to the focal length, lens type and acquisition date. The images were compressed in a TIFF format, without loss of quality. The images orientation and point extraction procedures were carried out using Leica Photogrammerty Suite (LPS 9.2) software package.

Table 1 - Main characteristics of the aerial photogrammetric survey.

Characteristics		1995 survey
Aerial photogrammetric camera		Wild RC 20
Focal length (mm)		152.83
Flying height (m)		5000
Number of photograms		12
Number of strips		2
Overlap (%)		> 60
Scan resolution (dpi)		1200
Ground pixel dimension (m)		0.7
Number of GCPs used		118
Residuals of exterior orientation	rX	-0.253
	rY	0.384
	rZ	-0.415

No camera calibration report was available, so the interior camera parameters were estimated and subsequently refined from the mathematical model generated during aerial triangulation. Aerial triangulation uses collinearity equations to establish a geometric relationship between the image, camera and the ground. The project data file was created and the various parameters were defined. They include, among others, camera model, ground control points, altitude information such as flying height and average ground elevation, the type of imagery and camera parameters (such as name, focal length and principle point coordinates), the order of images and strips and the coordinate system for the control points.

The standard procedure to generate a DEM using automated stereo-correlation process is based on fundamental steps that consist in interior orientation, exterior orientation (registration into a defined reference system) and point extraction. The interior orientation is performed to define the frame position inside the camera.

The exterior orientation is obtained by two subsequent steps: relative and absolute orientation. In the first case the aim is to create the stereoscopic model in an arbitrary relative system using points common to both images (tie points). A tie point is a point with unknown ground coordinates, and is visually recognizable in the overlap area between multiple images. Tie points are used to create a geometric relationship between the images in a project so they are positioned correctly relative to one another. LPS software uses Automatic tie point

collection to automatically identify and measure tie points across multiple images and strips of imagery. The absolute orientation is the transformation of the generated stereoscopic model into an external reference frame defined by the coordinates of several ground control points, recognized on the images [Fabris and Pesci, 2005]. Ground control points were collected from orthoimages TerraItaly 2006 with 0.5 m spatial resolution, while elevation coordinates necessary for height stabilization in the block bundle adjustment were collected from DEM 10 m resolution. The coordinate reference system is Gauss-Boaga/Roma40**.** Images and DEM are available at: http://www.sardegnageoportale.it/index.html. Ground control points are distributed over the whole area to ensure an even coverage of the image and to avoid clustering effects [Rocchini et al., 2012].
DEM95 was resampled to 5 m resolution, elevations are ellipsoidal heights referenced to the reference systems Gauss-Boaga/Roma40. DEMs created by photogrammetric technique occasionally contain blunders such as irregularly gridded data, mistagging of tops and depression. These spikes, holes and other noises caused by automatic DEM extraction can be corrected by editing the raster data values and replacing them with meaningful values. The Spike/Well check tool in ERDAS imagine was applied to identify pixels that are out of range with its surrounding neighbours. It also determines whether there are large spikes and wells in the data. Visual interpretation showed no significant gross errors in the maximum and minimum values of elevations contained in the DEM95.

DEM from TINITALY/01

The most popular data sources for the creation of DEM are the digitized contours derived from topographic maps. In this study we used a new digital elevation model, named TINITALY/01, that is currently the most accurate DEM covering the whole Italian territory [Tarquini et al., 2012]. The DEM was released by the Italian Ministry of the Environment and Territory (the DIGITALIA project). The DEM was obtained from heterogeneous vector datasets, mostly consisting in elevation contour lines and elevation points from several sources. The input vector database was carefully cleaned up to obtain a seamless Triangulated Irregular Network (TIN) derived by using the DEST algorithm (Determination of Earth Surface Structures) [Favalli and Pareschi, 2004; Tarquini et al., 2007]. The adopted coordinate systems for TINITALY/01 is Universal Transverse Mercator/World Geodetic System 1984 (UTM-WGS84). The 32 zone (for Western Italy) and the 33 zone (for Eastern Italy) is available in grid format as a 10 m cell size grid. Tarquini et al. [2007] carried out a comprehensive assessment of the accuracy of the TINITALY/01 DEM, finding a root mean square error in elevation (RMSE) between 0.8 and 6.0 m. The TINITALY/01 DEM is available for scientific purposes on the basis of a research agreement at: http://tinitaly.pi.ingv.it/.

ASTER GDEM version 2

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, http://asterweb.jpl.nasa.gov/) Global Digital Elevation Model (GDEM) version 2 was released on October 2011 by the National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade and Industry (METI). ASTER GDEM version 2 (GDEM V2) is obtained from data collected by the sensor Visible Near Infrared (VNIR), using bands 3N (nadir-viewing) and 3B (backward-viewing) with a resolution of 15 m with a swath 60 km wide. ASTER GDEM V2 is organized according to a regular grid of 30x30 m

UTM-WGS84 cartographic coordinates, while the orthometric heights were determined by using the corresponding ellipsoidal Earth Gravitational Model (EGM 96) geoid [ASTER Validation Team, 2011]. ASTER GDEM is made to order following the selection of tiles through the Earth Observing System (EOS) Data Gateway.

The overall vertical accuracy of ASTER elevations is specified to vary between 8.68 m and 18.31 m [ASTER Validation Team, 2011]. Generally error increases as the topography become rougher. This ASTER product is available at no charge for any user pursuant to an agreement between METI and NASA.

Check Points

In order to provide the benchmark to infer vertical accuracy, 3D coordinates of 1033 check points have been collected from topographic map with a scale of 1:10000. These points are homogeneously distributed in the area and the number is enough to guarantee error control reliability. Check points have a particular importance as a reference or planimetric and elevation, which are always located in areas which are presumed to be stable over the last decades, and have been reported with particular care**.** The elevations H are ground truth ellipsoidal heights. The vertical accuracies of the CPs are <±1.8 m, and is satisfactory for the control objectives (matching the criteria of 1:10000 topographic mapping) since the standard deviation expected of the DEM is twice the mean error of CPs.

Accuracy assessment

The magnitude of absolute and relative errors of DEMs data has been examined. The absolute accuracy is a measurement of the error between a DEM and the coordinates of the terrain. Accuracy is evaluated by indices such as the absolute mean error (AME), standard deviation (SD) and the root mean square error (RMSE), whereas shape reliability is evaluated through statistical analysis of a parameter set characterizing the spatial properties of a surface such as slope and aspect. Absolute accuracy is expressed as the vertical RMSE, who is an overall error indicator that takes into account both random and systematic errors introduced during the data generation process. The relative vertical accuracy is especially important for derivative products that make use of the local differences among adjacent elevation values, such as slope and aspect. A DEM with good relative accuracy is one that models the shape and dimensions of the terrain accurately, but may not necessarily be accurately registered to real geographic coordinates. The relative accuracy is expressed as the standard deviation of the vertical error [Jung Hum Yu, 2011]. The accuracy of the DEM95 is determined as the difference between the CPs and DEM95 and is denoted as CP - DEM95; similarly, the accuracy of the ASTER and TINITALY is denoted as CP - ASTER and CP - TINITALY. In order to describe and compare the elevation distributions in each DEM, elevations at the locations of CPs have been extracted from all DEMs and compared with the elevations of CPs to determine several descriptive statistic measures.

The process is as follows: First of all, ASTER and TINITALY has been transformed in Gauss-Boaga/Roma40 reference system using Traspunto software package, the most widely software package used in Italy for the automatic transformation of coordinates between reference systems [Travaglini, 2004]. After that, the DEMs have been clipped to the common study area, in order to have equal areas for all DEMs and eliminate bias due to the edge effect. Subsequently, all grids have been overlaid with CPs using Intersect Point

Tool from Hawth's Analysis Tools for ArcGIS [Beyer, 2004]. Finally, the DEM attributes (i.e. elevation, aspect and slope) have been extracted. All data points with their respective attributes have been organized in a spreadsheet table and analyzed by using the software IBM SPSS Statistics 19. Considering that the error possibly correlates with the elevation, the values of the CPs have been taken as the control variable, and carry out partial correlations between the errors of the DEMs. In fact, neither data scatter in the linear regression models nor vertical accuracy constitute sufficient criteria to achieve a full definition of DEM error because the error is expressed globally [Gonga-Saholiariliva et al., 2011]. Slope gradient and aspect are two of the most basic parameters affecting morphological and hydrological problems, and represents one set of the recommended variables to analyse distribution and concentration of certain spatial objects [Blaschke and Strobl, 2003; Moreno et al., 2003]. These have been computed in order to assess how well topographic details are represented for all DEMs. In order to ensure compatibility and comparability among of dataset across space, the grids could not be used with their original characteristics, then slope and aspect have been resampled with a grid size of 30 meters. While this may have biased slope and aspect evaluations by potentially inflating accuracies for areas of complex terrain, it also limits the effects of horizontal registration error [Bolstad and Stowe, 1994].

Results

Elevation profile analysis

Qualitative assessment of DEM95 is executed by comparing the elevation profiles of the three DEMs. The DEMs are depicted as elevation curves according to the directions of profiles North-South and West-East for the study area. The profiles have been chosen based on the area covering both low-gradient and high-gradient terrains (Fig. 2).

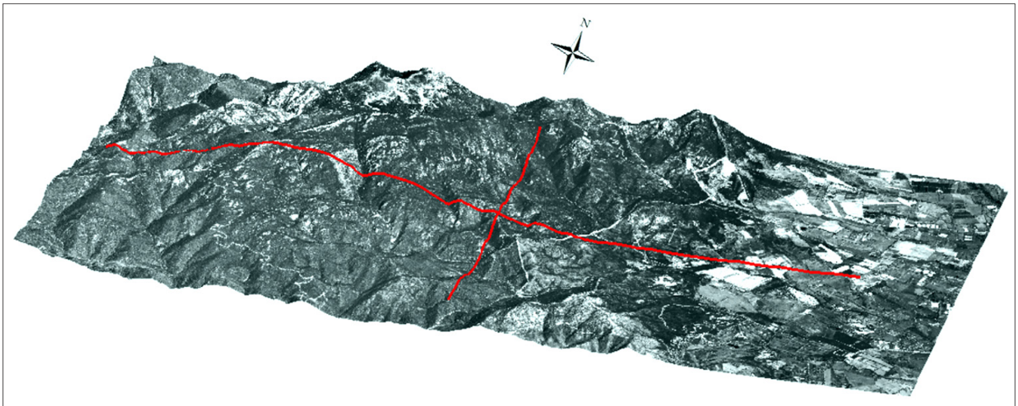

Figure 2 - 3D perspective view of the study area. DEM was draped by the mosaic image. Red lines shown transects used for plotting elevation profiles.

As shown in Figure 3, the black, blue and red curves represent DEM95, TINITALY and ASTER, respectively.

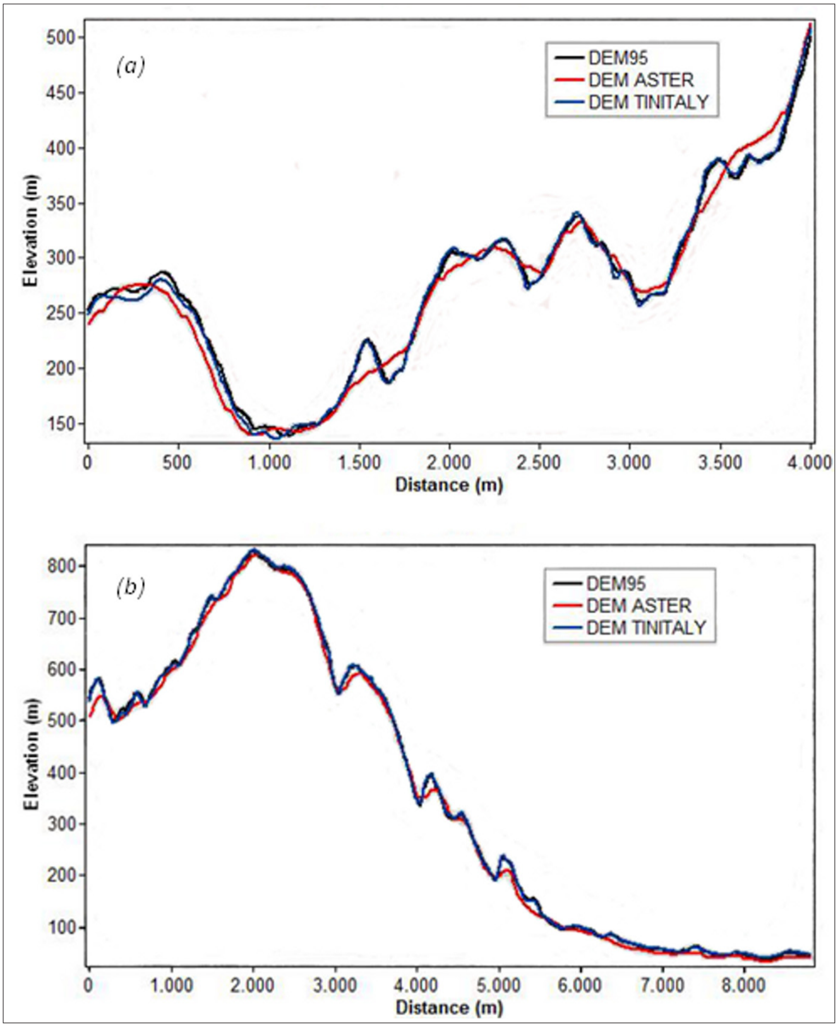

Figure 3 - Profile comparisons between elevations of DEM95, ASTER and DEM TINITALY: *(a)* North - South elevation profile, *(b)* West - East elevation profile.

In the profile North-South (Fig. 3a), length 4000 m, the three curves can be divided into three parts: in the left part, the ASTER is lower than DEM95 and TINITALY; in the middle part, the curves of DEM95 and TINITALY fluctuate along that of the ASTER; in the right part, the ASTER is for small sections higher than both DEM95 and TINITALY. This is probably due to the increased geomorphology complexity of the northern profile. ASTER curve has some evident fluctuations, is generally lower than DEM95 and TINITALY, that are relatively close and evidently differ, due to the higher accuracy of these. In the profile West-East (Fig. 3b), length 8800 m, the differences are less marked and the ASTER is generally close to but lower than the others DEMs. From the curves of the different data types for the two profiles, it can be seen that the trend of the DEM95 and TINITALY have similar characteristics.

Assessment of relative and absolute accuracy

Descriptive statistics of elevation values of CPs and of the three DEMs are reported in Table 2.

Table 2 - Descriptive statistics of CPs and the three DEMs.

Data	Mean (m)	Min (m)	Max (m)	SD (m)
CP	350.70	9.20	864.70	252.17
DEM95	347.25	8.00	857.00	251.05
TINITALY	349.68	9.20	860.08	251.65
ASTER	344.88	9.00	837.00	249.71

SD: Standard Deviation

The CPs are equally distributed among plains, hills and moderate relief at medium elevation and the TINITALY is a little closer to the CP than the other DEMs. A synthesis of the results of the accuracy assessment is given in Table 3 which shows the values of min and max and mean error, root mean square error, standard deviation, standard error and confidence interval (CI = 95%). As shown in the Table 3, the RMSE of DEM95 elevation is about twice to that of TINITALY, much lower than the one of ASTER GDEM.

Table 3 - Statistical differences between CPs and the respective points in the three DEMs. (AME: mean absolute error; Min: Minimum; Max: Maximum; Std err: Standard error; SD: Standard Deviation; CI: Confidence Interval for SD (95%); RMSE: Root Mean Square Error).

Data	AME (m)	Min (m)	Max (m)	Std err (m)	SD (m)	CI (95%)	RMSE (m)
CP - DEM95	3.44	-15.15	28.25	0.14	4.42	±0.27	4.90
CP - TINITALY	1.02	-5.39	26.92	0.07	2.31	±0.14	2.53
CP - ASTER	5.82	-98.80	50.60	0.36	11.58	±0.71	12.95

The error distribution frequencies of DEM95, TINITALY and ASTER are illustrated in Figure 4.

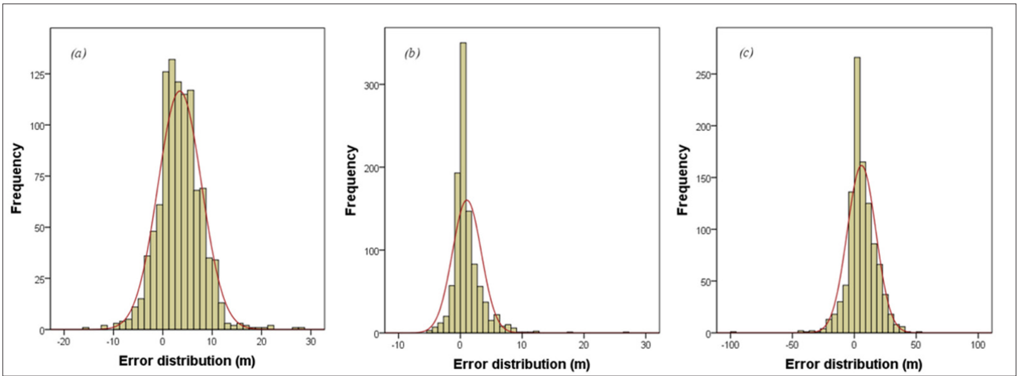

Figure 4 – Error distribution frequencies of (a) CP - DEM95, (b) CP - TINITALY, (c) CP - ASTER. Superimposed curve represents the normal distribution.

The overall range of the error distribution for ASTER elevation is wider than those for DEM95 and TINITALY and the most frequent errors are positives. The characteristics of the error distributions of DEM95 and TINITALY resemble each other, and the frequencies of positive errors are greater than those of the negative errors for both DEM95 and TINITALY, which indicates a small positive bias for both models.

Error correlation analysis

Considering that the error possibly correlates with the elevation, the values of the CPs have been taken as a control variable, and carry out partial correlations between the errors of the DEMs. In the comparison DEM95 - TINITALY the error correlation is $r = 0.43$ ($p<0.001$). As shown in Figure 5a, the errors of both DEM95 and TINITALY are mainly distributed from -10 to 10 m. In the comparison DEM95 - ASTER, the error correlation is $r = 0.37$ ($p<0.001$). The errors of both DEM95 and ASTER are mainly distributed from - 30 to 30 m (Fig. 5b). Therefore, the errors of the TINITALY and ASTER only have weak correlation.

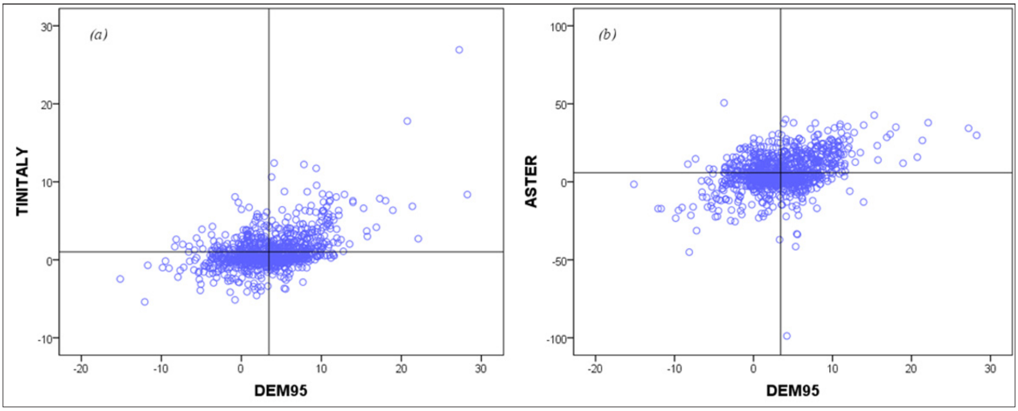

Figure 5 – Scatter plots between the errors of the (a) DEM95 - TINITALY and (b) DEM95 - ASTER.

Geomorphometric analysis

The geomorphometric analysis revealed a significant decrease in accuracy of all DEMs data when measurements are performed on terrain characterized by slope values greater than 8° (Tab. 4).

The relationship between the AME and aspect is shown in Figure 6. The aspect is divided into eight directions. The AME in each direction is the value in the 45° range centred on the specified direction. As the Figure 6 shows, the relationships for the DEM95, TINITALY and ASTER completely differ in terms of magnitude. For DEM95 and ASTER, the AME in each direction is almost the same and forms a near circle. For TINITALY, the AME for the southern, western and southeast direction is remarkably lower than it is for other directions.

Table 4 - Analysis of discrepancies between DEMs and CPs data with different slope values. (Std err: Standard error; SD: Standard Deviation; Min: Minimum; Max: Maximum; CI: Confidence Interval for SD (95%)).

Area / Data	DEM95			TINITALY			ASTER		
	Slope			Slope			Slope		
	< 4°	4°< x <8°	> 8°	< 4°	4°< x <8°	> 8°	< 4°	4°< x <8°	> 8°
Mean (m)	2.90	3.28	3.83	0.22	0.92	1.48	3.56	4.68	7.16
Std err (m)	0.18	0.24	0.23	0.05	0.11	0.12	0.43	0.59	0.57
SD (m)	3.24	3.35	5.23	0.87	1.51	2.89	6.57	8.82	13.74
Min (m)	-5.82	-9.05	-15.15	-5.14	-2.67	-5.39	-25.50	-20.10	-98.80
Max (m)	11.50	11.61	28.25	6.11	8.45	26.92	40.00	50.60	42.70
CI (95%)	0.36	0.48	0.45	0.10	0.22	0.24	0.84	1.17	1.13

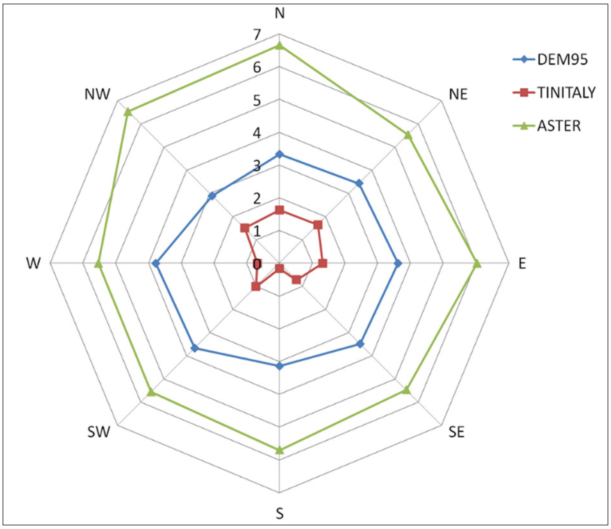

Figure 6 - Relationships between aspect and absolute mean error.

Discussion

Based on the results obtained in this study, the generation of DEM from aerial photos in areas of complex topography has showed that elevation RMSE range up to ± 4.90 m.
Specifically, the RMSE values obtained for DEM95 are comparable to those obtained by Walstra et al. [2007] and Zanutta et al. [2006], that used archive aerial photos for DEM generation. Previous studies report that the vertical accuracy of the DEM is a function of photo scale and is estimated as 1/9000th of the flying height of the aircraft carrying the camera system [Maune et al., 2001; Hapke, 2005]. In this study, the flying height of the photographs was 5000 m and this results in a vertical error of 0.55 m. However, this accuracy may be good enough for fine scale applications over large areas or where limitations on the accessibility of remote areas makes the collection of ground truth data impossible [Oksanen

and Sarjakoski, 2006; Hobi and Ginzler, 2012].
The RMSE values obtained for the other DEMs are consistent with the reported official accuracy (i.e. TINITALY: 0.8 m < RMSE < 6.0 m – [Tarquini et al., 2007]; ASTER: 6.1 m < RMSE < 15.1 m – [ASTER validation Team, 2011]), supporting the robustness of the validation dataset.
DEM95 had a lower accuracy than TINITALY, probably due to the fact that the area contains a great deal of vegetation, for which a lower accuracy is to be expected as compared with the latter, obtained from heterogeneous vector datasets. The errors of the TINITALY and ASTER have only weak correlation. One interpretation of this finding is that the poor correlation relates to the different resolutions of the original datasets.
For all DEMs, greater error values were associated with rugged terrain, while smaller errors were associated with plain, suggesting that terrain characteristics such as slope and aspect can influence DEMs accuracy [Gorokhovich and Voustianiouk, 2006].
Different results were obtained investigating the effects of land slope and aspect on the DEMs. As expected, the vertical error increased with surface slope. The magnitude of SD was about twice for terrains with slope values exceeding 8° compared to areas where slope values are less than 4° in DEM95 (3.2 m vs 5.23 m) in TINITALY (0.87 m vs 2.89 m) and ASTER (6.57 m vs 13.74 m). This result demonstrates that there is a correlation between the elevation error and land slope.
Also terrain aspect was found to have a relative influence on the magnitude of errors in the DEMs. The highest magnitude of errors was observed for measurements made on ASTER, the lowest magnitude of errors was observed in TINITALY. The error magnitude did not vary considerably with aspect in DEM95 and ASTER, while in TINITALY an irregular shape of the error was observed, with the lowest errors on slopes facing south (S), southeast (SE) and west (W), due to the better accuracy, while DEM95 did not show trends. In this case aspect did not particularly influenced the absolute mean error.
The accuracy of DEM95 is affected by the quality and parameters of the aerial photos taken, the height of the flight, the topographic characteristics of the area, the status and type of the vegetation cover as well as the human factor during the photogrammetric evaluation. The potential limitations of these data could be a lack of sensitivity to the variation in terrain surface due to the presence of trees and areas of steeper slopes.
Overall, the results obtained in this study indicate that the accuracy DEM95 is comparable to DEMs extracted with photogrammetric techniques from previous studies, and strongly encourage the use of archival materials to improve the geomorphological studies. Developments on data acquisition and processing software allows the reuse and enhancement of historical data for DEM generation, leading to better and faster results.

Conclusions

In this article we describe the accuracy of DEM95 created with photogrammetric techniques from archive aerial photos, and we compare it to ASTER GDEM version 2 and DEM TINITALY. Check points collected from digital cartography were used for the vertical accuracy control.
According to the results achieved, it is possible to state that photo-based DEM95 can be used for computation of terrain attributes such as slope and aspect, and is suitable for a range of environmental mapping tasks involving the use of DEM with a grid step of 5-20 m. This

implies that an automated DEM extraction of fine toposcale can be an efficient method for analysis of hydrological modeling, soil properties and vegetation pattern. These evaluations showed that photo-based DEMs are very competitive, very cheap and affordable, readily available and relatively precise, especially when other expensive high-resolution data (e.g. LiDAR) are not accessible.

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References

ASTER Validation Team (2011) - *ASTER Global Digital Elevation Model Version 2 – Summary of Validation Results*. Published by The ASTER GDEM Validation Team: METI, NASA and USGS in cooperation with NGA and other colloborators. August 2011, 27 pages. Available online: http://asterweb.jpl.nasa.gov/gdem.asp (last accessed 28/01/2012).

Beyer H.L. (2004) - *Hawth's Analysis Tools for ArcGIS*. Available online: http://www.spatialecology.com/htools/tooldesc.php (last accessed 29/01/2012).

Blaschke T., Strobl J. (2003) - *Defining landscape units through integrated morphometric characteristics*. In: Buhmann, E., Ervin, S. (Eds.), Landscape Modeling: Digital Techniques for Landscape Architecture. Wichmann-Verlag, Heidelberg, pp. 104-113.

Bolstad P.V., Stowe T. (1994) - *An evaluation of DEM accuracy: Elevation, slope and aspect*. Photogrammetric Engineering and Remote Sensing, 60 (1): 1327-1332.

Christoph S., Olaf B., Bernhard E. (2009) - *Combining digital elevation data (SRTM/ASTER), high resolution satellite imagery (Quickbird) and GIS for geomorphological mapping: a multi-component case study on Mediterranean karst in Central Crete*. Geomorphology, 112: 106-121. doi: http://dx.doi.org/10.1016/j.geomorph.2009.05.010.

Fabris M., Pesci A. (2005) - *Automated DEM extraction in digital aerial photogrammetry: precisions and validation for mass movement monitoring*. Annals of Geophysics, 48 (6): 973-988. doi: http://dx.doi.org/10.4401/ag-3247.

Fabris M., Menin A., Achilli V. (2011) - *Landslide displacement estimation by archival digital photogrammetry*. Italian Journal of Remote Sensing, 43 (2): 23-30. doi: http://dx.doi.org/10.5721/ItJRS20114322.

Favalli M., Paresci M.T. (2004) - *Digital elevation model construction from structured topographic data: the DEST algorithm*. Journal of Geophysical Research, 109: F04004. doi: http://dx.doi.org/10.1029/2004JF000150.

Gonga-Saholiariliva N., Gunnell Y., Petit C., Mering C. (2011) - *Techniques for quantifying the accuracy of gridded elevation models and for mapping uncertainty in digital terrain analysis*. Progress in Physical Geography, 35 (6): 739-764. doi: http://dx.doi.org/10.1177/0309133311409086.

Gorokhovich Y., Voustianiouk A. (2006) - *Accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics*. Remote Sensing of Environment 104: 409-415. doi: http://dx.doi.org/10.1016/j.rse.2006.05.012.

Grosse P., van Wyk de Vries B., Euillades P.A., Kervyn M., Petrinovic I.A. (2012)

- *Systematic morphometric characterization of volcanic edifices using digital elevation models.* Geomorphology, 136 (1): 114-131. doi: http://dx.doi.org/10.1016/j.geomorph.2011.06.001.

Hapke C.J. (2005) - *Estimation of regional material yield from coastal landslides based on historical digital terrain modeling*. Earth Surface Processes and Landforms, 30: 679-697. doi: http://dx.doi.org/10.1002/esp.1168.

Hirt C., Filmer M.S., Featherstone W.E. (2010) - *Comparison and validation of recent freely-available ASTER-GDEM ver1, SRTM ver4.1 and GEODATA DEM-9S ver3 digital elevation models over Australia*. Australian Journal of Earth Sciences, 57 (3): 337-347. doi: http://dx.doi.org/10.1080/08120091003677553.

Hobi M.L., Ginzler C. (2012) - *Accuracy Assessment of Digital Surface Models Based on WorldView-2 and ADS80 Stereo Remote Sensing Data.* Sensors, 12 (5): 6347-6368. doi: http://dx.doi.org/10.3390/s120506347.

Hohle J. (2009) - *DEM Generation Using a Digital Large Format Frame Camera.* Photogrammetric Engineering & Remote Sensing, 75 (1): 87-93.

Jarvis A., Rubiano J., Nelson A., Farrow A., Mulligan M. (2004) - *Practical use of SRTM data in the tropics: Comparisons with digital elevation models generated from cartographic data*. Working Document: Centro Internacional de Agricultura Tropical (CIAT), 198: 32 p.

Jung Hum Yu (2011) - *Interferometric Synthetic Aperture Radar and Radargrammetry for Accurate Digital Elevation Model Generation in New South Wales, Australia*. PhD thesis, The University of New South Wales, Sydney NSW 2052, Australia.

Kuhni A., Pfiffner O.A. (2001) - *The relief of the Swiss Alps and adjacent areas and its relation to lithology and structure: topographic analysis from a 250-m DEM.* Geomorphology, 41 (4): 285-307. doi: http://dx.doi.org/10.1016/j.bbr.2011.03.031.

Lisle R. J. (2006) - *Google Earth: a new geological resource*. Geology Today, 22: 29-32. doi: http://dx.doi.org/10.1111/j.1365-2451.2006.00546.x.

Marzolff I., Poesen J. (2009) - *The potential of 3D gully monitoring with GIS using high-resolution aerial photography and a digital photogrammetry system.* Geomorphology, 111 (1-2): 48-60. doi: http://dx.doi.org/10.1016/j.geomorph.2006.11.003.

Maune D.F., Kopp S.M., Crawford C.A., Zervas C.E. (2001) - *Introduction: digital elevation models.* In Digital Elevation Model Technologies and Applications: The DEM Users Manual, Maune DF (ed.). American Society of Photogrammetry and Remote Sensing: Bethesda, Maryland; pp. 1-34.

Mitasova H., Overton M., Harmon R.S. (2005) - *Geospatial analysis of a coastal sand dune field evolution: Jockey's Ridge, North Carolina.* Geomorphology, 72: 204-221. doi: http://dx.doi.org/10.1016/j.geomorph.2005.06.001.

Moreno M., Levachkine S., Torres M., Quintero R. (2003) - *Geomorphometric analysis of raster image data to detect terrain ruggedness and drainage density*. Lecture Notes in Computer Science, 2905: 643-650. doi: http://dx.doi.org/10.1007/978-3-540-24586-5_79.

Nelson A., Reuter H.I., Gessler P. (2009) - *DEM production methods and sources*. In: Hengl T., Reuter H. (Eds.), Geomorphometry, Concepts, Software, Applications. Developments in Soil Science, Vol. 33. Elsevier, Oxford.

Oksanen J., Sarjakoski T. (2006) - *Uncovering the statistical and spatial characteristics of fine toposcale DEM error*. International Journal of Geographical Information Science,

20 (4): 345-369. doi: http://dx.doi.org/10.1080/13658810500433891.
Pieczonka T., Bolch T., Buchroithner M.F. (2011) - *Generation and evaluation of multitemporal digital terrain models of the Mt. Everest area from different optical sensors*. ISPRS Journal of Photogrammetry and Remote Sensing, 66 (6): 927-940. doi: http://dx.doi.org/10.1016/j.isprsjprs.2011.07.003.
Pilesjö P., Persson A., Harrie L. (2006) - *Digital elevation data for estimation of potential wetness in ridged fields - Comparison of two different methods*. Agricultural Water Management, 79 (3): 225-247. doi: http://dx.doi.org/10.1016/j.agwat.2005.02.017.
Prokešová R., Kardoš M., Medvedová A. (2010) - *Landslide dynamics from high-resolution aerial photographs: a case study from the Western Carpathians, Slovakia.* Geomorphology, 115: 90-101. doi: http://dx.doi.org/10.1016/j.geomorph.2009.09.033.
Rivera A., Casassa G., Bamber J., Kääb A. (2005) - *Ice-elevation changes of Glaciar Chico, southern Patagonia, using ASTER DEMs, aerial photographs and GPS data.* Journal of Glaciology, 51 (172): 105-112. doi: http://dx.doi.org/10.3189/172756505781829557.
Rocchini D., Metz M., Frigeri A., Delucchi L., Marcantonio M., Neteler M. (2012) - *Robust rectification of aerial photographs in an Open Source environment*. Computers & Geosciences, 39 (2): 145-151. doi: http://dx.doi.org/10.1016/j.bbr.2011.03.031.
Sawada M., Cossette D., Wellar B., Kurt T. (2006) - *Analysis of the urban/rural broadband divide in Canada: Using GIS in planning terrestrial wireless deployment.* Government Information Quarterly, 23 (3-4): 454-479. doi: http://dx.doi.org/10.1016/j.giq.2006.08.003.
Schumann G., Matgen P., Cutler M.E.J., Black A., Hoffmann L., Pfister L. (2008) - *Comparison of Remotely Sensed Water Stages from Li-DAR, Topographic Contours and SRTM*. Journal of Photogrammetry and Remote Sensing, 63: 283-296. doi: 10. 1016/j.isprsjprs.2007.09.004.
Tarquini S., Isola I., Favalli M., Mazzarini F., Bisson M., Pareschi M., Boschi E. (2007) - *TINITALY/01: a new Triangular Irregular Network of Italy*. Annals Of Geophysics, 50 (3): 407-425.
Tarquini S., Vinci S., Favalli M., Doumaz F., Fornaciai A, Nannipieri L. (2012) - *Release of a 10-m-resolution DEM for the Italian territory: Comparison with global-coverage DEMs and anaglyph-mode exploration via the web*. Computers & Geosciences, 38 (1): 168-170. doi: http://dx.doi.org/10.1016/j.cageo.2011.04.018.
Toutin T. (2004) - *Review article: Geometric processing of remote sensing images: models, algorithms and methods*. International Journal of Remote Sensing, 25 (10): 1893-1924. doi: http://dx.doi.org/10.1080/0143116031000101611.
Tsombos P.I., Nikolakopoulos K.G., Lathourakis G. (2008) - *DEM from Cartosat data and comparison to DEM from other sources*. Proc. SPIE 7106, Sensors, Systems, and Next-Generation Satellites XII, 71061C (October 2, 2008). doi: http://dx.doi.org/10.1117/12.800019.
Travaglini D. (2004) - *Trasformazioni tra sistemi di coordinate: software disponibili, limiti e potenzialita*. Forest@ 1 (2): 128-134. doi: http://dx.doi.org/10.3832/efor0228-0010128.
Tucker G.E., Catani F., Rinaldo A., Bras R.L. (2001) - *Statistical analysis of drainage density from digital terrain data.* Geomorphology, 36 (3-4): 187-202. doi: http://dx.doi.org/10.1016/S0169-555X(00)00056-8.

Walstra J., Dixon N., Chandler J.H. (2007) - *Historical aerial photographs for landslide assessment: two case histories*. Quarterly Journal of Engineering Geology & Hydrogeology, 40 (4): 315-332. doi: http://dx.doi.org/10.1144/1470-9236/07-011.
Zanutta A., Baldi P., Bitelli G., Cardinali M., Carrara A. (2006) - *Qualitative and quantitative photogrammetric techniques for multi-temporal landslide analysis.* Annals of Geophysics, 49 (4-5): 1067-1080. doi: http://dx.doi.org/10.4401/ag-3117.

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