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Application of Digital Terrain Model to volcanology

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Abstract
Three-dimensional reconstruction of the ground surface (Digital Terrain Model, DTM), derived by airborne GPS photogrammetric surveys, is a powerful tool for implementing morphological analysis in remote areas. High accurate 3D models, with submeter elevation accuracy, can be obtained by images acquired at photo scales between 1:5000-1:20000. Multitemporal DTMs acquired periodically over volcanic areas allow the monitoring of area interested by crustal deformations and the evaluation of mass balance when large instability phenomena or lava flows have occurred. The work describes the results obtained from the analysis of photogrammetric data collected over Vulcano Island from 1971 to 2001. The data, processed by means of the Digital Photogrammetry Workstation DPW 770, provided DTM with accuracy ranging between few centimeters to few decimeters depending on the geometric image resolution, terrain configuration and quality of photographs.

Key words *Digital Terrain Model (DTM) – digital photogrammetry – Vulcano Island – deformations – morphological changes*

1. Introduction

A number of methods based on data acquired by means of remote sensing systems are now available for the generation of Digital Terrain Models (DTM) over large areas. These include satellite SAR interferometry, airborne laser scanning, aerial photogrammetry as well as spaceborne optical and radar stereo option. Among these techniques, Digital Photogrammetry is one of the most powerful tools for acquiring, through semiautomatic procedure, a large amount of 3D points for the generation of high spatial resolution DTM and the relative rectified images.

In digital photogrammetry images are processed with matching procedures based on well defined shape comparison techniques or on the grey level distribution in the corresponding zones of the images (Heipke, 1995; Kraus, 1998). The capability of the correlation algorithms to work at sub-pixel level affects the final precision of digital products, together with the quality of the image, the presence of shadows and the morphology of the surface.

In volcanic areas, digital photogrammetry techniques were experimented only recently, showing remarkable potentialities (Zlotnicki *et al.*, 1990; Achilli *et al.*, 1998; Baldi *et al.*, 2002, 2005), such as the possibility to accurately describe morphological features of ground surfaces, to study gravitative instability phenomena induced by volcanic activity and to detect and map areas involved in crustal deformation phenomena.

The objective of the work is to describe the photogrammetric digital procedure applied to

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high resolution images acquired over Vulcano Island, to discuss the quality of the results obtained and to perform a comparative analysis using multitemporal DTM.

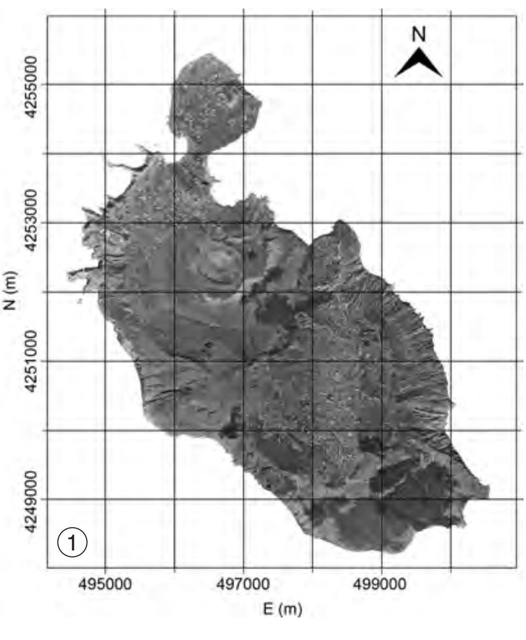
Low altitude photogrammetric data over Vulcano Island have been acquired several time during the last 30 years: the data analyzed in this work derive from the 1971, 1983, 1993, 1996, 2001 surveys. For the first two datasets (1971, 1983), we had at our disposal the DTM derived from images at 1:10 000 scale, while the 1:5000 images acquired in 1993, 1996 and 2001 were fully processed within this work and used for a detailed analysis of the main crater area.

2. Photogrammetric data of Vulcano Island

The 1996 aerial photogrammetric survey of the entire island, performed with a WILD RC20 film camera, consists of a block formed by 4 strips including 36 photos at 1:10 000 scale (Achilli *et al.*, 1997; Baldi *et al.*, 2000); kinematic GPS was used to determine the coordinates of the camera positions, allowing the reduction of the number of ground control points (22).

The images were digitized at 1000 dpi resolution, which corresponds to ground pixel resolution of about 25 cm. After the standard procedure for image orientation, the automatic correlation module of the Digital Photogrammetric Workstation DPW 770 Helava was used for automatic extraction of DTM from digital stereopairs; a 10-m grid DTM and an ortophoto (figs. 1 and 2) of the entire island were generated.

A more detailed analysis was performed for the cone area where images at larger scale (1:5000) were acquired in 1993, 1996 and 2001. In particular the north-east flank (Forgia Vecchia and surrounding area) (fig. 3) was carefully investigated due to presence of instability phenomena (Gabbianelli *et al.*, 1991; Rasà and Villari, 1991). In this case the ground resolution of the digitised images is about 12 cm; which



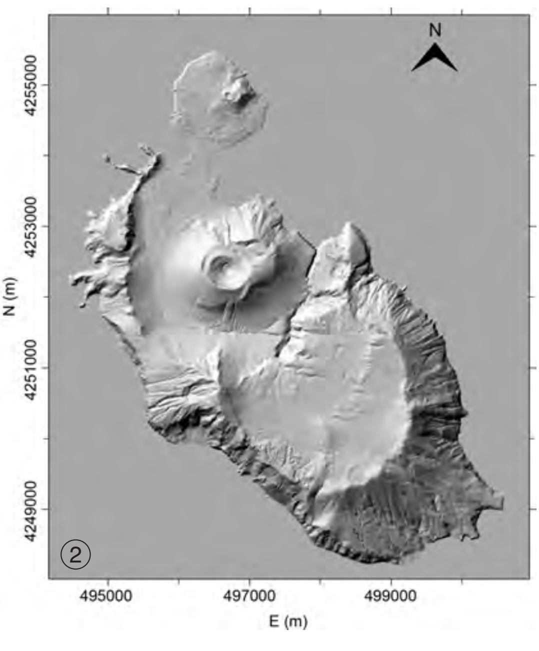


Fig. 1. Ortophoto of Vulcano Island.

Fig. 2. Shaded relief image of the 10×10 m grid DTM of Vulcano Island.

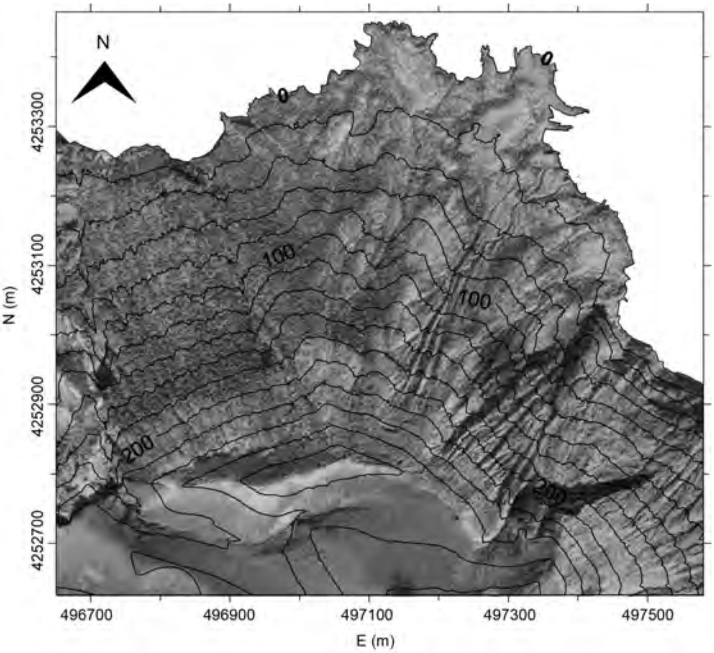


Fig. 3. «La Forgia Vecchia» and surrounding area.

Table I. Principal characteristics of 1993, 1996, 2001 models and DTMs.

Characteristics	1993 survey	1996 survey	2001 survey
Average image scale	1:5000	1:5000	1:5000
Scanning resolution	1000 dpi	1000 dpi	1000 dpi
Number of processed images	2	4	4
Number of ground control points	11	6	12
No. tie points	5	23	26
AT residuals			
X	~5 cm	~7 cm	~7 cm
Y	~5 cm	~6 cm	~7 cm
Z	~2 cm	~2 cm	~5 cm
DTM grid space	1 m	1 m	1 m
Number of DTM measured points	1231782	1840703	2658635
CPU time	$\sim 2^{h}$	$\sim 3^{h}$	$\sim 4^{h}\ 30^{min}$
Percentage of automatic 3D measures	~70 %	~70 %	~70%

allowed for the extraction a higher spatial resolution DTM (1×1 m grid). Table I shows the main characteristics of the three datasets and of the derived DTMs. The residuals estimated on the ground control points after the Aerial Triangulation (AT) adjustment show that the overall accuracy of the 3D measured points is at subpixel level.

The necessity of a manual editing procedure for at least 30% of the area is mainly due to the presence of highly vegetated surfaces where the matching procedure identifies 3D

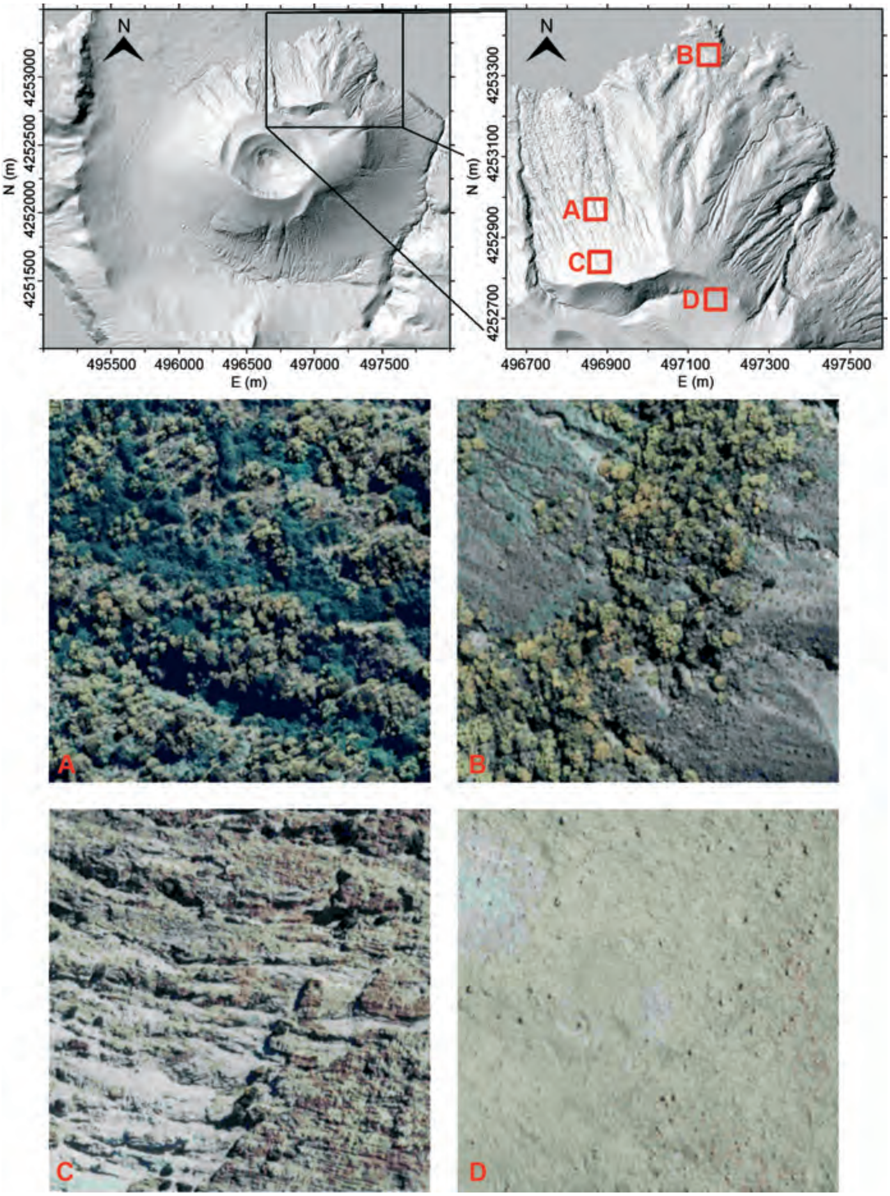


Fig. 4. The north-east flank of the cone; the four areas with different morphological characteristics are shown.

points, like those on top of the canopy, which should not be included in the DTM. In this case the editing procedure is mainly oriented to correct the outliers, to measure new points and to reconstruct the continuity of the ground surface.

The correlation index, a value which quantifies the quality of the stereo correlation match-

Table II. Mean value and standard deviation of height differences of digital elevation models relative to different terrain characteristics.

Area	Description	1993-1996		1993-2001		1996-2001	
		M (m)	σ (m)	*M* (m)	σ (m)	*M* (m)	σ (m)
A	Completely covered by vegetation	−0.71	0.60	−0.93	0.68	−0.22	0.63
B	Partially covered by vegetation	−0.10	0.20	−0.45	0.41	−0.35	0.37
C	No vegetation, rough terrain	0.12	0.20	0.29	0.22	0.17	0.22
D	No vegetation, smooth terrain	−0.06	0.05	−0.06	0.07	−0.001	0.07

ing between the image pairs (Davis *et al.*, 2001), is also influenced by shadows and bad illumination conditions. The measured DTM can be refined by carefully performing the editing procedure on the low correlation areas; despite this, the DTM accuracy strongly depends on the terrain characteristics (morphology and vegetation). This was verified comparing DTMs (1× ×1 m) extracted from the images of the 1993, 1996 and 2001 surveys, on four different areas characterized by dense or partial vegetation coverage (fig. 4, sector A and B), or by rough or smooth terrain (fig. 4, sector C and D). In the first two areas an editing procedure was applied; in the C and D zone the digital elevation model processed only by the automatic correlation approach was analysed. The results of the comparisons between the different models derived from the three surveys are listed in table II: the repeatability is of the order of few decimetres in presence of vegetation or uneven morphology, but is reduced to a few centimetres in favorable conditions.

The same results were obtained by Baldi *et al.* (2000); a comparison between the 1996 photogrammetric DTM and the coordinates of about 6000 points mainly distributed around the top of the cone, measured in the framework of three GPS kinematic surveys, indicates a standard deviation of the height differences of about 18 cm.

3. Differential Digital Photogrammetry (DDP)

The comparison of DTMs produced processing stereo-images acquired in successive epochs (DDP) may be used for the measurement of the vertical deformation of the observed area, allowing the evaluation of mass balance when large instability phenomena or lava flows occurred. In order to discriminate between vertical and horizontal components of the movement, artificial permanent targets or well shaped natural objects visible in all the images should be measured (Zlotnicki *et al.*, 1990).

Multitemporal stereo models, which are used for DTMs generation at different epochs, have to be oriented in the same reference frame; this may be accomplished by identifying and measuring the same ground control points (artificial), whose coordinates are known in an external and stable (fixed in time) reference system. A recently developed alternative approach can be used by adopting methods for direct georeferencing image data (GPS/INS integrated system) which provide position and attitude of the image sensor in an absolute/external reference system (Achilli *et al.*, 1997). In the absence of a sufficient number of ground control points or external orientation parameters, the reference system can be established by using natural control points measured on a selected model correctly oriented: these points should be clearly identifiable on all multitemporal data sets.

If the use of ground control points or common points recognized *a posteriori* on all the photos is not feasible, it is possible to obtain the registration of different (multitemporal) sets of 3D coordinates of the same area by the so called «least square surface matching procedure» (Baldi *et al.*, 2004).

The basic principles of this approach are well described by Karras and Petsa (1993), Pilgrim (1996a), Mitchell and Chadwick (1999); they describe a method for minimizing the vertical surface separation of DTM pairs, assumed to be affected by errors, and representing the same object in different reference systems. A possible approach involves the detection of the parameters for a rigid transformation in a common reference system of the two data sets, without the aid of control points (least square matching). The presence of local deformations may influence the estimation of the parameters, reducing the ability of these conventional matching algorithms to obtain the spatial registration, but some robust estimators can be applied (Li *et al.*, 2001) to increase the tolerable percentage of deformed areas. As pointed out by many authors (Karras and Petsa, 1993; Pilgrim, 1996b), one of the major advantages of the least square matching is that the process allows for various statistical techniques which make the match procedure very robust; furthermore, it can be integrated with techniques for detecting changes of the surfaces due to real deformations or to statistical outliers.

4. Application of DDP

The East flank of the cone was affected in 1988 by a landslide which moved to the sea (Tinti *et al.*, 1999); in this area the differential DTM method was applied to the 1971, 1983, 1993, 1996 and 2001 data.

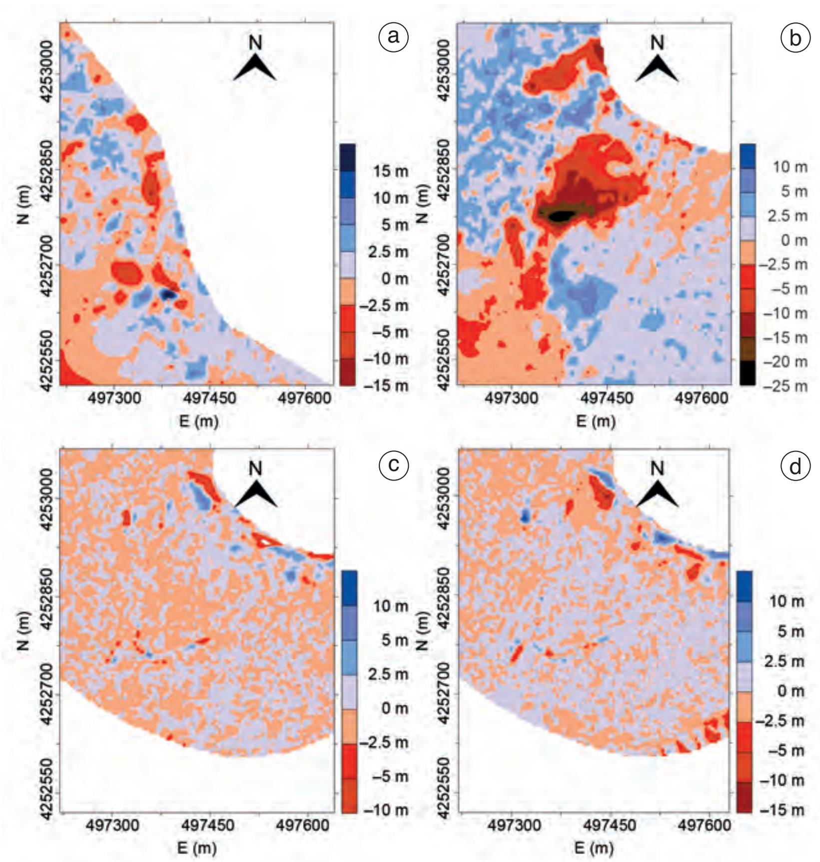


Fig. 5a-d. Comparison between DTMs in the landslide area: a) 1983-1971; b) 1993-1983; c) 1996-1993; d) 2001-1996.

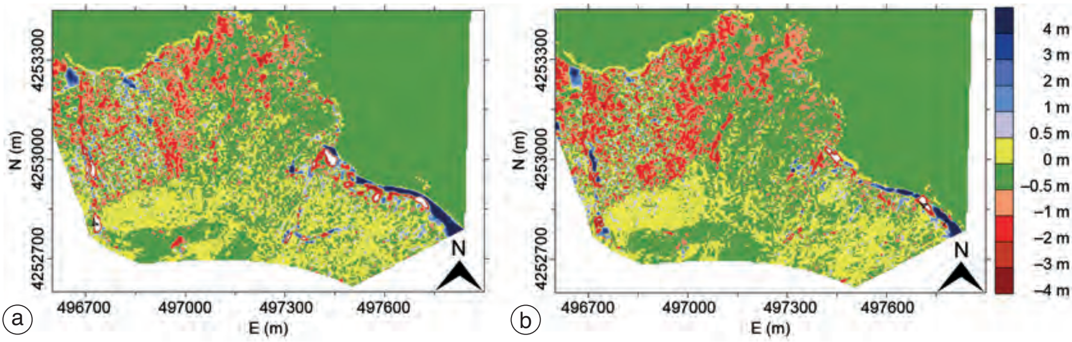


Fig. 6a,b. Comparison between a) 1996 and 2001; and b) between 1993 and 2001 DTMs.

For the last three DTMs the common reference system was defined using two models from the 1996 survey, oriented by 6 artificial ground control points measured with GPS; on these models 12 natural points, clearly visible in the 1993 and 2001 images and located in an area assumed stable, were chosen and their coordinates measured. They were assumed as ground control points useful for the orientation of the 1993 and 2001 models.

For the oldest surveys (1971 and 1983) only DTMs derived by stereo pair at about 1:10000 scale produced by other operators were at our disposal. In this case the registration was obtained by a least square surface matching procedure respect to the 1996 model (fig. 5a).

The selected region described by the digital models presents different morphological features, varying from highly steep slopes to smooth terrain, and includes the area involved in the 1988 landslide. The comparison between the 1983 and 1993 models clearly showed the area involved in the landslide and allowed us to evaluate its volume (about 193000 m^3) (fig. 5b).

The comparison between the recent and more accurate DTMs do not show successive important deformations (fig. 5c,d). In this case the scale of the images (1:5000) yielded residuals lower than 0.5 m on a large portion of the area (fig. 6a,b); the major differences are present in the vegetated or highly sloping areas characterized by bad illumination conditions or absence of a good stereoscopic vision of the surface in the images. Vertical variations (uplift) ranging between 0.5 and 2.0 m in the N-W part of the area correspond to the presence of vegetation which in many cases prevents the description of the ground surface, even if a normal editing has been performed where small portions of ground surface are visible. The mean value of these anomalous residuals is in agreement with the estimation of the annual growth of shrubs (~10 cm/yr), obtained measuring the top of 60 bushes distributed on the slope and recognized on the three models.

5. Conclusions

Airborne photogrammetric images provide powerful tools for Digital Elevation Model extraction, especially when coupled with the use of Global Positioning System (GPS) techniques for georeferencing and validating results. DTMs may be used for the definition of morphological characteristics such as slopes, volumes, or drainage patterns and integrated with multi-spectral remote sensing imagery for a large number of applications. The comparison of multitemporal highly accurate models of a volcanic area can be used for deformation monitoring, morphological changes detection and mapping revision of rapidly changing areas.

The resolution of the DTMs obtained by semi-automatic digital processing of airborne stereoimages from a photogrammetric camera can satisfy a wide range of accuracy requirements provided that certain operational and image processing procedures are adopted. This method is very useful for surveillance activities and deformation monitoring over active areas.

We analysed data derived from aerial photogrammetric surveys performed on Vulcano Island in the last thirty years. The results confirm the possibility of extracting DTMs with a few centimeters accuracy, starting from images at 1:5000 scale and processing them with automatic matching procedures. The precision decreases rapidly when the monitored area is characterised by complex morphology, poor illumination, or the presence of vegetation. The area involved in the 1988 landslide, located on the East flank of the cone, was well defined, and the mass involved in the event has been evaluated.

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