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Morphological updating on the basis of integrated DTMs: study on the Albano and Nemi craters

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Abstract. The Colli Albani Volcano has recently developed particular interest in the geophysical community for some peculiar characteristics imputable to a recent residual volcanic activity, thus evidencing that it cannot be considered extinguished yet.

On April 2006 an airborne laser scanning (ALS) survey of the Albano and Nemi craters has been carried out to obtain a high resolution digital terrain model (DTM) of the area. We have compared the accuracy of the ALS heights with those obtained by a fast GPS kinematic survey, obtaining maximum deviation within 50 cm. Then, we have integrated the ALS survey of the craters and the bathymetry of the Albano lake to achieve a complete DTM, useful for morphological studies. In addition, with a GNSS/RTK survey (July 2007) we have estimated the Albano and Nemi mean lake levels respectively at 288.16 m and 319.02 m (asl). Based on the integrated DTM and the newly estimated water level values, we have evaluated about $21.7 \cdot 10^6$ of m^3 the water volume loss of the Albano lake from 1993 to 2007, with an average rate of about $1.6 \cdot 10^6$ m^3/yr.

Keywords. Albano, Nemi, DTM, ALS survey, GNSS/RTK.

1. Introduction

Current papers show the importance of disposing high precision Digital Terrain Models (DTMs) of areas affected by geophysical, geotechnical or in general environmental risks devoted to a correct territorial planning (Luttrell et al. 2007, Cavaliè et al. 2007, Baldi et al. 2006, Baldi et al. 2002 and references therein). Since DTMs have recently increased their importance in the more various fields of interest, with engineering, geological and geophysical applications, current researches are devoted not only to their generation at different scales, but even to define suitable methodologies able to control their precision and reliability (Kraus et al. 2006, Kölbl 2001).

Important applications are related to the hazard assessment of active and quiescent volcanoes, strongly dependent from the morphology of the edifice structure. In particular, in active volcanoes the definition of the path of lava flows is necessarily based on the knowledge of detailed DTMs (Vicari et al. 2007), whereas in quiescent volcanoes the landslide hazard evaluation have to face peculiar problems like the presence of sub-aerial and submerged unstable slopes (Mazzanti et al. 2007); so that the unification of surface DTM and bathymetry is recognized as a useful tool to investigate these questions (Tommasi et al. 2006).

The Colli Albani area (Rome) is a volcanic complex located in central Italy, about 15 km SE of Rome, within latitudes 41.6°–41.9° North and longitudes 12.5°–12.9° East (Figure 1). This area has been identified as a quiescent rather than extinct volcano only recently and, for this reason, received relatively little attention in respect to other, historically active, volcanoes of Italy. From 2005 to 2007 the Department of the Civil Protection financed the project DPC115 V3_1, the first one specifically oriented to the definition of potential hazards and crisis levels at Colli Albani. Considering gas emissions, seismic swarms, and ground deformation as the most compelling activities of this area, and starting from the actual level of knowledge, one of the priority of the project was to study the dynamics of the District at shallow and surface levels and their interferences with human activities, including local-scale ground deformation, stress field, slope stability, recent eruptive processes, crater lake evolution, quaternary mass flows. In this framework, we decided to assess a detailed digital database for representing the morphology of the Albano and Nemi craters (Figure 1) useful to researchers of different disciplines working on this area. The digital morphology is derived from integrating the ALS survey of the two craters and the bathymetric survey of the Albano lake. From this database and the newly estimated water levels of the two lakes obtained after a GNSS/RTK survey, we provide morphological updates of the craters and water level and volume variations of the lakes.

2. Geophysical background of the Colli Albani area

Colli Albani are considered a quiescent Volcanic District that belongs to the potassic and ultrapotassic Roman Magmatic Province, a northwest-trending chain of volcanoes developing along the Tyrrhenian Sea margin of Italy during middle and late Pleistocene time (De Rita et al. 1988, Trigila 1995). The volcanic history of the Colli Albani Volcanic District is dominated by recurrent eruptive histories started about 561 ka and ending with the most recent and voluminous activity of the Albano maar (<70 ka) phase, that cannot be considered extinguished yet (Freda et al. 2006, Funiciello et al. 2003). In fact, at present, this area is characterized by

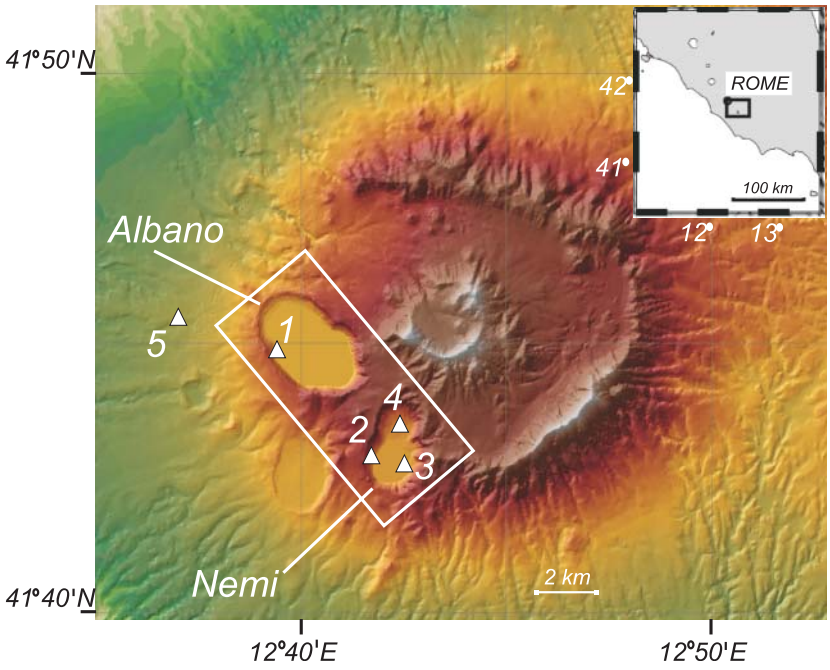

Figure 1: The Colli Albani area, the white square indicates the area of the laser scan survey; 1–5 GNSS/RTK surveyed sites (Table 3).

- recurrent seismic activity occurring as swarms, with many low magnitude events and seismic intensities never exceeding the VIII degree MCS (Mercalli–Cancani–Sieberg scale) (Feuillet et al. 2004, Amato et al. 1994);
- temperature and water composition variations (Boni et al. 1995, Calcara et al. 1995);
- gas emissions, mainly CO_2 and in minor part H_2S (Carapezza and Tarchini 2007, Tuccimei et al. 2006, Carapezza et al. 2003, Pizzino et al. 2002, Chiodini and Frondini 2001 and reference therein);
- significant ground deformations detected by high precision leveling, GPS and PS-InSAR time series. The mean rate of uplift ranges from 3 to 7 mm/yr, interval depending on the different survey techniques and the involved time span (Amato and Chiarabba 1995, Anzidei et al. 1998, Salvi et al. 2004).

Seismic activity is considered the main risk source for the villages located in the Colli Albani area, besides the Rome district and the old downtown (Tertulliani and Riguzzi 1995), whereas it is not yet clear which could be the level of hazard due to slow deformations.

Seismic swarms originate recurrently in the more recent volcanic structures, the freatomagmatics craters of the West side of the Colli Albani, in particular the Albano crater (Amato et al. 1994). Seismic tomography analyses recognized the presence of a low velocity volume, identified as magmatic chamber, located about 6 km below this recent area; on the contrary, a high velocity volume was identified under the oldest part of the volcano (Chiarabba et al. 1997).

The analysis of strain and principal axes deduced from seismology showed a preferential NE-SW extensional direction (Selvaggi and D'Ajello Caracciolo 1998), thus suggesting vertical deformations not directly linked with seismic activity (Amato and Chiarabba 1995).

Recent papers highlight the relevance of the detected high water level variations and catastrophic withdrawal of the Albano lake since pre-historic age as possible indicators of sudden variation of CO_2 flow and upwelling of hydrothermal fluids (Anzidei et al. 2008 and reference therein).

3. Bathymetric survey of the Albano lake

The Albano lake is the deepest volcanic lake in Italy and fills the youngest maar of the Colli Albani. A maar is a volcanic crater caused by a phreatomagmatic eruption, which is an explosion caused by a contact of groundwater and hot magma.

In November 2005 a high precision bathymetric survey of the Albano lake has been carried out. The bathymetric survey is well described in detail in Anzidei et al. (2006). Briefly, we want to recall here that to survey the submerged part of the Albano crater, two different sonars have been used: the multibeam Reason Seabat 8125 for depths within 100 m and Reason Seabat 8101 as far as the bottom of the crater (121.8 m asl).

The positioning of the watercraft has been defined by two GPS stations, the rover located on the mobile vehicle, working in RTK mode with differential corrections transmitted by a GSM modem and the refer-

ence GPS station (ALBA), located near the lake river, whose coordinates were estimated with centimeter accuracy with respect to the permanent station of INGR (Devoti et al. 2008), situated on the roof of the Istituto Nazionale di Geofisica e Vulcanologia in Rome, about 15 km NW from the lake.

Due to the various ranges of depths and the consequent employ of two different kinds of sensors, the surveys allowed obtaining data at different resolution level. The highest resolutions are achieved to shallow depths, within 100 m, the lowest to the others. To avoid the problem to manage irregular grids, due to the irregular resolutions, as first step the observations were interpolated on a regular grid with a mesh of 2 m, based on the lowest resolution. The mean accuracy of the bathymetry is about 50 cm (Anzidei et al. 2006).

All the measured depths are referred to the mean lake level, estimated at the moment of the survey at 336.7 m with respect to the WGS84 reference ellipsoid (Anzidei et al. 2006). The newly estimated maximum depth from bathymetry reaches −167.5 m and corresponds to the distance between the mean lake level and the bottom of the central crater (Anzidei et al. 2006). The high resolution bathymetric survey allowed defining in great detail the topographic shape and the morphology of the bottom and near the shore areas of the Albano crater (Figure 2, Anzidei et al. 2006). The floor is composed by coalescent and partly overlapping craters and wide flat surfaces separated by some evident scarps. Submerged shorelines are identified at depths between −20 m and −41 m and indicate the occurrence of significant lake level changes, likely between 7.1 and 4.1 ka (Anzidei et al. 2008). The presence of submerged debris flow channel and material accumulation from sub-aerial slopes is recently matter of landslide susceptibility analysis (Mazzanti et al. 2007).

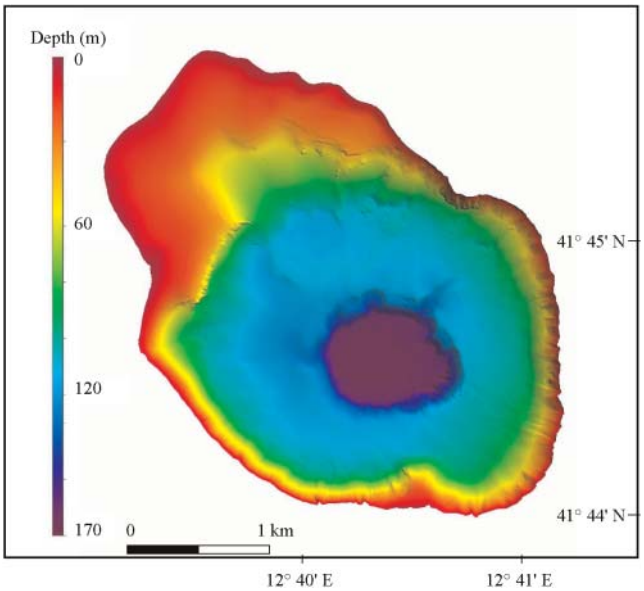

Figure 2: The bathymetry of the Albano lake (modified after Anzidei et al. 2006).

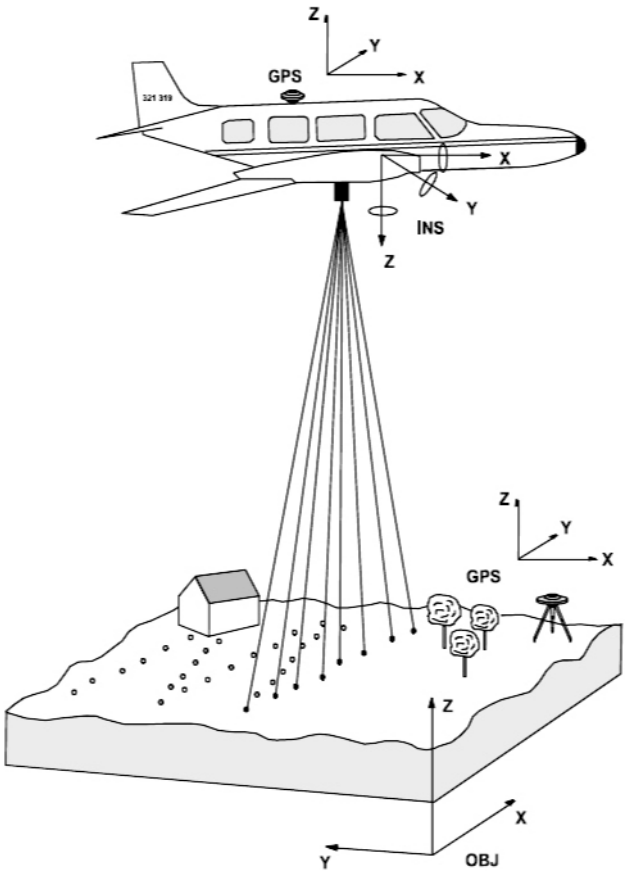

Figure 3: Sketch of the ALS survey (from http://geomatic.unipv.it/casella).

4. Airborne laser scan survey

The airborne laser scan (ALS) survey has been commissioned to the Compagnia Generale Ripreseaeree s.p.a. (CGR) to obtain a high resolution DTM of the Albano and Nemi craters. The flight has been planned to cover an area of about 35 km^2 including the Albano and Nemi lakes and some surroundings (Figure 1).

The survey has been carried out on 13 April 2006 by an aircraft equipped with three main instrumental systems: a laser scanner device, a GPS devoted to the positioning of the aircraft and an inertial measurement unit (IMU) composed by three accelerometers and three gyroscopes to record the attitude variations of the aircraft during the flight (Figure 3).

The laser scanner device employed is the system Optech ALTM 3033 characterized by a highly collimated laser beam in the infrared, pulsed with a fixed frequency. The survey was planned to cover the whole area by 13 stripes with an overlap of about 30% from a mean flight height of 1200 m with an expected nominal accuracy of about ±15 cm (Table 1).

Table 1: ALS survey and data availability.

Survey features
• Flight height 1200 m
• Mean density of points about 1 per m^2
• Swath width 462,17 m
• Scan angle $\pm$ 11 degree
Products
• Digital Terrain Model with mean accuracies
– Height within 50 cm
– Planimetry within 1 m
• Digital Surface Model (with vegetation and manufacts)
• DSM and DTM in Gauss–Boaga and WGS84 coordinates with orthometric and ellipsoidal heights
Unification with bathymetry
• DSM and DTM in Gauss–Boaga and WGS84 coordinates with orthometric and ellipsoidal heights

The area investigated by the ALS has highly variable morphology; in fact there are sectors of the craters characterized by steep slopes and other completely flat areas, most of them represented by the air-water interface (the lake surface area). Moreover some areas are highly vegetated and others are densely populated, making crucial the filtering procedure to separate the ground echoes from off-terrain echoes to obtain a reliable representation of terrain (Figure 3). Consequently, the raw data were carefully filtered step by step. The first step consists of eliminating gross errors or anomalous sites, simply recognizable being much higher or lower than the surrounding scattering points. The first may be produced by objects that do not rest on land, like flying birds or suspended electrical cables, whereas the second may originate from multiple reflection effects. The elimination of this kind of outliers allows obtaining a Digital Surface Model (DSM), i.e. the representation of terrain with vegetation and buildings. As example of the quality and information content of the DSM, we show a detail of the state highway Appia (s.s. Appia) at the first crossroads of the Genzano di Roma village a) from the DSM and b) from the satellite Quickbird (Figure 4).

The second step consists of the vegetation filtering by using the double echoes originating nearby the vegetation itself: in fact, as usual, a portion of the laser beam passes through gaps in the foliage and generates a second echo after the terrain reflection. This procedure is able to separate the two echoes if the vegetation heights are at least some decimeters.

The third step consists of the removal of artifacts and buildings by suitably implemented algorithms (Pfeifer and Mandlburger 2008), in our case the software Terrascan©, by analyzing the presence of strong gradients in the observations. This step is accomplished first automatically and then manually, to achieve a refined filtered file.

At the end of the whole procedure, the large amount of data (about $24 \cdot 10^6$ height values) does not permit to manage the whole digital model in one file. Then, the surveyed area has been divided in 17 plates corresponding to 17 different files. The DTM is available on request (riguzzi@ingv.it) as WGS84 ellipsoidal and orthometric heights and in two forms: as sparse points (ASCII format file, type .xyz) and as regular grid obtained from a bilinear interpolation (ASCII format file, type .asc) with mesh of 1×1 m.

5. Fast quality check of the DTM

As usual, DTMs can be realized in different formats depending on the type of the chosen grid. The removal or reduction of random measurement errors is possible with suitable interpolation techniques when doing the gridding.

The more known are surely the *Grid* formats, obtained from regular grids, and the *TIN* formats, obtained from irregular triangle grids (Figure 5). How is it possible to verify the quality of the ALS DTM? Does the *Grid* model provide a reliable representation of the Albano and Nemi craters?

The point density variations are not very large in ALS-datasets. Only after filtering, there is lower point density in urban areas and in forest areas. In general, *TIN* formats are considered more refined because are able to adapt the mesh size to the density of the original points that in this way are not modified. However, badly shaped triangles can lead to very wrong results when looking at the derivatives of the surface (slope, etc.). Thin triangles can be very steep, if the two points with small height difference are close together.

On the contrary, the *Grid* models modify the heights of the original points and being regular they are not completely adaptable to the density of the original data and to eventual morphological steep variations. Nevertheless, the *Grid* formats are widely used being simpler to manage and to process regular grids. The memory consumption of *Grid* formats is much lower, which allows storing a point density larger than the original one and maintaining the details found in the original data (Ackermann and Kraus 2004, El-Sheimy et al. 2005, Maune 2001).

Therefore we want to verify which of the two formats is able to better describe the terrain morphology of the Albano and Nemi craters. Starting from the sparse data (Figure 5), we have realized the model *TIN*, whereas the *Grid* model was already available (see previous section).

Then we have compared the heights pertaining to each model with the heights estimated after a kinematic GPS survey, carried out just before the ALS survey. The aim was to verify the congruence between differently estimated heights, in sample areas with soft morphology, taking into account that the nominal accuracies of both the surveys are similar, at decimeter level. It is useful to note that this

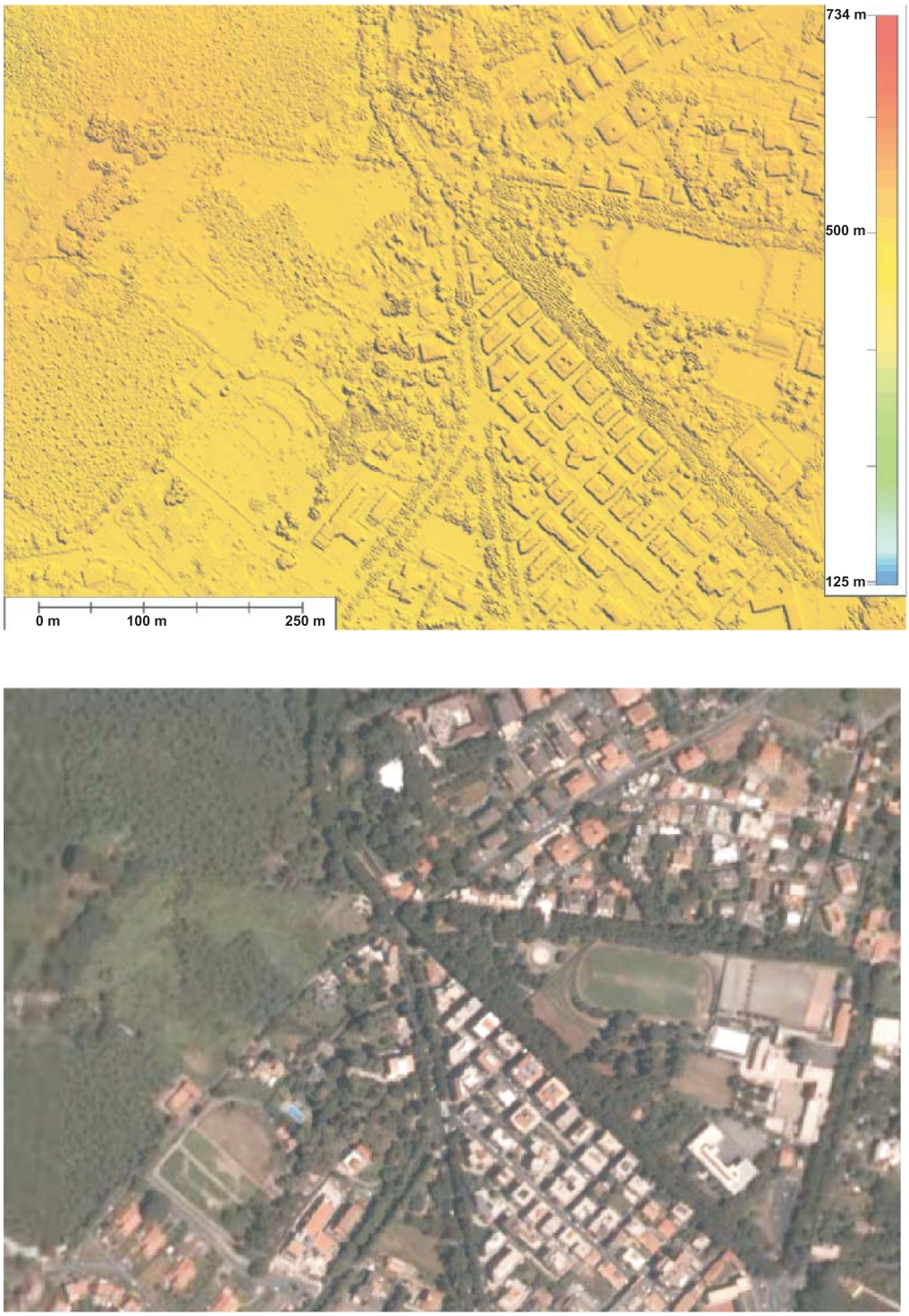

Figure 4: Detail of the s.s. Appia at the first crossroads of the Genzano di Roma village: a) image from the Digital Surface Model and b) from the satellite Quickbird.

comparison is performed on the ellipsoidal WGS84 heights since they are available for the GPS points, the ALS sparse and the gridded points. The comparison is performed by the software Arcgis© (vers. 9); the area is divided in 17 squared areas (Figure 6), for each one of them we have realized a *TIN* and a *Grid* model starting respectively from the sparse points and from the already gridded data. In the planimetric positions corresponding to the GPS measured points we have computed the heights both for *TIN* and *Grid* models, using the bilinear interpolation for the *Grid* model and the planar interpolation for the *TIN* model.

Despite what we expected, the adoption of the *TIN* format does not provide significant improvements: in other words it seems that a planar interpolation on a triangle mesh is not able to model the terrain mor-

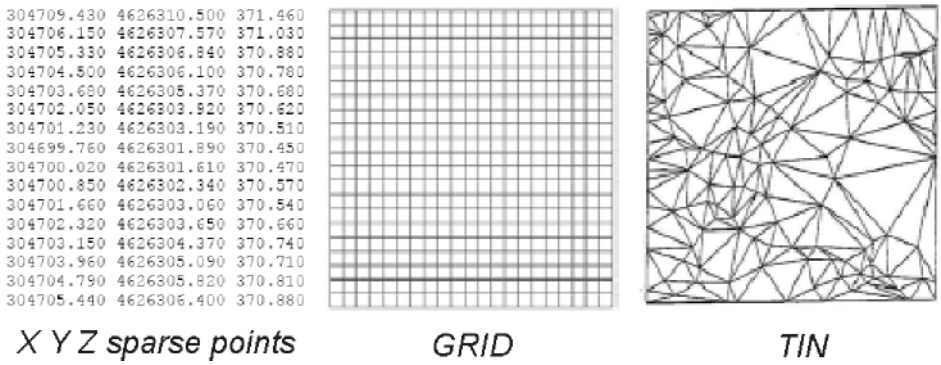

Figure 5: The raw data (.xyz) of the laser scan represent the position of surveyed sparse points; the *Grid* and *TIN* formats are generated after the processing.

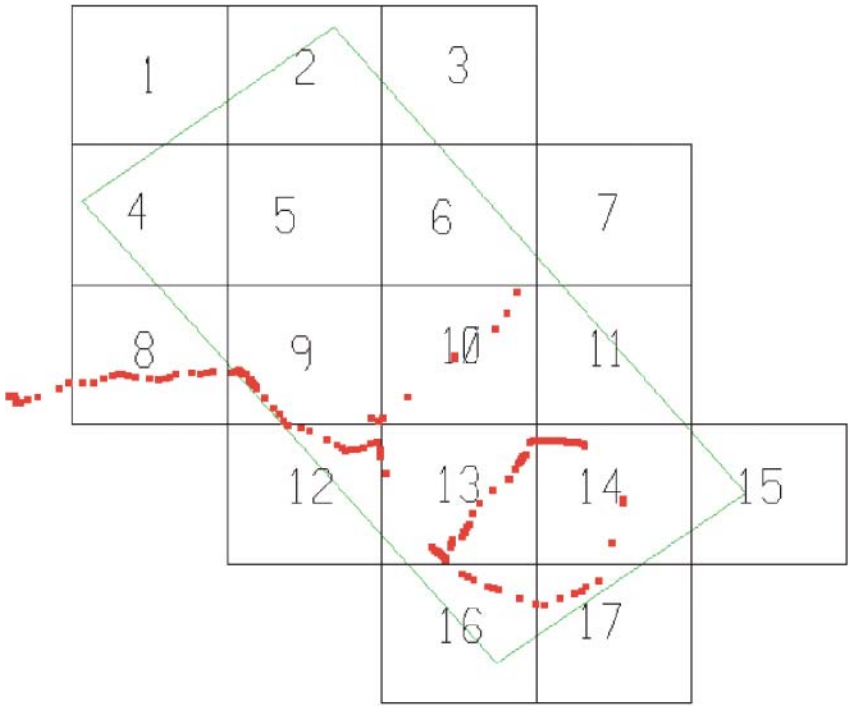

Figure 6: The area scanned by the ALS survey (green) divided in 17 squares and the trace of the points obtained after the fast GPS kinematic survey (red).

Table 2: Absolute values of height differences between models (*Grid*, *TIN*) and GPS survey.

	Grid	*TIN*
mean (m)	0.67	0.67
median (m)	0.54	0.53
rms (m)	0.52	0.52

phology of the Albano and Nemi craters better than bilinear interpolations on a regular square mesh (Table 2).

The fast GPS kinematic survey was performed by equipping a car with two *Trimble* GPS receivers and determining the vertical offset of the two *Zephir* antennas w.r.t. the road level with a simple local topographic survey (Figure 7). Since the investigated area is almost completely covered by trees (except for the lake and the urban areas), a preliminary survey was

Figure 7: Fast GPS kinematic survey: the antenna mounting on the roof of the car.

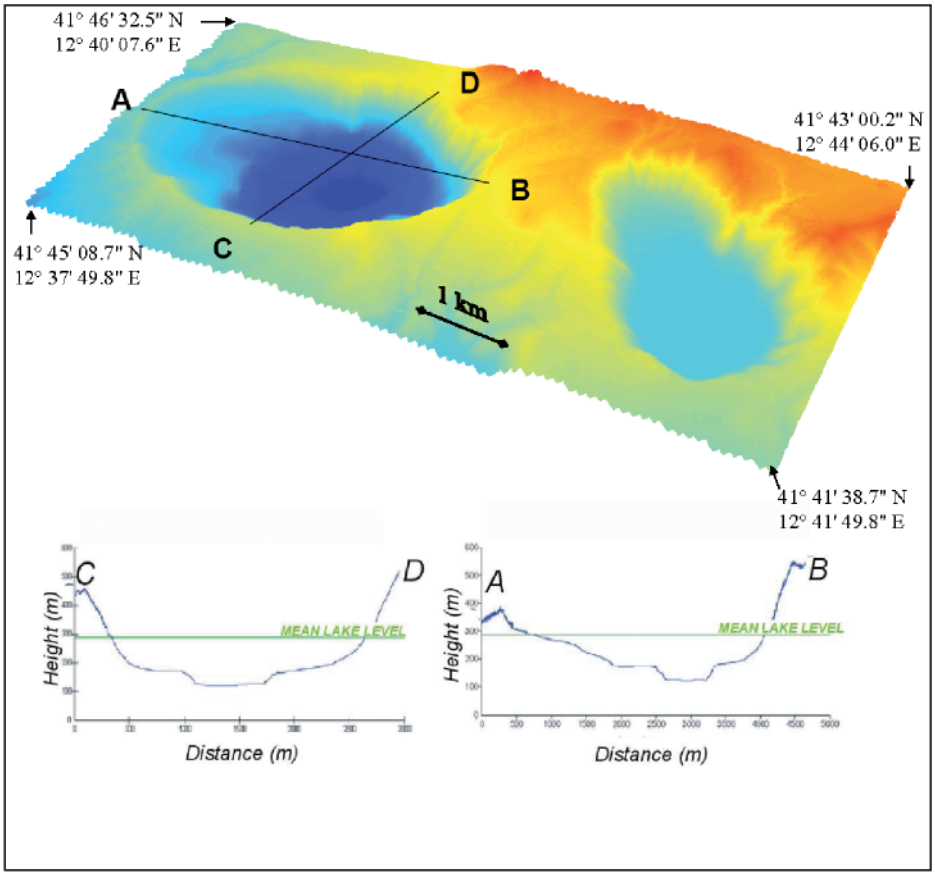

Figure 8: DTM after the unification of bathymetry and ALS survey.

performed, in order to assess the integrity of the GPS measurements w.r.t. the loss of lock. It was clearly shown that the phase measurements were too much corrupted by cycle slips, whilst the pseudoranges were good enough to guarantee a 3D submetric accuracy, completely suited for our purposes. It's obvious that a crucial problem of a kinematic survey is the reliability, since every point redundancy is assured only by the geometric strength of the satellites constellation and by the power of the signal. Therefore it is suitable to use three or more master stations in order to independently estimate three or more receiver positions during the shifting and hence carrying out an inner check; moreover, this redundant configuration allows the accuracy estimation of each point. In this experiment three master stations are considered, which are georeferenced in the WGS84-ITRF2000 with a centimetric accuracy and located in a range of about 30 km centered on the Nemi lake area.

Both the GPS master stations and the rover GPS are dual frequency receivers equipped with geodetic antennas. The kinematic survey was carried out with a sampling interval of 10 s, being the car speed around 50 km/hour, we have about one point each 100–150 m; the survey was concluded in three hours. After the processing and the outlier rejection, we obtain an average accuracy of 0.3 m along the horizontal and 0.6 m along the vertical. Note that when the surveys are carried out in volcanic areas, the accuracy, i.e. the capability of reproducing reliable values, is strictly dependent from the topographic variability and vegetation; consequently, taking into account that the fast GPS kinematic survey has a mean altimetric precision of about 50 cm, the heights estimated from GPS and ALS surveys are in good agreement. Similar results are reported in recent papers (Barbarella and Gordini 2006, Foxgrover and Bruce 2005).

After the quality check, we have unified the DTM obtained by the ALS survey and the bathymetry, cutting the area covered by the Albano lake (Figure 8). This step has been carefully carried out by overlapping a georeferenced orthophoto of the Albano lake, acquired during the laser survey, to the ALS DTM and eliminating all the heights located within the lake perimeter (corresponding to the unreliable values of the water heights from the ALS survey). The error introduced with this procedure, due to the 2D-tracing of the shore line, is within the mean accuracy level of the DTM. Then, we have unified the two cleaned, georeferenced height datasets by Arcgis having in origin different grids (laser 1 m; bathymetry 2 m); we have chosen to interpolate the 2 m-gridded bathymetry to 1 m with the nearest neighbor algorithm, the most conservative procedure, to avoid discarding 75% of the available ALS data.

6. GNSS/RTK survey to determine lake levels

The GNSS/RTK (Global Navigation Satellite System/Real Time Kinematics) technique allows estimating the position of the surveyed sites in real time with a precision comparable to that achievable with the classic static GPS surveys. It is based on the capability of processing simultaneously two data flows; one coming from a GPS receiver on site and the other coming from a network of GPS permanent stations with precisely determined coordinates.

We have carried out this kind of survey with two aims: the first, to measure the water level of the two lakes, since the ALS survey in our case is not able to provide reliable data on water tables (CGR report 2006); the second, to control the congruence of the heights obtained from different typologies of surveys, in other words to verify if the GNSS/RTK heights were in agreement with those retrieved by the ALS survey and with a leveling benchmark located in the area.

The GNSS/RTK survey has been carried out on 5 sites connecting the receiver by a GSM to the Internet site of the RESNAP-GPS, a regional network devoted to the real time positioning and navigation maintained by the University *La Sapienza* of Rome. The server receives the request of differential corrections from the rover receiver, identifies its position and provides to send him the appropriate differential corrections. Thereafter, the receiver is able to estimate rapidly its own position (or better the antenna position). The time spent from calling the network to get a precise position is about 2 minutes. All the information about the GNSS/RTK surveys by the RESNAP-GPS network is available at http://w3.uniroma1.it/resnap-gps.

The sites selected for the GNSS/RTK survey (Figure 1) are: the Albano shoreline water level (1), the Nemi drainage tunnel (2), the Nemi shoreline water level (3), the Nemi Roman ship museum (4), the leveling benchmark (5).

All the heights obtained after the surveys are WGS84 ellipsoidal and are characterized by a mean precision within 5 cm (Table 3). To obtain the orthometric heights (asl) it is essential to know the geoid undulations. In this area the geoid is always above the reference ellipsoid of about 48 m. The precise values of the geoidal undulations are estimated by the International Geoid Service (Barzaghi et al. 2002) and provided by the Istituto Geografico Militare (IGM). Table 3 shows the results of the sites after the GNSS/RTK survey. The sites 2, 4 and 5 of Table 3 are three control sites for which we dispose the ALS heights (2, 4) and the orthometric height from high precision leveling surveys (5). The control points show a very good agreement between the heights measured by different techniques, if the precision of each single technique is taken into account.

7. Morphometric updates of Albano and Nemi craters

The Colli Albani Volcanic complex is composed by many different craters generated during the different eruptive phases of which Albano and Nemi represent the more recent sites of activity.

The Albano and Nemi lakes occupy the low part of these craters, the first at 288.16 m (asl) and the second at 319.02 m (asl), The surface of the Nemi lake lies about 31 m above the Albano lake surface. Their present water level is well below the drain tunnels built in each lake during the Roman age (398–397 BC). These artificial pipes today do not drain any water as they are some meters above the lake levels, thus testifying in some way the water volume reduction occurred in recent times. The Nemi lake underwent to another human intervention, its water level was further lowered by about 23 m from 1928 to 1932 in order to facilitate the recovery of two ancient Roman ships, thereafter the water level was increased again. The water surfaces and the perimeters are estimated at the moment of the ALS survey; the water levels are achieved after the GNSS/RTK survey (July 2007), all reported in Table 4 and Table 5, unit in meter above the mean sea level.

The main morphometric characteristics of the two lakes result sometimes different from those reported by recent papers (Chondrogianni et al. 1996, Funiciello et al. 2003 and reference therein).

The Albano crater rim ranges between 367.0 m (NW) and about 530 m (asl) toward E-SE, where the slopes are steeper; the distance from the water surface and the lowest rim is 78.8 m. The Nemi cra-

Table 3: GNSS/RTK survey, WGS84 coordinates, geoid undulations and orthometric heights.

site	GNSS/RTK WGS84			Italgeo99 geoid N (m)	GPS RTK H_{orth} (m)	ALS H_{orth} (m)	IGM leveling H_{orth} (m)
	Lat (deg)	Long (deg)	h_{ell} (m)				
1	41 44 37.117	12 39 18.488	336.60	48.447	288.16	–	–
2	41 42 43.500	12 41 40.933	371.00	48.487	322.51	322.7	–
3	41 42 27.252	12 42 27.581	367.51	48.487	319.02	–	–
4	41 43 17.456	12 42 07.277	376.77	48.487	328.29	328.4	–
5	41 45 56.502	12 37 04.116	231.92	48.390	183.53	–	183.576

Table 4: Morphometric features of the lakes.

	Albano	Nemi
Area (km^2)	5.79	1.72
Perimeter (km)	9.5	5.4
Low-rim height (m)	367.0	426.0
Distance Lr-wl (m)	78.8	107.0

Table 5: Orthometric water heights (asl).

	Albano (m)	Nemi (m)
GPS RTK	288.16	319.02
Bottom level	121.8	–
water thickness	166.36	–

Table 6: Ellipsoidal water heights (WGS84).

Surface level	Albano (m)	Nemi (m)
Bathymetry – Nov. 2005	336.7	–
GPS RTK – Jul 2007	336.60	367.51

ter rim ranges between 426.0 m (SW) and about 650 m (E) (asl) where has almost vertical walls, reaching about the slope of 83° near the Nemi village; the distance from the water surface and the lowest part of the rim is 107.0 m.

Table 6 shows the water levels in WGS84 ellipsoidal heights for the Albano lake from bathymetry (Anzidei et al. 2006) and for Albano and Nemi lakes from our GNSS/RTK survey. The discrepancy between the Albano lake levels obtained from the bathymetric and the GNSS/RTK surveys may be explained taking into account the measurement uncertainties and the periodical variations due to seasonal influence.

It is important to note that the water level of the Nemi lake results nowadays at 319.02 m (asl), about 3 m above the topographic height (316 m) reported on the IGM tables (Istituto Geografico Militare, Sheet 150, 1:25000), whereas the Albano water level is about 4.8 m below the topographic height (293 m) reported in the same table. These large differences are probably due to two different causes: at the moment of the IGM survey (probably photogrammetric) the Nemi lake was recharging after the ships recover and it had not yet reached the equilibrium level, on the contrary the Albano lake underwent to a more or less continuous lowering.

8. Albano and Nemi lakes volume changes

Many studies, involving different research fields, have been carried out about level variations of the Albano lake (Capelli and Mazza 2005, Capelli et al. 2000, Dragoni 1998, Boni et al. 1995). The phenomenon is in fact more complex than expected at a first look.

In the past, until the 4th century B.C., catastrophic exondations occurred. The repetition of these events was prevented by a drain-tunnel dug by the Romans to control the water level, used until recent times. According to some authors these phenomena could be triggered by sudden injections, in the lake bottom, of hot and CO_2-rich fluids that are certainly present underneath the volcano; in principle, similar events are still possible nowadays (Funiciello et al. 2003, Anzidei et al. 2008).

In the Colli Albani area different superimposed and isolated water tables are present, due to the peculiar stratification of the volcano edifice (Bersani and Castellani 2005); the main documented levels are the shallower perched, the regional and some different confined aquifers (Capelli and Mazza 2005). The piezometric level (the height (asl) reached by water in a well) of the perched aquifer crops out in the lakes of Nemi and Albano. The regional piezometric level is presently located at approx. 200 m asl and its drainage has a SW direction. The Albano lake is now 166.36 m deep (with bottom at about 121.8 m asl, Table 5), thus intercepting both water flows and incurring in both level variations. In the last decade the water level progressively decreased. The main causes are still under debate, among them an important role is probably played by: the increasing water extraction from various wells, different values of seasonal rainfall, and deviations of water adductions for different aims (Capelli and Mazza 2005).

For the first time, using the information provided by the DTM and from the GNSS/RTK survey, it is possible to make more detailed evaluations of the lake lowering, neglecting the discussion of its causes, and using the integrated DTM with bathymetry it is possible to infer the water volume changing. To make such estimates we adopted well known "cut & fill" algorithms, implemented in the principal software for DTMs managing.

At the beginning we evaluated the change of lake volumes at different water levels: this information can give some useful indications for researchers in different fields. We started to compute the volumes from heights near to the drain-tunnel, reported as 292 m asl (Ministero LL PP 1978) and proceeded with decreasing heights, including the value of 288.16 m, the present water level estimated by the GNSS/RTK survey on July 2007 (Table 7). Taking into account the precision of this value and the accuracy of the bathymetric survey (0.5 m), we computed the maximum variation of the current lake volume as 6627094 m^3, with a relative error of about 1%. We take into account that in 1993 the lake was more or less at the level of drain tunnel, reported as 292 m asl (Tanga et al. 1996), and then decreased without reaching this level anymore. If we hypothesize a linear trend with constant volume decreasing in these years, it is possible to estimate the annual loss of

Table 7: Volumes of the Albano lake at different water levels.

Time (year)	h asl (m)	volume (m^3)
	293	472025901
1993	**292**	**466115542**
	291	460237073
	290	454385524
	289	448566137
2007	**288.2**	**444404564**
	288	442800840
	287	437097299
	286	431438370
	285	425825600
	284	420255486
	283	414723105
span	level loss	volume loss
2007–1993	3.8	21710978
yearly	0.27	1550784

water volume from 1993 to 2007 in about 1550784 m^3, Table 7.

Presently it's not easy to assess the real accuracy of the starting water level; for this reason, assuming pessimistically an error of about 50 cm and taking into account the uncertainty of the ALS DTM (20 cm), we derive a relative error on the water volume variation of about 40%. On the contrary, if we assume an initial water level uncertainty of the order of 10 cm, the relative error on the water volume loss decreases to about 20%.

In Table 7 are also reported the total amount of water level decreased from 1993 to 2007, 3.8 m, and the average loss level rate, about 27 cm/yr. Note that it is possible to retrieve a similar average value from Figure 6 of Capelli and Mazza (2005), being the slope of the trend about 22 cm/yr.

Supposing also that the volume trend will remain constant in the future, we can infer that in about 310 years the emptying of the Albano lake could be completed.

It is important to underline that these estimates have just the value of approximate projections, since it is hard to predict the trend of the lake level in the next years, being not completely predictable the amounts of each different cause contributing to the drawdown; moreover we hope that the provisions applied by the authorities devoted to the environmental control of this beautiful area can limit the water table loss.

In opposition to the Albano lake lowering, the Nemi lake level results increased of about 3 m, as reported in the previous section; although the bottom of the Nemi lake is located at about the surface level of the Albano lake, this could be an indirect proof that the two lakes belongs to two different aquifers.

9. Conclusions

The integration of the ALS survey, bathymetry of the Albano lake and the GNSS/RTK survey has produced a complete DTM useful for morphological studies of the Colli Albani volcanic area (Figure 9).

We are aware that it is almost impossible to assess the real accuracy of the DTM, however we attempt to infer its quality level by comparing the heights obtained from different techniques; in morphologically simple areas, between the ALS and kinematic GPS surveys we have differences within 50 cm and between the ALS and GNSS/RTK surveys this value is reduced to 20 cm (see Table 3). Although these accuracies may be considered optimistic, we believe them acceptable for most of the morphological/geophysical requests.

About the hydro-geological applications, the unified DTM and the GNSS/RTK survey have permitted to evaluate the present water levels of the Albano and Nemi lakes with high accuracy, the worrisome

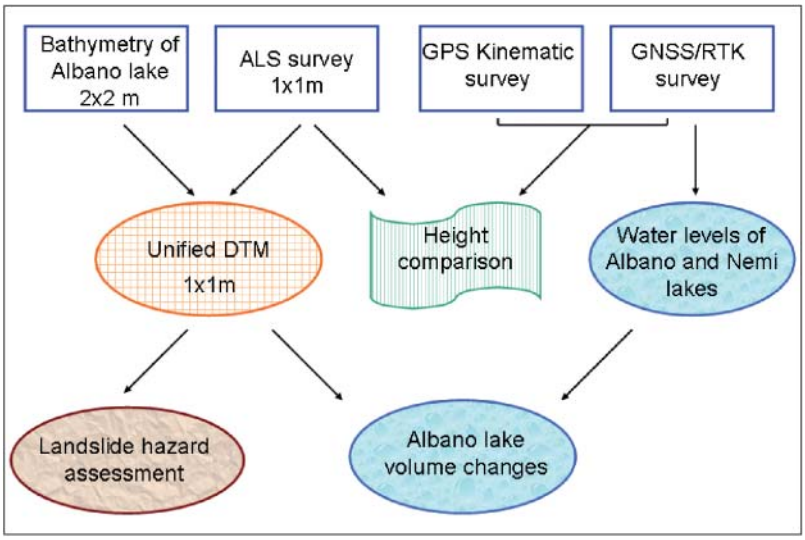

Figure 9: Sketch of the workflow.

volume decreasing of the Albano lake since 1993 and the indirect proof that the two lakes could belong to two different aquifers.

About the landslide hazard assessment, the work is in progress; recently, the unified DTM has allowed to identify combined sub-aerial/sub-aqueous debris flows; Avolio et al. (2008) have recognized from the DTM the landslide occurred in the eastern slope of the Albano lake on 7 November 1997 after an intense rainfall event. The initial debris flow, evaluated of about 300 m^3, reached the shoreline with an increased volume of some thousands of m^3; part of the material was deposited along the coastline, whereas a greater quantity entered into the water, generating a little tsunami wave and underwater accumulation.

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