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Full-Waveform Terrestrial Laser Scanning for Extracting a High-Resolution 3D Topographic Model: a Case Study on an Area of Archaeological Significance

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Abstract
This paper describes a method, which uses full-waveform terrestrial laser scanning to survey the surface of the slope below the Temple of Juno, located in the Valley of the Temples in Agrigento (Sicily, Southern Italy). The surface is characterized by the presence of large rock blocks, which have fallen down from the upper side; possible further detachments of rock blocks would cause a situation of general instability, with a very high risk to the archaeological structures in the near future. The methodology was designed to evaluate the potential of full-waveform laser scanning technology for the production of a very high resolution 3D topographic model of the slope, to be used as a support for the interpretation of geomorphological processes and for geotechnical analysis.
Keywords: Terrestrial laser scanner, 3D model, full waveform, DTM, geomorphology.

Introduction
The 3D modeling of natural environments is a challenging task, mainly as a result of the complexity and variability of the landscape and the difficulty of the surveys. Nevertheless a correct representation of such environments as slopes or rock cliffs is very useful for geomorphological and geotechnical analysis, as well as in designing technical interventions to ensure the safety of people and structures. In more recent years the use of new systems, usually characterized by high accuracy, has resulted in the production of reliable and detailed 3D topographic models [Borgatti et al., 2010].
These models constitute a major technical aid for geologists and geotechnical engineers in obtaining insights into the geological characteristics of a site and/or studying the mechanical dynamics of unstable areas. The production of a detailed 3D topographic model has several advantages especially for hazard mapping [Di Mauro and Van Cranenbroeck, 2012]: firstly it represents a valid tool for performing static modeling analysis and assessing stability dynamics by producing geo-structural models [Ferrero et al., 2011]; secondly, it facilitates the identification of the morphological features of rock structures (such as discontinuity

orientations, fractures and roughness) as well as precise sizes and positions of rock elements [Slob et al., 2004]; thirdly, it can provide the basis for the simulation of potential rockfall paths [Alba et al., 2005].
Digital photogrammetry and laser scanning enable any type of environment to be surveyed with high precision in order to obtain detailed 3D topographic models [Bitelli et al., 2004]; in particular, long range terrestrial laser scanning has become one of the most effective and rapid techniques for acquiring 3D metric information, even in relatively large areas and sites that are difficult to access. It is particularly advantageous in emergency situations, where high risks may potentially be posed for people and/or infrastructures. In particular, the use of laser scanners for monitoring of landslides and rockfalls makes it possible to estimate deformations and movements in multi-temporal sequences [Barbarella and Fiani, 2013] to a high degree of accuracy, including the possibility of sharing high density data on GIS platforms [Huat and Ali, 2012]. Another important aspect is related to the opportunity to integrate data obtained from a terrestrial laser scanning survey with those acquired by other means of geomatic surveying techniques, in particular for the purpose of performing metric comparisons by combining data provided by close-range photogrammetry or ground-based InSAR [Mazzanti and Brunetti, 2010; Salvini et al., 2013].
Terrestrial laser scanning for geomorphological investigations has to deal with a number of critical factors: due to the irregular shapes of many natural features, occlusions and shaded areas can be numerous and sometimes difficult to prevent, especially if the scan position is distant from the surface. Other issues are related to the maximum resolution, which is mainly determined by the distance between the instrument and the object, and to surface reflectivity, which is related to its roughness [Sturzenegger and Stead, 2009].
Additional critical aspects usually arise during the digital reconstruction and modeling phases, in which various operations of filtering and vegetation removal are required. In densely vegetated areas the laser beam may meet with particularly significant obstructions. In addition, a decrease in point density occurs when the distance from the laser scanner increases.
Major progress has been made in improving the ability of terrestrial laser scanners to filter vegetation. The use of a new generation of terrestrial laser scanners, which exploit full-waveform technology, adding value to the dataset produced, has yielded significant benefits. These devices are able to provide multiple return echoes and relative information on the intensity and width of the return signal, thus allowing a certain degree of automatic segmentation of points, facilitating more accurate 3D modeling.

Study area and aim of the work

In this study a laser scanning survey was carried out in order to model a large slope within the archaeological park of the Valley of the Temples in Agrigento (Sicily, Southern Italy). The park covers an area of about 1,300 hectares and is of great historical and cultural interest; in 1997 it was included on the UNESCO World Heritage List. The park's archaeological structures are located on a long ridge outside the modern town of Agrigento and include most of the ancient city and its public monuments, such the remains of several Doric temples and a large concentration of necropolises, fortifications and sanctuaries. The most impressive remains are those of the temples, in particular the Temple of Concordia, the Temple of Juno (or Hera Lacinia) and the Temple of Hercules (or Heracles), which are among the best preserved and restored works in the area.

The survey that forms the basis of this paper was conducted in April 2012, with a full-waveform terrestrial laser scanner. The use of such technology provided a detailed model of the slope and of many rock elements, as identified in the observed area (Fig. 1).
The aim of the work was to evaluate the potential of full-waveform technology and to develop a processing methodology to produce an effective 3D topographic model for geomorphological and geotechnical investigations as well as hazard assessment. An effective workflow process has made it possible to obtain a multi-resolution 3D model, split up into several parts or sub-models. This model has been used as a base for extracting two-dimensional geometric primitives (contour lines and vertical sections) and for calculating the volumes and positions of the various rock elements as well as the distances between them. The possibility in the final model to divide and separate the most representative geomorphological features entailed providing it with the necessary information to deduce the evolution and the dynamics of mechanical detachment of rock blocks from the summit of the ridge.

Figure 1 - Sparse rock blocks below the Temple of Juno.

Full-waveform terrestrial laser scanning technology

Laser scanning technology based on the time-of-flight measurement principle makes it possible to acquire dense 3D point clouds by recording accurate information concerning the range and reflectance of a single point with respect to each single backscattered pulse. Previously, in airborne laser scanner systems, significant technological innovations had already made it possible to acquired additional information from a single pulse. This is possible since a single laser signal can theoretically detect multiple objects along its path.

These instruments are called *multi-pulse* laser scanners and they allow more than one return echo to be recorded.

The analysis of the waveform of the return laser signal, which is the basis of so-called full-waveform technology, represents a further innovation in the field of laser scanning technology and was commercially introduced in 2004, in a small number of airborne laser scanners designed to detect large forested areas [Mallet and Bretar, 2009; Pirotti et al., 2012]. Only in 2008 was the first commercial full-waveform terrestrial laser scanner (*LPM-321*) introduced by Riegl.

Full-waveform technology allows a *pulse-detection* post-processing method to be applied to the digitized backscattered signal, in which a theoretically infinite number of echoes can be identified, with respect to a single emitted signal [Wagner et al., 2004]. In laser scanning technology returning discrete echoes, together with information about range (which is essentially provided by recording the time of the peak energy), instruments can also record data about the reflectance (amplitude at peak) of every point. In full-waveform laser scanning technology these parameters are integrated with others specifically concerning the waveform, such as amplitude and pulse width. The former is a logarithmic ratio comprising both parameters belonging to the device (emitted laser pulse peak power and receiver aperture) and parameters related to the final target (essentially its reflectance and range), while the latter is defined as the width depending on the geometry of the target and describes the range distribution of all individual scatterers contributing to one echo. Range, amplitude and pulse width all contribute to acquire a complete tridimensional and decomposed multi-parameter dataset, which is subsequently modulated by a Gaussian function for classification purposes [Ullrich et al., 2007].

Progress within *full-waveform analysis* (i.e. the process of discriminating the signal thus contributing to segmentation of the data) allows vegetation and soil to be precisely discriminated; more recently, systems of greater complexity are capable of performing a full classification of species of trees and other vegetation [Reitberger et al., 2009].

In airborne systems, *full-waveform analysis* is performed *off-line*, as the recorded raw data are analyzed and decomposed only in the post-processing phase. The full-waveform terrestrial laser scanners available today (also called *echo-digitization* laser scanners) use a method analogous to that employed by aircraft systems, with the only difference that the preliminary phase of waveform decomposition, i.e. the extraction of range, amplitude and width, is entirely processed in real time by the instrument, with obvious benefits in terms of time; essentially, the laser signal is processed entirely *on-line*. They combine the advantage of an immediate result with the ability to recognize multiple targets and thereby increase metrical accuracy. Multi-target detection helps in separating points belonging to the soil or continuous surfaces from points belonging to different layers of vegetation [Pfennigbauer and Ullrich, 2008] with some limitations regarding the minimum distance between two nearby targets that can be distinguished directly from a single pulse, usually referred as Multi-Target Resolution (MTR). MTR in full-waveform terrestrial laser scanners is typically about 0.80 m (e.g. with the *Riegl VZ-400*); echo pulses separated by shorter distances within the same laser shot cannot be physically distinguished, so that the measured range can be only estimated [Guarnieri et al., 2012; Pirotti et al., 2013c].

These systems are particularly useful in surveying sites in non-urban environments, where generally there may be significant accessibility constraints and dense vegetation [Pirotti et al., 2013b]. Usually, various types of digital products can be obtained from full-waveform laser data: high precision DTMs (Digital Terrain Models) and DSMs (Digital Surface Models) [Hug et al., 2004], vegetation density maps and derived canopy height models [Pirotti et al., 2013a]. In addition to the production of high precision terrain models for topographic purposes, this new generation of laser scanners is fully employed for urban classification and city modeling, as well as surveys in architectural and archaeological contexts [Doneus et al., 2009]; some experimental systems have even been tested recently for security and safety purposes [Wallace et al., 2010].

The technical potential of full-waveform terrestrial systems is widely used for investigations in geological environments, where considerable distances can be achieved (up to 6 kilometers with the *Riegl VZ-6000*), and forestry applications. The production of detailed 3D topographic models for studies on rockfall dynamics and slope stability [Fowler at al., 2011] is facilitated by the automatic classification of data, allowing geological features to be more accurately modeled even in the presence of high density vegetation and various physical obstacles, such as fences and trellises. More recently, full-waveform technology has been used for applications concerning the biomass surveys (in particular trees), as it is able to discriminate between points belonging to compact biological entities (trunks and branches) and points belonging to entities with a low degree of obstruction (mainly leaves and twigs) [Yao et al., 2011]. This classification has proven to be very useful in improving the accuracy of estimations of biomass and timber volume, as well as general information on the tree structure itself [Pirotti, 2011].

Concrete improvements are expected in the level of *on-line* processing data for terrestrial systems: in fact, the ability to perform a real-time echo-signal digitization, although useful in speeding up survey operations and halving the time of post-process editing, still presents some limitations with regard to the maximum amount of data that can be effectively managed and decomposed during the pulse detection phase, thus making it impossible to perform, a more detailed classification of points.

The case-study: the slope below the Temple of Juno

The area around the city of Agrigento has a long history of problems related to geological instability. In particular the large area comprising the Valley of the Temples shows a morphological evolution conditioned by specific geological and geo-structural characteristics.

The Valley is characterized by a long ridge formed by a geological Pleistocene succession, known as the *Agrigento Formation*, which overlies the Middle-Upper Pliocene clays of the *Monte Narbone Formation*. The latter consists of about 200 meters of regularly bedded grey-blue marly clays, which form the base of the slopes in the Valley of the Temples. The *Agrigento Formation* is characterized from the base upward by clayey-sandy silts, marly sands and calcarenites. The calcarenites show several sets of discontinuities, which are made more pronounced by erosion and dissolution processes, resulting in the separation and detachment of calcarenite blocks from the top of the long ridge upon which the Temples were built [Pagliarulo and Parise, 2000].

The eastern sector is one of the most critical as regards slope and rock mass instability, due to the superimposition of a rigid body (the calcarenites) over plastic materials (clayey silts and underlying marly clays). The different geo-mechanical behavior of the two layers has caused

the calcarenites to break into blocks in a checkerboard pattern. The phenomenon is further conveyed by the action of atmospheric agents such as rainwater and wind, which contribute to wide fractures through a slow process of infiltration and erosion [Cotecchia, 1996].
The investigated site was limited to the area below the Temple of Juno (an area of about 16,000 square meters with a difference in height of about 150 meters); this part is characterized by one of the most critical conditions because the temple is built very close to the margin of the upper ridge (about 2-3 meters away from the columns: see Fig. 2). The conditions of instability can be clearly deduced by the presence of medium-to-large-sized fallen blocks all along the margins of the archaeological site and by the traces of ancient stabilization operations, essentially consisting of mural consolidations and substructure walls, just around the Temple.

Figure 2 - Aerial view of the investigated area: the temple is very close to the margin of the calcarenitic ridge.

Data acquisition

The survey was carried out over two days using a *Riegl VZ-400* time-of-flight full-waveform terrestrial laser scanner. This instrument is capable of a maximum range of 600 m, with a capture rate up to 125,000 points per second. It is characterized by a 360° horizontal field of view and a 100° vertical field of view and an angular resolution of 1.8 arcsec, corresponding to a maximum resolution of 5 mm at a distance of 100 m.
The particular conformation of the site has strongly influenced data acquisition, since obtaining the required full coverage of the area is made difficult by a number of occlusions caused by the presence of numerous blocks and rock fragments spread over the entire slope. From the outset it was clear that performing acquisitions only from external areas would be insufficient to cover the entire area and to obtain a satisfactory level of detail. To

ensure complete coverage and a detailed reconstruction, the survey was planned in order to perform the scans directly within the area, so as to avoid such occlusions due to the presence of larger rock blocks.

A total of seventeen scans were performed from fourteen different scan positions, with resolutions ranging from 2 cm to 10 cm at a distance of 100 m; six scan-positions were located in the lower part of the slope and eight at the top (Fig. 3).

Some retro-reflective cylindrical targets were strategically placed in order to align and merge all of the scans. A GNSS survey of the retro-reflective cylindrical targets was carried out in RTK mode. The coordinates of each cylindrical target were determined with the aim of geo-referencing the final model in the UTM-ETRF2000 reference system. This operation was performed with the aim to make laser scanner data comparable with other data obtained in subsequent surveys.

Figure 3 - Scan-positions: fourteen scans were performed within the area in order to cover as many parts as possible (each color represents a single scan).

Data processing and modeling

The workflow was characterized by a sequence of operations with an initial phase of registration, geo-referencing, filtering (including exploitation of the online *full-waveform analysis* and classification produced by the laser scanner) and merging of each scan, followed by a phase in which the entire point cloud was processed into three distinct groups of data; in the final step all the sub-models were assembled together for the production of the final 3D model (Fig. 4).

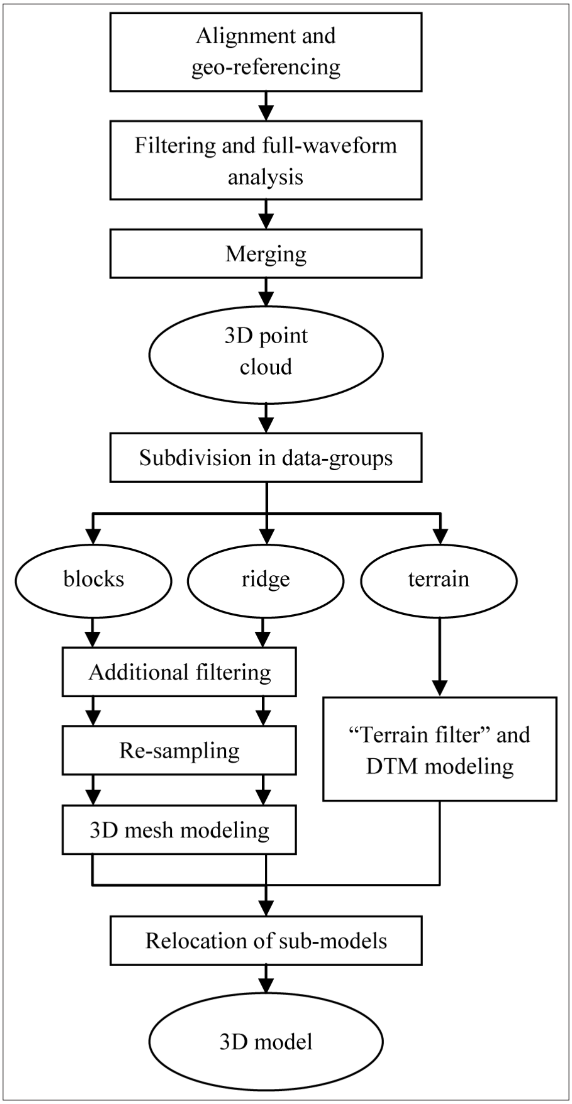


Figure 4 - The data processing workflow: after preliminary alignment and filtering the merged point cloud was subdivided into three groups of data, which were separately processed and then relocated in the final 3D model.

Point cloud data were processed and modeled using *Riegl Riscan Pro* software, while a number of additional modeling operations, in particular the reconstruction of rock blocks and the upper ridge, were performed with *Geomagic Studio*.
All of the scans were initially registered by means of automatic recognition of the cylindrical retro-reflective targets, followed by the application of an iterative tool, “Multi Station Adjustment”, based on an Iterative Closest Point (ICP) algorithm, which minimizes errors in alignment of all the scans by calculating the best overall fit between them. The scans were at first aligned with respect to an arbitrary reference system; they were then georeferenced in the UTM-ETRF2000 reference system through the coordinates obtained from the GNSS survey.
After registration, an initial automatic noise filtering process was applied, and non-useful points (namely those points obviously belonging to the vegetation or external to the area of study) were removed. A second filtering phase was carried out by exploiting the full-waveform capability of the instrument in order to discriminate between various backscattered echoes and identify four main categories of points (also referred to as *targets*): *single*, *first*, *other* and *last*. However, only two of the categories contain points that are actually usable for modeling purposes: the *single target* group, consisting of points which provided a single echo (corresponding to blocks and rock walls, architectural artifacts, etc.) and the *last target* group, i.e. containing points which represent the last pulse detected within a signal decomposed into multiple return echoes and which presumably belong to the ground or a compact surface below the vegetation. The *first* and *other target* categories contain all of the intermediate echoes that occur when the laser beam undergoes multiple reflections. In these types of terrestrial laser scanners, with the exception of the first pulse, it is not possible to divide the multiple reflections, which instead are classified within a single category. For this reason, the points belonging to the *first* and *other target* categories were generally classified as “vegetation” and not used for modeling operations. The advantage of *full-waveform analysis* is two-fold: the total number of points is reduced drastically, and the long, laborious process of manually removing the points is largely avoided. The discrimination of all registered echoes was applied individually to all scans. This initial operation reduced the total number of useful points by over 60%.
The merging of all scans generated a point cloud with over 72 million points (Fig. 5), a number that is still too high to be processed efficiently. Furthermore, the density of the points in some areas is highly redundant. Therefore, the whole point cloud was divided into three distinct groups through a semi-automatic identification of the most prominent geomorphological features: one group of points belonging only to rock blocks, another relative to the ridge and finally a group containing the points belonging to the slope (Fig. 6). The modeling operations were carried out individually for the three groups in order to obtain partial geometrical models with different resolutions which were later reassembled to obtain the final product. A geometrical model decomposed into sub-sets was deemed to be the most useful for extracting metric information and facilitating the investigation of the main geomorphological processes. All of the sub-sets were individually re-sampled using *Riscan Pro* according to a spatial *octree* procedure to optimize further operations [Wang and Tseng, 2011; Schöna et al., 2013].

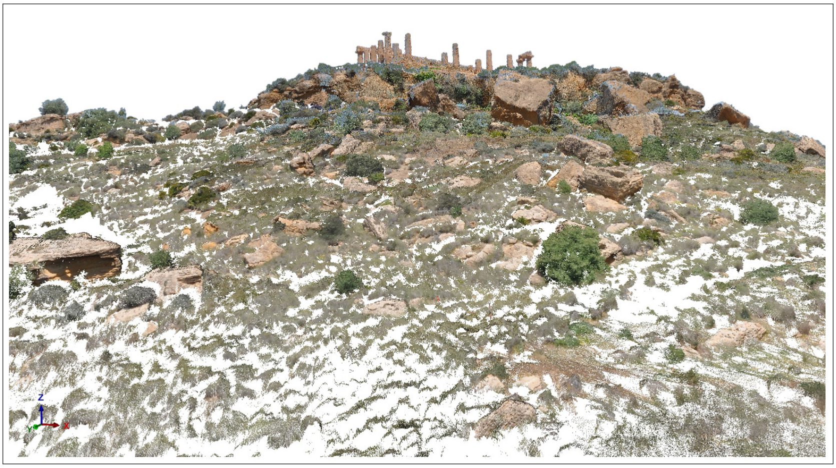


Figure 5 - Final point cloud of the investigated area.

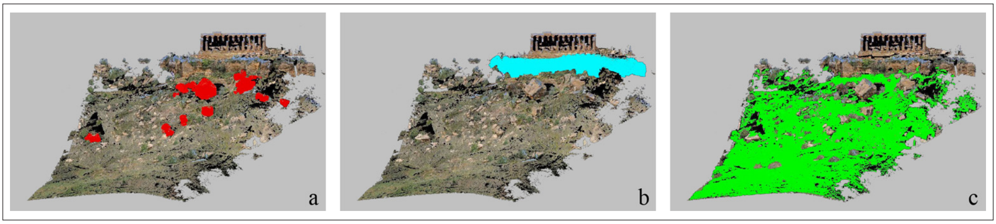


Figure 6 - Subdivision of the point cloud in three groups of data: (a) blocks, (b) ridge, (c) slope: identification of the groups was conducted by a semi-automatic classification as well as manual selection.

Regarding the rock blocks, a number of additional filtering steps were carried out to eliminate any disconnected elements and small areas with residual vegetation. This was achieved using specific filters based on the selection of isolated points (or small groups of points) exceeding a predetermined distance threshold from neighboring points. Finally, the individual sub-models representing the blocks, thus filtered, were re-sampled at a resolution of 2 cm, in order to preserve as much detail as possible (Fig. 7). The models were closed at the bottom with flat or simplified geometric surfaces since it was not possible to collect data from the lower part in contact with the ground. This operation certainly introduced a degree of approximation in estimating the exact volumes of blocks, but it was deemed negligible for the purposes of this analysis.
The upper ridge was modeled using a similar procedure, although the filtering operations were more challenging, due to the presence of areas with very dense vegetation, which are not completely eliminated by *full-waveform analysis*. As a result, the surface is characterized by areas with significant empty spaces or with a very low point density, which were partially filled by the subsequent triangulation operation by means of an approximate geometrical reconstruction. As in the case of the rock blocks processing, the group of points related to the ridge was re-sampled to 2 cm in order to preserve the most significant morphological details (Fig. 8).

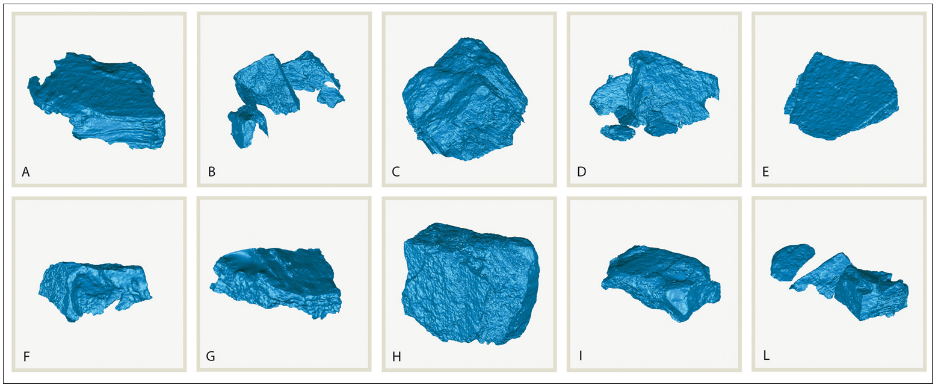


Figure 7 - High-resolution 3D models (2 cm) of the more prominent rock blocks.

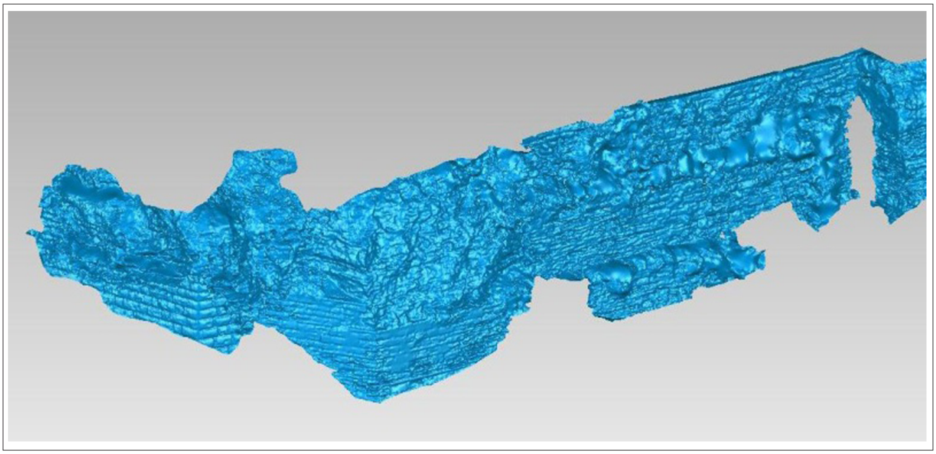


Figure 8 - High-resolution 3D model (2 cm) of a portion of the upper ridge.

In order to model the slope, the points were filtered by means of an iterative tool provided by *Riscan Pro*, "Terrain Filter", which can extract all residual points belonging to the vegetation and to unrelated elements, so that the remaining points can be processed for the construction of a DTM of the area. The filter works through an iterative sequence of operations that generates a series of *2.5D raster* models with progressively higher resolutions; corresponding equidistant surfaces are then calculated, enabling distant and external points which are insignificant for the purpose of digital reconstruction to be eliminated [Axelsson, 2000]. The resolution of the DTM was set at 20 cm.
In the final step of the modeling process, the comprehensive 3D model of the site was therefore obtained through the relocation of the sub-models previously produced (blocks and upper ridge) within the DTM (Fig. 9). In the resulting model it is therefore possible to select individually the various groups of objects. It was also advantageous to keep the various entities separated, in order to activate/deactivate the individual elements when necessary. This facilitated the operations of extraction of metric information (distances and volumes) and the generation of geometric elements (contour lines, vertical and horizontal sections).

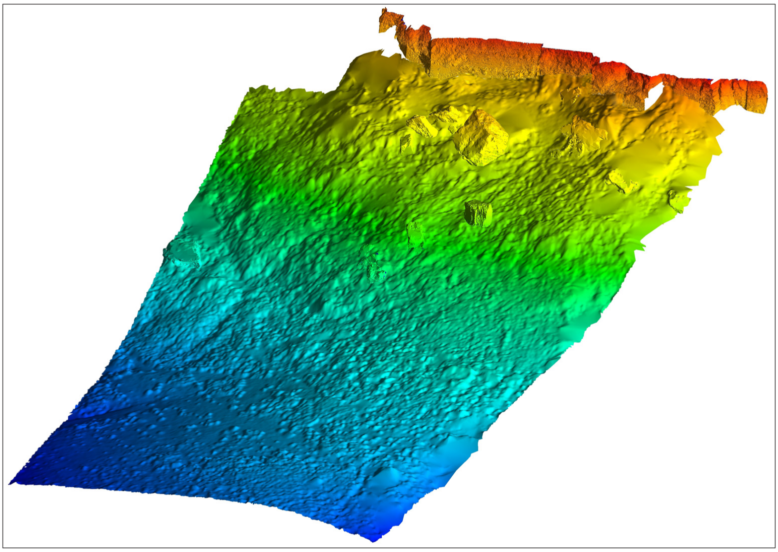


Figure 9 - Multi-resolution 3D model obtained from the relocation of all sub-models (blocks and upper ridge) on the DTM of the slope.

Considerations about the digital reconstruction process

The use of full-waveform laser scanners offers numerous advantages, that include the ability to obtain a more reliable DTM and much more detailed surfaces. Nevertheless, the quality of the obtained results must be interpreted and evaluated with respect to the acquisition range, together with considerations concerning the laser footprint size, which depends on the angular resolution of the instrument [Pirotti at al., 2013b]. It is far from obvious that at short distances the laser footprint is smaller and consequently not always able to easily overcome all of the various interposed obstacles, in particular vegetation. The degree of precision obtainable must take into account the presence of such constraints, which may affect accurate surface reconstruction, resulting in several different sources of error [Coveney and Fotheringham, 2011]. For the production of high resolution models, it is extremely important to be certain that the filtered points really belong to the object's surface. Without such certainty, a valid 3D product cannot be obtained. Moreover, the filtering and re-sampling processes involved may lead to an insufficient number of points and/or a low-density point cloud that may affect the triangulation process.

In the survey of the slope below the Temple of Juno it was possible to identify two main patterns of vegetation: a varied presence of grass and sparse shrubs on the slope and many compact groups of bushes partially covering the upper calcarenite ridge. As explained in the previous paragraph, for the slope surface (resolution of 20 cm), a high degree of automation was applied during the point filtering process; in contrast, the digital reconstruction of the ridge, for which a resolution 2 cm had been set, was carried out by means of semi-automatic filtering applied only to localized, limited areas. After the triangulation process had been completed, several holes and gaps appeared, all of them concentrated in those parts where bushes had been partially removed.

In order to better evaluate the level of penetration of the laser beam and the efficacy of the modeling procedures used, the quality of the final digital reconstruction was analyzed. Specifically, the analysis was applied to a small portion of the ridge consolidated with a masonry block wall, showing prominent geometric regularity but characterized by the presence of a considerable amount of bushes (Fig. 10).

Figure 10 - Portion of the ridge characterized by dense bushes; in this area the ridge is largely consolidated with a masonry block wall.

The digital reconstruction of the ridge was generated with a high density triangulated 3D surface that is marked by some irregularities (disconnected triangles, spikes and gaps), specifically in the areas with more abundant vegetation (Fig.11). In these areas it was not possible to obtain a highly accurate geometrical correspondence between the reconstructed surface and the object. A comparison between the triangulated surface, which was almost exclusively reconstructed by automatic procedures, and the set of all points belonging to the vegetation, which were discriminated both by means of eco-digitization and by additional filtering, was conducted to verify the qualitative aspects of the reconstruction. The decision to reconstruct these parts with this procedure, instead of using (for example) ideal plans according to the regular geometry of the wall, was motivated by the desire to understand the level of effective automatic reconstruction that could be reached with the available dataset. Using *Geomagic Qualify* the generated surface was associated with different sets of points: *first targets*, *last targets* and *residual vegetation*. All three sets were alternatively compared with the surface along a predetermined vertical section (Fig. 12). It must be underlined that these sets of data are independent from the different acquisition distances, since they are the result of all the acquired scans.

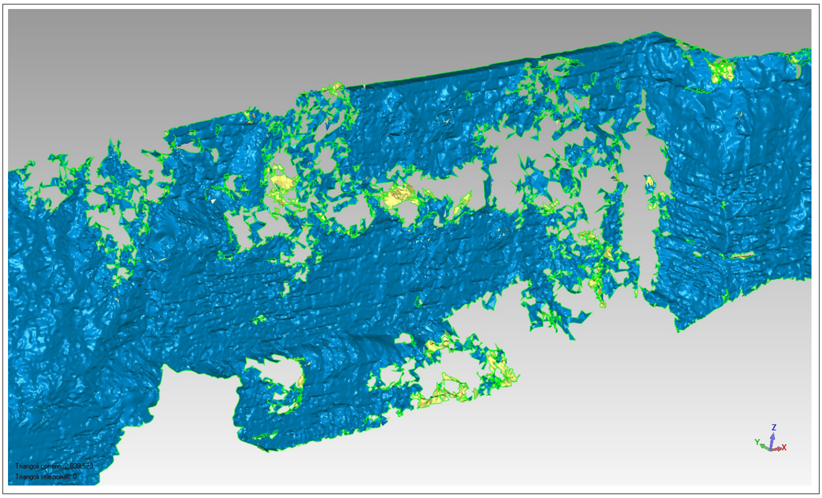


Figure 11 - Discontinuities and gaps on the 3D model of the ridge for the presence of vegetation.

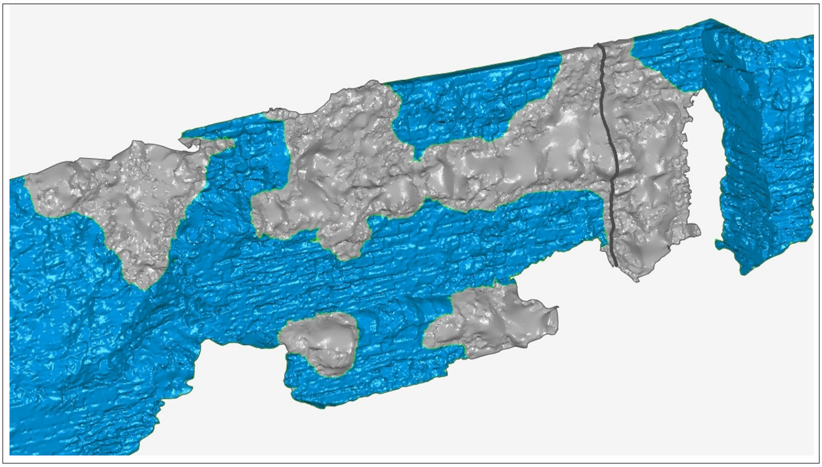


Figure 12 - 3D model of the ridge after automatic editing (the parts in gray are the reconstructed areas below vegetation) and the vertical section used for comparison.

The analysis enabled the maximum distance between the farthest point and the surface to be determined. In all the comparisons performed there are at least two specific zones which show the largest deviations, from a value of 1.192 m (*residual vegetation*) to 1.259 m (*last targets*), while the maximum value of penetration is 1.529 m, considering the *first targets* set, i.e. the set of points which theoretically is the farthest from the surface (Fig. 13). Obviously, although the final result of the reconstruction does not correspond to the real shape, especially when a high level of morphological detail is required, the advantages provided by the discriminative power of full-waveform technology are evident, in comparison to what could be achieved with a mono-echo laser scanner, where it would have been impossible to go so deep. Nevertheless, when dense and compact obstacles are interposed between the laser source and the surface, the choice of a resolution as high as 2 cm could be a critical issue throughout processing. In such circumstances, especially when abundant vegetation is in direct contact with the inner surface, the choice of a convenient metric resolution must be evaluated with respect to the effective level of penetration of the laser beam and to the subsequent signal discrimination offered by full-waveform technology.

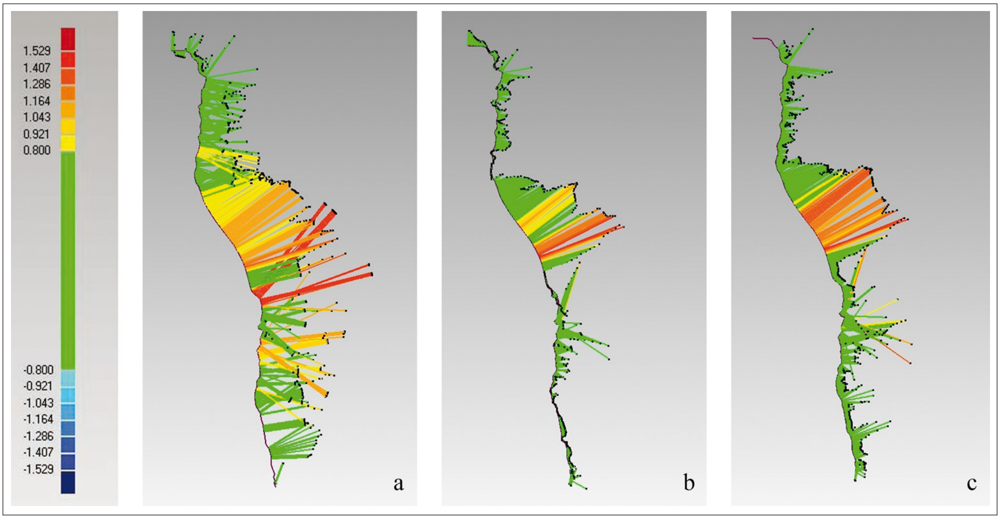


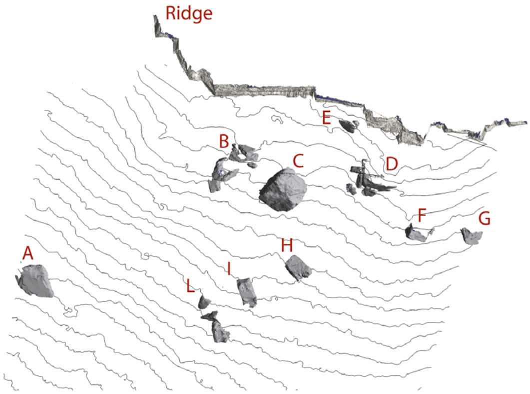
Figure 13 - 2D comparison along the vertical section between the generated model and different sets of points representing the vegetation: (a) *first targets*, (b) *last targets* and (c) *residual vegetation*.

Starting from the evaluation of the angular resolution of the laser scanner, it should be possible to conduct further investigations in order to evaluate how the different scan positions, as well as different orientations, can influence the choice of the best resolutions and modeling procedures to adopt. This would provide a significant test to verify if optimum conditions exist for the acquisition of areas with complex characteristics similar to those found in this case study, in consideration of the variation of the laser footprint and different values of amplitude and pulse width.

Geometrical data extraction and first results

The extraction of useful data for geo-structural analysis from a DTM or a DSM clearly depends on the quality of the generated model, which must necessarily have a high degree of accuracy; this is essentially related to the acquisition and data processing phases. The reliability of geometric information also depends on the possibility to identify particular groups of points or geometric entities (such as polylines) through a process of partial segmentation based on geometric parameters. This can usefully be adopted in CAD programs for the discrete analysis of geometric elements and of their interactions [Hoffmeister et al., 2012]. The segmentation procedure can be performed either manually, through a direct

recognition of the features concerned directly in the model itself, or automatically, by using specific algorithms based on the analysis of maximum and minimum curvature values on the surface [Umili et al., 2013].
As seen during the data processing phase, the proper use of geometric models to describe a geological environment needs a more complex and non-uniform 3D visualization, typically termed multi-scale and multi-resolution visualizations, so that different sources of geological and geomorphological data may be identified and combined during the analysis process [Jones et al., 2009]. In some cases, a "decomposable" 3D model can be totally or partially further reduced in resolution for quick calculations, where a high level of detail should prove unnecessary.
For the examined case, the detailed reconstruction of the rock blocks has made it possible to classify and calculate the volume and position of each individual block with respect to the upper ridge (Fig. 14). The individual volumes, albeit related only to the outcropping parts, are of considerable use in making a number of hypotheses about the volume of the original ridge. According to this calculation it would be possible to assume the original volume of the upper ridge on the basis of an empirical law describing the behavior of fallen and removable blocks and considering the geotechnical properties of the materials involved in the rock fragmentation process [Nocilla et al., 2009].



Rock blocks volumes in m^3			
A	94.64	F	42.11
B	131.17	G	18.43
C	506.46	H	86.93
D	147.46	I	40.74
E	13.26	L	47.82

Figure 14 - Positions and volumes of the main rock blocks.

The overall model also serves as a base for the extraction of a number of geometric primitives, such as contour lines and vertical sections, which can be used to check and analyze the spatial distribution of the rock blocks, evaluating the distances between them and the ridge. Furthermore, the ability to select blocks individually makes it possible to perform partial analyses of the development of the rock fall along one predetermined direction (Fig. 15).
With regard to hazard evaluation in geo-structural studies, the model is perfectly suited to be used as a basis for integration and comparison with data obtained from other surveying techniques.

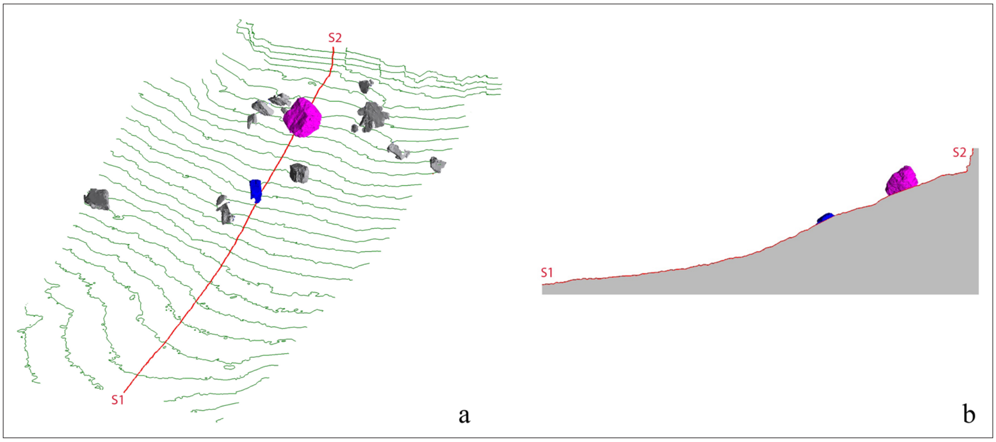


Figure 15 - (a) Axonometric view of the contour lines with the main rock blocks; (b) cross section through two blocks.

Conclusions

With regard to surveys of geological environments, the use of terrestrial laser scanning data allows high-precision topographic models to be obtained, with a far higher level of detail than can be obtained using traditional methods. In addition, such instruments are the most effective in terms of speeding up acquisition operations.
In this work a 3D reconstruction of a slope below the Temple of Juno in the Valley of the Temples in Agrigento was generated. The production of a 3D topographic model divided into three parts with different resolutions was useful in extracting metric information, with the ability to identify and select only the entities of interest. The model was managed and "built" in order to constitute a tool for the extrapolation of different geometric information (numerical and geometrical) for geological and geotechnical purposes. The ability to calculate the volumes of individual elements and to extract any section along different directions facilitated the interpretation of the dynamics of detachment of rock blocks, leading to a hypothesis of reconstruction of the original volume of the upper ridge. The decomposition into three sub-models proved to be advantageous also for visualization purposes.
The high acquisition capacity of full-waveform laser scanners has proven satisfactory in terms of accuracy of the final model, although the need to fill a small number of areas with partial or total absence of useful data may constitute a limitation in terms of the level of

uniformity that can be obtained. The high level of achievable detail is facilitated by the use of these types of instrument, which are particularly efficient in those situations where major limitations exist as a result of the presence of artificial and natural obstacles and long acquisition distances; these constraints cannot be generally overcome with traditional long range terrestrial laser scanners.
In the case examined, a total overlap of the various rock outcrops was possible, since the survey was carried out directly within the area of interest. This circumstance facilitated the production of a complete 3D model with almost no occluded areas; nevertheless such a final result was obtainable not only through an efficient planning of the survey but, above all, by means of a complex processing workflow. The different procedures employed during the data processing and modeling phases were selected according to the level of detail required, which was differentiated according to the geomorphological element to be reconstructed (e.g. blocks, ridge, terrain). In general, a more accurate level of detail requires full and uniform coverage during the acquisition phase, which can be achieved only by carefully assessing the influence of the laser footprint on the surface. This factor is normally a function of acquisition distance and angular resolution of the instrument and can directly affect the result of point classification, thus facilitating or, conversely, hindering a clear separation between points belonging to the vegetation and/or non-relevant objects from real useful points. For higher resolutions, the discriminating factor should not be such as to create ambiguity in the classification process, otherwise there is a risk of obtaining highly deformed reconstructions in certain critical areas.
During the modeling phase a number of problems related to the exact morphological representation of the site were encountered both in the lower part of the rock blocks, where it was impossible to acquire useful data, and in a few areas with abundant vegetation covering the upper ridge. Further difficulties were encountered during the editing process, which made high demands on processing time for certain operations, especially compared with the relatively rapid acquisition phase.
Further studies and investigations may be carried out regarding the development of interactive models, where metric information will be directly connected to the different display scale and to the maximum resolutions associated with the individual elements. Such a multi-scale, multi-resolution approach represents a key factor that can be extensively applied to other cases in which a detailed virtual reconstruction characterized by high ease of use is required.

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