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# Monitoring of large landslides by Terrestrial Laser Scanning techniques: field data collection and processing

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## Abstract
We have monitored a large landslide that causes extensive damage by using Terrestrial Laser Scanners (TLS) and Global Positioning System (GPS) receivers. Our surveys have confirmed that the slope undergoes a continuous change. When using TLS some operational difficulties arise. We have used different TLSs types to better evaluate the reliability of our surveys; a full wave TLS has allowed to make easier the data filtering. All surveys have been framed in the same absolute reference system; this has been done by connecting both targets and laser stations to a Global Navigation Satellite System (GNSS) Permanent Reference Stations network. A direct comparison among the DEMs allows to infer the movements of the landslide.

**Keywords:** Monitoring, landslide, LiDAR, TLS, georeferencing, DEM/DTM.

## Introduction
Landslides are a major problem in many countries [http://www.safeland-fp7.eu/Pages/SafeLand.aspx]. Geomatic techniques give a great contribution to the knowledge of both the surface shape and the kinematics of landslides by providing data which are used from geologists, geomorphologists and geotechnics for interpreting the phenomenon. In the analysis of landslides (predicting, monitoring and alerting for early warning, monitoring for change detection, etc.) a variety of geomatic techniques can be used, ranging from the most-known and consolidated techniques to the most innovative ones like Synthetic Aperture Radar (SAR) [Metternicht et al., 2005], Interferometry [Luzi et al., 2006], Airborne Laser Scanning (ALS) [McKean and Roering, 2004] and high resolution satellite images [Kliparchuk and Collins, 2011]. All of them present some critical aspects and strengths as far as landslide monitoring applications are concerned, depending on the specific characteristics of the landslide considered. One of the most widely used and well-known techniques for monitoring a landslide are the terrestrial surveys by Total Stations and GNSS receivers. They are useful

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when one has to measure the positions of single points which are materialized on the terrain. The accuracies achieved using these surveying methods are very high but the points one can measure are few and they must be accessible. Generally the method does not allow a complete description of the movements of the single areas of a landslide. GNSS receivers and Total Stations can also be used for surveying a big number of points which are not materialized on the terrain but the availability of Terrestrial Laser Scanners makes this approach obsolete. Although these instruments are characterized by lower instrumental accuracy than the Total Stations, they have the advantage to supply huge amounts of data in very short time and thus they allow a precise and detailed description of the surface surveyed [Prokop and Panholzer, 2009]. The current Terrestrial Laser Scanner (TLS) instruments are more and more efficient from the point of view of both the scanning frequency and the range capability and also for the ability to record multi-echoes. The first commercially available TLSs provided only one backscattered echo per emitted pulse; later the first and last echo (first and last pulse) of the backscattered signal could be measured. Recently, a new generation of TLSs has appeared that is able to digitize and record the entire backscattered signal of each emitted pulse [http://www.riegl.com/nc/products/terrestrial-scanning/produktdetail/product/scanner/33/]. They are called full-waveform laser scanner systems [Mallet and Bretar, 2009]. Measurement processing is the most challenging and time-consuming phase in landslide monitoring. Since for surveying one needs more laser stations on the terrain, the first step of the process is to make a co-registration of multiple clouds of points, which are partially overlapped. To carry out this specific task, called “Alignment”, a number of procedures are implemented in the scientific and commercial software packages, such as a well-known and effective algorithm, the Iterative Closest Point (ICP). The algorithm has been developed by Besl and McKay [1992], and, with a different scheme for the research of the corresponding points, by Chen and Medioni [1992]. This algorithm aims to minimize the 3D distance between partially overlapped surfaces in a set of 3D images. After each iteration, the algorithm multiplies each 3D image transformation matrix by the incremental transformation matrix that improves the best image alignment with respect to the other 3D Images. The incremental matrix is computed using a linear least-squares technique. Many variants of ICP have been proposed (point-to-point, point-to-tangent plane, point-to-projection, etc.) improving efficiency in terms of speeding up of both the research and pre-alignment algorithms. A detailed examination of the various approaches is given in Gruen and Akca [2005], Monserrat and Crosetto [2008]. After having aligned all the scans coming from a TLS survey, a Digital Surface Model (DSM) for each measurement campaign is available. If the goal of survey is monitoring the ground deformation over time two or more DSM should be compared in order to monitor the displacements of a number of points of the terrain [Fiani and Siani, 2005; Abellan et al., 2009]. A number of different approaches can be used. For examples one can directly compare the DSMs obtained over time by simply fixing a number of points belonging to particular objects visible in the two different point clouds [Ujike and Takagi, 2004]; the estimated transform parameters can then be used in order to transform all the points of a cloud in the reference system of the other one and so a comparison between them is then possible [Hesse and Stramm, 2004]. A more general approach allowing a full three-dimensional analysis useful for point clouds comparison is based on the algorithm called LS3D, proposed by Gruen and Akca [2005]. The authors themselves have introduced a number of variants so as to make it more efficient. The algorithm is based on the principle of least squares adjustment; it makes use of statistical criteria for both outliers detection and the evaluation of the quality adjustment. In our case, i.e. for landslides, the theoretical precision derived from using TLS surveying systems and specific algorithms for data registration and comparison can be greatly reduced by the presence of vegetation. While the trees are indeed an obstacle to the visibility of the terrain from the point of view of the laser station, also the low vegetation masks the real shape of the ground. Thus we need to accurately filter the vegetation from the DSM in order to obtain the Digital Terrain Model (DTM) for each surveying period. Only after this step we can effectively make a comparison between the terrain surfaces overtime. The availability of multi echo data is a great help in order to filter the vegetation. The ILRIS $3_6$D, which is one of the TLSs we used for our test, belongs to the class of instruments that allow to measure both first and last pulse of the backscattered signal. Since when using this instrument it is not possible to acquire both echoes at one time, we choose the last pulse option and only in a few tests we repeated twice the scans over the same portion of landslide (once choosing the first pulse and once choosing the last one). Of course in these conditions the responses do not come at the same time, and hence one suffers both a lower efficacy and an increasing surveying time. The TLSs belonging to the last generation of instruments allow to acquire more echoes; for example Riegl VZ series instruments are full waveform systems. They can provide, if properly equipped with software tools, a full wave form analysis very effective for the filtering of the vegetation [Elseberg et al., 2011; Guarnieri et al., 2012; Mallet and Bretar, 2009]. Always in the attempt to effectively filter the vegetation one can analyzes the radiometric intensity of the response by comparing the three RGB values [Alba and Scaioni, 2010]. The last option is manual filtering. This is a time-consuming operation if used on large areas, but it remains the only possible one if one cannot use a full wave form TLS instrument. In this paper we describe the approach we used for TLS surveying and data processing in a "real world" case study, i.e. a large landslide that has many critical aspects in the monitoring over time. The presence of thick vegetation, the difficulties in TLS positioning for visibility reasons, the instability of the slope from which we are able to make the surveying measurements, the availability of practically no "stable" areas around the landslide are all causes that make both the survey campaigns and data elaboration very hard. Our aim is to develop a methodology that is "sustainable" so as to provide a number of numerical and graphical products useful to allow both the geo-morphological interpretation of landslide phenomena in progress and to monitor the surface shape changes occurred over time.

## Case study

The phenomenon we are considering is taking place in Pisciotta (Campania Region, Italy), on the left side of the final portion of a stream, and causes extensive damage to both an important state road and to two sections of the railway line connecting North and South Italy (close to its East coast).

Not long ago, due to a landslide event, the railway has been endangered and disrupted by the river's waters flowing in the valley: mud and soil brought by the landslide into the river after heavy and prolonged rains have caused the blockage of both tunnels and the interruption of rail traffic on the main north-south railway line in Italy for about one day. The landslide is active and it is defined of "type slow" according to the classification of Cruden and Varnes [1996]. The movement of the soil is of the sliding rotational type, with the typical slipping that occurs along deep surfaces. In Figure 1 we show an extract of the corresponding geological map [Guida and Siervo, 2010], which underlines the development of the landslide. The figure also shows the relation to the complexity of the local geology and to the evolutionary sequence of the landslide; here the rocks are a mix of "marnoso-arenacee", calcareous and clayey of the Cilento flysch. Our case study is a wide area of nearly ten hectares. Some difficulties in surveying the landslide can be caused by the area orientation, by the slope gradient, by the presence of a canopy layer and by how visible the landslide is from a number of stable points.

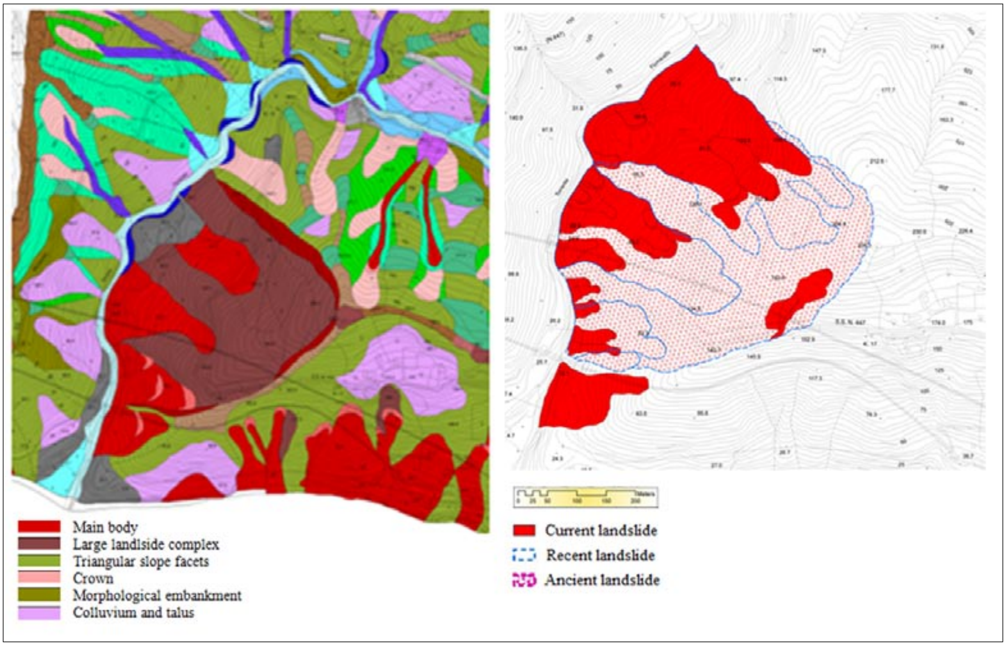



**Figure 1 - Left panel: an extract of the geological map; right panel: the evolutionary sequence of the landslide (reworking from Guida and Siervo, 2010).**

***Traditional monitoring***

Since 2005, when the ground movement monitoring started, a traditional topographical survey was performed by materializing a set of vertexes on the landslide body and controlling its position: this was done by measuring angles and distances from the slope facing the area. These operations allowed a first estimate of the magnitude of the ground movement, but such a control network is not sufficient to describe mass movements and changes in the shape of the slope.

The first surveying campaigns were carried out by the "Provincia di Salerno" (PdS), which is the management authority for the road which was damaged by the landslide; a

specialized company, Iside Srl, is monitoring the landslide trend on behalf of PdS. The data we discuss here were kindly provided to us by the PdS. The phenomenon monitoring activity was carried out from 2005 to 2009 using topographic and geotechnical methods [Iside, 2007]: it was mainly oriented to the monitoring of the area close to the road.
The system they realized was basically done from a number of sensors, like fixed weather stations, piezometers, inclinometers, strain gauges and from a topographical network. The network consists of:
- two fixed points placed on the "stable" side of the mountain and materialized with pillars where a total station was placed;
- about fifty vertexes materialized permanently with metal rods near the road.On most of the control points Iside group have mounted retro-reflective micro prisms that can be measured from the two fixed pillars by means of a Total Station; six vertexes are not visible from the two fixed points and thus they are measured using GPS. As we said, the points are placed along the road (the main interest of the customer, Fig. 2); by using them it is impossible to compute the correct amount of the moving material or to define precisely the area affected by the landslide. It is however possible to determine reliably and accurately the movements of the single observed points and in this way to obtain a precise information on the dynamics of the phenomenon. Each control point is measured from the two pillars placed outside the landslide slope by means of two angles and two distances. Although the surveying scheme is not optimal because of the closeness of the two fixed points, the choice that was made was based upon on their stability and upon the visibility of the landsliding area. In the period 2005-2009 two surveys per month were performed, and for all points of the topographical network Iside group produced a number of graphs that show the trend of the planimetric and altimetric displacements and the related mean velocity. As an example we show in the right panel of the Figure 2 the position of six of these control points.

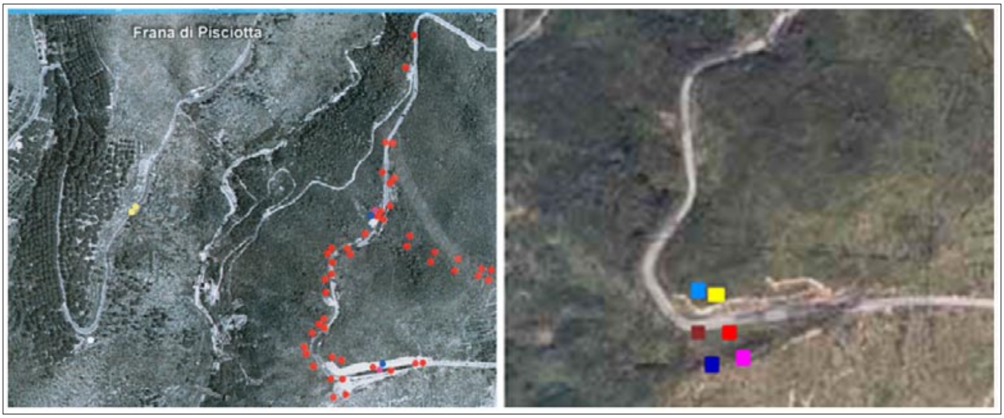



**Figure 2 - Topographical monitoring by the Iside group: left panel: the control points location; the right panel: a few details about points P01÷P06 (http://www.centroiside.net).**

For each survey the measurements of two angles and two distances have been adjusted by fixing the planimetric positions of the two pillars where the Total Station has been placed.

The planimetric coordinates ***x*** of each point have therefore been calculated independently, according to:

$$Ax = f + v \quad [1]$$

where A is for the design matrix, f for the discrepancy vector and v for the residual vector. The heights have been calculated by averaging the two measurements coming from the trigonometric levelling.
In Figure 3 we show the graphs of the planimetric and altimetric positions resulting from the Total Station surveying done from the two pillars that have been considered as stable over time. In the same figure we also report the speed (in units of centimetre per day).
Charts are indicative of both the strong dynamics of the points and of the very different behaviour of points that are close in space: the two southern points coloured in magenta and in black have moved far less than the other four. The results of the periodic surveys show that the amount of planimetric displacements in a period of about four years is about 7 m while the altimetric one is 2.5÷3.5 m. The average daily speed of the landslide is approximately 0.5 cm per day with peaks of up to 2 cm per day in planimetry and of about 0.2 cm per day with peaks up to 1.5 cm per day in height. The consequences of these movements are visible on a long stretch of road that appears to be completely disrupted (Fig. 4).
The topographical surveying of a small number of points along the road does not allow a quantification of the volumes of material in landslide or to delimit the area affected by the phenomenon.

## Methods

The goal of the surveying campaigns we have been running from 2010 to date has been to describe numerically the terrain morphology of a landsliding slope and its variation over time. For this purpose we decided to use the Terrestrial Laser Scanning surveying methodology in order to obtain a reliable 3D model of the landslide surface.
Monitoring requires a strict programme of surveying and data processing methodologies that can be repeated systematically at different times, always avoiding to change any detail of the procedure. If this is not done the differences of the details of the procedures can falsify the real movements and deformations of the object. In this paragraph we discuss the choices we made about the landslide that we surveyed.

### *The choice of the site for the TLS stations*

When one surveys a landsliding area, the choice of the site where the TLS will be located is both difficult and crucial. The visibility between the instrument and the area that has to be studied is indeed often limited due to terrain morphology (vertical and horizontal undulations, steps, slope, ripples, etc.). Also often the laser beam is slightly tilted with respect to the ground surface yielding negative effects on the view of the landslide. In addition, the soil is often covered with vegetation and trees. The trees can hide the ground for an extent that depends on the beam inclination with respect to the landslide surface; this makes the faithful reconstruction of the terrain surface difficult. Grass and shrubs also make difficult to distinguish the ground surface from the vegetation.

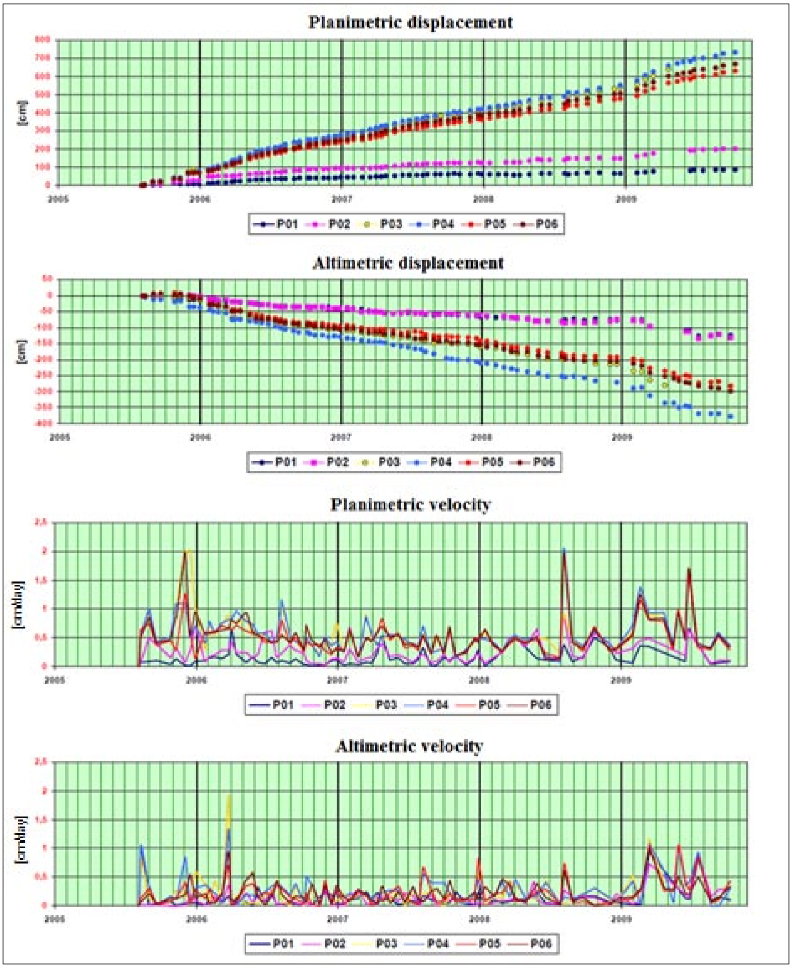



**Figure 3 - Charts of the planimetric and height movements of the six vertices P01 - P06 in the period 2005-2009 and respective mean velocities (PdS property).**

**Figure 4 - Roadway deformation and deep cracks in the road.**

It can be therefore not easy to extract the DTM from the DSM. This difficulty can influence the reliability and the precision of the survey, especially in the case of the monitoring of ground deformations, performed through the comparison of repeated surveys carried out at regular intervals of time. The estimate of the shape change of a landslide along with the answer to the question of which portions of it have remained stable after a certain interval of time, and the estimate of the amount of material that has moved or has been removed too, are thus issues that are hard to solve.

Taking into account these elements, in the three surveys we carried out we have used three different TLS instruments to verify whether in a medium distance terrestrial survey any of them should be preferred to the other ones as far as data filtering is considered. We selected two long range models (Optech ILRIS $3_6$D and Riegl VZ-400) and a 150 m range system (Leica Scanstation C10); we used the latter in the lower part of the landslide, where the distance between the station points and the landslide slope are smaller. The Riegl is a “full wave” instrument and it has been used to test whether this technology is able to give significant improvements in data processing. In the lower part of the landslide, during the same campaign, we used in rapid succession the Riegl VZ400 and the Leica C10 in order to make a direct comparison between the two instruments.

***Near and absolute reference frame***

When the purpose of a TLS survey is to monitor ground deformations, it is essential to identify a set of points that are stable in time. They must be the fixed reference system in which a number of repeated measurements that were made at different time can be framed.

If within the point cloud there are a number of areas that one believes to be stable over time, the comparison can be done by adapting the clouds obtained in two subsequent different measurements (at different times) over that area. This procedure can give much optimized results especially if the stable parts are on the border of the cloud.

If this is not the case one needs to materialize a reference system that remains stable over time, where the points measured in repeated surveys may be framed. Such fixed points (we will refer to them as “near reference frame”) should be placed outside the monitoring area, close enough to make easy and accurate the connection between them and the points in landslide (both the laser station and the targets); anyhow they should be placed, if it is possible, far enough not to feel the effects of the phenomenon under study. If one uses GPS receivers to connect the survey area to the near reference frame there is no need for visibility from them to the landsliding area.

In every survey we have to measure both the laser station points and the target positions. The laser stations must be placed as close as possible to the surveying area, on a stable area in frontal position with respect to the landslide, and a complete visibility towards it is needed. The targets, useful in order to record and georeference the data must be placed in the landsliding area and must be well distributed in the space, if the sites are accessible [Soudarissanane et al., 2008].

Since it is crucial to be sure that the reference system one uses in multi-temporal surveys is stable over time it is also advisable that the points belonging to the near reference frame are themselves monitored with respect to farther points that are stable (“remote reference frame”). An efficient and not expensive solution to this issue is to use as “remote reference” a number of GNSS Permanent Stations (PS) belonging to National geodetic frames (a regional densification of the IGS global network).

Such stations, which are now used in all countries, may be tens of km away from the monitored area. The connection between them and the local frame therefore requires a prolonged standing of GPS receivers on the points of near reference frame; the needed measuring time depends of course on the distance. It is usually sufficient to let the GNSS receiver measure during a whole day (i.e. while doing the laser survey).
The great advantage in doing this it is that the targets and thus the laser survey are both georeferenced in the Geodetic System ITRS (International Terrestrial Reference System), which is constantly monitored over time. Moreover one does not need to add any survey, but only needs to download the data acquired by the Stations and to calculate the baselines. Surveys carried out over a many years span can thus be referred to the same reference system.
It is well known that in the reference system we are talking about the coordinates vary over time due to the motion of the plate to which it belongs; in Europe the Euro-Asian plate moves of about 2 cm/year with respect to the ITRS. To make the PS coordinates more stable over time, a Geodetic System defined exclusively by reference stations materialized on the stable part of the plate should be used. In Europe such a system is the ETRS89 (European Terrestrial Reference System 89). Thus the ETRF89 (European Terrestrial Reference Frame 89) geodetic frame should be used for monitoring purposes since in this frame movements of the reference stations used for the laser scanner surveying over time are very small (a few mm/year). Note that the frame that is used today in Italy is ETRF2000. It is clear, however, that movements of magnitude of a few cm per year do not affect the accuracy of the laser scanner survey of the landslide; we believe that the accuracy of our measurements is not better than a few cm.
Let us describe the scheme that we have used for georeferencing the survey made in Pisciotta in the absolute reference system. The near reference frame is done by the two pillars (I1 e I2) materialized by Iside group (for the previous surveys carried out by Total Station); from these points only the upper part of the landslide is visible. The absolute reference frame is materialized by a network of NRTK (Network Real Time Kinematic) Permanent Stations of the Campania Region [http://gps.sit.regione.campania.it/indexmain.php]; their coordinates are defined in the International and European Geodetic Systems.
We ran a GPS surveying campaign in order to frame our surveys in the selected Reference Frame, i.e. ITRS89_ETRF2000. In all surveys we connected the two pillars with the two closest Reference Stations of the NRTK Network: Sapri (RF1) and San Marco di Castellabate (RF2), which are respectively 38 and 26 km away from the area test. We took a number of dual frequency GPS static observations, of duration of at least 10 hours at a 15 second epoch update, for two consecutive days (i=RF1, RF2; j=I1, I2; d=1,2 days).
Once the data from the Permanent Stations have been downloaded we were able to calculate the GPS baselines between them and the two pillars for each surveying day, $b^{(d)}$, and its variance matrix $\Sigma_b^{(d)}$; then we adjusted for every day the four points network, keeping fixed the coordinates of the Reference Stations in the System ETRF2000, obtaining the adjusted coordinates x for the two pillars which constitute the near reference frame:

$$A^{(d)}x^{(d)} = b^{(d)} + v^{(d)} \quad ; \quad \sum\nolimits_x^{(d)} = \hat{\sigma}_{od}^2 \left( A^{(d)t} P^{(d)} A^{(d)} \right)^{-1} \quad d = 1,2 \quad [2]$$

The adjusted coordinates obtained for each day were averaged in order to obtain the final coordinates of the points I1 and I2 of the near reference frame for that epoch:

$$x = \frac{\left(x^{(1)} + x^{(2)}\right)}{2} \quad ; \quad \sum_x = \sum_x^{(1)} + \sum_x^{(2)} \quad [3]$$

At last we transformed the geocentric coordinates into ellipsoidal coordinates and eventually to cartographic ones in the system UTM_ETRF2000.

In a second step we ran a static GPS survey in order to calculate the positions of both the TLS station points and of the targets referring to the two near reference points. Since the distances are less than one kilometer, the GPS measures took less time duration of about 20-40 minutes.

We adjusted the two GPS baselines between the two pillars and the single point (or TLS station or target) by fixing the coordinates of the pillars at the values obtained from the previous calculus. We computed the position of both the phase center of the GPS antennas and of points at the ground level $\boldsymbol{X_G}$.

Since the retro-reflective targets were placed at the top of a rod of known length $h_T$, it has been necessary to calculate the geocentric coordinates $\boldsymbol{X_T}$ of their centers starting from those of the corresponding points on the ground $\boldsymbol{X_G}$; we computed the ellipsoidal coordinates $\lambda_G$, $\varphi_G$, $h_G$ and hence the components of the normal vector to the ellipsoid $\nu_G$ along the axes of the geocentric system,

$$v_G = \left[\cos\varphi_G \cos\lambda_G \quad \cos\varphi_G \sin\lambda_G \quad \sin\varphi_G\right]^T \quad [4]$$

where $^T$ indicates the vector transposition, and finally the coordinates of the target centers, using the relation

$$X_T = X_G + h_T v_G \quad [5]$$

All point coordinates have been computed in 3-D geocentric (and ellipsoidal) coordinates referred to the ETRF2000 frame. The planimetric components of the positions of the targets have been transformed into the Cartographic System UTM_ETRF2000, the elevation component into an ellipsoidal height; our point of view is indeed that using orthometric heights in a ground deformation monitoring makes little sense since the geoid undulation do not change from a survey epoch to another.

***Terrestrial Laser Scanner data processing***

Usually each different brand of TLSs uses a specific software package that is able to correctly process data coming from the instrument. We used Leica Cyclone in order to process Leica Scanstation C10 data, Riegl Riscan Pro for Riegl VZ400 data, Optech Parser and Innovmetric Polyworks for Optech Ilris $3_6$D ones. The latter software package is not tied to one particular instrument but is commonly used for TLS data processing. It is anyway good practise to export the data in text format too in order to be able to use other software packages having features that are optimized for a given processing stage. The data processing steps are the same for all types of software.

**Data downloading**

A number of specific software tools allow to download data in a proprietary format. In this first step it is also possible to sub-sample the data in order to "lighten" their processing. For example, one can delete from the data set any observation that has been taken even if one does not think to use it, such for example as direct measurements and RGB data. One can also select the pulse (first, last, single etc.) to be used in the data processing.

**Scan alignment**

In order to align multiple scans so to obtain a single point cloud instead of the many ones that were acquired in each survey, all software tools we tested follow a similar strategy. This is a very important step for the metric quality of the final product. One must take special care in the scan pre-alignment phase, especially in the choice of the area overlapping between adjacent clouds and of homologous points. This phase, called co-registration, is mathematically realized by a six parameters transformation before the best fit alignment final step, usually based on the ICP algorithm.

The Optech ILRIS $3_6$D TLS instrument records multiple tasks for each cloud (each one with a width of 40x40 deg). When the instrument is well calibrated and rectified all tasks should be in a single reference system. Nevertheless, we have decided to set a large overlap between tasks in order to check the effective automatic co-registration.

Some standard registration procedures are based on point matching. Software uses the selected points as a starting point for an alignment algorithm; one can use both natural points and targets as tie points. Software tools are also available for applying rotations and translations to the selected points cloud. Both the software packages Polyworks and Cyclone use the least-squares iterative algorithm ICP to optimally align a set of 3D images by minimizing the 3D distances between the points of overlapping portions of the "reference" cloud and the "data" cloud. The strategy used by RiscanPro software package in order to minimize these errors is very similar, since the software has a plugin function called "Multi Station Adjustment" (MSA) that is a variant of the ICP algorithm. The MSA tries to improve the registration of the scan positions. For that purpose the orientation and the position of each scan position are modified in several iterations in order to calculate the best overall estimate. To compare the scan positions the tie-points, the tie-objects and poly-data objects (reduced point clouds) are used.

**Editing**

The editing processing step serves mainly to clean the scan from everything that does not belong to the bare soil; in our application this concerns essentially the vegetation (but also pylons, artefacts, etc.). This process can be carried out by the various software tools in many ways, starting from the simple (basically manual) one, up to very specific procedures. Multiple backscattered echoes per emitted pulse are useful for an initial screening.

Among the software packages we used, only in RiscanPro an algorithm for filtering of raw data is implemented. Here two different spatial filters are applied in order to eliminate the vegetation: octree and an iterative filter. In the octree filter for each 3D model the global point cloud is divided into a number of equally sized cubes (cells) which are again iteratively divided. The division into sub cubes is done on demand by filling the points into the octree and stopped as soon as a given minimum cube size is reached (in our case 0.2 m). Assuming that laser returns closer to the ground are unlikely to belong to vegetation and after orienting the cells so that the laser Z axis is roughly parallel to the local vertical line, the point with the minimum Z coordinate inside each cell is then selected as terrain. The iterative method is based on the ALS data filtering algorithm developed by Axelsson [2000]. The original point cloud is firstly projected on a reference plane and then rasterized on a regular grid by selecting the point with minimum laser elevation (Z axis orthogonal to the plane). Next it is compared to the obtained Digital Elevation Model (DEM) and only the points closer than a distance threshold are kept. This process is repeated iteratively by reducing at each step the size of both the grid cell and the threshold, until the vegetation is completely removed.

**Global georeferencing**

All software packages allow the georeferencing of point clouds. The procedure consists in assigning a set of 3D coordinates to the center of a number of targets "visible" in the point cloud. Their position with respect to a given reference system is known since they have been measured on the ground. Software tools generally allow the automatic recognition of the target shape (cylindrical, spherical or flat) at least on the type of targets suggested by the manufacturer of the associated TLS instrument. In order to accurately estimate the position of the center it may be necessary to border the portion of points of the target to be used for the fitting calculus. A correct georeferencing in a reference system that is stable over time allows, when ground monitoring, the possibility of an effective comparison between scans in an absolute system. Especially when there are no terrain details that can be considered stable and that are placed in a suitable position within the cloud, a precise georeferencing of the cloud is of course a critical step.

## Surveying campaigns

The rugged morphology of the surveyed area has been a strongly conditioning element in the choice of the sites where the stations have been placed. The strong dynamics of the landslide implies that the measurement campaigns have to be carried out in a very short period of time. This is why we ran both the TLS and the GPS survey during the same day. Each surveying campaign lasted 2-3 days.

In order to survey the upper region of the landslide area the laser stations have been located in a few points on the stable side facing the landslide at several hundred meters away. In all our survey campaigns we have recorded laser scan measurements coming from a number of TLS stations, located on the stable slope at different altitudes, so to measure both the upper and the lower part of the landslide, down to the stream; here the distance are smaller and short range instruments can be used, obtaining a larger density of points. In the lower part of the ridge there is a railway bridge and the terrain above the entrance of the tunnel can be measured with high accuracy; not far from this, towards the valley, there is another longer bridge and another tunnel.

We carried out a LiDAR "zero" survey and about four months later a repetition measurement using a long-range Terrestrial Laser Scanner, Optech Ilris $3_6$D; a further surveying campaign was carried out one year later by using two different instruments, a long range (Riegl VZ400) and a medium range one (Leica Scanstation C10). The VZ400 is a laser instrument capable to analyse the calibrated relative reflectance, in the attempt to filter the effect of the obstacles (for instance the canopy layer) and thus to allow to generate a faithful DTM starting from the DSM we had acquired. This TLS instrument was used for surveying the upper part of the landslide. This is the most complex goal due to the presence of a canopy layer. The mean distance from the TLS station to the landsliding slope is of 200 m. The second laser scanner, the C10, has been used in the lower part of the landslide, where natural ground motion and man-made actions have made the soil bare, making easier the shape reconstruction. In this case the laser - targets distances range from 20 m to 80 m. In Table 1 we report data concerning some technical features of the TLSs used in the surveys.

**Table 1 - A few characteristics of the Terrestrial Laser Scanners we used.(Information extracted and revisited from http://www.geo-matching.com).**

| | Optech Ilris $3_6$D (ver. 1.0) | Leica ScanstationC10 | Riegl VZ400 |
|---|---|---|---|
| **Min. range (m)** | 3 | 0.1 | 1.5 |
| **Max. range (m)** | 1500 | 300 | 600 |
| **Beam diameter at exit (mm)** | - | 6 | 7 |
| **Beam divergence (mrad)** | 0.17 | 0.24 | 0.3 |
| **Spot at 50 m distance (mm)** | 20.5 | 6 | 18 |
| **Max. Horiz. Field of view (deg)** | 40 (360 with pan/tilt) | 360 | 360 |
| **Max. Vert. Field of view (deg)** | 40 (150 with pan/tilt) | 270 | 100 |
| **Min. Horiz. & Vert. step size (deg)** | 0.0011 | 0.0002 | 0.0024 |
| **Max. measurement rate (KHz)** | 2 | 50 | 300 |
| **Uncertainty of Horiz. & Vert. Step size (deg)** | 0.0045 | 0.0030 | 0.0034 |
| **Software name** | Ilris Controller | Leica Cyclone | RiscanPro |

In Figure 5 we show the planimetric and the altimetric schemes of our first campaign. One can see the positions of the TLS station points and of the targets; we also show the different areas analyzed with the different tilts. The June 2010 campaign was based on a very similar design. For the last campaign the measurement scheme is almost similar even if we used many more TLS station points.

To georeference the data recorded from the laser scanners we need to recognize, inside the point cloud, a number of points that are known both in the cloud reference system (i.e. the internal TLS system) and in the reference one; we have used different types of targets, both spherical and of the type (cylindrical and planar) suggested by the manufacturers of the instruments for their 'automatic' recognition in the cloud when using the processing software packages Cyclone and RiscanPro (Fig. 6). Our targets are reflecting spheres with a diameter of 15 and 30 cm; in the bottom part of the figure we show the 15 cm diameter spherical targets, located on the railway tunnels. We have chosen the spherical since this allows the best reconstruction from all possible viewpoints, wherever the laser stations are.

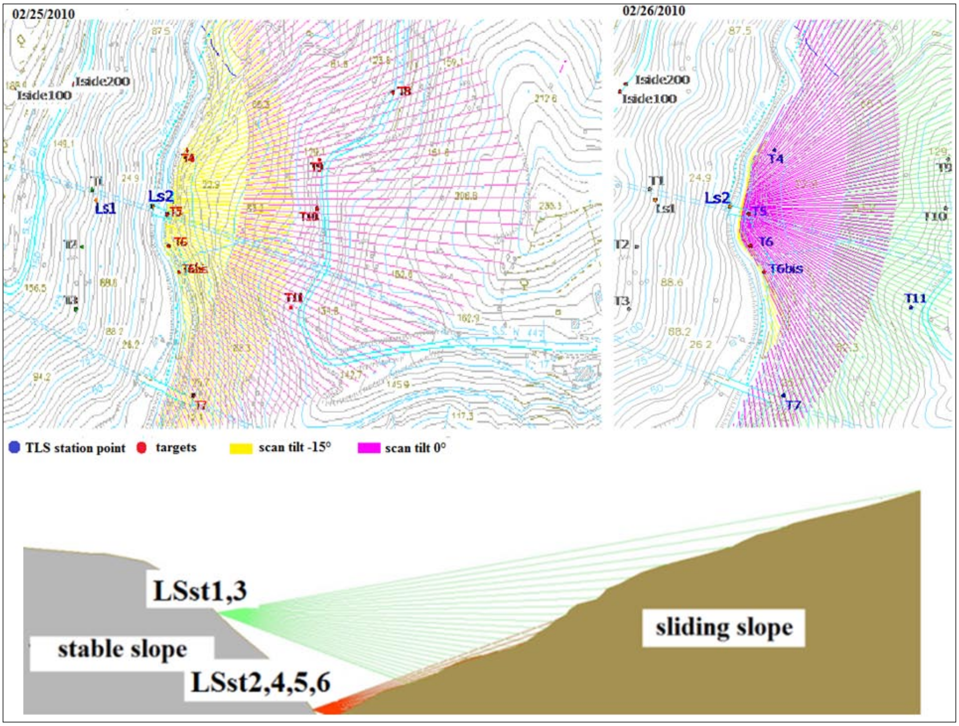



**Figure 5 - Planimetric and altimetric schemes of our 1st surveying campaign. In the panel in the upper left we show the planimetric coverage of the data scanned during the 1st surveying day; in the panel in the upper right we show the coverage of the 2nd day; in the panel below we show the altimetric scheme of the same campaign.**

## Data processing

The first step of the processing of the data from the campaign surveys aims at determining the positions of both targets and TLS stations in the selected reference framework. All the scans will be referred in one single frame and we will be able to compare them over time. For the data from TLS the data processing steps are: scans alignment, editing and georeferencing. Each of the first two surveying campaigns has produced slightly less than twenty million points, while during the third campaign TLS instruments recorded more than one hundred million points (Tab. 2).

### *Surveys framing in an absolute reference system*

The target coordinates for all surveys have been measured according to the methods described here. The first step of the process is the connection between the Reference Stations of the NRTK network and the two points I1 and I2 of the near reference frame. For doing that we ran a GPS survey. The standard deviations obtained for the coordinates of the pillars were in the order of 0.3 cm for the planimetric coordinates and of 1.5 cm for the height. The differences between the results of the adjustments have been almost the same for the three surveys; no significant shift between the epochs of activity has been detected. The second step concerns the connection between both targets and laser stations and the pillars of the near reference frame. Here too, the adjustment of all the sets, each of them made from two baselines, provided error parameters which are of the same order of magnitude. Table 3 shows a summary of the values (in mm) obtained for the major (a) and minor (b) semi axis of the standard relative error ellipse and of the relative standard deviation in height. The third survey has been much less precise than the other first two due to the presence of noise in the GPS signal acquired from the receiver placed on Iside2; because of that the GPS baselines between that point and the targets in landslide were not always measured.

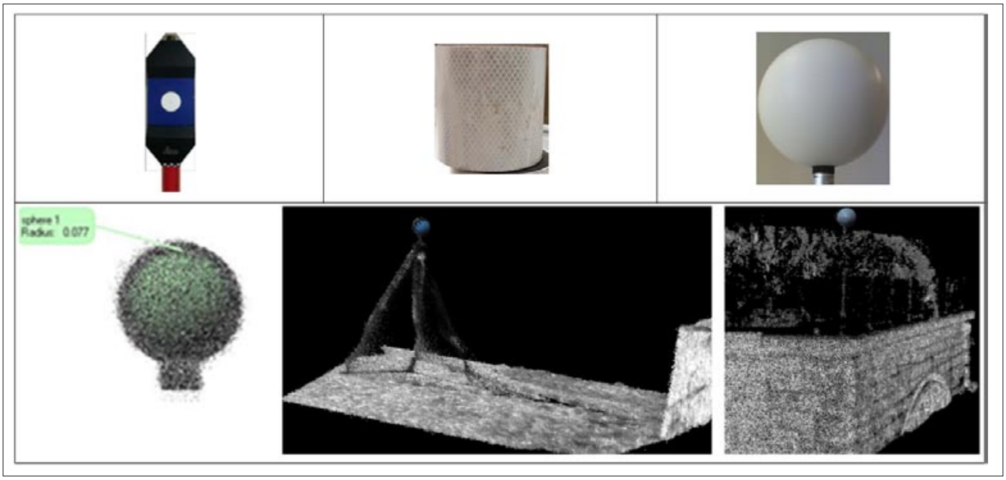



**Figure 6 - The targets we used. Upper right panel: the spherical target (15 cm diameter) we used for georeferencing the point clouds. The same target is also visible in all the panels below.**

**Table 2 - A few synthetic data about our surveys.**

| Campaign | TLS instrument | # of TLS Stations | Tilt | # of Scans | # of visible Targets | Point clouds (Millions of shots) |
|---|---|---|---|---|---|---|
| **First** | Optech Ilris 3 D$_6$ | 2 | -15 ; 0°<br>-20 ; 0° ; +10 | 5 | 5 | 27.4 +<br>0.5÷2.5 (each target) |
| **Second** | Optech Ilris 3 D$_6$ | 2 | -20 ; 0°<br>-30 ; 0° | 4 | 5- 7 | 20.4 +<br>0.5÷1.5 (each target) |
| **Third** | Leica Scanstation C10 | 4 | n a | 5 | 4-5 | 108 |
| | Riegl VZ400 | 4 | n a | 4 | 9 | 35 |

**Table 3 - Major (a), minor (b) semi-axes of the standard error ellipse, standard deviation in height.**

| Standard error (mm) | February 2010 | | | June 2010 | | | June 2011 | | |
|---|---|---|---|---|---|---|---|---|---|
| | a | b | St dv h | a | b | St dv h | a | b | St dv h |
| **Mean** | 3 | 1 | 5 | 2 | 2 | 6 | 13 | 8 | 26 |
| **St. Dev.** | 1 | 1 | 3 | 2 | 1 | 4 | 9 | 5 | 23 |
| **Maximum** | 5 | 3 | 9 | 6 | 4 | 13 | 29 | 20 | 73 |

***Scan alignment***

The first step of the data processing is the scans co-registration. We used three different software packages in order to process the data recorded by the three different TLSs; they all use similar strategies for the alignment.

To align the Optech data obtained in the first two campaigns we used IMAlign, a tool included in the Polyworks software package. At first, the scans were manually co-registered by picking a sufficient number of tie points. The software uses the picked points as starting points for its best-fit alignment algorithm (ICP) that is ran in the background. From the operative point of view, first we aligned the n tasks belonging to each scan collected from a single TLS station with a specified tilt, by locking the central task and adding one by one, one to the right and one to the left of the central one, the further tasks, so as to minimize the effects of error propagation. We did this for all the tilts and for each day. To this global scan we have added the detailed scans done on the targets. In theory, all the process should not be needed since the scans have been acquired in the same instrumental coordinate system (since they were registered by the same station point). On our data we noticed, however, that when we operated the manual procedure we got better result in terms of error residuals than the automatic one. At last, the scans of the two surveying days have been aligned, eventually producing a single global scan describing that specific measurement campaign. In Figure 7 we show an example of the alignment of the individual tasks. The software tool computes histograms of the alignment errors for all 3D images. In Figure 8 we show the error in the alignment for the two surveys we carried out in the year 2010. In the error histograms the mean and standard deviation of the alignment error distribution are shown by vertical dotted lines. The first and last non-empty histogram bins are shown with two vertical half-lines displayed in red. In Figure 9 we show the clouds of aligned points.

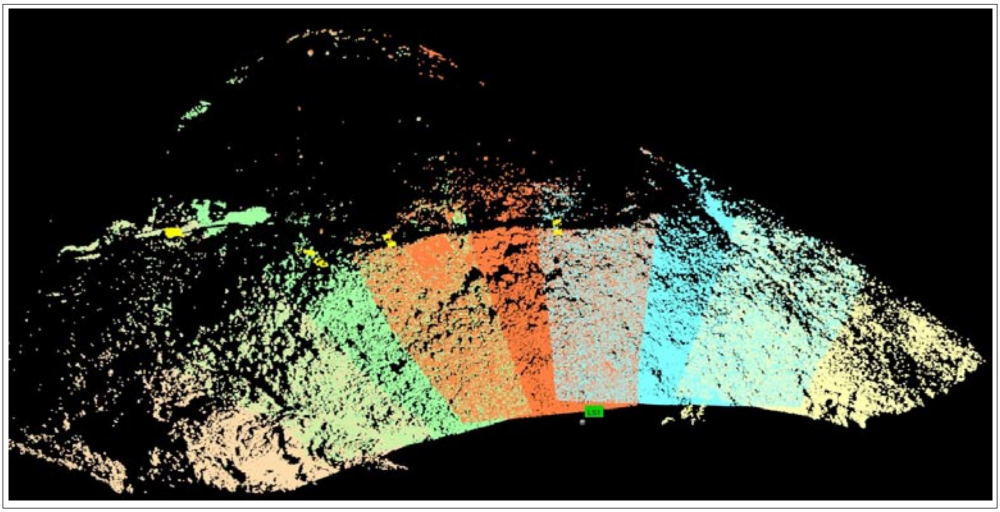
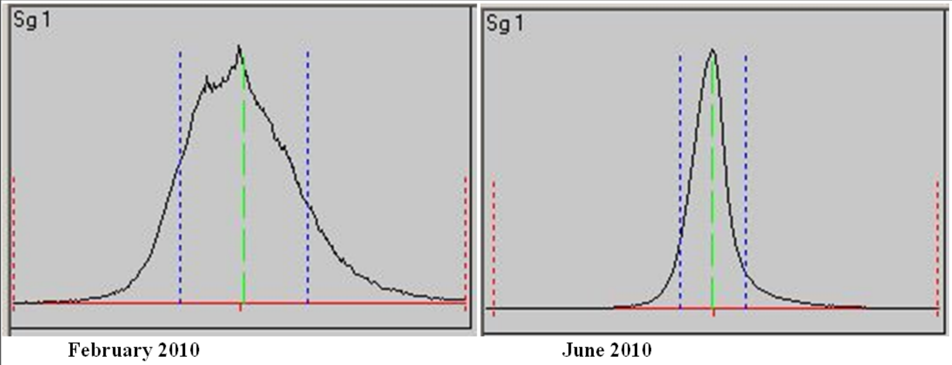


**Figure 7 - Individual tasks of a scan from TLS Optech that we manually aligned.**




| | Max. error | Min. error | Mean error | St. Dev. | Peak | # of points |
|---|---|---|---|---|---|---|
| February 2010 | 30 | -30 | 0.6 | 8.5 | 4930 | 353266 |
| June 2010 | 20 | -20 | -0.0 | 2.8 | 26791 | 701290 |

**Figure 8 - Above: histograms showing image alignment errors; left panel: the histogram of February 2010, right panel: the histogram of June 2010. Below: alignment errors (cm) for the scans from Optech.**

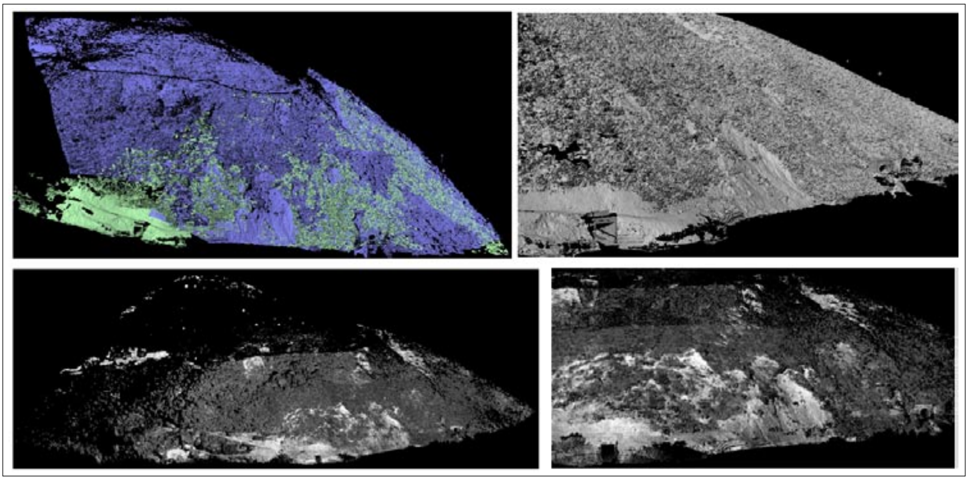


**Figure 9 - Alignment of the scans from Optech (2010). Left panels: above we show the result of the February campaign and below the result of the June campaign. Right panels: a detail of the scans made on the railway galleries (above February and below June).**

We used the software RiscanPro in order to process the data registered from Riegl VZ400. The first step of our data processing was to select only the "last" and "single" pulses and eliminate the "first" and "others" from the data set. Afterwards we made first an approximate manual recording, selecting n pairs of corresponding tie-points; then we ran the MSA iterative procedure in order to improve the registration of the scan positions so as to give in output a single aligned point cloud. The alignment of our data is affected by a standard deviation of the order of 4 cm.

Lastly, we used the Cyclone software package to process the data recorded by the TLS ScanStation C10 in the third measuring campaign. Cyclone is based on an alignment strategy which is similar to those used by the other software packages we used. Here, the integration of the scans into a single coordinate system is derived by using a system of constraints, which are pairs of equivalent or overlapping objects that exist in two scans. We created cloud constraints in addition to the geometric constraints between the spherical targets we used. In Figure 10 we show a view of the aligned point cloud by the Leica C10; here we are in the lower part of the landslide, close to the stream. In the same figure one can also see both the TLS stations locations and the position of some targets that were later used for georeferencing; in the right side of the figure we show an enlarged view of the railway and of the tunnel. The mean absolute error is of the order of 3 cm.

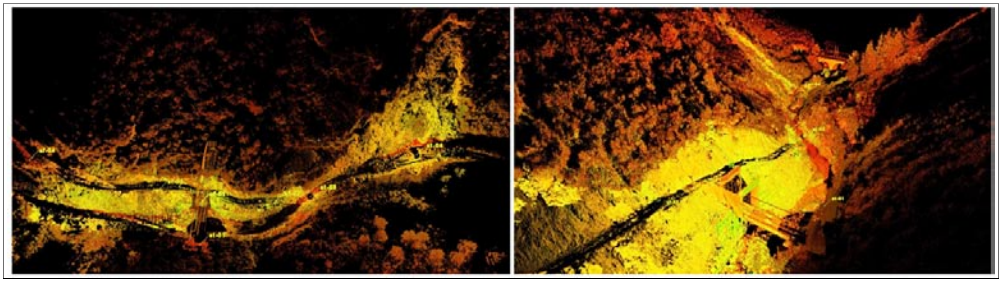


**Figure 10 - Alignment of the scans from Leica (2011). Left panel: a general view; right panel: a detail of the scans acquired on the upstream railway gallery.**

***Editing***

Once all the scans of each survey have been aligned and we have obtained a single scan for each campaign, the resulting scans must be edited in order to remove from the data set the points which correspond to the vegetation. This allows, after georeferencing in a single absolute reference system, a reliable comparison among scans taken at different times. To do this we used the Cyclone software package for both the two Optech surveys of 2010 and the Leica of 2011 one and the RiscanPro tool for editing the data registered by Riegl in 2011. The two editing tools have very different approaches: the former is primarily manual while the second is semi-automatic. In the first case, in order to filter the vegetation and to derive the bare soil from the DSM, we have dissected the cloud of points in many "tapes" of about 5 meters each and, in a 2D side view, we have deleted manually (with the mouse) the points that were found (visually) not to belong to the ground. This procedure is very time consuming and does not guarantee a good result. Obviously, for thinner "tapes" results are better. The data obtained with the TLS Riegl Z400 have been instead edited using the RiscanPro software tool in order to separate the vegetation from the ground. The global scan has been edited by applying the two different spatial filters implemented in the software package: "octree" and "iterative filter", which we have already described. In Figure 11 we show the result of the editing step; in the upper side of the figure you can see the DTM of the bare soil and in the lower side the vegetation which has been removed.

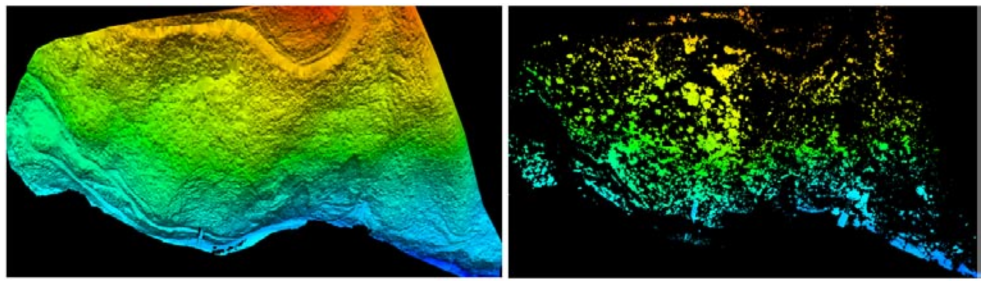


**Figure 11 - Riegl survey. Left panel: the bare soil as it appears after vegetation filtering; the right panel: the vegetation that has been removed by filtering.**



## Results and discussion

We have georeferenced the point clouds obtained during out measuring campaigns using the coordinates of the target centers we measured in the same reference system (geodetic frame ETRF2000, UTM coordinate system and ellipsoidal height); in principle this allows a reliable comparison among scans taken at different epochs. All software packages we used allow to georeference the data by estimating the parameters of a conformal transformation with a procedure based on a least squares fit (six and seven parameter transformations give very similar results). For evaluating the quality of the fit we have computed the values of the residuals on the target coordinates. In Table 4 we show some statistical parameters for the georeferencing of the point clouds of the three campaigns.

Our third survey was the least accurate one and we had to delete one target from the set as the corresponding residual was too high; the software packages we used do not provide a rigorous statistical analysis.

Starting from the clouds georeferenced in a cartographic system we obtained a number of high resolution DTMs that allow the geomorphologists to study the landslide from their point of view; the results of these studies can then be directly compared with information obtained in a different way (see Fig.1).

**Table 4 - Residuals obtained in the georeferencing process.**

| Campaign | TLS instrument | Software | Max error (cm) | Min error (cm) | St. Dev. (cm) | Res X (cm) | Res Y (cm) | Res Z (cm) |
|---|---|---|---|---|---|---|---|---|
| 1st | Optech Ilris 3 D 6 | Polyworks | 1.8 | 1.2 | 0.5 | 0.8± 0.4 | 0.3± 0.2 | 0.8 ± 0.4 |
| 2nd | Optech Ilris 3 D 6 | Polyworks | 6.2 | 4.5 | 1.1 | 2.4± 0.9 | 1.8± 0.7 | 3.2 ± 1.1 |
| 3rd | Leica Scanstation C10 | Cyclone | 7.6 | 5.6 | 2.0 | -0,1± 2.7 | 01± 4.2 | 0.0 ± 4.1 |

In Figure 12 we show in the upper panel an overall image of the DTM of the slope (2nd survey) and in the lower panel the "wire-frame" of a particular area (in the left panel the DTM from the 1st survey and in the right panel that of the 2nd one).

To elaborate a reliable DTM performing an accurate editing of the vegetation is not enough; one also needs to perform another editing to eliminate all the points which do not belong to the ground surface. We give an example in Figure 13 where we show the contour lines derived from an unedited DTM of the railway tunnel. As one can see the contour lines are not locally representative of the real morphology. In Figure 14 one can see the corresponding 3D wire-frame. This is happening since the laser beam enters the tunnel. Because of that in the set of measured points there are not only the correct points that belong to the ground surface but also spurious points that belong to the interior of the tunnel (and should not be there). These spurious points, that do not allow the correct reconstruction of the DTM, have to be removed. Since all the surveys have been framed in the same reference system it is possible to compare the data obtained in different epochs: this allows us to identify and analyze how the areas with largest deformation evolve in time, and to estimate the directions of landslide movement.

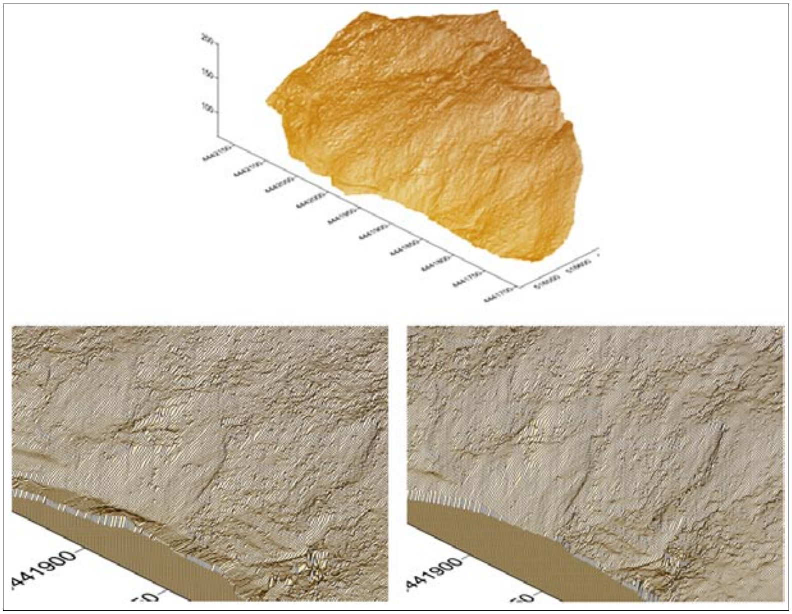



**Figure 12 - DTM of the slope (2nd survey) in the upper panel. The "wireframe" of a particular area in the lower panel (left panel: the DTM from the 1st survey; right panel: that of the 2nd one).**

The comparison between scans of different epochs can be done using the laser scanning software packages or with other commercial software packages (for example Surfer® by Golden Software Inc.) or public-domain ones (for example GMT - Generic Mapping Tools). If one uses specific software which is dedicated to laser scanning data processing, it is generally possible to follow two alternative approaches. The first one is to load all the clouds that you need to compare (two or more) in a single project; all of them had been previously georeferenced in a same coordinate system. The other approach is to co-register and align all the clouds on common points, which are located on elements of the scenery which should not have moved significantly in the time elapsed between the surveys.
In the first case, it is important to check that the georeferencing of the scans in the absolute system is sufficiently accurate. One should always check the procedure on points located on stable features of the scenery which are present in all the surveys; in the DTMs we want

to compare these details should have the same position (not taking into account accidental errors of measurement as framing, co-registration, georeferencing). In the landslide we studied we expect that both the upstream and the downstream railways
tunnels, clearly visible on the scans, should not have moved significantly in the time elapsed between the surveys. We have compared on these details the DTMs obtained from surveys spaced in a time period of four months (the first two surveys) and we have found a good agreement, as one can see in Figure 15 (data processing has been done with Cyclone).
An effective way to compare the ground deformation at different times is to make a number of profiles directly on the DTMs. An example of the terrain profiles we made is shown in Figure 16, where one sees a section made on the railway tunnel upstream; in the left panel one can see the whole landsliding slope, while in the right one we show a detail of the same section that highlights and quantifies the difference in altitude between the profiles in correspondence of the same planimetric position. The profiles were traced on the advice of the geologists which are studying the landslide.

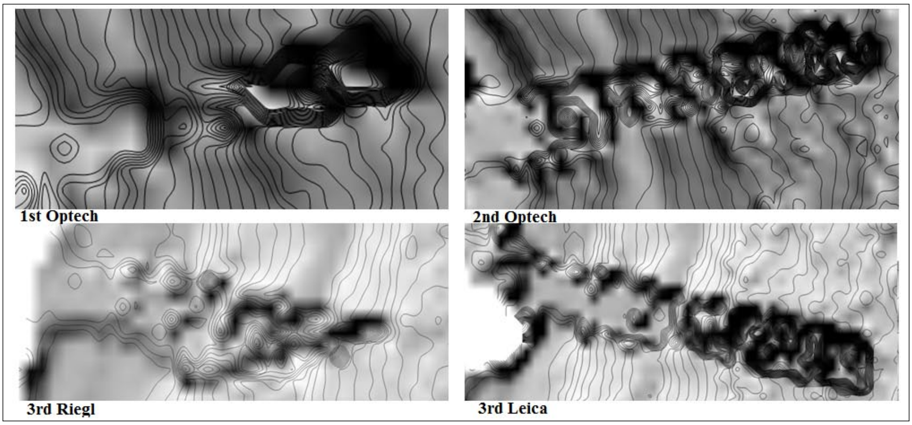



**Figure 13 - Contour lines of the railway tunnel.**

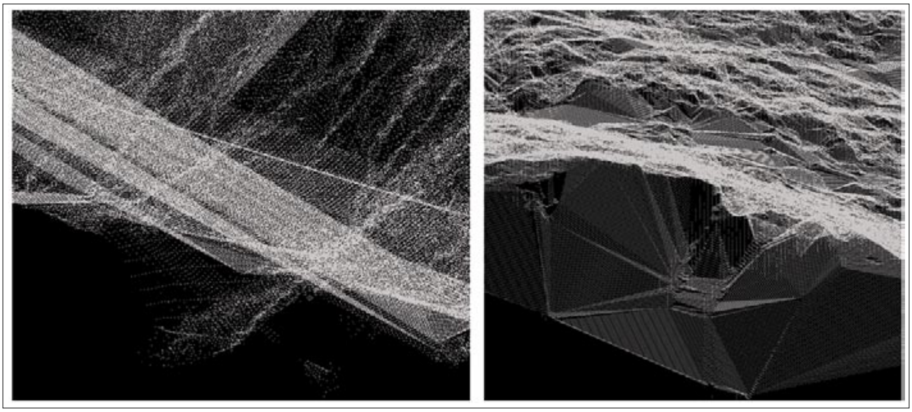


**Figure 14 - Details of the 3D wire-frames of the railway tunnels. Left panel: the gallery towards the mountain; right panel: the gallery towards valley.**

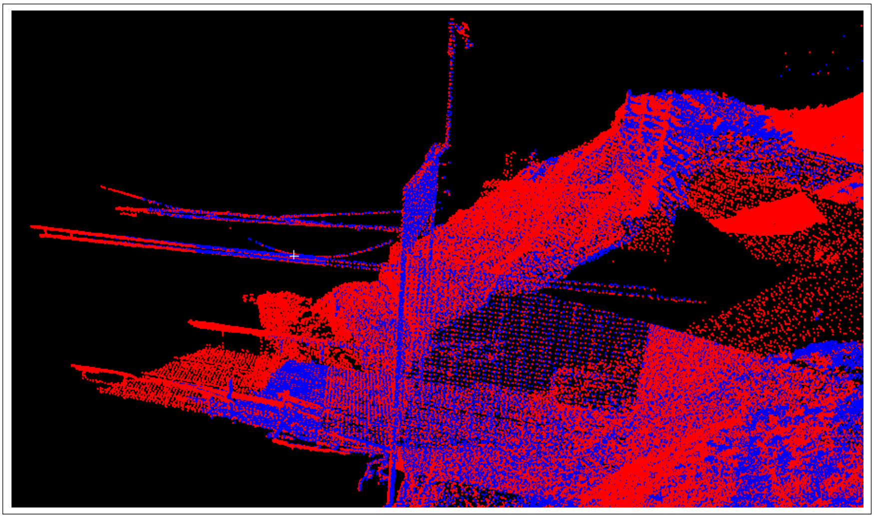


**Figure 15 - Comparison on the tunnel mouth in the first (red dots) and in the second (blue dots) survey.**

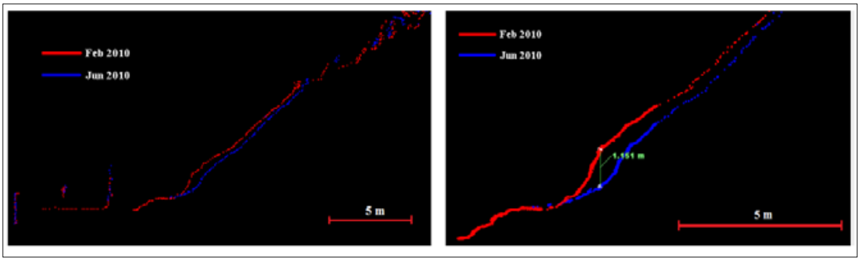



**Figure 16 - Terrain profiles along the railway tunnel upstream. Left panel: the whole landsliding slope; right panel: a detail of the same section that highlights and quantifies the difference in altitude between the profiles relating to two surveys taken at different time.**

In order to follow the second approach useful to compare the surfaces over time we co-registered and aligned the scans of the three surveys on a number of very stable points. We have chosen the "homologous" points on the two railway tunnels. The common reference system we used to frame the three point clouds is the absolute system of the last clouds we surveyed. We made this test in the Cyclone environment. The result of the alignment of the first two scans on the third one are reported in Table 5. In Figure 17 we show an example of a terrain profile we traced; it starts from the more stable side of the mountain, crosses the stream and rises along the landsliding slope.

**Table 5 - Residuals of the alignment of the first two scans on the third one.**

| Survey | Res. Plan. (cm) | Res. h (cm) |
|---|---|---|
| $1^{st}$ | 1±0.6 | 0±0.4 |
| $2^{nd}$ | 3.1±1.9 | 0±1.7 |

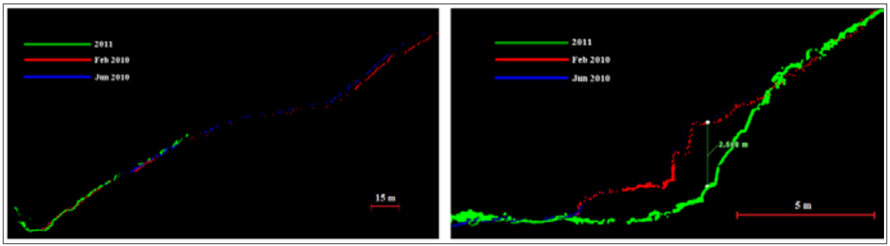



**Figure 17 - Terrain profiles along the landslide. Left panel: the whole landsliding slope; right panel: a detail of the same section.**



A last analysis we have done on our data concerns the identification and the boundary of homogeneous areas from the point of view of the movements they underwent. In order to simplify the calculations and to allow a more detailed study, we have divided in small portions the area covered by the DTM and we have calculated the change in altitude for each of them. The different portions have been selected by assuming geological homogeneity of the terrain. We have used Polyworks to make a comparison of the data coming from the first two surveys. The laser surveys have shown a strong dynamics of the slope. In Figure 18 we show an example of the results of our analysis.

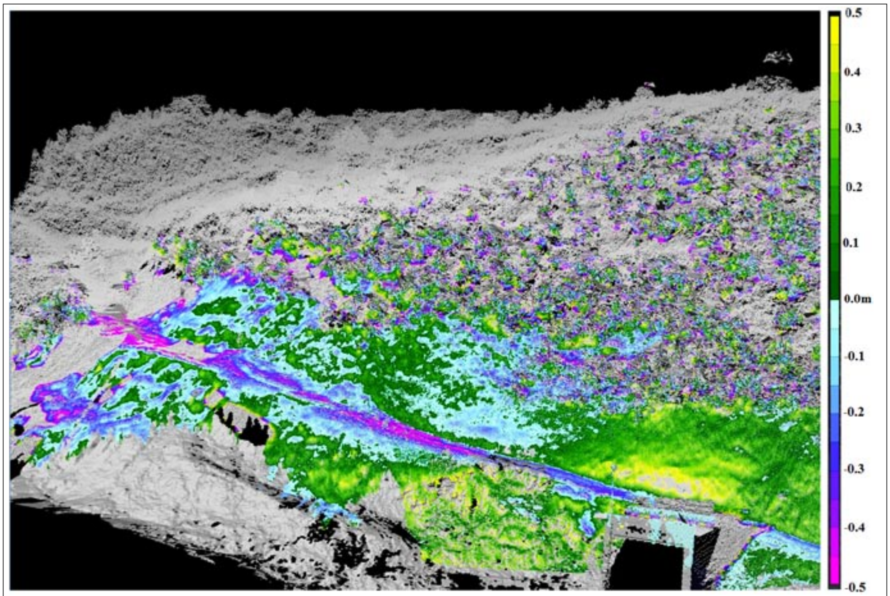



**Figure 18 - Comparison between two successive surveys (2nd vs 1st) (from Polyworks®).**

We have elaborated a number of DTMs and made comparisons between them using software packages different from those specialized in laser data processing. In Figure 19 we show an example of the comparison done with Surfer® on the first two surveys. In the left panel we show a contour level map (at an inter-distance of 1m) of the differences between the two grids produced by interpolating the points belonging to the clouds on the nodes of a regular grid (at a step of 1 m in both direction); we use the "kriging" algorithm. In the right panel we show a contour line map (at an inter-distance of 1m) of the residuals of the points belonging to the second surveys with respect to the 1 m gridded surface of the first survey. Once again it is necessary to segment the whole area into smaller portions in order to perform a more detailed study.

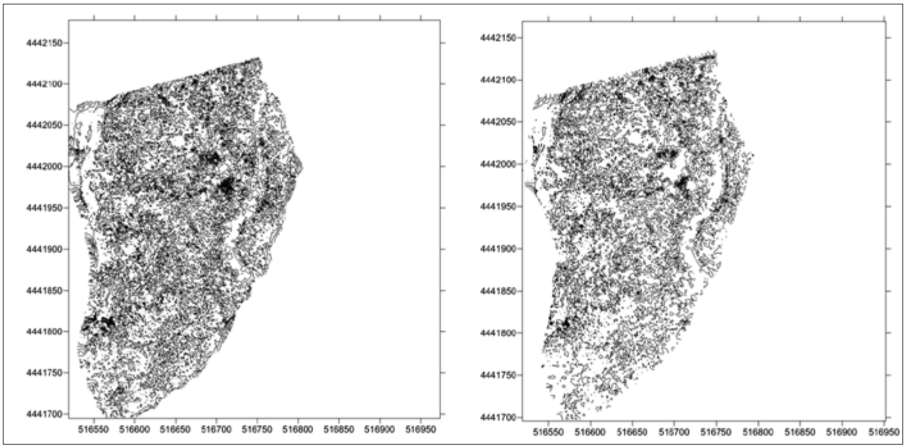



**Figure 19 - Contour line maps (the distance two adjacent contour lines is one meter) (from Surfer®). Comparison between the first two surveys. Left panel: the two surveys are interpolated on the same grid, and the differences of the heights on the grid nodes are shown. Right panel: the second survey is interpolated on a grid, and the difference of the cloud points of the first survey and the related facet of the second survey is shown.**

## Conclusions

Landslide monitoring can be carried out by using different types of terrestrial instruments. The most accurate results are given by Total Stations and by GPS receivers. In this way one can survey the position of few points which should be however accessible and well materialized. When we need a detailed description of the movement of a slope we use a TLS which enables a much lower accuracy on the individual points but allows to achieve a much more detailed modelling of the surface of the landslide. The huge number of points surveyed in this case requires nevertheless much more processing work. It is important to carry out both types of surveys since the data that can be acquired from each instrument are complementary.

For the landslide we studied the co-registration of individual clouds required a long and accurate processing work since the pan/tilt base of the TLS Optech, the instrument we used in the first two surveys, although calibrated in laboratory, often did not perform properly. We have preferred to manually record each task (tens for each tilt of each laser station). We think that the malfunction may be due to the transport of the instrument in rough terrain and to the use of tripods, which has prevented the correct rotation of the base.

The use of laser instruments with greater acquisition rate has enabled to get a very detailed description of the closest areas, while the use of a full wave form instruments helped to simplify the vegetation editing step.

The manual filtering process is very time-consuming and it has not always been crowned with complete success. The use of an instrument of the type "full wave form" and of a software tool

that can take advantage of this feature (the digitization of the response) allows to carry out a first separation between the vegetation and the soil, in a simple way and with great efficiency; one eventually needs to carefully check how reliable the results of the separation are. The editing of the data to reduce noise requires a large amount of work; without this however it is not possible to use the data for a quantitative precise analysis of the movements.
In order to compare the surveys of the various eras, since no stable areas where we could select a number of points to be used as double points to record the clouds were available on the boundary of the area surveyed, we framed the targets in an absolute reference system by connecting a near reference system to the GNSS permanent stations frame which are continuously monitored. The distance of the reference frame from the area of interest (a few tens of kilometres) introduces an uncertainty greater than what you would have if you used a closer reference system.
Using an absolute reference system as the ETRF2000 (as we did) is a good idea since the DTMs generated from point clouds data can be directly georeferenced in a UTM cartographic system, simplifying both their inclusion in national topographical maps and the task of comparing them with other data available for the landslide.
Once obtained a number of DTMs georeferenced in the same reference system, one can derive the products that traditionally geologists and geomorphologists use in order to study the shape and dynamics of the landslide (i.e. contour line maps, terrain profiles, evaluation of the ground masses moved). On these derived products a number of object-based image analysis software tools can be used for further geomorphological studies.

## References


Abellán A., Jaboyedoff M., Oppikofer T., Vilaplana J.M. (2009) - D*etection of millimetric deformation using a terrestrial laser scanner: experiment and application to a rockfall event*. Natural Hazards and Earth System Sciences, 9: 365-472. doi: http://dx.doi.org/10.5194/nhess-9-365-2009.

Alba M., Scaioni M. (2010) - *Automatic detection of changes and deformations in rock faces by terrestrial laser Scanning*. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVIII, Part 5, Commission V Symposium, Newcastle upon Tyne, UK., pp. 11-16.

Axelsson P. (2000) - *DEM generation from laser scanner data using adaptive TIN models*. International Archives of Photogrammetry and Remote Sensing, 33 (B4/1): 110-117.

Besl P.J., McKay N.D. (1992) - *A method for registration of 3D shapes*. IEEE Transactions on Pattern Analysis and Machine Intelligence, 14 (2): 239-256. doi: http://dx.doi.org/10.1109/34.121791.

Chen Y., Medioni G. (1992) - *Object modelling by registration of multiple range images*. Image and Vision Computing, 10 (3): 145-155.

Cruden D.M., Varnes D.J. (1996) - *Landslides Types and Processes*. Landslides: Investigation and Mitigation, Turner A.K. & Schuster R.L. Eds., Transportation Research Board Special Report 247. National Academy Press, WA., pp. 36-75.

Elseberg J., Borrmann D., Nuchter A. (2011) - *Full Wave Analysis in 3D Laser Scans for Vegetation Detection in Urban Environments.* Proceedings of the XXIII International Symposium on Information, Communication and Automation Technologies (ICAT).

Fiani M., Siani N. (2005) - *Comparison of terrestrial laser scanners in production of DEMs for Cetara tower*. Proceedings of XX CIPA International Symposium, Torino, Italy.

Gruen A., Akca D., (2005) - *Least squares 3D surface and curve matching*. ISPRS Journal of Photogrammetry and Remote Sensing, 59 (3): 151-174.

Guarnieri A., Pirotti F., Vettore A. (2012) - *Comparison of discrete return and waveform terrestrial laser scanning for dense vegetation filtering*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXIX-B7, Melbourne, Australia, pp. 511-516.

Guida D., Siervo V. (2010) - *Seminar on Landslides in Structurally Complex Formations*. Geologist Regional Ass. in Salerno, Italy.

Hesse C., Stramm H. (2004) - *Deformation measurements with laser scanners – Possibilities and challenges.* Proceedings of International Symposium on Modern Technologies, Education and Professional practice in Geodesy and Related fields, Sofia, Bulgaria.

Iside S.r.l. (2007) - *Servizio di monitoraggio dei corpi franosi insistenti sulla ex s.s. n. 447 tra km 70 e 72 nel Comune di Pisciotta*. http://www.centroiside.net (accessed 20 December 2012).

Kliparchuk K., Collins D. (2011) - *Evaluation of Stereoscopic GeoEye-1 Satellite Imagery to Assess Landscape and Stand Level Characteristics*. Proceedings of the ISPRS Canadian Geomatics Conference and Symposium of Commission I, WG I/3, Calgary, AB, Canada.

Luzi G., Pieraccini M., Mecatti D., Noferini L., Macaluso G., Galgaro A., Atzeni C. (2006) - *Advances in ground based microwave interferometry for landslides survey: a case study.* International Journal of Remote Sensing, 27 (12): 2331-2350. doi: http://dx.doi.org/10.1080/01431160600554975.

Mallet C., Bretar F. (2009) - *Full-waveform topographic lidar: State-of-the-art*. ISPRS Journal of Photogrammetry and Remote Sensing, 64 (1): 1-16. doi: http://dx.doi.org/10.1016/j.isprsjprs.2008.09.007.

McKean J., Roering J. (2004) - *Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry*. Geomorphology, 57: 331-351. doi: http://dx.doi.org/10.1016/S0169-555X(03)00164-8.

Metternicht G., Hurni L., Gogu R. (2005) - *Remote sensing of landslides: An analysis of the potential contribution to geo-spatial for hazard assessment in mountainous environments*. Remote Sensing of Environment, 98: 284-303. doi: http://dx.doi.org/10.1016/j.rse.2005.08.004.

Monserrat O., Crosetto M. (2008) - *Deformation measurement using terrestrial laser scanning data and least squares 3D surface matching*. ISPRS Journal of Photogrammetry & Remote Sensing, 63: 142-154. doi: http://dx.doi.org/10.1016/j.isprsjprs.2007.07.008

Prokop A., Panholzer H. (2009) - *Assessing the capability of terrestrial laser scanning for monitoring slow moving landslides*. Natural Hazards and Earth System Sscience, 9: 1921-1928. doi: http://dx.doi.org/10.5194/nhess-9-1921-2009.

Soudarissanane S., Lindenbergh R., Gorte B. (2008) - *Reducing the error in terrestrial laser scanning by optimizing the measurement set-up*. Proceedings of the XXI Congress, The International Society for Photogrammetry and Remote Sensing, Vol. XXXVII, Comm. V, Beijing, China, pp. 615-620.

Ujike K., Takagi M. (2004) - *Measurement of Landslide Displacement by object extraction with ground based Portable Laser Scanner*. Proceedings of the 25th Asian Conference on Remote Sensing, Chiang Mai, Thailand.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