UTILIZATION OF AIRBORNE LIDAR DATA FOR LANDSLIDE MAPPING IN FORESTED TERRAIN: STATUS AND CHALLENGES

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ABSTRACT:

With the advancement in sensor technology and point clouds processing algorithms, the capability of Airborne LIDAR data for landslide mapping in forested terrain is much promising. Most of the available air-based platform products either from an aerial-photograph, satellite imagery or synthetic aperture radar are not appropriate for interpretation of landslide features which are covered by dense vegetation. Mapping the landslides in such environment requires additional information that can help the interpreters to recognise landslide characteristics and later on be used to distinguish landslide activities. In this research, we present the status and challenges of utilizing the high-resolution airborne LIDAR data for landslide mapping in forested terrain. European dataset in Barcelonnette, Southern French Alps has been used. Amongst the important issues in this research is bare earth extraction. In order to preserve the important geomorphological feature, bare earth extraction based on hierarchical robust filtering is presented with a suitable filter parameterization. Finally, high-resolution Digital Terrain Model (DTM) is used to calculate the local topography roughness and characterize the landslide morphology.

KEY WORDS: Airborne LIDAR, bare earth extraction, landslide mapping

1. INTRODUCTION

1.1 Research Motivation

The frequency and destructive capacity of natural disasters are increasing around the world; landslides in particular are becoming important geomorphic agents which shape the surface of the earth. Evidence of these changes in the forms of mountainous areas, hills, valleys, rivers and streams, combined with preparatory and triggering factors on unstable terrain, shows that landslides can shift to be seen as a natural disaster. Moreover, landslides can attract widespread attention when there are many casualties and properties are damaged. It is important that these destructive events are well-documented and predicted in order to decrease the number of the casualties and major damages in different geographic and socioeconomic regions. In order to better understand the future behavior of these events, hazard assessment and knowledge on past events are essential.

A comprehensive landslide mapping is a basic requirement and important for quantifying both landslide hazard and risk. For sparsely vegetated areas, there are many mapping techniques available for making a landslide inventory map. For instance, through field-based observation of geomorphology (Rupke et al. 1988; Weber and Associates, 1990; Wills et al., 2002), image interpretation on single aerial photograph (Donati and Turrini, 2002; He at al. 2003) or multi-temporal aerial photographs (Kaab, 2002); (Van Westen and Lulie Getahun, 2003) and of high resolution satellite images (Gupta and Saha, 2001; Lin et al. 2002) and satellite-based or ground-based synthetic aperture radar (Singhroy et al., 1998) is possible. However, these mapping techniques are labour intensive, time-consuming and are not suitable for the rugged terrain. These methods were unsuccessful in areas that are covered by dense vegetation or that is rapidly re-vegetated. The occurrence of landslides in these environments requires new mapping techniques and Airborne *Li*ght *D*etection *a*nd *R*anging (LIDAR) is a promising technique for such applications

In this paper, current landslide mapping techniques that has been used in forested terrain will be elaborated. Special attention on status and challenges of airborne LIDAR data is given. High-resolution airborne LIDAR data is utilized in order to produce a complete bare earth that preserves important landslide features. Hence, a local topography roughness that calculated based on LIDAR-derived DTM is also presented.

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1.2 Landslides in Forested Terrain

Landslides belong to a broader group of slope processes referred to as mass movement. Herein, mass movements are defined as a variety of processes that result in the downward and outward movements of slope-forming materials under the influence of gravity. Soil creep, one of the mass movement processes, is almost imperceptibly slow and diffuse, whereas landslides, capable of moving at high velocity, are discrete and have clearly identifiable boundaries, often in the form of shear surfaces (Crozier, 1999).

Landslides occurred under forest faces difficulty to map in terms of completeness, efficiency and reliable of mapping techniques. In addition, visual interpretation based on available imagery needs special attention to recognize those environments. Thus, three criteria's should be considered. They are associated to the morphological, vegetation and drainage conditions of the slope. These characterizations become more important and act as indicators when dealing with visual interpretation. One example of the criteria's is shown in Table 1.

Table 1: Diagnostic morphological characteristics (Soeters and Van Westen, 1996)

Morphological characteristics	Description
Step-like morphology	A step-like morphology is related to retrogressive sliding. Image characteristics: step-like appearance of the slope.
Semicircular niches	Semicircular niches are associated with the head part of a slide with the outcrop of the failure plane.
Back tilting of slope faces	Back tilting of slope faces indicates rotational movement of slide blocks. This feature appears as oval or elongated depressions with imperfect drainage conditions.
Hummocky relief	Irregular slope morphology. Micro relief associated with shallow movements or small retrogressive slide blocks.
Formation of cracks	The formation of new cracks is an indication for recent activity. Crack formation occurs with sliding and toppling movement. They appear as lineaments more or less parallel to the existing scar.
Steeping of slopes	The steeping of a slope can indicate the presence of a landslide scar.

It is understood; landslides are a part of the natural evolution of landscapes and contribute to the formation of environmental activity. When landslides occur, they can move quickly down slope at rates of several m/s, or they can creep slowly at rates of only a few mm/year. Landslides can move instantaneously following a triggered event such as intense rainfall. Additionally, they can perform a delayed response to critical triggering conditions, for example after a prolonged rainfall event with a gradual rise in pore water pressures.

Further information on standardization of terminology for landslide activity can be referred to UNESCO-WP/WLI (1993a). Besides that, other standardizations also cover the nomenclature for landslides (IAEG-Commission on Landslides, 1990; UNESCO-WP/WLI, 1993b; Cruden and Varnes, 1996), landslide causes (UNESCO-WP/WLI, 1994), rate of movement (IUGS-Working group on landslide, 1995) and remedial measures for landslides (IUGS-Working group on landslide, 2001).

1.3 Landslide Mapping Techniques

Various mapping techniques that are applicable for landslide studies directly related to the use of conventional techniques such as field observations and aerial photo interpretation; of high resolution optical and infrared imagery (Ikonos, Quickbird, IRS CartoSat-1), satellite-based interferometric SAR (InSAR, and DlnSAR of Radarsat, ERS, Envisat, TerraSAR-X, COSmo/SkyMed, ALOS) and in recent years, airborne LIDAR.

Field mapping will involve conventional surveying methods or by using mobile GIS and GPS for the collection of landslide attributes. Field mapping also has been applied together with photo-interpretation to determine landslide distribution and classification relatively to age, degree of activity and typology (Carrara et al., 1991). Field-based approach is extraordinarily time intensive, required more labour and has difficulty for inventory map updating, especially in forested area. It is very precise to pointing out of smaller landslide features and recent active slides.

Aerial photograph interpretation (API) still remains the most applicable technique for landslide mapping (Metternicht et al., 2005). Interpretation of single and multiple aerial photos is used intensively for the mapping and monitoring of landslide characteristics (e.g. distribution and classification) and factors (e.g. slope, lithology, geostructure, landuse/land cover, rock anomalies). An obvious drawback of this technique is that in some cases, landslide features are often hidden or obscured by tree cover on aerial photographs. A combined approach of visual interpretation using aerial photos together with field based observation is recognized as labour-intensive and time-consuming. (Nichol et al., 2006) reported that for a complete stereo cover of an area of 1000 km^2 approximately 400 photo prints at a scale of 1:10,000 were needed. Furthermore, previous research on the use of aerial photos in complex environment did not show reliable results for landslide identification. Brardinoni et al. (2003) reported that 85% of the Vancouver landslides which were mapped in the field and were located in densely forested regions could not be recognized on aerial photographs.

Satellite imagery has been used intensively for the landslide inventory mapping. Using optical imagery system, recognition of a landslide can be carried out by considering the size of the features, the contrast between landslides and surrounding areas and the morphological expression (Mantovani et al., 1996). Optical imagery has also demonstrated the difficulty for mapping landslides in heavily forested terrain. Issues of detecting landslides in multi-temporal satellite imagery have still not been overcome due to persistent cloud and forest cover.

Radar technique can be performed either by airborne or satellite-based. Platforms in space are particularly diverse because of the large areas that can be captured within a short span of time. Recently, Interferometric Synthetic Aperture Radar (InSAR) has become a preferable technique for landslide mapping and many studies have been conducted in order to produce a suitable method which can delineate landslide features. However, there are some drawbacks of InSAR, especially related to geometric noise due to the difference in satellite look angles, the vegetation affect on the signal and the atmospheric factors (Catani et al., 2005). InSAR shows to be unsuitable for landslide mapping in forested terrain due to the dense vegetation effect which causes de-correlation (Rott, 2004) and the movement velocities are too high.

The disadvantages of traditional methods have demanded the much need of latest technology for effectiveness in terms of time, cost, speed and quality. The unsuitability of some technology has imposed the essential application of using higher-confident technique which can provide high-resolution topographic data for landslide morphology elements and deformation studies.

1.4 High-Resolution Airborne LIDAR

The first commercial topographic mapping systems to use airborne LIDAR are available in the early 1990s. Most of the LIDAR systems use a near infra-red laser which is unable to penetrate fog, smoke, or rain (Norheim et al., 2002). By providing direct range measurements between the laser scanner and the landscape on Earth, LIDAR is the state of the art technology for topographic mapping. LIDAR has demonstrated its ability to pass through the gaps between forest foliage and record terrain echoes under vegetation cover. Airborne LIDAR has a relatively small footprint (90 square km per hour). It is costly to create terrain models for areas much larger than 20,000 km^2 (Smith, 2005).

Landslide mapping in forested and rugged terrain has become a challenge in terms of time compilation and updating phase. Landslides mapping for areas that are partly or completely located beneath dense vegetation thus, require a new mapping technique. Airborne LIDAR is a promising technique providing optimal information for an expert image-interpreter to determine types and activity of landslides. Previous research shows that they are still lacking in methods to utilize single or multi-temporal airborne LIDAR in order to delineate small landslide features and measure the displacement of landslides that occur in mountainous, highly vegetated and rapidly re-vegetated landscapes.

2. STUDY

2.1 Barcelonnette Basin, France

The Bois Noir catchment is located in the Barcelonnette Basin which represents the climatic, lithological, geomorphological, and land-use condition of the Southern French Alps and is highly affected by landslide hazards (Flageollet et al., 1999). It is located in the dry intra-Alpine zone, surrounded by a mountainous climate with a Mediterranean influence. Average annual rainfall in this catchment is between 400 to 1300 mm per annum. Generally, the area is characterized by rugged topography, covered by coniferous forests and grasslands with elevation ranging from 60 to 1700 m. Figure 1 indicates the location of Bois Noir catchment in Barcelonette Basin, France. This study area is characterized by Callovo-Oxfordian marls covered by morainic deposits up to 15m thick.

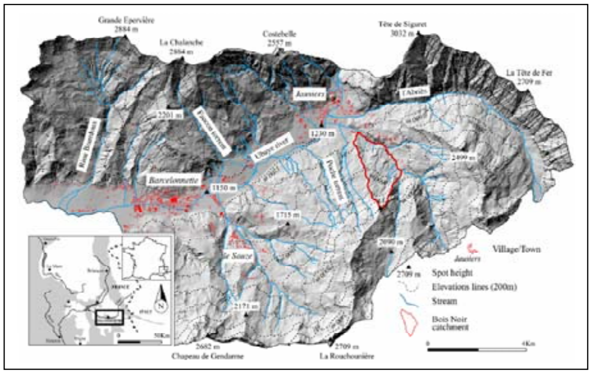

Figure 1: Barcelonnette Basin (Southern French Alps) and location of the Bois Noir catchment

Bois Noir catchment is affected by large rotational or translational slides. Most of the active translational slides are shallow within 2m to 6m. They are located on gentle slopes at the contact of moraine deposits and the black marls bedrock which creates hydrological discontinuity. The active rotational slides are located along streams and occur principally in moraine deposits or on contact with bedrock (Thiery et al., 2007).

Figure 2 shows the location of the Bois Noir landslide in aerial photography (AP) for 1956, 1982, 1995 and 2004. This multi-temporal AP indicates that the location of the track has moved approximately 20 meters during the period 1982-2002. It clearly shows that the velocity of the Bois Noir landslide can be categorised as slow and that it is an active landslide. Furthermore, Figure 3 illustrates the cross section of the Bois Noir landslide in 2004. This complex landslide consists of a rotational slide on the upper part at an elevation of 1660m, followed by a translational slide along the 120m stretch.

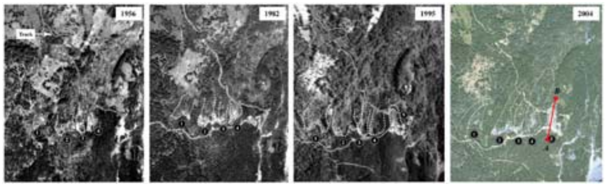

Figure 2: Landslide observation from 1956 to 2004.

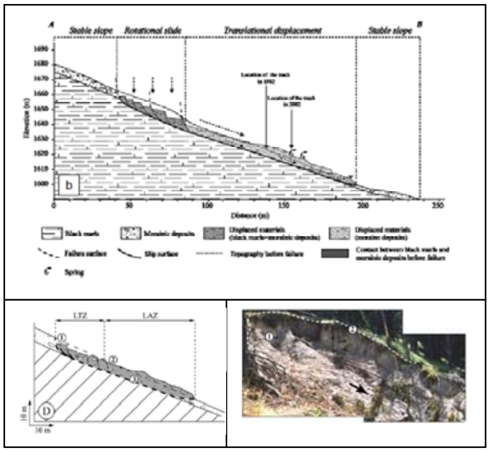

Figure 3: Cross section of the landslide

2.2 Available LIDAR Dataset

The Airborne LIDAR data were acquired by Helimap System SA use a helicopter at average flight height 300m. Laser scanner system, RIEGL LMS-Q560 has been used during the data acquisition in 2007. By using latest state-of-art digital signal processing, it meets the challenges to map geomorphology beneath dense forest. A detailed specification of laser scanner RIEGL LMS-Q560 is shown in Table 2.

Table 2: Airborne LIDAR Specification

Airborne Laser Scanner ***RIEGL* LMS-Q560**	
Laser Pulse Repetition Rate	up to 240 000 Hz
Effective Measurement Rate	up to 120 kHz @ 45 deg scan angle up to 160 kHz @ 60 deg scan angle
Minimum Range	30 m
Accuracy	20 mm
Precision	10 mm
Laser Wavelength	near infrared
Laser Beam Divergence	≤ 0.5 mrad
Laser Pulse Rate	Up to 250,000 pulses per second
Scanning Mechanism	Rotating polygon mirror
Scan Pattern	Parallel scanning lines
Scan speed	10-160 scans/sec
Number of Targets per Pulse	Digitized waveform processing is unlimited Online monitoring data output is first pulse or last pulse
Scan angle range	± 22.5 deg = 45 deg total (± 30 deg = 60 deg total
Angle step width	$\Delta\delta \geq 0.004$ deg (for pulse repetition rate in excess of 100kHz)
Angle Readout Resolution	0.001 deg
Intensity Measurement	For each echo, high-resolution 16-bit intensity information is provided

Besides the multi-temporal aerial photograph compiled from 1956 till 2004, an orthophoto has also been produced associated to the LIDAR data acquisition. Figure 4 shows an orthophoto of Bois Noir that indicates most of the area is covered by dense vegetation on undulating topography. Landslide features is quite difficult to interpret on image and its interpretation is essential steps to produce a landslide inventory map and later on can be used to investigate through field mapping.

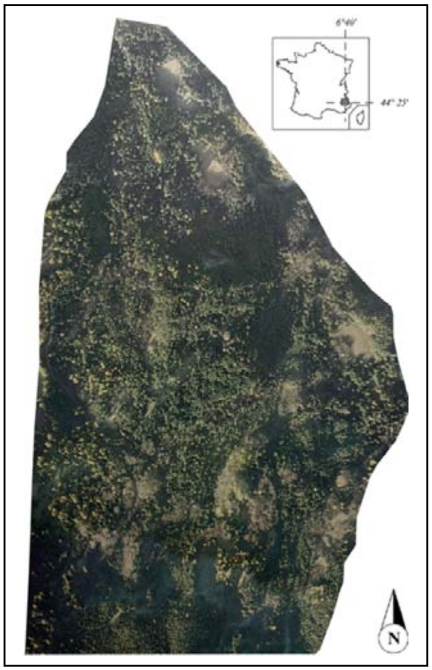

Figure 4: Orthophoto of Bois Noir

3. BARE EARTH EXTRACTION

Laser-based technology is capable of delivering very dense and accurate point clouds of a landscape in a relatively short time. Thus, all the data are inherently in three-dimensional and completely digital (Baltsavias, 1999, Kerle et al., 2008). Largely, researchers developed semi (automatic) methods to detect and interpret individual objects in landscapes. Many tasks of LIDAR pre-processing are required to achieve certain level of quality data before it be used for specific applications. Bare earth extraction is one of them. Herein, bare earth is defined as the topsoil or any thin layering covering it (Sithole, 2005) and extraction of bare earth is process of identifying landscape surface without the objects such as buildings, trees and others. This process is important, because the extracted data has a direct impact on the quality of modelling.

There are various filtering algorithms that are available in the commercial LIDAR processing software. Algorithms for separation between objects and ground points are discussed by dividing them into four major groups. The four groups are based on mathematical morphology, progressive TIN densification, surface interpolation and segmentation. In the past, many different solutions for the classification of the LIDAR data were published (Sithole and Vosselman, 2004).

First group of algorithms is recognized as the morphological approach (Kilian, 1996), which was originally developed for binary images. The algorithms basically used an assumption that the lowest point in a neighbourhood belong to the bare Earth. Furthermore, this algorithm works by calculation of a rough terrain model based on the lowest point. All points with height difference exceeding a given threshold is filtered out and then a terrain model is determined. Axelsson (2000) developed the second group, known as the progressive densification methods. This algorithm starts with a rough approximation of the terrain model with initial terrain points (typically the lowest point within a certain grid cell) and iteratively densifying the terrain model.

The third group of filter methods work based on surface interpolation (Kraus and Pfeifer, 1998). They used a surface model that iteratively approaches the DTM calculated based on the entire point set by adapting the influence of the individual input points. The last group is segmentation based methods that was developed and published (Tóvári and Pfeifer, 2005). In the first step, these methods segment the ALS data with a local neighbourhood analysis and subsequently classify the segments by different strategies.

The major DTM filtering techniques are designed to provide the bare earth information. There are some advantages and disadvantages on their strategy to achieve a reliable result on separating the bare earth from airborne laser data (Sithole, 2005). An experimental comparison between various filtering algorithms is published in Sithole and Vosselman (2004).

3.1 Hierarchical Robust Filtering

This method was developed and originally designed for laser data in wooded area (Kraus and Pfeifer, 1998; Pfeifer et al., 1998). As mentioned earlier, this algorithm that belongs to third group is developed for terrain modelling and embedded in SCOP++ software. A method so called robust interpolation by considering a rough approximation of the terrain is well-adapted in this software.

The strategy that has been used in hierarchical filtering involves four different processing approaches as follows; 1) thin out, 2) interpolate, 3) filter and 4) sort out. Thin out refers to a raster based thinning algorithm which lays a grid over the complete data domain and selects one point for each cell. In the interpolate step a terrain model is derived from the current data set by interpolation without differentiating data points. Also in the filter step a terrain model is computed, but this time a weighting function. As shown in Figure 5, a weight function is used to give low computational weighting to likely off-terrain points and high weighting to likely terrain points is exploited. At h above g the weight function has a half of its maximum value (h is the half–width value). The value s determines the steepness of the weight function at this point. At t in the right tail the weight function is cut off. Then, in the sort out step, only data points within a user-defined distance from a calculated DTM are used (Wagner et al., 2004).

In addition, linear prediction-based method with a certain individual accuracies for each measurement is works iteratively. In the first step all points are used to estimate the covariance function of the terrain. The surface is computed with equal weights for all points. This surface performed in an averaging threshold between ground points and off-ground points. Basically, the ground points are considered under condition: below an averaging threshold surface; negative filter values and positive residuals. Moreover, the off-ground points are refer to the above or on the averaging surface, have positive filter values and have negative residuals. Figure 6 demonstrates a concept of Digital Terrain Model (DTM) computation using robust interpolation method.

In order to provide a reliable DTM, which is suitable for characterizing terrain and vegetation anomalies, trial and error method has been used to acquire an optimal parameterization of DTM. In practice, the parameterization of computing DTM would consider a grid width determination and mean accuracy of the airborne LIDAR raw data. Besides that, filtering factor on controlling the weight function and tolerance associate to filter strategy is used in this study.

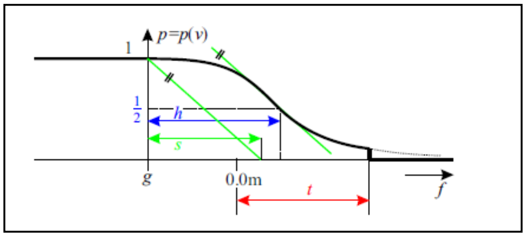

Figure 5: Weight function

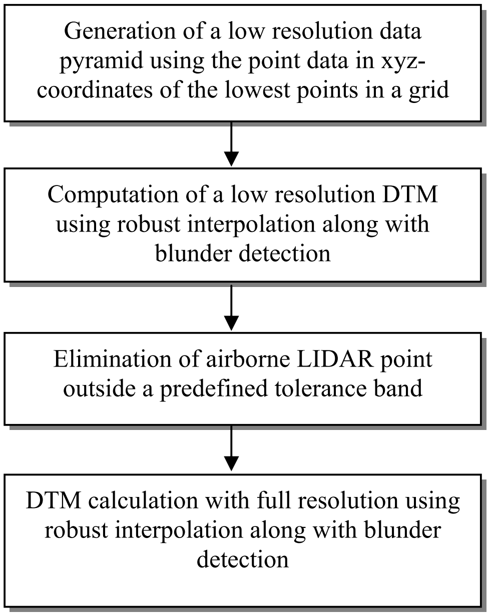

Figure 6: DTM computation using robust interpolation

Figure 7 shows a Digital Terrain Model (DTM) of Bois Noir and two spots of stereo image. This map is shown together with hill-shading that derived to enhances the visualization of particular features which perpendicular to the azimuth of the illumination. Thus, the planar and altitude angles of the illumination zone are taken into consideration. The stereo image is produced based on single LIDAR data using ILWIS software. With an anaglyph glasses, the study area can be viewed in three-dimensional. It gives more insight and understanding to the landslide processes. Moreover, in some cases, the landslide activity can be determined.

An appropriate quality terrain model indicates some features associate to landslide evolution such as crown area, main scarps, secondary scarps, body, toe, accumulation zone, and transportation zone. Result as shown in Figure 7 is used as reference on the field by expert image-interpreter during intensive fieldwork in June 2009. As stated by Haneberg (2004) that LIDAR shaded relief maps allow a much more detailed interpretation of the landslide mechanism than the deformation features within the large landslide. Later on this map is fully employed for visual interpretation together with stereo image. It also helps to generate more reliable secondary maps such as slope map, aspect map or plan curvature map.

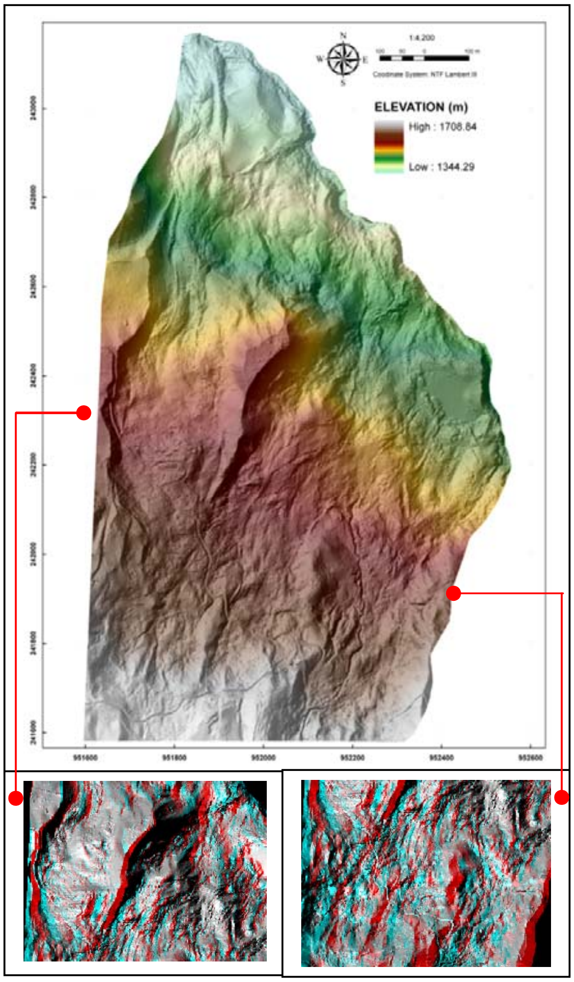

Figure 7: DTM of Bois Noir and stereo images

Current status on generating bare earth using available filtering algorithms which are embedded in some commercial software shows the possibility to produce terrain models. However, those filtering algorithms, in particular situation are simply filter out ground points which belong to landslide features. Indeed, to preserves important landslide features (e.g. main scarps that occur on steep slopes or rock blocks located on the body of landslide) remain big challenges.

An automatic bare earth extraction without much works on manual editing would help end-users to utilize LIDAR data for further examination. In addition, DTM resolution, interpolation methods, and LIDAR data reduction in terms of storage and manipulation amongst the issues arise dealing with high-density of airborne LIDAR data.

Those challenges are not entirely solved and new methods are being published in order to overcome those situations. At some point, the single or multi-temporal airborne LIDAR data is currently the method of choice.

3.2 Topographic Roughness

The mapping of spatial and temporal patterns of the landslide surface deformation can be used to examine individual slide kinematics and mechanics. The surface of landslides normally is rougher on a local scale, than on adjacent stable slopes. Figure 8 shows the basic idea about topographic roughness in a DEM as revealed by unit direction vectors. In smooth topography (upper image) the local vector has similar orientations. In rough terrain (lower image), the local vector orientations are highly variable.

By adopting Glenn et al (2006) method, the roughness of landslide surfaces is calculated using point clouds without interpolation. Thus, it would give more reliable roughness indicator. Besides that, the quality of roughness map directly related to generated bare earth. The better bare earth represents the ground surfaces, the higher quality of topography roughness can be produced. The roughness calculation starts by separate vector points into specific grid cells (e.g. 5 x 5m) which contain 5 to 50 data points.

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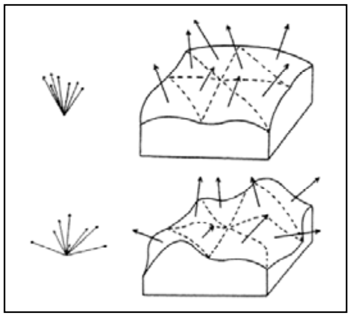

Figure 8: Topographic surface roughness in a DEM

Then, the lowest elevation points are selected within each cell that later on being used to interpolate baseline elevation surface that acts as reference surface. From this surface, the height of remaining point clouds is calculated. The topography roughness in each cell was defined by calculating the standard deviation of these heights above the reference surface. Figure 9 shows the topography roughness of Bois Noir landslides.

The roughness of landslides topography varies according to the causal geomorphic processes. For the Bois Noir landslides, they vary from 1 cm to almost 1 m with higher roughness near to escarpment areas and along the steep slopes. Lower topography roughness relatively covered the flat surfaces and stable areas. Within the active landslides in southern part, topography roughness ranges from 50 cm to 90 cm in average and becoming less till 1 cm for un-deformed surfaces.

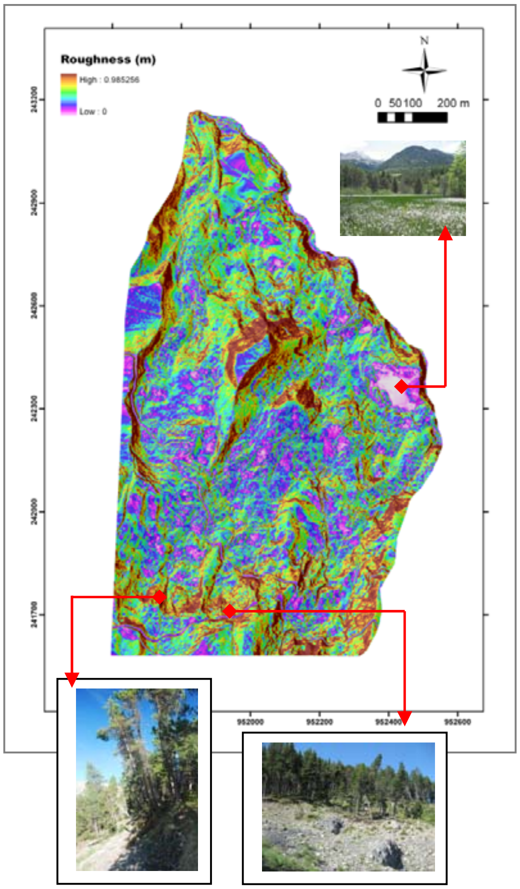

Figure 9: Topography roughness of Bois Noir landslides

3.3 Irregular Trees and Rock Characterization

Schulz (2007) presented that imagery derived from LIDAR data was used to identify and map landslides in Seattle, which resulted in four times more than had been mapped previously using aerial photographs. Besides the importance of terrain information, irregular trees and rock blocks can be indicator to landslides, especially dealing with complex landslides occur under dense vegetation. Some photographs about irregular trees and rocks in Bois Noir are show in Figure 10.

By taking advantages offered by airborne LIDAR system to penetrate between forest foliage, information on vertical structure is possible to extract from point clouds and discover the patterns of irregular trees. It gives additional knowledge to better understand the future behaviors of landslides. This research becomes more significant in tropical environment which is more rapidly re-vegetated. The characterization of irregular trees and rock blocks create new challenges for landslide mapping in order to exploit important trees and rock blocks information that can contribute to analyzing the vegetation effect and soil deformation of the landslide processes.

Figure10: Rock blocks (top) and irregular trees (bottom) -Bois Noir Landslides

3.4 Discussion

Airborne LIDAR is one of the most reliable techniques for terrain data collection and offer a vast application to Earth's science. Extracting the ground points from huge amount of airborne LIDAR data is becoming a standard practice among spatial geo-information and earth observation community. The effective processing of the raw airborne LIDAR data and the generation of an efficient and high-quality terrain model remain challenges. Indeed, pre-knowledge, field inspection and investigation are needed to acquire a high filtering quality.

High-resolution digital terrain model derived from airborne LIDAR data is essential to provide optimal information to an expert image-interpreter for detecting landslides and classifying them according to type, movement mechanism, and activity status in forested mountainous terrain.

Besides the features on the ground surface, the irregular vegetation and rock blocks can be good indicators to cognize the landslide processes. Understanding the pattern of irregular trees such as bended tree, over-tilted tree and back-tilted tree can help to evaluate the landslide geomorphic.

Furthermore, airborne LIDAR provides detailed point clouds on particular surfaces can be used to investigate the spatial and temporal variations of landslides. The availability of a multi-temporal LIDAR will open up a new direction and perspective on the change detection approach including the landslide displacement.

Since airborne LIDAR can measure both the canopy height and the terrain elevation underneath at once, airborne LIDAR is complementary to current mapping techniques such as photogrammetric. All the advantages from LIDAR create a new potential research in geomorphology, forestry and landslide mapping in the near future.

3.5 References and/or Selected Bibliography

References from Journals:

Baltsavias, E., 1999. Airborne laser scanning – relations and formulas. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 199-214.

Brardinoni, F., Slaymaker, O., Hassan, M.A., 2003. Landslide inventory in a rugged forested watershed: a comparison between air-photo and field survey data. *Geomorphology* 54, 179-196.

Carrara, A., Cardinalli, M., Detti, R., Guzzetti, F., Pasqui, V., Reichenbach, P., 1992. GIS techniques and statistical method models in evaluating landslide hazard. *Earth Surface Processes and Landform* 16, 427-445.

Catani, F., Farina, P., Moretti, S., Nico, G., Strozzi, T., 2005. On the application of SAR interferometry to geomorphological studies: estimation of landforms attributes and mass movements. *Geomorphology* 66, 119-131.

Donati, L., M. C. Turrini., 2002. An objective method to rank the importance of the factors predisposing to landslides with the GIS methodology: application to an area of the Apennines (Valnerina; Perugia, Italy). *Engineering Geology* 63(3-4): 277-289.

Flageollet, J.-C., Maquaire, O., Martin, B., Weber, D., 1999. Landslides and climatic conditions in the Barcelonnette and Vars basins Southern French Alps, France. *Geomorphology* 30, 65–78.

Glenn NF, Streutker DR, Chadwick J, Glenn DJ, Thackray GD, Dorsch SJ., 2006. Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity. *Geomorphology* 73, 131-148.

He, Y., Xie, H., Cui, P.,Wei, F., Zhong, D., & Gardner, J. (2003). GIS-based hazard mapping and zonation of debris flows in Xiaojiang Basin, southwestern China. *Environmental Geology*, 45, 285– 293.

IAEG Commission on Landslides. 1990. Suggested nomenclature for landslides. *Bulletin of the International Association of Engineering Geology* 41: pp. 13-16.

IUGS—Working group on landslide, 1995. A suggested method for describing the rate of movement of a landslide. *Bulletin of the International Association of Engineering Geology* 52, 75–78.

IUGS-Working group on landslide, 2001. A suggested method for reporting landslide remedial measures. *Bulletin of Engineering Geology and Environment* 60, 69–74.

Kaab, A., 2002. Monitoring high-mountain terrain deformation from repeated air- and spaceborne optical data: examples using digital aerial imagery and ASTER data. *ISPRS Journal of Photogrammetry and Remote Sensing* 57(1-2): 39-52.

Kraus, K., N. Pfeifer., 1998. Determination of terrain models in wooded areas with airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing* 53(4): 193-203.

Lin, P. -S., Lin, J. -Y., Hung, H. -C., & Yang, M. -D. (2002). Assessing debris flow hazard in a watershed in Taiwan. *Engineering Geology*, 66, 295–313.

Metternicht G, Hurni L, Gogu R. 2005. Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. *Remote Sensing of Environment* 98, 284-303.

Nichol, J.E., Shaker, A., Wong, M-S., 2006. Application of high-resolution stereo satellite images to detailed landslide hazard assessment. *Geomorphology* 76, 68-75.

Rupke, J., E. Cammeraat, et al., 1988. Engineering geomorphology of the Widentobel catchment, Appenzell and Sankt Gallen, Switzeland. A geomorphological inventory system applied to geotechnical appraisal of slope stability. *Engineering Geology* 26: 36-68.

Schulz W.H., 2007. Landslide susceptibility revealed by LIDAR imagery and historical records, Seattle, Washington. *Engineering Geology* 89 (2007) 67–87

Sithole, G., Vosselman, G, 2004. Experimental comparison of filter algorithms for bare-earth extraction from airborne laser scanning points clouds. *ISPRS Journal of Photogrammetry and Remote Sensing* vol. 59(1-2), pp. 85-101.

Thiery, Y., J. P. Malet, et al. 2007. Landslide susceptibility assessment by bivariate methods at large scales: Application to a complex mountainous environment. *Geomorphology* 92(1-2): 38-59.

UNESCO-WP/WLI, 1993a. A suggested method for describing the activity of a landslide. *Bulletin of the International Association of Engineering Geology*(47): 53-57.

UNESCO-WP/WLI, 1994. A suggested method for reporting landslide causes. *Bulletin of the International Association of Engineering Geology* 50, 71–74.

Van Westen, C.J. and Lulie Getahun, F., 2003. Analyzing the evolution of the Tessina landslide using aerial photographs and digital elevation models. *Geomorphology*, 54(1-2): 77-89.

Wills, C.J., McCrink, T.P., 2002. Comparing landslide inventories, the map depends on the method. *Environmental and Engineering Geosciences* 8, 279-293.

References from Books:

Crozier, M.J., 1999, *Landslides*, In D.E. Alexander and R.W. Fairbridge (eds), Encyclopedia of Environmental Science, Dordrecht: Kluwer, pp. 371–375.

Cruden, D.M., Varnes, D.J., 1996. *Landslide types and processes*. In: Turner, A.K., Schuster, R.L., (Eds.). Landslides investigation and mitigation, special report 247. Transportation Research Board, National Research Council, pp.36-75.

Kerle, N., Heuel, S., Pfeifer, N., 2008. *Real-time data collection and information generation using airborne sensors*. Geospatial Information Technology for Emergency Response – Zlatanova & Li (eds). pp.43-74.

Sithole, G., 2005. *Segmentation and Classification of Airborne Laser Scanner Data*, Ph.D. thesis, TU Delft.

Smith, R.E., 2005. *Topographic Mapping*. In: S. Grunwald (Editor), Environmental Soil-Landscape Modeling: Geographic Information Technologies and Pedometrics. CRC Press, New York.

Soeters, R., van Westen, C.J., 1996. *Slope instability recognition, analysis and zonation*. In: Turner, A.K and Schuster, R.L., (Eds), Landslides Investigation and mitigation. Transportation Research Board, special report 247, National Academic Press, Washington, D.C., pp. 129-177.

UNESCO-WP/WLI, 1993a. *Multilingual Landslide Glossary*. Bitech Publishers Ltd., Richmond, Canada. 34 pp.

References from Other Literature:

Axelsson, P., 2000. DEM generation from laser scanner data using adaptive TIN models. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXIII (Pt. B4/1), pp. 110-117.

Gupta, R., Saha, A., 2001. Mapping debris flows in the Himalayas, natural resource management. GISdevelopment.net, pp. 4.

Haneberg,W.C., 2004. The ins and outs of airborne LiDAR: an introduction for practicing engineering geologists. AEG News 48 (1), 16–19.

Kilian, J., Haala, N., Englich, M., 1996. Capture and evaluation of airborne laser scanner data. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences vol.34, part 2. pp. 311-315.

Norheim, R.A., Queija, V.R. and Haugererud, R.A., 2002. Comparison of LiDAR and INSAR DEMs with dense ground control, Proceedings of the ESRI 2002 User Conference. ESRI, San Diego, pp. 9.

Pfeifer, N., Kostli, A., Kraus, K., 1998. Interpolation and filtering of laser scanner data–implementation and first results. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences vol 32, part3/1, Columbus, pp 153-159.

Rott, H. (2004). Requirements and applications of satellite techniques for monitoring slope instability in Alpine areas. Workshop on risk mitigation of slope instability. Ispra, Italy' JRC-Institute for the Protection and Security of the Citizen.

Singhroy, V., Mattar, K.E. and Gray, A.L., 1998. Landslide characterisation in Canada using interferometric SAR and combined SAR and TM images. Advances in Space Research, 21(3): 465-476.

Thiery, Y., Malet, J.P., Maquaire, O., 2007a. Is it possible to link statistical and deterministic models for assessing landslide hazard. European Geosciences Union General Assembly 2007, 15-20 April 2007, Vienna, Austria.

Tovari, D., Pfeifer, N., 2005. Segmentation based robust interpolation – a new approach to laser data filtering. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences vol. XXXIV, pp. 79-84.

Wagner, W., Eberhofer, C., Holaus, M., Summer, G., 2004. Robust filtering of airborne laser scanner data for vegetation analysis. Proceedings of the ISPRS working group VIII/2, Freiburg, Germany, pp. 56-61.

Weber and Associates., 1990. Landslide Map, including ground deformation from the 1989 Loma Prieta earthquake. Unpublished mapping for California Department of Parks and Recreation, 8 sheets, scale 1:4800

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