scape Soil Conservation And Protection for Europe

Monitoring soil erosion from high resolution DTMs : Present possibilities and future prospects

Hein Bouwmeester

IBED – Physical Geography, University of Amsterdam, NL
h.bouwmeester@solum.nl

Introduction

The need for controlling mass wasting processes is rising. Costs and environmental damage are increasing due to a changing climate and a more intensive use of land. The vast amount of research on soil erosion and mass movement of nearly all different terrain-forms adds to a thorough knowledge of the causes and effects of soil degradation. To increase efficiency and reduce overhead costs it is important that governments and institutions work together in developing a more global vision and approach. Laser scanning techniques are maturing and can provide essential tools in the struggle against soil degradation, especially on large scales.
Airborne Laser Scanning (ALS) provides useful tools in the determination of the geographical spread and magnitude of erosion and mass movement events. ALS allows the gathering of high-resolution 3D terrain data swiftly and at relatively low costs. The acquired 3D point data can more or less automatically be converted to a Digital Terrain Model (DTM). This can help identify erosion risk areas and to apply adequate control measures at the right locations. Furthermore, the visual attractiveness of different analyses may add to the acknowledgement of the rather profound problems involved.

This paper is merely an outline of several possibilities of laser altimetry and a view of its current status in remote sensing and geomorphology. It is divided into two sections. Section A will discuss several possibilities in the use of laser altimetry in the monitoring of soil degradation on different scales. It will conclude with some recommendations and remarks on further research. Section B discusses the general principle of laser altimetry, the accuracy of the measurements as well as the processing needed after the actual flying.

A.1 Application of high-resolution DTMs in erosion monitoring

Several possibilities of ALS in the monitoring of erosion are discussed:

1) Hazard mapping of erosion sensitive areas with high resolution DTMs
2) Linking of DTMs to photogrammetric imagery
3) Linking of DTMs to a GIS
4) Comparison of sequential DTMs
5) Identification of ground features with DTMs
6) Application of space-borne laser scanning

A.1.1 Hazard mapping of erosion sensitive areas with DTMs

The most straightforward and common use of ALS is altitude derivation of large areas at relative high accuracy and the conversion of these xyz-data into high resolution DTMs. Slope properties such as slope-angle and slope-length can easily and precisely be derived from a DTM. These properties influence soil erodibility and thus enable user groups to exactly pinpoint erosion-sensitive areas. Most GIS packages include algorithms for slope-angle derivation. The slope-length can be determined by making use of (e.g.) the sediment delivery model, developed by the University of Leuven. From large DTMs, areas of interest can be selected that have (e.g.) a slope-angle of more than 5º and a slope-length of more than 300m. The areas of interest can then be further refined with vegetation and soil properties, as described in sections A.1.2 and A.1.3.

In Europe various regions such as the entire Netherlands, Flanders in Belgium, several states and sections of Germany, Austria, Italy and Switzerland have been converted into DTMs by commercial companies in assignment of local governments. The DTMs were ordered mainly for hydraulic engineering, coastal defence and infrastructure studies. One of the supplying companies (Terra Imagining) charged the Belgium government € 300 per km^2 for in total 800 km^2. Because the sums of money involved are rather high, a fast acquisition of a country- or even of a continent-covering high resolution DTM seems unlikely. However, local governments seem cooperative in supplying researchers with already available DTMs, acquired initially for other purposes. It is expected that the total area covered by LS altimetry within Europe will expand rapidly. Noteworthy is that a high resolution DTM of 20 years old is still useful and relatively accurate, since on most surfaces no large morphological changes take place in short periods.

A.1.2 Linking a DTM to photogrammetric imagery

The possibilities of the DTM can be drastically enhanced if linked to photogrammetric imagery. The most obvious link is the addition of images with multispectral or hyperspectral capabilities to the DTM, which permits the classification of vegetation types. As vegetated areas are to some extent less erodible than others, landuse identification will lead to improved hazard mapping. The areas of interest as defined by the DTM alone in section A.1.1 can be further refined by adding vegetation properties.

A study in the very gently sloping Venice lagoon by Silvestri et al. (2003) proposes that altimetric accuracy can be improved by linking LS data to hyperspectral imagery. In this case-study a hyperspectral sensor was used to differentiate salt marsh vegetation, which was found to be associated with very narrow ranges in ground elevation. The fractional cover of different halophytic species was used as a reliable ecological indicator for the estimation of ground elevation. The derived DTM could be calibrated with the DTM derived from LS data and resulted in mean altimetric values of promising precision.

Presently, several companies are experimenting with cameras connected to the laser and POS. The aerial photographs are in real time geo-referenced and converted into ortho-photographs, which allow further possibilities. Georeferencing of photogrammetric images becomes easier and more accurate using high resolution DTMs but remains a time-consuming task (McIntosh et al., 2002).

A.1.3 Linking the DTM to a GIS

The Alterra institute in the Netherlands provides digital soil and geomorphologic maps (scale 1:50.000) and landuse maps in raster format (cellsize 25m). The source data comes from field studies, available hardcopy maps and satellite images. Linking these maps to the DTM provides obvious benefits and can be realised quickly and automatically. With the digital soil map or geomorphologic map spatial soil erodibility can be added to the area of interest (A.1.1). With the addition of rainfall data all factors influencing soil loss in the Revised Universal

Soil Loss Equation (RUSLE) are within reach and very reliable hazard maps of big areas could be made.

What is required for environmental monitoring and control is the set-up of a central European Global Information System (GIS). The GIS would be a welcome addition to the World Data Center System and could facilitate and above all stimulate further research. Many institutes and governments possess fragmentised but detailed data that would (if combined) form a powerful GIS. Data such as DTMs, ortho-photos, satellite imagery, soil maps, landuse maps, etc. provide possibilities not only for environmental scientists but also for other disciplines. A GIS is not scale-dependent permitting the addition of data and regional updating anytime.

A.1.4 Comparison of sequential DTMs

Another possibility of ALS is the creation of repetitive DTMs of the same area of interest. By simple subtraction of gridcells morphologic changes can be tracked. Until now the accuracy of DTMs derived by LS appear insufficient for tracking small-scale surface changes resulting from (e.g.) average soil losses in Belgium. If we assume a total error in altitude for a single DTM of 29 cm (see chapter B.4), two consecutive images would have an error of double that amount. Despite the facts that mean error per DTM is often less than 5 cm (Huising and Gomes Pereira 1998) and accuracy improvements are possible through object-matching, larger morphological changes seem necessary before becoming detectable and (more important) significant. Transported sediment has the tendency to concentrate itself as colluvium downslope. The altimetric shifts of these relatively small eluvial areas is likely to be larger than in the upstream source areas. It may therefore be possible to detect and quantify soil movement by using a sequence of DTMs.

Very typical in the Mediterranean is the terraced landscape in hilly and mountainous regions. In a time of intensification many terraces in upland areas deemed marginal are abandoned. By lack of maintenance they seem vulnerable for collapse resulting in frequent landslides and soil slips. Terraces form linear features along the contours of slopes. This distinct shape-characteristic may well be detectable on DTMs using edge detection algorithms designed originally for the extraction of dikes and buildings (McIntosh and Krupnik, 2003). Since the majority of the terrace walls (edges) remain intact between two consecutive DTMs, it is expected that relative accuracy can be increased through object-matching. Volumetric and temporal changes on all scale levels of terraced landscapes seem traceable. The importance of small footprint laser systems must be stressed as large footprint lasers will frequently miss terrace walls resulting in smooth slopes, where stepped ones would be more appropriate.

In the US, various projects with the bathymetric laser in monitoring coastal erosion and deposition have been undertaken (White, 2003). A bathymetric laser emits a beam in two wavelengths, usually 1064 nm and 532 nm. The infrared wavelength is reflected by water surfaces while the green one penetrates it and is reflected by the bottom surface. This allows the tracking of altimetric changes on the beach as well as under water. As large amounts of sediment-transport often take place during and after extreme events, morphological changes are well traceable on the hurricane-struck coast of North Carolina in a one year time-span.

A.1.5 Identification of ground features

ALS has been successfully applied to extract surface features. Algorithms to automatically extract dikes, power lines and buildings from the raw data have been designed mainly for infrastructure planning purposes (Brugelman, 2002). However, extensive manual correcting is often required caused by misinterpretations of these algorithms (section B.5). For the monitoring of soil erosion and mass movements abrupt changes in slope, slope curvature and rill- and gully- systems are probably of greater interest. If footprint-size is small enough these features may very well be detectable.

McKean and Roering (2004) used high resolution DTMs to characterize a 50 ha landslide complex near Christchurch, New Zealand, by quantifying local surface roughness. Spatial patterns of surface roughness are employed to distinguish slide from non-slide, identify individual morphologic domains and estimate the relative activity of adjacent domains. The outline of the slide could easily be automatically detected, since its surface was rougher than on adjacent unfailed slopes. This roughness can be constructed by measuring the variability in slope and aspect of the gridcells. The procedure was successfully tested on several other slides in the neighborhood. Unfortunately, other rough elements may exist in the landscape that do not allow a fully automated terrain analyses of wider areas without manual intervention.

A.1.6 Space-borne Laser Scanning

Many satellites launched in recent years are equipped with laser scanning equipment (LIDAR). The obvious advantage of space borne LS is the possibility to cover enormous territories in relatively short periods. Disadvantage are high costs, the large potential error caused by atmospheric multiple scattering and the large footprint. The Vegetation Canopy LIDAR (VCL) has successfully surveyed all major forests and woodland types worldwide. ICEsat is equipped with the Geoscience Laser Altimeter System (GLAS) and is currently measuring vertical distributions of clouds and aerosols, changes in ice-thickness at the poles along with altimetric land measurements. Scanning from space may have the future as laser systems improve allowing smaller footprints and higher pulse rates.

A.2 Flying proposals

As mentioned before, DTM derivation through low altitude laser scanning does not come cheap. Assuming a commercial price of €300 per km? it would cost some € 150 mil. to cover Spain, € 100 mil. for Germany and €1,5 bil. for the whole of Europe including the Ukraine. For best performance flying should be undertaken at night between November and March. At night there is a minimum of background radiation, while in the winter there is a minimum of disturbing vegetation and trees have no leaves. The point distribution should be as regular possible with a mean point distance of not less than half of the wanted DTM gridsize. For detection of morphological changes a small footprint and a high accuracy is suggested. For a cheaper and quicker mapping flying-height, footprint-size and/or gridsize could be increased.

A.3 Proposals and concluding remarks

In this section several possibilities of ALS have been briefly touched. Laser scanning has proven its value in hydraulic engineering and in urban and rural planning. The technique seems applicable to environmental sciences in general and in the tracking of soil degradation in specific cases. There are opportunities in erosion hazard map production, the linkage of DTMs to photogrammetric and digital data, the analysis of chrono-sequences of high resolution DTMs, in the distinguishing of surface features and in space borne mapping. Further research on any of those subjects seems legitimate and promising.

B.1 Principle of laser scanning

A laser scanning system is dubbed LIDAR (LIght Detection and Ranging) and consists of a laser and a POS (Position and Orientation System), which is an integrated DGPS (Differential Global Positioning System) receiver and INS (Inertial Navigation System). The laser is mounted on a platform connected to the POS, a data acquisition device and ideally to a camera. The DGPS measures in real time the exact position of the platform; the INS constantly corrects this position taking into account the aircrafts motions. The near-infrared laser is repeatedly fired at the earth's surface at rates up to 80.000 pulses per second, although typical frequencies for low flying laser scanning systems are between 2 and 8 kHz. As the photons hit a surface object they are typically scattered: photons backscattered at nadir (usually in sufficient number) are collected by a receiving telescope aboard the craft. The travel time of these return signals can be recorded to nearly 10^{-10} s, which are then converted to actual distance between the laser and the reflecting object, using for laser travel time the speed of light. Laser scanning (LS) systems can be dubbed blind systems since they produce so called sub-randomly distributed 3D point clouds, meaning only the laser-beam and not the individual photons can be aimed at particular objects or object features.

Most laser systems operate at flying heights between 600 and 1000 m. From this height the sampling density on the ground ranges from about 20 points per m^2 to 1 point per 20 m^2, depending on the laser used. At a typical scan-angle of 20° to 30° the swath-width depends on the flying height but is typically 400 m. The actual point density depends on the laser system used, flying height, flying speed and scan angle. These variables should be well considered prior to flying because accuracy and precision of the resulting DTM can be strongly influenced by measurement density, as is described in the section concerning accuracy.

B.2 Footprint size

The footprint (laser-beam) is displaced over the surface by the aircrafts motion and the lasers' platform. Footprint-size depends on 1) the laser system used (type of laser and scan angle) and 2) the flight height of the aircraft. Typical diameters for low altitude laser footprints are 1m and for high altitude 25m or more. Small footprint lasers have the advantage of being swiftly employable and relatively inexpensive, since many commercial operators possess the needed equipment. Large footprint systems fly on higher altitudes thus enabling wide swaths, which allow fast and cheap data collection. Although large footprint lasers have higher pulse-frequencies, point density is often much lower. In general, the larger the footprint the smoother the DTM. For detection of canopy height large footprint multiple-pulse lasers may be favourable as they are more likely to penetrate the vegetation (Drake et al., 2001). Another disadvantage of large footprint scanning is the increase of complexity of the returned waveform as multiple reflecting surfaces are more likely to be encountered, often resulting in more post processing time needed.

B.3 Evaluation of measurements

A check for accuracy is usually done with one or more plane areas with little or no vegetation (e.g. football fields, landing strips). On this plane a grid with a 10m spacing is set. Within the grid the x, y and z coordinates of a quantity of check-points are determined with a terrestrial DGPS. These measurements are 'nearly true' altitude values with an accuracy (RMSE) of 3 cm (Huising and Gomes Pereira, 1998). A great quantity of x, y and z points are then acquired with a LS device and projected into the grid. These LS points are interpolated to the known check points. From the difference the accuracy of the by LS acquired points is calculated. A disadvantage of this accuracy determination is that error-estimates are only calculated at locations where the terrain is generally flat. Thus errors on hilly or rough terrain are frequently underestimated (Gomes Pereira and Janssen, 1999).

B.4 Accuracy and errors

Total error is often split in a bias (the systematic error) and a standard deviation (the stochastic error), which is hardly sufficient but used anyways for practical purposes (Crombaghs, 2002). The systematic errors are often locally constant and can therefore, in the processing-phase, be minimized by calibration and redundant information processing to values well below 5 cm. Stochastic error (10 to 200 cm) result from the measuring-uncertainty of the signal-to-noise ratio of the received signal, the width and angle of the beam and surface roughness. It is this error that causes the greatest offset and proves difficult to eliminate. After the necessary processing and correcting on flat or nearly flat terrain a total error of 8 to 15 cm remains, while on hilly terrain the error is between 25 cm and 38 cm. The RMSE of the combined terrains equals 29 cm with a mean error close to 0 (Gomes Pereira and Janssen, 1999). A disadvantage ensuing from the by LS derived sub-random point cloud, is that only altimetric accuracy can be computed and never the error on the x and y axis. However, we may assume this horizontal error will be more or less equal to the altimetric one.

The accuracy in altitude measurements is strongly related to the used laser system and terrain morphology. The use of an adequate strategy for data collection and processing will, to a great extent, improve the accuracy and fidelity of the results (Means et al., 1999; Huising and Gomes Pereira, 1998; Petzold et al., 1999; Axelsson, 1999; Elberink et al., 2002). In general, accuracy can be increased by:

1) Increasing point density, which allows more adequate filtering and is therefore especially useful in rugged and/or densely vegetated areas.
2) Addition of more ground control points, introduction of bigger overlap areas of the swaths, the introduction of cross-strips perpendicular to the flying lines or even multiple flying to allow better correction in strip-offsets.

Evidently there is a trade-off between precision requirements and operating costs. A problem is that expenditure increases faster than precision. Increasing point density on flat terrain from for example 1 per 16 m^2 to 1 per 4m^2 results in a slightly lower stochastic error (from 14 to 12 cm) while it increases total costs by 50%. Besides, changes in LS methodology have to be applied simultaneously in order to reach the appropriate effect (Elberink et al., 2002).

B.5 Processing

At the turn of the century, worldwide some 40 commercial contractors could deliver raw point data or interpolated DTMs at various cellsizes. As a rule of thumb contractors assume processing requires three times as much time as the actual flying (Eurosense). The automated filtering techniques and algorithms used for DTM production and distinguishing of surface features still lead to quite some misclassifications. Final manual editing by using photogrammetric stereo models, comparisons with topographic maps or by simply using common sense is in most cases necessary. A major cause of manual corrections are obstacles such as vegetation and buildings scattered over the surface. Point density has to be high enough to enable filtering algorithms in correctly removing anomalies from surfaces (conversion DEMs to DTMs). Erodibility often increases with the absence of soil-protecting vegetation, which is beneficiary for accuracy within areas of interest. Again we are confronted with the trade-off between precision-demands and costs, as a flawless DTM (if possible) comes at high expense. Nevertheless, far lower costs are involved when compared to derivation of a DTM by use of photogrammetric methods alone. Calculations of the German Survey and Monitoring Agency show laser scanning requires about 30% of the budget that is needed for more conventional approaches (Reiche et al., 1997). It is likely operating costs have declined since then, because filtering and processing techniques are evolving rapidly.

References

- Ackermann, F., 1999, Airborne Laser Scanning – present status and future expectations, ISPRS Journal of Photogrammetry & Remote Sensing 54, 64-67.
- Axelsson, P., 1999, Processing of laser scanner data - algorithms and applications, ISPRS Journal of Photogrammetry & Remote Sensing 54, 138-147.
- Blanchard, W.F., 2003, Achieving GPS-Galileo interoperability: the challenges ahead, Space Policy 19, 95-99.
- Baltsavias, E.P., 1999, A comparison between photogrammetry and laser scanning, ISPRS Journal of Photogrammetry & Remote Sensing 54, 83-94.
- Baltsavias, E.P., 1999, Airborne laser scanning: basic relations and formulas, ISPRS Journal of Photogrammetry & Remote Sensing 54, 199-214.
- Bouwmeester, H., 2003, Geographic distribution of soil erosion in Limburg, the Netherlands analysed through remote sensing, unpublished paper, University of Amsterdam, p. 8.
- Brugelman, R., 2002, Automatic breakline detection from airborne laser range data, Ministry of Transport, Public Works and Water Management, Netherlands.
- Crombaghs, M., Elberink, S.O., et al., 2002, Assessing Height Precision of Laser Altimetry DEMs, Ministry of Transport, Public Works and Water Management, Netherlands.
- Drake, J.B., Dubayah, R.O., 2001, Estimation of Tropical Forest Structural Characteristics using Large-footprint Lidar, Department of Geography, University of Maryland, USA.
- Elberink, S.O., Brand, G., Brugelman, R., 2002, Quality Improvement of Laser Altimetry DEM's, Ministry of Transport, Public Works and Water Management, Netherlands.
- Gomes Pereira, L.M., Janssen, L.L.F., 1999, Suitability of laser data for DTM generation: a case study in the context of road planning and design, ISPRS Journal of Photogrammetry & Remote Sensing 54, 244-253.
- Hofton, M.A., Blair, J.B., 2002, Laser altimetry return pulse correlation: a method for detecting surface topographic change, Journal of Geodynamics 34, 477-389.
- Huising, E.J., Gomes Pereira, L.M., 1998, Errors and accuracy estimates of laser data acquired by various laser scanning systems for topographic applications, ISPRS Journal of Photogrammetry & Remote Sensing 53, 245-261.
- McIntosh, K., Krupnik, A., 2002, Integration of laser-derived DSMs and matched image edges for generating an accurate surface model, ISPRS Journal of Photogrammetry & Remote Sensing 56, 167-176.
- McKean, J., Roering, J., 2004, Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry, Geomorphology 57, 331-351.
- Silvestri, S., Marani, M., Marani, A., 2003, Hyperspectral remote sensing of salt marsh vegetation, morphology and soil topography, Physics and Chemistry of the Earth 28, 15-25.
- Wehr, A., Lohr, U., 1999, Airborne laser scanning – an introduction and overview, ISPRS Journal of Photogrammetry & Remote Sensing 54, 68-82.
- White, S.A., Wang, Y., Utilizing DEMs derived from LIDAR data to analyze morphologic change in the North Carolina coastline, Remote Sensing of Environment 85, 39-47.