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**Article**

# Topographic airborne LiDAR in geomorphology: A technological perspective

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with 7 figures and 2 tables

**Summary.** Airborne LiDAR, also referred to as Airborne Laser Scanning, is widely used for high-resolution topographic data acquisition with sub-meter planimetric and vertical accuracy. This contribution gives a review of recent developments of LiDAR systems (e.g. full-waveform LiDAR) and advances in data processing and analysis for geomorphological applications. An overview of applications in geomorphology and related fields using different LiDAR data products (e.g. Digital Terrain Model and 3D point cloud) is given, indicating a great variety of fields of applications and data analysis approaches. These applications range from visual interpretation of LiDAR derivatives (e.g. shaded relief map) to semi-automatic geomorphological mapping and fully automatic object detection (e.g. surface discontinuities). A quantitative analysis of the temporal trend of peer-reviewed journal publications confirms the increased consideration of airborne LiDAR data for mapping, modeling and exploiting Earth surface processes and landforms. Almost 50 % of the papers of the last 15 years were published in the last two years 2008 and 2009. Airborne LiDAR technology is developing rapidly leading to both a great opportunity and challenge for integrating new technological developments into existing workflows and stimulating new innovative approaches.

**Keywords:** Airborne LiDAR, Airborne Laser Scanning, Geomorphology, DTM, Point Cloud, Classification

## 1 *Introduction*

Detailed topographic information is essential in a great variety of research fields aiming at modeling, mapping, exploiting and increasing the understanding of natural phenomena located at the Earth surface. Topographic airborne LiDAR, also referred to as Airborne Laser Scanning (ALS), has revolutionized the acquisition of elevation data by providing a tool for rapid, highly accurate and cost-effective data acquisition (Flood 2001), relevant for regional and local geomorphological studies (French 2003, McKean & Roering 2004, Jones et al. 2007, Tarolli et al. 2009 and references therein). This active remote sensing system with its direct determination of elevation is capable to retrieve terrain (i.e. bare Earth) point measurements even under forest cover, allowing the generation of Digital Terrain Models (DTMs) with a high degree of automation, which is not possible with traditional methods such as field surveying and photogrammetry (Kraus & Pfeifer 1998, Liu 2008). Furthermore, the vertical structure of surface objects such as vegetation can be assessed by the third dimension inherent in the 3D point cloud, widely used for studying forest structure (Lim et al. 2003, Hyyppä et al. 2008), ecosystems (Lefsky et al. 2002) and in natural hazard management (Geist et al. 2009).

This paper reviews the recent advance and development of using airborne LiDAR data for studies in the scientific fields exploiting Earth surface processes and landforms, with a particular focus on the technological perspective highlighting developments on the LiDAR sensor side and


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their implications on recent and future applications. The focus is laid on topographic LiDAR systems, which cannot penetrate water surfaces compared to bathymetric systems (GUENTHER et al. 2000), and further limited to small-footprint sensors (0.2-2 m footprint diameter) providing the source for high-resolution DTM generation. The nature of airborne data acquisition (e.g. time and costs, point density and accuracy) constrains the area of investigation to regional scales compared to spaceborne systems with global coverage and high temporal repetition. Furthermore, the scale of detectable surface features is restricted by the sampling density and accuracy of current systems, which can provide sub-meter vertical and planimetric accuracy with point densities rarely above 25 pts./m$^2$ (cf. AHOKAS et al. 2003, MALLET & BRETAR 2009). Airborne LiDAR is still developing rapidly on the sensor side, which is reflected by the sensor parameters (e.g. increased pulse repetition frequencies up to 240 kHz; LEMMENS 2009) and capabilities (e.g. full-waveform recording; WAGNER et al. 2006) of currently operating systems. However, data analysis, processing and management of the arising large data volumes and the resultant applications lag behind the sensor development and thus raise a particular challenge for integration and utilization of the full potential in geomorphological studies.

The aim of this paper therefore is to assess the recent development on sensor and application side as well as discuss the benefits and limitations of airborne LiDAR with and beyond the use of standard products –particularly the DTM – covering the investigation of the 3D point cloud and the most recent full-waveform data. Section 2 gives an introduction to the airborne LiDAR technology and data analysis. Section 3 reviews applications of different LiDAR data products and Section 4 presents a quantitative literature survey of peer-reviewed articles published within the last 15 years. Section 5 discusses current trends and advances and the last section concludes the review.

## 2 *Airborne LiDAR principles and analysis*

### 2.1 *The LiDAR technique*

LiDAR (Light Detection and Ranging) is an active remote sensing technology with the basic principle of measuring distances between the sensor device and the target surface (JELALIAN 1992). The acronym LaDAR (Laser Detection and Ranging) specifies that laser light is applied for range measurement. The term *laser scanning* is often used synonymously to LiDAR and can be found more frequently in the publications of the European scientific community. In fact, laser scanning further describes that the laser beam is scanned over the entire field of view resulting in an area-wise acquisition with a large number of single measurements (PFEIFER & BRIESE 2007, VOSSELMAN & MAAS 2010). At current state laser scanning is limited to airborne, terrestrial and mobile platforms (e.g. cars and boats) (Fig. 1). Space-based sensors such as the GLAS (Geoscience Laser Altimeter System) onboard the ICESat satellite are laser profilers measuring elevation profiles along the ground track and do not exhibit a scanning pattern (ZWALLY et al. 2002). The following overview of research activities concentrates on Airborne Laser Scanning (ALS) systems, for simplicity called airborne LiDAR in the remainder of this article.

Most commercial airborne sensors, either mounted on a fixed-wing aircraft or helicopter, are based on the LiDAR principle of pulse round-trip time measurement of an emitted laser pulse. The short laser pulse (typically a few nanoseconds) travels from the sensor through the atmosphere

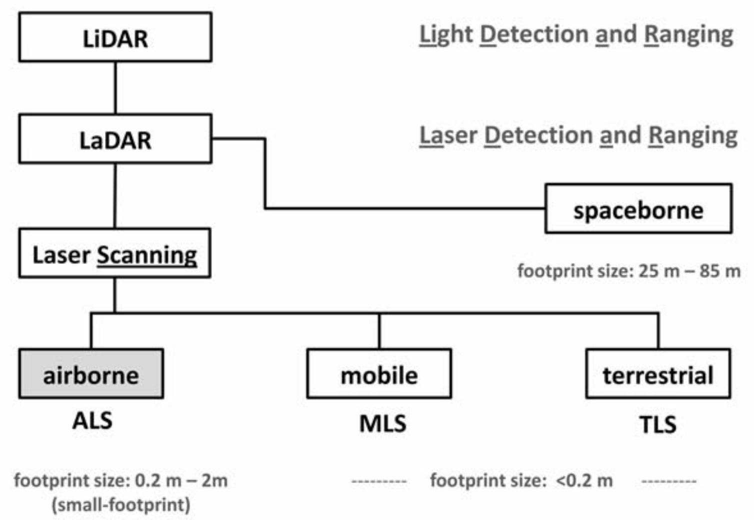


Fig. 1. LiDAR terminology and classification. Note: Footprint sizes are approximated values and dependent on beam divergence, distance to target and incidence angle (cf. Baltsavias 1999a, Mallet & Bretar 2009).

and is then reflected at one or more objects illuminated by the laser beam. The backscattered energy is registered at the sensor's receiver and the elapsed time between emission and arrival is used to compute the distance between sensor and target by dividing the recorded time by two (half traveled way) and multiply it with the group velocity of light (ca. $3 \cdot 10^8$ m/s). The airborne LiDAR system is a multi-sensor measurement system comprising three major time-synchronized components (Fig.2, Wehr & Lohr 1999): (1) a laser scanner unit, (2) a Global Navigation Satellite System (GNSS) and (3) an Inertial Measurement Unit (IMU). The *laser scanner* is composed of the laser range finder unit based on the time-of-flight distance measurement and of a beam deflection device introducing the scanning pattern. For instance, an oscillating mirror deflects the laser beam into a restricted angular field (e.g. ±20° scan angle) perpendicular to the flight direction resulting in a zig-zag pattern on ground due to the forward motion of the airplane (Baltsavias 1999a). The GNSS device, mostly the Global Positioning System (GPS), provides the absolute position of the sensor platform, generally used in differential mode by integrating ground reference stations and the IMU records the angular attitude of the platform (roll, pitch, and yaw/heading) with high frequency (e.g. 200 Hz). All three components together enable the direct derivation of the absolute position (X,Y,Z) of each recorded reflection.

Measurement rates (pulse repetition frequency) of up to 240 kHz can be achieved by current commercial systems with flying heights above ground up to 6000 m but typically less than 1000 m (Lemmens 2009, Pfeifer & Briese 2007). The accuracy of the 3D coordinates depends on the accuracy of the single components, i.e. the distance measurement, GPS positioning and direction determination of the laser beam (Baltsavias 1999a), and is stated to be of altimetric accuracy < 0.1 m and planimetric accuracy < 0.4 m (Lemmens 2009). A more detailed discussion of theoretical planimetric and vertical accuracies can be found in Baltsavias (1999a). In practice, the LiDAR data accuracy may deviate from the theoretical numbers due to the dependence on various

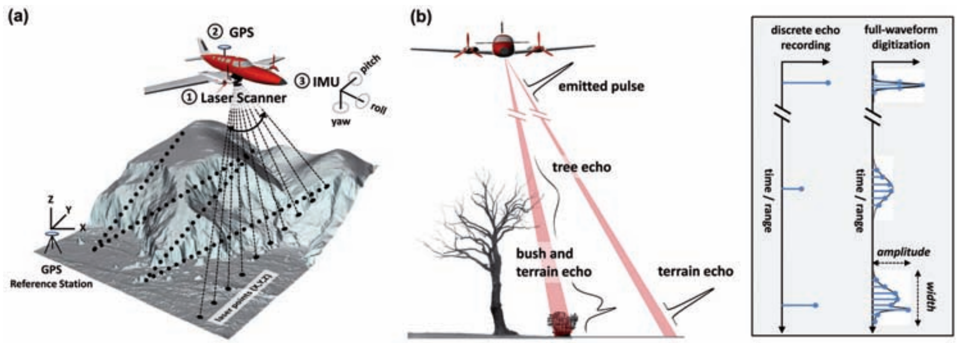


Fig. 2. (a) Airborne LiDAR principle and system components and (b) detection of multiple echoes by discrete and full-waveform recording systems.

influencing factors, such as used system components and their calibration, flight and scan settings/conditions as well as the influence of the surface (e.g. slope and vegetation). Hence, only a quality control procedure can assess the actual accuracy values of the dataset (cf. Ahokas et al. 2003, Briese et al. 2009). In the airborne case a flight campaign is performed in single overlapping flight lines, also called strips or swaths. The flight strips generally have a length of certain kilometers with a width of some hundred meters depending on flying height above ground and maximum scan angle (Baltsavias 1999a). A large overlap of adjacent strips increases the point density and allows for strip adjustment removing systematic errors and increasing accuracy (Kager 2004, Pfeifer & Briese 2007).

Small-footprint airborne LiDAR systems emit laser beams with a certain beam divergence resulting in an illuminated area (also called *footprint*) of typically between 0.25 m to 1 m diameter at the ground surface. The footprint size is directly related to flying height above ground and the laser beam divergence (Baltsavias 1999a). For example, from 1000 m above ground a beam divergence of 0.3 mrad results in a footprint diameter of 0.3 m. Objects in different elevations may be illuminated by this cone of light causing more than one *echo* that can be recorded at the sensor's receiver. The term echo is often referred to as "reflection", "return" or "pulse". For example, an emitted laser pulse can lead to a first echo originating from the tree canopy and a last echo from the underlying ground surface (Fig. 2). With respect to the recording of the backscatter two generations of small-footprint LiDAR sensors are distinguished: (i) the traditional discrete echo recording systems and (ii) the recent full-waveform digitizing systems (Wagner et al. 2006, Mallet & Bretar 2009). Discrete echo recording systems are able to detect only a small number of echoes on-line and store usually from only one up to four echoes per laser shot (Baltsavias 1999b, Lemmens 2009). Additional to the distance measurement of each echo a value for the strength of the reflection – referred to as *signal intensity* – is most often stored by commercial sensors. The recorded signal intensity is determined by the emitted pulse power, the range (i.e. distance to target), areal extent of target (e.g. extended target or line target such as a powerline), target reflectance and directional reflectance behavior at laser wavelength and the atmospheric attenuation. A detailed discussion on the signal intensity can be found in Höfle & Pfeifer (2007). The new generation of commercial sensors is able to record the entire time-dependent variation of the received signal power, i.e. the full waveform of the backscatter. This enables the detection of distinct echoes of a single laser shot in a post-processing step with higher accuracy in range determination and better separability of superimposed echoes. Furthermore, full-waveform data allows for deriving the signal amplitude as well as the width of each echo, which can be stored together with the 3D-coordinates. The signal amplitude is a parameter for the strength of the received echo depending on target area and reflectance of the surface in the laser's wavelength (i.e. radiometric information). The echo width is altered by a certain vertical distribution of scatterers within the laser beam (i.e. sub-footprint geometrical information) with plane surfaces having small and rough surfaces large echo widths. Wagner et al. (2006) showed that radiometric calibration of the LiDAR data makes it possible to derive the backscatter cross-section, a physical quantity known from radar remote sensing, which can be a valuable parameter in assisting 3D surface classification (Höfle et al. 2008, Wagner et al. 2008)

Both mentioned types of sensors have in common that the primary product for users is the 3D *point cloud*. The original point cloud is a collection of all recorded and extracted echoes in the case of full-waveform LiDAR, respectively, where each laser point can have additional attributes such as signal amplitude and echo width.

A prominent advantage of airborne LiDAR compared to photogrammetry is the ability to penetrate vegetation by "seeing" through small gaps in the canopy, making it possible to derive accurate DTMs even in densely forested areas (Kraus & Pfeifer 1998). More generally, as an active remote sensing technique the 3D data acquisition is performed directly (i.e. no stereo pair required) and can be conducted under any sun light conditions, even at night, and no surface texture (e.g. areas with snow cover) is required. Recent sensor systems are able to capture high point densities (> 10 pts/m$^2$) in a cost-effective manner, providing a very detailed terrain description (< 1 m horizontal resolution of DTM) with assessable accuracy and quality (Karel et al. 2006, Jones et al. 2007). So far, airborne LiDAR gained a high degree of automation including steps from data acquisition through to DTM generation (Section 2.2). Potential drawbacks of airborne LiDAR are that no global coverage will be achieved in the near future and that repetitive acquisitions are limited to specific local studies (e.g. Geist & Stötter 2007). The arising acquisition costs and the data volume for large areas are still a limiting factor for operational wide area applications, in particular valid for the 3D point cloud and full-waveform data.

Airborne LiDAR is a rapidly developing technique that has made a big step forward in the last five years by providing full-waveform recording for commercially available small-footprint systems (Wagner et al. 2006, Mallet & Bretar 2009). Most recent developments mainly aim at increasing the pulse repetition frequency, either physically for one scanner (e.g. see the "multiple pulse in air" principle in Roth & Thompson 2008) or by operating two scanners simultaneously (Pfeifer & Briese 2007), altogether making airborne LiDAR campaigns more cost-effective while increasing point density and hence resolution and accuracy of final data products. As important as the sensor achievements are the increasing automation and operationality on the data processing side (e.g. Mandlburger et al. 2009a) and the definition of data standards (e.g. the *LAS file format*[1]

[1] ASPRS Standards Committee: http://www.asprs.org/society/committees/standards/lidar_exchange_format.html (last access 01.08.2010)

for 3D point clouds), making airborne LiDAR more interesting for an even larger field of applications including non-LiDAR experts.

A more detailed technical review on airborne LiDAR systems can be found in WEHR & LOHR (1999), PFEIFER & BRIESE (2007) and VOSSELMAN & MAAS (2010). A good overview of commercial LiDAR sensors is given in LEMMENS (2009).

### 2.2 *LiDAR data analysis and classification*

The analysis of LiDAR data products starting with the 3D point cloud, possibly with full-waveform attributes, can be grouped into (i) a *direct* use of data and information derived from LiDAR such as digital elevation models (DEMs) and (ii) an *indirect* application of further refined data such as roughness parameters of land cover maps serving as input for geomorphological studies (Fig. 3). Basically, the direct input extracts information from the LiDAR observables (i.e. elevation and radiometric data) whereas the indirect integration is based on a prior abstraction and processing (e.g. classification and object detection).

A first step in geomorphological interpretation is the visual inspection of data, for example, 3D perspective views or images color-coded by height. Drawing profiles or slicing of the data helps to get a better impression of the surface acquired such as in complex situations with mixed

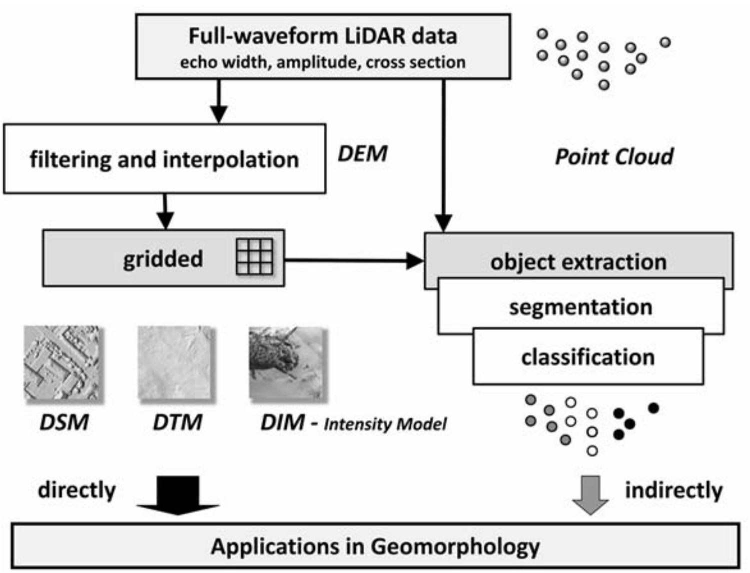


Fig. 3. Overview of airborne LiDAR data processing workflows starting from the original point cloud with possibly full-waveform attributes up to the derived data layers (e.g. DTM and land cover maps) serving as input for geomorphological studies (modified from Geist et al. 2009). Left, the generation of raster derivatives and on the right hand side raster and/or point cloud based classification is outlined. *Directly* is meant to be the direct use of the recorded elevation and radiometric information, whereas *indirectly* points out a higher degree of abstraction such as the prior classification and detection of objects (e.g. structure lines and elementary landforms).

surface and object types. Deeper understanding is gained by visualizing derivatives such as contour lines, slope, aspect and surface curvature or to drape color information from optical sensors over the LiDAR elevation data. Care has to be taken when adding ancillary data not acquired simultaneously in order to avoid misinterpretation caused by temporal differences in both data sets. Also differences in registration, accuracy, and resolution have to be taken into account if combining different data sets.

For applications in geomorphology the separation of terrain echoes (i.e. bare Earth) and echoes on objects such as buildings and trees – called *filtering* – is of major importance. Various methods and approaches are published either working directly on the point cloud or on already rasterized Digital Surface Models (DSMs). An introduction to filtering and an overview of the most prominent approaches can be found in Sithole & Vosselman (2004) and Pfeifer & Mandlburger (2008). An overview of processing methods, analysis, and comparison of widely distributed software products and applications of digital elevation models is given by Hengl & Reuter (2009). Elevation models representing the geomorphological relevant surface can be characterized by geomorphometry and landform classification providing input for applications in geomorphological mapping and process modeling. DTMs are the basis for landform characterization and delineation. Landforms vary in their appearance depending on the representation scale. The scale dependency makes the boundary definitions of regions vague and therefore difficult to delineate. This turns landform classification into an ambiguous multi-resolution problem. A first segmentation of landscape or categorization of geomorphological units is the derivation of geomorphological elementary forms such as plane, channel, ridge, pass, peak and pit derived for a certain target scale (Wood 1996, Fisher et al. 2005, Minár & Evans 2008).

In order to reach high automation for classification often object-based approaches are used. They either work directly in the point cloud (object-based point cloud analysis – OBPA, Rutzinger et al. 2008) or in the derived rasterized models and images (object-based image analysis – OBIA, Blaschke 2010). These approaches can be combined or iteratively applied where first the input data is segmented into homogeneous areas to define patches of points or pixels, which represent a part of an object. These segments are also called object primitives. Then segments are merged to the object of interest by applying a classification on statistical features. Features describing segments can be either related to the statistical distribution of the point or pixel values and their geometrical and topological characteristics such as segment shape, size, and neighborhood relations. Originally coming from the field of land cover classification OBIA is also used for DTM extraction (Tóvári & Pfeifer 2005) and geomorphological object classification (van Asselen & Seijmonsbergen 2006).

## 3 *Applications of airborne LiDAR remote sensing*

### 3.1 *Overview*

The review on applications of airborne LiDAR data for studying Earth surface processes and landforms is structured by the major LiDAR data product and information investigated and used for analysis, comprising (i) digital elevation models (e.g. raster-based), (ii) the LiDAR point cloud, (iii) the integration of radiometric information and (iv) the most recently available full-waveform

LiDAR data, hence, the technological perspective is emphasized. The presented studies cover a large variety of fields of applications from a methodological and data processing point of view such as DTM enhancement, land cover classification, geomorphological mapping and input for process simulation models as well as a thematic consideration such as mass movement processes and landforms, fluvial and coastal studies, and glacier and volcano related investigations. Furthermore, the studies range from experimental local case studies to already adopted and operational integration of topographic airborne LiDAR. Recent technological developments of LiDAR sensors are covered by looking deeper into the potential and added value of LiDAR radiometric and full-waveform attributes.

### 3.2 *Raster-based approaches*

Rasterized models or images derived from LiDAR point clouds and their attributes, respectively, are widely used in manifold applications in geomorphology and related fields. The reduction of accuracy and loss of 3D information by aggregating points to pixel cells do not harm geomorphological applications in general. Especially for regional scale applications, where no 3D effects (or 3D objects) are expected and a surface representation as a single valued function (2.5D) is sufficient the usage of rasterized LiDAR data is feasible and still offers advantages to traditional DTM products from photogrammetry or terrestrial surveys (i.e. penetration of vegetation and large area coverage). The target raster cell size depends on the point density, which is a function of the flight planning settings (e.g. flying altitude, speed and overlapping of strips) and sensor settings (e.g. scan angle, pulse repetition and scan frequency).

Rasterized LiDAR data such as DTMs are used for presentation and visualization purposes such as interactive 3D geologic maps (Stumpf & Luman 2007). Furthermore, derivatives such as shaded relief maps, first and second order derivatives are used for manual interpretation, semi-automatic object detection and interpretation (Notebaert et al. 2009). LiDAR data offers the possibility to detect and interpret geomorphological objects, which are difficult to access and hardly visible in the field or cannot be detected in other remote sensing data. Features such as tectonic structures (Cunningham et al. 2006, Arrowsmith & Zielke 2009, Székely et al. 2009) even if covered by vegetation might be evident by small local elevation changes in the range of decimeters. These minor changes in elevation can still be observed as the high vertical accuracy of LiDAR is not lost by rasterization. Compared to DEMs derived from other sources such as radar, GPS surveys or topographic maps the benefits of LiDAR for geomorphological mapping in terms of high accuracy, representation of detail, coverage of large areas and cost effectiveness is clearly given (Chiverrell et al. 2008, Smith et al. 2006a). Although LiDAR offers detailed elevation information, manual mapping approaches using LiDAR products are influenced by the experience and subjective interpretation of the expert limiting the repeatability and transferability of the efforts as well as demanding for verification with independent reference and field data (Van den Eeckhaut et al. 2005, Berendsen & Vollenberg 2007). The strong need for reference data and independent validation, of course, also applies to semi-automatic remote sensing based approaches.

A further support for geomorphological interpretation is the automatic derivation of *breaklines* in LiDAR DTMs. Breaklines are terrain features marking changes of the terrain surface (Liu 2008). Breakline detection is often an essential step for DTM data reduction or improvement (e.g. hybrid DTMs) because they maintain the dominant characteristics and discontinuities of a surface (BRIESE 2004). Breakline detection is either done in the LiDAR point cloud (see Section 3.3) or the DTM. A common approach is the extraction and vectorization of DTM regions with high curvature (BRÜGELMANN 2000, RUTZINGER et al. 2007). Geomorphological objects such as landslide bodies and torrents are often modified by younger anthropogenic structures (e.g. roads). These structures disturb the recognition of the natural appearance of geomorphological units. The separation of natural and anthropogenic breaklines based on size, shape, slope, and curvature assists the retrieval of an undisturbed representation (RUTZINGER et al. accepted).

Airborne LiDAR DTMs are used for automated geomorphological mapping, but also to delineate specific geomorphological landforms such as landslides, fluvial fans, and glaciers for inventories. VAN ASSELEN & SEIJMONSBERGEN (2006) show that typical geomorphological units in mountainous areas can be reliably mapped (50 %–79 % classification accuracy) using an OBIA approach on LiDAR DTMs. The classified units exhibit homogeneous morphometrical characteristics indicating similar material and genesis.

Several studies use LiDAR DTMs to derive topographic signatures for characterizing *landslides* (MCKEAN & ROERING 2004, GLENN et al. 2006) or automated mapping of landslides (BOOTH et al. 2009) even in forested areas (VAN DEN EECKHAUT et al. 2007) in order to create or update inventories. GLENN et al., 2006, relate surface roughness parameters derived from LiDAR DTMs to the age and activity of landslides. BOOTH et al. (2009) apply signal processing techniques to quantify deep seated landslides by investigating spatial variation and characteristics of landslides aiming at automatic creation and update of landslide inventory maps. The verification with independent inventory data shows that the applied methods improve objectivity and are well-suited for the description of geomorphological processes in a wide range of scale. LiDAR DTMs are also used for the mapping of *volcanic* deposits of eruptions (CSATHO et al. 2008, VENTURA & VILARDO 2008). FAVALLI et al. (2009) demonstrate the importance of a proper LiDAR data preprocessing such as strip adjustment to be able to derive lava thickness maps. An overview of *glacier* landform mapping and monitoring using airborne LiDAR is given by e.g. BALTSAVIAS et al. (2001) and SMITH et al. (2006a). Elevation and derived surface roughness is used to detect and map the extent of glaciers (KODDE et al. 2007, KNOLL & KERSCHNER 2009). The application of most interest in the field of glaciology is the estimation of glacier mass balances where LiDAR DTMs from different epochs provide information on volume changes (FAVEY et al. 1999, KRABILL et al. 2002, GEIST et al. 2005, BARRAND et al. 2009) and glacier surface velocities (BUCHER et al. 2006). The combination of radar and airborne LiDAR measurements or time series of airborne LiDAR measurements are used to estimate snow depth distributions (HOPKINSON et al. 2004, DEEMS & PAINTER 2006, LEUSCHEN et al. 2008).

A further active application area of airborne LiDAR data is the detection and analysis of fluvial landforms such as mapping of *river* valley environments (e.g. recent and paleo river channels, alluvial fans and valley floor edges; JONES et al. 2007). VOLKER et al. (2007) identify dominant formative processes on alluvial fans by separating forms, which are caused by debris flows (relatively dry) and fluvial forms (wet) analyzing the morphometry of these surfaces. Since river environments are highly dynamic systems, applications also comprise the mapping of changes in fluvial channel morphology in vertical and horizontal dimension (NOTEBAERT et al. 2009) or to quantify riverbank erosion (THOMA et al. 2005). SMITH et al. (2006b) have studied pre- and postevent situations of a jökulhlaup in order to quantify changes of the morphology due to the flood caused by the melting ice masses. *Coastal morphology* is shaped by rather dynamic processes with frequently changes of the coastline, beaches and sand dunes due to wind and water level changes, which can be also related to each other i.e. if singular events such as hurricanes occur accompanied with floods. LiDAR data is used to collect data on the coastline, i.e. the tidal datum (ROBERTSON et al. 2004, LIU et al. 2007), beach face landforms (VAN GAALEN et al. 2009) or to extract the tidal channel networks (MASON et al. 2006) over many kilometers of the coast. Several studies monitor alongshore variations (BROCK et al. 2004) such as morphodynamic *changes of beaches* (SALLENGER et al. 2003) or patterns in *sand dunes* (WOORLARD & COBY 2002, HOUSER et al. 2008, MITASOVA et al. 2009) also related to storm events if multitemporal LiDAR data is acquired. Such studies assist the monitoring of the recovery of nourishment zones after storm events (i.e. calculate volume changes and erosion rates) and beach fill projects (SHRESTHA et al. 2005, GARES et al. 2006).

Besides object detection and mapping airborne LiDAR data are an essential input in various *process simulation models* in order to be able to predict or simulate scenarios of future events and risk estimation of hazards. Various examples show the added value of integrating LiDAR elevation information for modeling processes such as floods (COBBY et al. 2003, WEBSTER et al. 2004, RUFIN-SOLER et al. 2008), debris flows (WICHMANN et al. 2008, CONWAY et al. 2010), rockfall (DEPARIS et al. 2008, LAN et al. 2010) and avalanches (SCHMIDT et al. 2005, MCCOLLISTER & COMEY 2009). A prerequisite for using LiDAR DTMs in hydraulic modeling is the enhancement, conditioning and reduction of LiDAR data by applying a suited filtering and interpolation strategy and to integrate existing riverbed elevation data (e.g. profiles of river cross sections) in order to retrieve a hydrological consistent DTM (MANDLBURGER et al. 2009b). Such DTMs are also suited to identify habitats derived from river geometry and morphology (HAUER et al. 2009) and further hydraulic modeling (FRENCH 2003). Surface and vegetation roughness are key parameters needed in flood modeling. LiDAR data is suited particularly for roughness estimation because of its ability to penetrate high vegetation (GEERLING et al. 2007, STRAATSMA 2008, STRAATSMA & BAPTIST 2008).

### 3.3 *Point cloud based approaches*

Most work has focused on preprocessing, filtering and interpolation of DTMs, so far only little attention has been given to processing point clouds directly in order to derive valuable geomorphological information. An intermediate step in DTM generation and/or to refine DTMs is the derivation of breaklines (Section 3.1). In order to maintain the high accuracy of the original LiDAR measurement a point cloud approach such as developed by BRIESE (2004) is favored. An intersecting moving plane algorithm derives 3D vector breaklines, which can be either used for DTM enhancement or directly for detecting geomorphological structures in floodplains (MANDLBURGER & BRIESE 2009). The advantage of this point cloud processing method is (i) the achievement of higher vertical and horizontal accuracy and (ii) the possibility to derive breaklines also in very steep terrain, where a reliable representation cannot be achieved with raster DTMs. In Fig. 4a visual comparison of raster (RUTZINGER et al. 2007) and point cloud derived breaklines (cf. BRIESE et al. 2009) is shown. Further studies working on the 3D point cloud and including the radiometric information are described in detail in Sections 3.4 and 3.5.

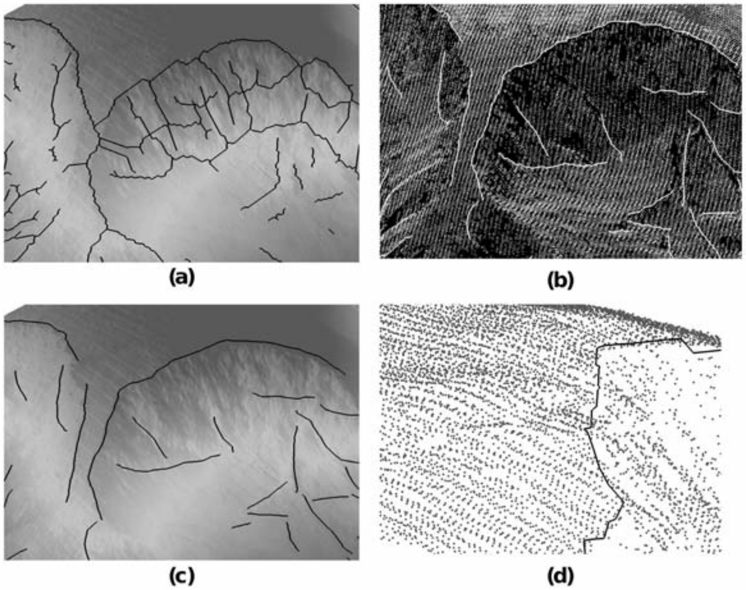


Fig. 4. Comparison of breaklines for a single test area derived from (a) the raster model (i.e. DTM) using the method of Rutzinger et al. (2007) and (b–d) from the 3D point cloud (cf. Briese et al. 2009). (b) and (d) show a perspective view of the point cloud including the resulting 3D breaklines.

### 3.4 *Radiometric data inclusion*

The traditional discrete echo recording systems obtain a value often referred to as *signal intensity* or *signal amplitude*. The detailed definition of this intensity values in terms of processing, conversion and physical quantity is not provided by the sensor manufacturers and may differ between sensor systems. In the literature the intensity is often related to the total or peak power (amplitude) of the received signal (Höfle & Pfeifer 2007, Kaasalainen et al. 2009). In case of full-waveform recording sensors the signal amplitude can be derived in post-processing without any assumptions. As described in detail in Höfle & Pfeifer (2007) the recorded LiDAR intensity has to be corrected for spherical loss (i.e. due to distance to target), atmospheric and topographic effects in order to derive a value proportional to target reflectance in the wavelength of the laser, which is of main interest. Physically founded correction procedures based on the radar range equation are applied (Jelalian 1992) or empirical correction models can be used. Without radiometric reference targets placed in the area of investigation such a procedure can only be a relative correction and not an absolute calibration of the intensity values. This means the corrected values are proportional to target reflectance and become free of known disturbances, but are not a physical quantity and may not be comparable between sensors, flying dates and system settings (e.g. emitted pulse power and beam divergence). However, most often the required data for correction (e.g. the sensor position of each echo) and for radiometric calibration (e.g. ground reference targets with known reflectance) are not available. Hence, up to now most studies using laser intensities do not correct or just use a straightforward normalization by range. Compared to passive optical remote sensing the LiDAR intensity has the advantages of an active system such as less sensitivity to sun light conditions, but on the other hand the radiometric data originates from only one channel of monochromatic light, which is usually in the near-infrared spectrum between 1064 and 1550 nm. As a consequence support of surface classification and object detection may only be provided between classes with high spectral separability in the laser's wavelength.

The radiometric data provided by most currently operating airborne LiDAR sensors represent a complementary source of information to the geometrical description of the scanned surface and which is already georeferenced (in 3D) as it is provided as additional attribute for each recorded echo. This becomes evident particularly for surfaces where no abrupt elevation changes with higher magnitude than the precision of the LiDAR sensor (<dm) are apparent but surface classes/types are altering. So far, to the knowledge of the authors the LiDAR intensity has not been used to retrieve physical surface properties (e.g. grain size and moisture) but it has been primarily applied for object detection and surface classification. Besides the general studies aiming at raster-based land cover classification by considering the LiDAR intensity (e.g. Antonarakis et al. 2008 and Brennan & Webster 2006), papers within the scope of this review are dealing with the classification of water bodies, glacier surfaces, volcanic materials and vegetation. Mainly raster-based classification procedures are in use where the intensity is provided as additional image layer, but also 3D point cloud approaches have been developed recently.

Brzank et al. (2008) use a fuzzy classification to detect water surface laser points of the Wadden Sea, which are indicated by low height – absolute height above sea level – and low intensity. Höfle et al. (2009) use a 3D point cloud segmentation algorithm to classify and delineate water bodies making use of a local roughness parameter and intensity-based laser point features (e.g. local intensity variation) derived from model-driven corrected intensity data. Additionally, they model the location of laser shot dropouts occurring due to high absorption of near-infrared light at water bodies. To prove their generic concept of point cloud classification, they successfully detect and derive the water-land-boundary of a regulated river (Inn/Austria) as well as in a five years multitemporal dataset of a proglacial braided river (Hintereisferner/Austrian Alps). To assist in wetland mapping and wetland hydrology, Lang & McCarthy (2009) classify an intensity image in order to locate inundated and non-inundated forested areas by means of the good separability of these two classes in the LiDAR intensity data. The evaluation shows a much higher performance of the LiDAR data than the traditionally applied false color near-infrared aerial image. The studies presented on water body detection report high success with classification accuracies above 90 %. In glaciological research only few studies have investigated the added value of LiDAR intensity, mainly for improving glacier and periglacial surface interpretation and classification. Such studies are presented by Lutz et al. (2003), Arnold et al. (2006) and Hopkinson & Demuth (2006). After radiometric correction Höfle et al. (2007) included the intensity in a procedure of 3D point cloud segmentation with supervised classification. The glacier facies ice, snow and firn could be separated with high accuracy. The listed studies state a high potential for surface differentiation using the intensity but do not present operational tools for large areas nor the retrieval of surface target parameters (e.g. grain size and moisture), particularly due to the limitations of having only one wavelength as well as the lack of a radiometric calibration procedure that includes ground reflectance targets. Another evolving field of application of LiDAR intensity data is the mapping of volcanic products such as lava flows. Even the age of lava flows (i.e. relative chronology) can be assessed by including the intensity information because cooling, weathering and vegetation cover of lava flows influence the spectral response (MAZZARINI et al. 2007, FORNACIAI et al. 2009). SPINETTI et al. (2009) visually demonstrate the good separability of tephra and lava flows of different ages and also state that hyperspectral satellite and spectral field data could be used to calibrate the LiDAR intensity values. Further potential of using LiDAR intensities can be found in vegetation and tree species classification, respectively (e.g. MOFFIET et al. 2005, CHUST al. 2008 and KIM et al. 2009). These findings may be a valuable input for models related to erosion, hydrology, stem volume and biomass estimation as well as habitat mapping requiring high-resolution distributed and stratified information on land cover parameters such as tree species, canopy density and structure (e.g. canopy roughness).

### 3.5 *Next generation: Full-waveform LiDAR data*

The small-footprint full-waveform LiDAR systems record the entire waveform of the energy reflected backwards to the sensor usually digitized with a temporal sampling interval of 1 nanosecond (cf. Fig. 2; WAGNER et al. 2006, MALLET & BRETAR 2009). Compared to discrete echo recording systems this allows for customized and transparent echo detection and extraction (i.e. range determination) in a post-processing step. Particularly superimposed echoes such as the overlapping response of a bush with low height and the underlying terrain may be identified and separated by applying sophisticated echo extraction methods, which is not possible with the on-line echo detection of traditional LiDAR systems. Additionally, the amplitude and width – usually defined as Full-Width at Half Maximum (FWHM) – can be determined for each range measurement. WAGNER et al. (2006) and BRIESE et al. (2008) show that radiometric calibration supported by radiometric reference data can be used to derive the backscatter cross-section as additional product of full-waveform LiDAR. The cross-section is widely known from radar remote sensing as a measure of the radiant energy scattered back towards the sensor and integratively describes all target parameters (e.g. target area, directionality and strength of reflection) and is free of effects such as from distance to target or atmospheric attenuation (BRIESE et al. 2008), hence being a valuable source of information that can be used in surface classification (WAGNER et al. 2008).

The benefit of this new generation LiDAR systems lies mainly in the enhanced echo detection leading to a higher amount of detected echoes, increased accuracy in range determination particularly for complex surfaces as well as in the provision of additional clearly defined echo attributes serving as input for improving DTM generation and land cover classification (WAGNER et al. 2008, CHAUVE et al. 2009a, MÜCKE et al. 2010). Improved DTM generation is mainly based on the removal of low non-terrain objects (e.g. bushes) that can hardly be identified in traditional 3D point clouds due to their minor changes in elevation but they are identified by taking into account the widening of the echo (DONEUS et al. 2008). MÜCKE et al. (2010) present a new method of assigning probability of echoes belonging to the terrain by considering the echo width and amplitude and the relationship of these two parameters where weak echoes (i.e. low amplitude) tend to have a higher variability in echo widths (LIN & MILLS 2010). It is possible to improve DTM quality particularly in areas with low non-terrain objects that can hardly be penetrated and also to reduce computation time of the terrain point filtering due to less iterations when using a pre-classified (i.e.

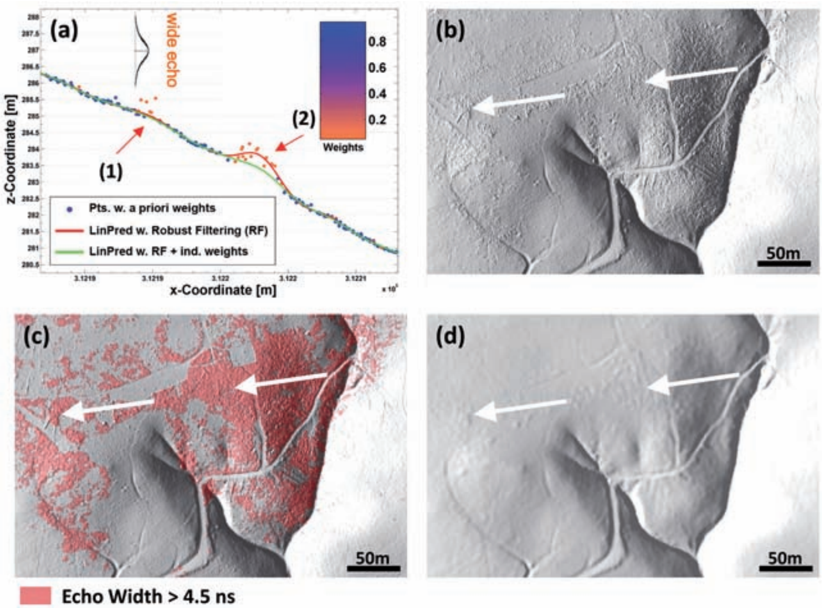


Fig. 5. (a) Result of hierarchic robust filtering: Red line = conventional hierarchic robust filtering after 10 iterations; Green Line: robust filtering with individual weights after 2 iterations. At (1) terrain points are existent and at location (2) no terrain points exist where red line is attracted by elevated points (modified from Mücke 2008). (b) 0.5 m-DSM with average elevation of last echoes within 1 m vertical distance to DTM surface. (c) 0.5 m-DSM of last echoes close to terrain overlaid with areas indicated by large echo widths (>4.5 ns) and (d) 1 m-DTM derived without considering full-waveform attributes. Areas marked with arrows are covered by low vegetation exhibiting a rough surface with widened echoes.

weighted) point cloud (Mücke 2008). In Fig. 5 the potential of improving DTM generation by integrating full-waveform attributes is illustrated. The areas marked with arrows are covered by low vegetation indicated by widened echoes leading to a "rough" DTM surface when not considering the echo width as it is still standard in state-of-the-art DTM generation tools.

Regarding full-waveform assisted land cover classification, Bretar et al. (2009) state that a detailed 3D land cover map is an important input for hydrological models and the parameterization of hydrological production function (e.g. derivation of plant cover). They use a supervised point cloud classification (i.e. Support Vector Machines) of four prominent surface classes in badlands – namely land, road, rock and vegetation. The class vegetation could be detected with highest accuracy when using only LiDAR-based input data such as echo width, amplitude and normalized laser point height (i.e. above DTM). Reitberger et al. (2009) and Höfle et al. (2008) confirm the large potential of full-waveform LiDAR data for land cover classification, such as for 3D single tree detection as well as tree species classification.

Compared to small-footprint topographic LiDAR full-waveform recording and analysis as well as operational applications are further established in the fields of bathymetric LiDAR (Guenther et al. 2000) and large-footprint (10–70 m diameter) data acquisition (Hofton et al. 2000).

## 4 *Quantitative assessment of peer-review journal record*

The variety of geomorphologically relevant applications using airborne LiDAR has been structured and summarized in the previous sections. In order to derive figures of the chronological development of research activities, a quantitative analysis of the publication record in the scope of this review is performed. The basis of this analysis are the assumptions that (i) the quantity of papers published per year is a parameter reflecting research efforts and interest and (ii) important contributions and groundbreaking results are published in international journals – even if prior published in conference proceedings. It is aimed that the quantitative paper analysis gives insight into development of research outcome over time and the stage of integration of airborne LiDAR as source of data. It is not aimed to misuse the extracted data to rate scientific relevance and "impact" of specific studies.

### 4.1 *Methods*

The chosen methodology of the quantitative analysis makes use of a commercial citation and publication tracking system – the *ISI Web of Science*[2] – run by the former Institute of Scientific Information (ISI), now Thomson Scientific[3]. The Web of Science provides access to the citation databases of the Science Citation Index (SCI) and SCI Expanded, which cover a large number of scientific journals (more than 6600 in total). This implies that the most prominent journals of a scientific field are covered but it also excludes publications in younger or regional journals not (yet) listed in the index and also contributions in books and conference proceedings. Hence, the publication record derived by this search tool can never be a complete list of all contributions, but it is assumed that a representative temporal trend and distribution of research applications can be investigated.

In order to avoid a classification of journals into *geomorphological journals* and to remain objective no manual selection and classification of journals has been performed. Three different search strategies are applied and compared, limited to publications falling into the years from 1995 to 2009 (including 2009). All queries use the *topic* search field, which includes a search on paper title, abstract and keywords of each record (Table 1). The first query includes a search on all pa-

Table 1. Performed search strategies for extracting publications of the ISI Web of Science for the years 1995 to 2009 and derived total number of relevant papers.

| No. | Query String for Field "topic" | Limitation to Subject Area | Relevant Papers |
|---|---|---|---|
| 1 | (airborne lidar OR airborne laser scanning) AND geomorph* | - | 57 |
| 2 | airborne AND (lidar OR laser scan*) | *GEOGRAPHY, PHYSICAL* | 198 |
| 3 | airborne AND (lidar OR laser scan*) | *GEOGRAPHY, PHYSICAL* excluding *REMOTE SENSING* | 89 |

[2] ISI Web of Science: http://www.isiknowledge.com (last access 01. 08. 2010)
[3] Thomson Reuters – Science: http:// science.thomsonreuters.com (last access 01. 08. 2010)

pers covering the topic terms airborne LiDAR or airborne laser scanning as well as a limiter on papers containing a term starting with "geomorph". This search includes all papers having, for example, "geomorphology" as one of their keywords or having the term "geomorphological" (e.g. geomorphological mapping) in the abstract or title. The second search does not limit to the term "geomorph" but reduces the resulting list by accepting only papers that are published in a journal listed in the subject area of *physical geography*. The third query refines the result of the second search by further excluding papers published in a journal related to the subject area of *remote sensing*, meaning that all papers of the third search are also contained in search number two.

### 4.2 *Results*

The quantitative publication analysis returns a total number of 57 relevant articles for the first search, 198 for the second and 89 for the third one that have been published in the investigated 15 years between 1995 and 2009 (Table 1). The relative low number of the first search using the keyword "geomorph" is clearly showing an underestimation of relevant papers, since not every geomorphological study explicitly uses this search term in title, abstract or keywords. An equivalent search in the Scopus[4] publication database delivers 70 articles compared to 57 in the Web of Science, which can be explained by the more extensive database of Scopus also covering book series and conference papers. The second query with 198 articles overestimates the number of studies because also primary remote sensing journals are listed in the subject area of "physical geography".

Table 2. Resulting number of articles according to journal sorted by quantity of papers derived by the third search strategy. Additionally the three topmost remote sensing journals in terms of search number two are listed at the bottom of the table.

| Journal Name | Search No. | | |
|---|---|---|---|
| | #1 | #2 | #3 |
| JOURNAL OF COASTAL RESEARCH | 3 | 28 | 28 |
| GEOMORPHOLOGY | 13 | 23 | 23 |
| EARTH SURFACE PROCESSES AND LANDFORMS | 8 | 15 | 15 |
| PROGRESS IN PHYSICAL GEOGRAPHY | 2 | 6 | 6 |
| INTERNATIONAL JOURNAL OF GEOGRAPHICAL INFORMATION SCIENCE | – | 3 | 3 |
| GEOGRAFISKA ANNALER SERIES A-PHYSICAL GEOGRAPHY | – | 2 | 2 |
| GLOBAL ECOLOGY AND BIOGEOGRAPHY | – | 2 | 2 |
| LANDSCAPE ECOLOGY | – | 2 | 2 |
| PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING | 1 | 48 | – |
| ISPRS JOURNAL OF PHOTOGRAMMETRY AND REMOTE SENSING | 4 | 47 | – |
| PHOTOGRAMMETRIC RECORD | – | 10 | – |

[4] Scopus: http://www.scopus.com (last access 01.08.2010)

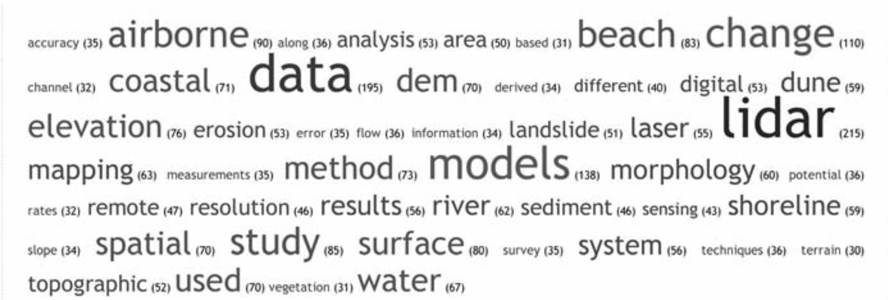


Fig. 6. Weighted list (*tag cloud*) of words included in the abstracts and keywords of the 89 articles returned by the third search strategy (cf. Sinclair & Cardew-Hall 2007). The 50 topmost words were selected using the setting "group similar words".

Therefore, the third search strategy has been introduced, excluding remote sensing journals. In Table 1 and Table 2 it is clearly indicated that the last fifteen years have been dominated by peer-reviewed journal articles dedicated to remote sensing, as more LiDAR related articles in the area of physical geography are published in primary remote sensing journals (55 % with 109 of 198 articles). Excluding the remote sensing journals (search strategy 3) three journals are predominant sources for LiDAR related papers. More than 74 % of the articles are published in the Journal of Coastal Research (28), Geomorphology (23) and Earth Surface Processes and Landforms (15).

To answer the question what has been published, the author's keywords are investigated. Additionally, the influence of studies dealing with bathymetric LiDAR is assessed, as the focus of this paper is laid on topographic LiDAR applications. The bathymetric LiDAR studies are excluded from search number two by adding a search string for excluding terms starting with "bathy" (i.e. by adding "NOT bathy*" to the search string) that may be apparent in the article title, abstract or keywords. The amount of papers is reduced from 198 to 180 whereas only about the half of the removed 18 papers can be clearly dedicated to bathymetric LiDAR studies. This shows that mostly topographic LiDAR applications are captured by the chosen search strategy, indicating a dominance of topographic LiDAR studies. The variety of published applications using airborne LiDAR has been identified and reported in the previous section. Additionally, in order to get a visual summary of the published contents a weighted list, also referred to as tag cloud, is generated using the TagCrowd[5] online tool (cf. Sinclair & Cardew-Hall 2007). Fig. 6 emphasizes again the high interest in using topographic LiDAR for coastal studies (e.g. "coastal", "shoreline" and "beach"), river and water-related processes and forms, as well as investigations on landslides, sediments and erosion processes. Most prominently digital elevation models are in use, frequently stated to detect spatial and temporal changes in morphology.

The most influential studies in terms of how often they were cited are the technology-based articles of Wehr & Lohr (1999) giving an introduction to the airborne LiDAR technology and Kraus & Pfeifer (1998) being pioneers in improving DTM generation in forested areas. In the third search (excluding remote sensing journals) the Earth surface process related studies of McK-

[5] TagCrowd: http://www.tagcrowd.com (last access 01.08.2010)

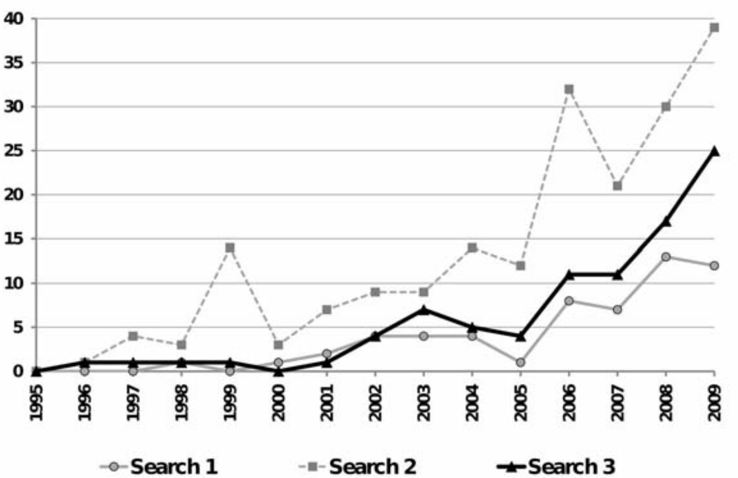


Fig. 7. Chronological development of airborne LiDAR-related publications captured by the ISI Web of Knowledge. The number of peer-review journal publications per year is shown for the 15-years period from 1995. In Table 1 the total number of papers and the defined search strategies are listed

EAN & ROERING (2004) investigating landslides and STOCKDON et al. (2002) extracting the shoreline position are the highly cited papers. The authors want to note that the total number of citations is strongly dependent on the year of publication and cannot be used as relative measure.

The development of LiDAR-related publications separated by search strategy is shown in Fig. 7. All three search strategies indicate a significant trend towards an increase of papers per year over the last 15 years. Exceptions are the years 2005 and 2007 where this upward trend was clearly intermitted. The peak in the year 1999 that is just found in search 2 can be explained by an extensive theme issue on airborne laser scanning in the ISPRS Journal of Photogrammetry and Remote Sensing. The most recent increase has been rapidly, as indicated by the number of papers of the second search that was more than doubled from 2007 to 2009. The authors also want to note that the presented data may be influenced by a certain bias caused by a general trend of publishing more frequently in ISI ranked journals and that the authors are aware that research activities have a temporal shift from discovery, measurement and experiment, respectively, to the year of publication, such as due to a long review process.

## 5 *Discussion*

### 5.1 *Trend in quantity of peer-reviewed journal articles*

The considerable increase in scientific publications related to the airborne LiDAR technology is strongly related with the grown *availability* of LiDAR data, which can be explained by both, the larger number of administrative authorities applying LiDAR for their area-wide topographic data acquisition (e.g. The Netherlands and Switzerland) and updating but also the intensified interest of researchers obtaining datasets for research projects, such as the unique multitemporal dataset of the Hintereisferner, a glacier in the Ötztal Alps/Austria with 18 LiDAR campaigns until 2009 (e.g. GEIST & STÖTTER 2007). The availability goes along with the technological development allowing cost-effective, high density and accurate data acquisitions with automated raw data processing chains. The time series (Fig. 7) clearly shows that the peak of peer-reviewed references per year has not been reached so far. The diffusion of the LiDAR technology into the research field of physical geography or geomorphology in particular is still going on. An even more distinct situation is observed for terrestrial LiDAR as HERITAGE & HETHERINGTON (2007) conclude that "*Whilst laser scanning has impacted significantly on areas of engineering, it remains under-exploited as a technique for studying the character and dynamics of the natural environment*". Research and development have been focused on the sensor and LiDAR data side, which is confirmed by the contents of the highly cited papers (e.g. KRAUS & PFEIFER 1998). Apart from the scientific quality and innovation of a paper, the total number of citations of a paper is related to age (years since publication) and the number of papers published thereafter that can potentially cite the paper of interest. Hence, the highly cited papers using LiDAR data for studying Earth surface processes and landforms will evolve the next years. The early innovator papers, such as KRAUS & PFEIFER (1998) and WEHR & LOHR (1999), play a special role because they are widely cited through all disciplines. Since the LiDAR technology is developed permanently further – as we can see with full-waveform sensors as well as radiometric calibration and information extraction – the research, development, diffusion and use phase will be coexistent in newly published articles and let assume that the LiDAR technology will and has already been adopted and accepted for selected tasks, such as primary source for DTM generation, especially in forested areas.

### 5.2 *LiDAR data analysis and integration*

The literature review raised the dominance of raster-based applications and the DTM to be the most prominent data source. Dependent on the scale of interest the DTM may be appropriate and the 2.5D characteristic of the elevation model is sufficient. Raster models provide the major advantage of being a simple data structure that can be processed very fast with standard software (e.g. GIS tools). In comparison real 3D applications from airborne LiDAR – e.g. working on the 3D point cloud – are still rare, which can be explained by the lack of out-of-the-box software tools providing management and analysis functionality (e.g. for point cloud segmentation) that can be combined with standard GIS and remote sensing software, where most of the existing mapping workflows are implemented. Furthermore, the need for such advanced 3D processing workflows has to be given, which is related to phenomena in a detailed scale (below resolution of elevation models) and a morphology emphasizing the vertical component such as crevasses and sheer rock faces or distinct objects of interest such as trees (KODDE et al. 2007, JANERAS et al. 2004, REITBERGER et al. 2009). For local studies of vertical surfaces terrestrial LiDAR is mainly applied, offering a better sampling in the vertical direction with higher resolution. However, terrestrial LiDAR is coupled with limited areal coverage and the required accessibility and visibility at ground level (cf. HERITAGE & HETHERINGTON 2007).

In terms of scale, resolution and accuracy airborne LiDAR has its strength and unique feature in the acquisition of topographic datasets in a regional scale (1 $km^2$ up to 100 $km^2$ in a single acquisition campaign) while providing sub-meter accuracy and resolution (cf. Heritage & Hetherington 2007). The temporal resolution and areal coverage are practical limitations, driven by costs and realization of large flight campaigns in a very short time. An evolving research objective is the investigation of multi-sensor datasets, assessing the benefit of complementary data sources and their limitations (Geerling et al. 2007, Straatsma & Baptist 2008 and Bretar et al. 2009). For example, the integration of passive optical imagery can improve the interpretation and automatic classification of natural phenomena, particularly where multiple spectral channels contain valuable means for the physical description and separation of objects (in object and feature space). However, the co-registration of multiple sensor data to a common reference frame is still a challenge, such as either labeling the point cloud with multispectral data or transforming the imagery data into a common reference system and data model (e.g. orthophotos; Habib 2008). However, when strictly combining LiDAR data (i.e. data fusion) with passive optical imagery the major advantages of the active remote sensing system may be diminished such as the insensitivity to light conditions (e.g. flight by night possible and no shadows) and the 3D characteristics of the LiDAR point cloud (e.g. vertical structure of vegetation). When integrating different data sources (e.g. remote sensing and field observations) the time shift in data acquisition should be as short as possible because temporal offsets can contain changes of the surface, which hamper the fusion, interpretation and classification of the datasets. The synergy and combination of airborne LiDAR with other sensor data (e.g. radar and passive optical imagery) as well as LiDAR mounted to different platforms (e.g. terrestrial, mobile and spaceborne) and with different wavelengths (e.g. bathymetric LiDAR) contain a large potential and has to be investigated further in order to derive protocols and best practice for studying natural processes with different temporal and spatial activity. Particularly, change detection such as important in natural hazard management has a great demand on detailed topographic data with short update cycles with at least after major events that may be only provided in a cost-effective way when combining different data sources, such as terrestrial and airborne LiDAR (Geist et al. 2009).

Furthermore, the studies included in the review show a great variety of applications ranging from visual interpretation of LiDAR data derivatives (e.g. contour lines, slope and shaded relief maps) assisting field observation to semi-automatic and even automatic classification as well as set up of expert-driven workflows for specific task such as toolboxes for geomorphological mapping using remote sensing data (e.g. van Asselen & Seijmonsbergen 2006). Jones et al. (2007) investigated high-resolution LiDAR for interpretative geomorphological mapping of river valley environments concluding that GIS technology fed by LiDAR data "*enables the user to identify and delineate geomorphological features in a manner similar to field mapping*" such as providing base maps for field investigation. From a methodological point-of-view Blaschke (2010) highlights the convergence of remote sensing and GIScience in the Geospatial Object Based Image Analysis (GEOBIA) providing a "*way that mimics the human interpreter*". In general, LiDAR based workflows are capable of delineating geomorphological features with high spatial accuracy (e.g. structure lines), but compared to the geometrical representation the assignment of semantics to the detected features requires expert knowledge, either put into a sophisticated classification rule base (fully automatic) or done manually. However, since natural phenomena generally exhibit a continuous spatial representation and do not have distinct boundaries, the object-based workflows aiming at distinct object detection (e.g. trees and buildings) may be limited. In this respect the definition of objects bound to spatial scale has to be taken into account (Fisher et al. 2005). For instance, a single stone may be identified as object in terrestrial LiDAR data, whereas in a less detailed scale using airborne data the delineation of rockfall debris approximates the area of interest by geomorphometric surface parameterization (e.g. roughness).

### 5.3 *Recent advances on LiDAR side and impacts on geomorphological applications*

The studies applying the new generation topographic LiDAR sensors with full-waveform recording capability state a high value of the additionally available physical quantities such as echo amplitude, width and cross-section, in particular for surface classification where no distinct geometrical separation of classes is possible. The limitations to integrate these new features into existing but also new workflows are mainly the high requirements for data storing and processing. More information than a plain XYZ point cloud has to be available to the analyst such as the sensor position for each laser point in order to derive the laser range vector, which is a prerequisite for radiometric correction and calibration (Wagner et al. 2006). Furthermore, up to now out-of-the-box tools for management, processing and calibration full-waveform data is mainly restricted to software provided by vendors of LiDAR sensors and data, which do not include surface analysis and classification workflows. First science-driven solutions are on its way to provide operational tools that can be used by non LiDAR experts, such as *FullAnalyze* (Chauve et al. 2009b) and *OPALS* (Mandlburger et al. 2009a). Indirectly, sensor development and improvements in LiDAR processing algorithms provide a direct benefit for users of all different levels of LiDAR data such as from DTM to attributed point cloud. For example, full-waveform LiDAR can improve terrain filtering and thus improves the quality of the resultant DTM, which has an impact on applications using the terrain model. Additionally, recent systems with higher pulse repetition frequency allow for cost-effective acquisition at higher point density. The eventual effect of enhanced quality and resolution of input data for natural process modeling is an active area of investigation, such as for debris flow (Wichmann et al. 2008) and hydraulic modeling (French 2003, Mandlburger et al. 2009b). However, pure data-driven LiDAR processing (e.g. elevation model derivation) with improved terrain filtering and resolution may not necessarily lead to better base data for specific geomorphological applications. Jones et al. (2007) report that unfiltered data is better suited for geomorphological mapping than filtered because interesting features could be removed or smoothed. Hence, a close interaction between LiDAR algorithm development (e.g. terrain point filtering) – currently still a black-box for software users or data product recipients – and target application is required in order to exploit the full potential of the acquired datasets. This includes a proper quality description in terms of precision and accuracy of the derived products.

## 6 *Conclusions*

The remote sensing technique of small-footprint topographic airborne LiDAR has developed very rapidly and has come into widespread use for operational and highly detailed topographic mapping. This review demonstrates the most recent advances on the LiDAR sensor and processing side and points out the large diversity and potential of applications using LiDAR data for studying Earth surface processes and landforms. LiDAR datasets are used in different processing levels, ranging from the original point cloud to the DTM, and also in different depths of integration into applications, starting with LiDAR derivatives (e.g. shaded relief map) assisting visual interpretation and field investigation up to integrating LiDAR data in process models (e.g. mass movement and fluvial process models) and automatic geomorphological mapping workflows. The quantitative publication assessment of peer-reviewed journal articles of the last fifteen years advocates that the intensified exploitation is a very recent phenomenon. Explanations for this drastic increase in papers are the rapid technological development offering higher resolution and accuracy in a cost-effective way, the substantially increased availability of data due to a more general accessible market (i.e. data capturing providers) as well as data acquisitions conducted by authorities (e.g. countrywide LiDAR campaigns) made available for research. An acceptance of using LiDAR data in geomorphology has been reached by pioneer studies being published in the last fifteen years. The availability of LiDAR data will increase in the near future and recent sensor developments such as full-waveform recording will be available and utilizable by a broader community. Further progress is still being required in order to develop operational management and analysis tools making use of the full potential inherent in this new datasets. Due to the technical specification and practical limits in temporal, spectral and spatial resolution as well as spatial coverage, a combination with remote sensing data from other platforms (e.g. terrestrial, mobile and spaceborne) and sensors (e.g. radar and passive optical imagery) will be of high interest, however, established solutions are still to be found. Concluding, the presented review has shown that airborne LiDAR is a beneficial source of data and information providing the expert with a tool to deepen the understanding of geomorphological processes, their distribution and spatial extent that has not been possible before.

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