GEOMETRICAL ASPECTS OF AIRBORNE LASER SCANNING AND TERRESTRIAL LASER SCANNING

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ABSTRACT:

This paper reviews the current state of laser scanning from airborne and terrestrial platforms for geometric reconstruction of object shape and size. The current performance figures of sensor systems are presented in an overview. Next, their calibration and the orientation of the acquired point clouds is discussed. For airborne deployment this is usually one step, whereas in the terrestrial case laboratory calibration and registration of point clouds are (still) two distinct, independent steps. As laser scanning is an active measurement technology, the interaction of the emitted energy with the object surface has influences on the range measurement. This has to be considered in order to explain geometric phenomena in the data. While the problems, e.g. multiple scattering, are understood well, there is currently a lack of remedies. Then, in analogy to the processing chain, segmentation approaches for laser scanning data are reviewed. Segmentation is a task relevant for almost all applications. Likewise, DTM (digital terrain model) reconstruction is relevant for many applications of airborne laser scanning, and is therefore discussed, too. This paper reviews the main processing steps necessary for many applications of laser scanning.

1 INTRODUCTION

Laser scanning, often also referred to as LiDAR (light detection and ranging), has been operational for surface and object reconstruction since the mid 1990s. It is continuously developing in sensor as well as in data processing aspects. Higher measurement rates, increased precision, wider range spectrum, and extraction of target or object properties beyond the range are some of the developments on the sensor side. The development of calibration procedures for both airborne and terrestrial devices is one important development for the early stages of data processing. Additionally, a diversification in applications can be seen. The first applications were in capturing terrain elevation (Kilian, Haala, and Englich 1996), but forestry (see e.g. the overview in (Hyyppä et al. 2004)) and industrial reconstruction became standard areas of application (e.g. Rabbani, Dijkman, van den Heuvel, and Vosselman (2007)) in the meantime, too.

This paper reviews the state of art in airborne and terrestrial laser scanning. The first publications on laser scanning (and laser profiling) in photogrammetric journals and conference proceedings were often linked to one or more applications: laser profiling for terrain elevation (Lindenberger 1989; Lindenberger 1993), laser scanning (Lohr and Eibert 1995), terrain elevation and buildings (Kilian, Haala, and Englich 1996), power lines (Reed and Lynch 1996), forest stand parameters (Naesset 1997), terrain elevation (Flood and Gutelius 1997), surface characteristics (Lin 1997; Ritchie and Pachepsky 1998), digital terrain modeling (Kraus and Pfeifer 1998), and a wide range of applications in Vol. 54(2-3) of the ISPRS Journal, special issue on airborne laser scanning. Only later dedicated data pre-processing algorithms were published, especially on strip adjustment and segmentation (Burman 2000; Crombaghs, Brügelmann, and de Min 2000; Behan, Maas, and Vosselman 2000; Filin 2002). Terrestrial laser scanning went through a similar history but matured and entered the photogrammetric community a bit later. A special issue of the ISPRS Journal on terrestrial laser scanning is in preparation. With over ten years of development it stands to reason to review the current state of these pre-processing algorithms, give an overview of the relevant literature, and judge the development.

The so-called intensity measurements are rarely used (Höfle and Pfeifer 2007), and also full waveform laser scanning (Wagner et al. 2006), and even more so, multispectral laser scanning (Wehr et al. 2006; Wehr et al. 2007), still have to proof their value for exploitation in different applications. Thus this review will be confined to the geometrical aspects of airborne laser scanning (ALS) and terrestrial laser scanning (TLS) and will not go into details of retrieving material properties of objects scattering back an incident laser beam. For the physical principles of *laser radar* the reader is referred to Jelalian (1992) and Wehr and Lohr (1999). With the diversification of applications, it would also be impossible to review the state in each application, and this review will concentrate more on laser scanning itself and procedures useful or necessary in all applications.

We are therefore mainly treating the point cloud, starting from the sensors acquiring the data, and proceeding, in steps, to model generation. While reporting the state of the art according to our best knowledge, we allow ourselves to point out fields, where we expect research to concentrate in the coming year(s). This is solely the opinion of the authors and necessarily speculative. The paper is structured by first reviewing the state of the art in data acquisition and pre-processing, where the latter term means that the original measurements are processed and a specific application is not the driving force behind the processing. Next, the geometrical consequences, i.e., effects on the point cloud, of the interaction of the laser signal with the object are investigated. Naturally, this has physical causes, formulated in terms of multiple scattering properties, object transparency, and the like. However, at least currently, this cannot be handled on a physical basis and has to be analyzed, and if possible corrected, in a data driven manner. Then generic processing steps as segmentation are reviewed, including also DTM reconstruction. The latter, while being an application itself, is used in many further applications, which justifies including it in this review.

2 DATA ACQUISITION

This section presents the state of the art in laser scanning systems, their calibration and transformation of the point clouds acquired into a superior, possibly global, coordinate system.

Due to the fact that the sensor technology is developing fast we will not describe specific scanners of different vendors, as at the moment of printing the article, the information may be outdated already. Therefore, rather the main performance parameters are given. Surveys of currently available devices are regularly published (GIM 2007; POB 2007). Airborne and terrestrial (also called close-range) deployment will be treated separately, as the different deployment of the scanners, at fixed positions over periods of time vs. on a moving platform, has a large impact on the first steps of data processing. However, with the advent of scanning from moving platforms on the ground (also termed mobile laser scanning), and the longer history of using profile scanners on trains, it would be more appropriate to distinguish between *dynamic and static scanning*. In the first case scanning is performed by a univariate beam deflection unit and area wise data acquisition is established by the dynamics, i.e. the movement, of the scanning platform (aircraft, land vehicle or a boat). In the second case the exterior orientation of the platform is constant for one scan position, and two dimensional coverage in the angular domain is performed by rotating components of the device (e.g., a mirror or the upper instrument part). Profiling (Lindenberger 1989), on the other hand, is what is obtained by univariate beam distribution, e.g. obtained from satellite platforms (Zwally et al. 2002) or used for continuous monitoring or elongated structures (Hesse, Neuner, and Kutterer 2005).

2.1 Airborne Laser Scanning

2.1.1 Current Systems ALS systems use almost solely the pulse time of flight measurement principle for ranging (Riegl 2007; Optech 2007; Leica 2007; TopEye 2007; TopoSys 2007; Fli-Map 2007). One exception is the research system ScaLARS, which applies the phase difference measurement principle (Hug and Wehr 1997). Currently, there are two different types of commercial ALS sensor systems available: discrete echo and full-waveform scanners. While discrete echo scanners detect a representative trigger signal for multiple echoes in real time using analogue detectors, full-waveform ALS systems digitize the entire analogue echo waveform, i.e. the time-dependent variation of received signal power, for each emitted laser pulse. Digitization is performed typically with an interval of 1 ns (corresponding to 15cm one-way distance) and the determination of the individual echoes has to be performed in post-processing (Wagner, Ullrich, Melzer, Briese, and Kraus 2004). In ALS mainly two laser wavelengths are in use: 1.06μm and 1.5μm. The pulse repetition rate (PRR) of current "top end" devices is 100kHz to 200kHz[1]. The operating altitude of the systems is different, with some systems restricted to a flying height of less than 1000m above ground, whereas others can be used 5km above ground level. Many ALS systems are currently only able to record the reflections of one laser pulse before the next is emitted. This restricts high PRR to lower flying heights (not more than 100kHz for 1500m maximum one-way slant range). Recent sensor developments lead to the ability of multipulse systems which allow to have multiple laser signals in the air simultaneously (Optech 2007; Leica 2007).

The maximum field of view in ALS data acquisition, measured perpendicular to the forward movement of the aircraft is depending on the scanner used and reaches from $\pm 7^\circ$ to $\pm 30^\circ$. ALS systems are used on fixed-wing aircraft as well as on helicopters. While fixed-winged aircraft are typically used for the acquisition of large project areas, helicopters are preferred for following a linear feature (e.g. for corridor mapping) or for difficult topography.

The scanning mechanisms applied are mainly those deflecting the laser beam in a plane perpendicular to the flying direction, using an oscillating or a multi-faceted rotating mirror (Latypov 2005). For rotating mirror scanners the PRR is typically only a burst measurement rate, and the number of pulses used for measuring ranges, i.e. the effective measurement rate, is lower (Riegl 2007). The rays with larger nadir angles are not provided to the users or are reflected within the scanner housing. Oscillating mirrors have the advantage that the turning points can be set to angles appropriate for a specific project. However, as the mirrors have to be accelerated the point distribution on the ground can be less homogeneous than for rotating mirror scanners, especially when using a harmonic angle acceleration. By using mirrors with different angles at the facets, forward, nadir, and backward looking can be performed with one scanner (Fli-Map 2007). The fiber scanner used in one of the TopoSys scanners is special in the sense that no angle position of the mirror has to be measured as the emission direction is fixed and governed by the single fibers directly. Palmer scanners (Wehr and Lohr 1999) are used by TopEye, ScaLARS and NASA's ALTM (Finnegan et al. 2005). While generating a less regular ground point pattern they offer an advantage in calibration, as each "point" is measured twice.

2.1.2 Calibration and Strip Adjustment For the transformation of the ALS data (range and angle observations) into one common coordinate system the position and angular attitude, i.e. the exterior orientation, of the platform have to be known in order to allow direct geo-referencing. Typically, this is realized by a combination of a global navigation satellite system (GNSS) receiver and an inertial measurement unit (IMU). Together with the laser scanner they form a multi sensor system. During data acquisition data streams are recorded by each instrument at different frequency and are synchronized via the GNSS time measurements. Calibration of this multi sensor system is the process of determining the relative orientation, i.e. shifts and rotations, between the components (GNSS antenna, IMU, and laser scanner) and time lags in the synchronization. To some extent these parameters can be determined by total station measurements on the ground, but a number of parameters, e.g. the IMU–laser scanner relative orientation or time lags, are better determined during flight. Scanner vendors provide special software that allow derivation of these parameters if dedicated flight patterns are performed. Typically only flat surfaces are used for this alignment, but as Filin (2003) has shown, inclined surfaces with different aspect are a prerequisite for determining all relative orientation parameters of the multi sensor system.

Approaches for the calibration have been presented in (Burman 2002; Filin 2003; Kager 2004). In Skaloud and Lichti (2006) a method for dedicated determination of the three bore-sight angles and the range finder offset is described. These models are all based on the observations range, angle (of beam deflection), and observations of exterior orientation (i.e. position and angular attitude). The points measured by the ALS system are either related to ground truth and/or to points of another strip (control and tie information in the form of surface patches, respectively). The discrepancies encountered in those are minimized by determining the calibration parameters.

In calibration the task is, as described above, to reconstruct the geometric layout of the multi sensor system. For applications of

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[1] Next to increasing the pulse generation rate of the laser, an option to increase the measurement rate is mounting two laser scanners on one platform, as offered currently e.g. by (Diamond Airborne Sensing 2007).

ALS data, the effects of an insufficient calibration and of errors in the exterior orientation determination are more of interest. The task of strip adjustment is to correct these errors. This can be done either by calibration, or by applying corrections to the points directly: $\mathbf{p}'_{\mathbf{i},\mathbf{j}} = \mathbf{p}_{\mathbf{i},\mathbf{j}} + \mathbf{c}_{\mathbf{j}}(\mathbf{p}_{\mathbf{i},\mathbf{j}})$. The point $\mathbf{p}_{\mathbf{i},\mathbf{j}}$ with index i in strip j is corrected by applying a correction function $\mathbf{c}_{\mathbf{j}}$ for strip j. The first publications on strip adjustment chose that approach.

In the simplest case the functions $\mathbf{c}_{\mathbf{j}}$ are only shift vectors, $\mathbf{c}_{\mathbf{j}} = (x_j, y_j, z_j)$ and do not depend on the location within the strip. In (Crombaghs, Brügelmann, and de Min 2000) and (Kraus and Pfeifer 2001) the correction function applies to the height component only, using a linear function (vertical offset and tilts in and across flight direction), and polynomials, respectively. The approach of Kraus and Pfeifer (2001) allows correcting shorter wavelength deformations, too. A method that is not restricted to vertical correction, but also removes discrepancies in planimetry was developed by Kilian, Haala, and Englich (1996), where the function $\mathbf{c}_{\mathbf{j}}$ has parameters for constant offset and time dependent drifts for shift in and rotation around the three coordinate axes, requiring that the time of the measurement is known. Vosselman and Maas (2001) describe a similar method, mentioning, that this model does not allow to correct short time effects caused by the limited GNSS accuracy. Knowledge on the measurement time is not required but replaced by parameterization along the strip axes.

Contrary to these approaches which model effects, not causes, calibration procedures can be extended to perform strip adjustment, too. This has been demonstrated by Burman (2002) and Kager (2004).

In ALS there is still a process of model identification going on. Calibration methods and strip adjustment should be generic enough to allow handling all airborne laser scanners on the one hand, and correct the causes of the errors, and not only effects, on the other hand. Specialized developments are often beneficial for data acquisition (e.g. the roll angle compensation of Optech), but less practical for implementation of on-the-job sensor calibration techniques. Especially the lack in the availability of the original observations (i.e., trajectory, angles, and ranges) complicates these efforts from a scientific point of view.

Although methods have been published, and the increase in precision is notable, on-the-job calibration is not standard yet. There is a lack of software available to data providers. Next to calibration, also efforts to improve the flight path are necessary. The global navigation satellite system can be seen as correction for the low frequency errors in the high frequency observations of the flight path and sensor attitude by IMU measurements. However, the GNSS component itself is subject to errors that occur over the entire strip or parts of it (e.g., wrong ambiguity fixes)[2]. Under such circumstances an offset and drift component as unknowns in strip adjustment are not enough (Ries, Kager, and Stadler 2002). Also polynomial models do not work satisfyingly, and spline models for modeling the dynamic exterior orientation require careful balancing of the number of knots and their placing. Summarizing, solutions modeling the flight path have not been very successful yet, which may be attributed partly also to unexpected behavior encountered in flight path information, e.g. “jumps” in the flight path (Ries, Kager, and Stadler 2002).

The authors hold the view, that a tighter integration of the determination of the sensor trajectory with Kalman filtering of the GNSS/IMU data with the determination of sensor calibration and exploitation of homologous patches on the ground will provide the most precise solution. It allows to introduce redundancy in the determination of the flight path, which is absent in direct georeferencing (Skaloud 2006). Introducing redundancy increases, at least in theory, reliability and allows estimating the precision. There is also a potential to account for changing satellite constellations, GNSS outages, or periods with less than four satellites visible. In aero-triangulation the combined adjustment of images and GNSS observations is investigated in (Schmitz, Wuebbena, Bagge, and Kruck 2001) and (Ellum and El Sheimy 2006).

For well defined surfaces the precision of ALS, applying a rigorous model of laser strip calibration as described above, can reach a few centimeter. The determination of the flight path with GNSS gives a precision of ±5cm to ±10cm in each coordinate direction and becomes a limiting component of ALS precision (Csanyi and Toth 2007). Solutions may come from improvements in the GNSS, also by using multiple reference stations, or from more ground control. The latter can be in the form of surface patches, which is economically and practically less viable. Alternative navigation systems may emerge, although the current alternatives to GNSS for navigation in cities or inside buildings, e.g. based on mobile communication and other wireless networks (Karimi and Hammad 2004) are far from the accuracy provided by GNSS yet.

For full exploitation of the measurements of ALS not only the geometric aspects should be considered, but also the radiometry. The backscattered energy, in the form of photons, is typically converted to a voltage or current and then converted further into a digital number, not necessarily by a linear function. This is discussed in (Wagner et al. 2006; Ahokas et al. 2006; Höfle and Pfeifer 2007). Many airborne systems have two receivers (so-called low channel and high channel for detection of echoes with small and large amplitude, respectively), which has not been considered in calibration efforts so far.

2.2 Terrestrial Laser Scanning

2.2.1 Current Systems In contrast to ALS systems more variation in the sensor design of TLS systems can be observed. The wavelengths used are between 0.5μm and 1.5μm. Longer wavelengths are affected less by the atmosphere, but shorter wavelengths can provide smaller footprints. Terrestrial laser scanners use the pulse time of flight measurement principle (Riegl 2007; Leica 2007; Trimble 2007; Optech 2007; Callidus 2007; I-SiTE 2007) as well as phase based ranging (Zoller+Fröhlich 2007; Faro 2007; 3rdTech 2007). The second systems use the phase difference between the emitted and received backscattered signal of an amplitude modulated continuous wave (AM CW) to infer the range. Pulse time of flight ranging scanners are suited better for outdoor operation where longer ranges have to be measured and are typically panoramic scanners, with a field of view of 360° by e.g. 80°. The PRR of these sensors is around 10kHz and less, and precision lies between ±5mm and ±2cm.[3] Some systems offer the possibility to either measure the first or last echo, but simultaneous recording is usually not available.

Scanners applying the phase based ranging are typically hemispherical scanners that allow to scan into almost all directions (e.g. 360° by 135°). However, due to their ranging principle (limited range uniqueness, mostly below 100m) they are well suited for indoor usage and outdoor environments with a larger number of objects (e.g. piping installations, inner city areas), restricting

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[2] It shall be noted that satellite positioning is performed in a geometrical coordinate system (geocentric cartesian or ellipsoidal coordinates) whereas IMU measurements depend also on the local geoid.

[3] Leica recently introduced a terrestrial laser scanner with 50kHz PRR, but at the time of writing (August 2007) no independent reports of performance were available.

the view. The measurement rate is typically above 100,000 points per second, and the precision is ±2mm or better. With this ranging principle only one distance can be determined, because the backscattered signals from different reflectors are always overlaying each other. This results in a phase angle corresponding to a distance between the two or more reflectors.

Triangulating scanners, similar to structured light systems, are not discussed here. In (Blais 2004) a review is given. Additionally it shall be noted that currently efforts are on the way to generate standards for terrestrial scanners (Beraldin et al. 2007; Breuckmann et al. 2007).

2.2.2 Calibration Terrestrial laser scanners are, from the construction principle, similar to theodolites and total stations. This holds especially for strictly monostatic systems, where the axis of laser beam emission and the optical axis of the receiver are the same. Additionally, if the rotation around the vertical axis is performed by instrument rotation and the beam deflection in the vertical plane is performed by a rotating mirror inclined 45° against the beam, then an analogy between the instrument axes of a terrestrial laser scanner and a theodolite can be established.

Lichti (2007) models deviations in the observations by correction functions, some of which are based on the sensor model (e.g., trunnion axis error), whereas other parameters are found empirically (e.g., sinusoidal error in horizontal angle as a function of elevation angle). The physical corrections for the range measurement errors are a constant offset and harmonic functions at the wavelengths used in the amplitude modulation for the phase based ranging (Rueger 1990). This approach is driven by the model of the sensor and for a Faro laser scanner it resulted in an improvement of about 30% in each coordinate direction (Lichti 2007).

Abmayr et al. (2005) use the similarity of a terrestrial laser scanner to a theodolite and determine for a Z+F Imager 5003 consecutively trunnion axis error, collimation axis error and vertical circle index error. In (Parian and Gruen 2005) a different approach for the same scanner is presented. The TLS observations in the spherical coordinate system are transformed to observations of a cylindrical coordinate system, which is possible if not the entire hemispherical field of view is used. Then a calibration approach for panoramic cameras is applied, reducing systematic errors in the angle observations. By this method residuals at target points identified in intensity images for a Z+F Imager 5003 are reduced by 90%.

The approaches presented so far rely on targeted points. While such a well-controlled experiment allows to make observations in the entire (angular and range) domain, it is not typical for project execution. As the stability of the parameters cannot be guaranteed (Lichti 2007), the development of on-the-job calibration methods appears to be necessary (Reshetyuk 2006).

It should also be noted that special device constructions, e.g. the dual window design of the Leica Scan stations, have not been investigated, yet.

2.2.3 Registration/Orientation In TLS relative orientation, also termed registration, is currently performed standard-wise by either of two methods: ICP type algorithms on the one hand and explicit tie features on the other hand. With a sufficient number of homologous tie features (points, lines, or surfaces) the transformation parameters can be computed. For points this is possible without approximate values (Horn 1987). ICP algorithms do not require homologous points, and the exact correspondence is replaced by iteratively determined approximate correspondence of points or small surface elements.

The terms relative orientation and registration are used almost synonymously. Brenner, Dold, and Ripperda (2007) note that 'registration' is putting more emphasis on the active role of the point cloud in the process itself (Brenner, Dold, and Ripperda 2007). The term 'relative orientation', on the other hand, also refers to the relation between device coordinate systems. Next to registration and orientation also the terms (co)-alignment, consolidation, and stitching are regrettably in use.

If only the object itself is of interest, it is sufficient to determine the relative orientation between scans. If the object also has to be placed in a superior coordinate system, absolute orientation becomes necessary, too. If the superior coordinate system is earth fixed it becomes the task of geo-referencing.

Using homologous features for relative orientation, they have to be extracted first. This becomes simple, if artificial targets are placed in the scene, e.g. with retroreflective material. In that case, due to the high intensity value, they can be found automatically. Natural tie elements can be identified with lower accuracy in the intensity images by visual inspection or automatic procedures. Alternatively, object surfaces can be used as tie elements (e.g., cylinders and planes). A method for automatic extraction of these patches and computation of transformation parameters has been presented by Rabbani, Dijkman, van den Heuvel, and Vosselman (2007), Dold and Brenner (2006), and Brenner, Dold, and Ripperda (2007). Finding the correct correspondences between features of two scans automatically can be seen as a graph search problem and methods for pruning the graph become necessary to reduce the search time, e.g. by computing and comparing parameters as patch boundary length. Another way to increase automation is relying on high resolution images, where the task has been studied for a longer time and (e.g.) the technique of coded targets has been developed. Al-Manasir and Fraser (2006) presented an approach where artificial targets are automatically found in a digital image, taken with a camera with known relative orientation to the laser scanner. Böhm and Becker (2007) suggests using the SIFT operator (Lowe 2004) to find homologous points in the intensity image. For two scans from notably different viewpoints of a house, including even repetitive texture, the relative orientation could be computed correctly, although with limited precision.

The ICP (iterative closest point) method does not require homologous points and performs the orientation of two scans, given approximate values of sufficient quality, entirely automatically. This is advantageous, because placing targets can be impossible, especially if the object is not accessible, additionally it can become time consuming. ICP has been suggested by Besl and McKay (1992) and variants are studied in (Rusinkiewicz and Levoy 2001). Much research effort is currently spent in order to automate finding approximate parameters for ICP. This leads to finding corresponding features as described above, possibly with lower quality requirements.

The authors believe that the registration task will run fully automatically for certain applications in some years. However, in the general case (including terrestrial scanning in a forest, etc.), or not relying on domain knowledge, the task will remain difficult. An alternative may come from cheap exterior orientation devices, allowing to obtain approximate exterior orientation, which can be used for reducing search spaces.

In order to transform one or multiple scans, generally one point cloud, into a superior coordinate system control points and/or patches are required. This control information can either be distributed in the scene or the coordinates of a laser scanner stand point can be observed, e.g. by centering over a known point or by mounting a GNSS antenna on top of the scanner. Deviation of the stand axis from the vertical, defined by the local gravity field, may be observed and corrected with an electronic spirit level (inclinometer). Such a device is built into many terrestrial laser scanners. Concerning the targets used for absolute orientation the same as mentioned for relative orientation applies.

3 GEOMETRICAL ASPECTS OF SIGNAL–OBJECT INTERACTION

In laser scanning backscattered energy is used for range measurement. If the backscattering surface is flat, reflecting diffusely, oriented orthogonal to the laser beam, reflection appearing only at the material top surface (i.e., there is no penetration of the incident energy into the material), and the surface is not too close to the scanner (especially in the case of bistatic systems)[4], the systems in use measure the quantity of interest. Furthermore, no other targets may be in the instantaneous field of view. In many cases in ALS and TLS these requirements do not hold.

- Depending on the echo detection method (Fox, Accetta, and Shumaker 1993; Katzenbeisser 2003; Jutzi and Stilla 2003b) used, the angle of incidence or surface roughness may have an impact on the range. For flat, slanted targets, discrete return systems that analyze the leading edge of the signal may report ranges shorter than the range to the beam center (Jutzi and Stilla 2003a). This effect is diminished for smaller footprints and shorter pulses.
- In TLS the dynamic range of the backscattered energy is quite high. This originates in the larger range spectrum of 1:100 to 1:1000 (e.g., minimum distance 2m, maximum distance 1km), and in the variety of backscattering surfaces, too. The surfaces reach from dark materials to retro reflective targets. Quantized in terms of Lambertian scatterers, the detectable reflected energy may vary from 5% to 1000%[5]. This results, using the laser range equation (Jelalian 1992), in return energies with a ratio of $1 : 10^9$. Effects depending on the intensity have been reported by many authors for terrestrial scanning (Hanke, Grussenmeyer, Grimm-Pitzinger, and Weinold 2006; Valanis and Tsakiri 2004). It is also reported that runway markers found on air-strips have caused similar effects in ALS.

  It shall be noted that most airborne and terrestrial systems require a measure of the return energy for applying a range correction. Some preliminary results on the relation between observed intensity and range (and between intensity and object reflectivity) for a pulse time of flight terrestrial laser scanner have been presented by Pfeifer, Dorninger, Haring, and Fan (2007).
- In TLS penetration of the energy into different materials is generally not very well studied. For marble surfaces and red light Godin et al. (2001) have demonstrated the effect. This effect can reach significant magnitude, in the order of millimeter, for close ranges, typically encountered for triangulating laser scanners and for phase-based range measuring laser scanners.
- In ALS the terrain and (vegetation) objects upon it are the object of interest, but often it is impossible to measure only one, either the ground or the vegetation. Low (herbaceous) vegetation offsets the ground measurements. While the cause is basically well understood, i.e. scattering at all objects within the footprint and multiple scattering, the amount and the influencing factors are not very well known. They can be reported for a specific experiment, but prediction is not possible yet. In any case, the effects are in the order of cm to dm.

  Ahokas, Kaartinen, and Hyyppä (2003) have reported systematic influences of grass on the measured range. Bollweg and de Lange (2003) reported systematic upward shifts for long dense grass. In (Oude Elberink and Crombaghs 2004) it is shown that upward shifts occurred up to 15cm on low vegetation areas (creeping red fescue, thrift). A relation could be seen between the density of the vegetation coverage and the systematic error: 0% coverage meant no upward shift, 100% coverage showed a 15cm shift. The study of (Hodgson and Bresnahan 2004) fits less well into that picture, as the systematic shifts reported are all very small, i.e. below 6cm. Pfeifer, Gorte, and Oude Elberink (2004) reported shifts of 7cm for long dense grass and 10cm for a young forest.

  Hopkinson et al. (2004) have correlated height of low vegetation with standard deviation of heights and other textural characteristics. Concentrating on the experiments over low vegetation (below 0.5m) the errors are comparatively large with respect to the vegetation height and a functional relationship is not obvious.

Contrary to the research efforts and solutions presented in the sections 2.1.2 and 2.2.2 (ALS and TLS calibration) these problems cannot be confined to the measurement system itself, but target properties have to be considered, too. Even when recording the full waveform of the backscattered echoes, not much information beyond spatial and absorption/scattering characteristics can be extracted. The echo width holds information on the range distribution within the footprint, but this is not necessarily connected to the discrepancy between ground elevation and systematically shortened range measurement. Thus, material properties can only be derived if additional knowledge is provided by external sources as imagery, maps, or possibly range information at another wavelength.

Phantom points, also called virtual points, also hinder automatic exploitation, especially in TLS data sets. These points are encountered, when the footprint is distributed over different, hard targets in close proximity[6]. The measured range is then between those two or more surfaces. First steps for automatic removal of these points were made (e.g. Sotoodeh (2006)) by analyzing the spatial distribution of points (without consideration of the scanner position). There is no reliable method available yet. Considering the geometry of the measurement setup can contribute in identifying these points, as they are aligned along bundles or rays with the origin in the laser scanner.

Furthermore, multi-path reflections can occur (not only in TLS, but also in ALS data), resulting in too long ranges. A typical situation is that a surface along the propagation path of the laser beam features (some) specular reflection onto another, diffusely reflecting surface. A portion of its diffuse backscatter travels via the specularly reflecting surface back to the detector. In (Lichti, Gordon, and Tipdecho 2005) an overview of errors in TLS, including the influence of geo-referencing and beam width, is given.

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[4] For bistatic (two-eyed) systems the emitter and receiver field of view overlap only after a certain distance.

[5] Lambertian scatterers have a maximum backscatter of 100% (no absorption), but retro-reflective material scatters back more energy into the direction of the source.

[6] For pulse time of flight systems this depends on the pulse duration, whereas phase-based systems are always affected.

We believe that the above items will continue to play a role. For natural surfaces, thus rather in the airborne case, the "range errors" induced change spatially, as the vegetation is not entirely homogeneous. Surfaces encountered in terrestrial scanning are often more homogenous, especially compared to the measurement density, and the "error" is more of systematic nature. Applications requiring higher precision will become possible when tackling and solving these problems.

4 DATA PROCESSING

The early steps of data processing, which are not directly linked to an application, are typically segmentation or clustering of the laser scanning point cloud, removal of erroneous points, and thinning.

Segmentation and clustering are means to organize points, measured by laser scanning, into homogeneous groups. Points of a group shall be neighbors, and in this way larger entities are generated and the data is organized on a higher level. A *classification* of such groups or sets is then in the domain of a certain application, which provides a "meaning", a class attribute (e.g. "house roof", "vegetation", or "tree") for each segment. In many publications segmentation is presented as one step for a certain application, e.g. building reconstruction. In this section we want to specifically concentrate on general purpose approaches.

Segmentation and clustering have been studied for a long time in image processing where the neighborhood of elements, i.e. pixel, is given implicitly by the matrix layout. For point clouds of laser scanning, on the other hand, neighborhood is often defined via Euclidean distance, TIN topology, or a number k defining the k nearest points as neighbors (kNN). An overview for neighborhood in ALS data is given in (Filin and Pfeifer 2005).

A general overview on segmentation algorithms is provided by (Hoover et al. 1996), and overviews dedicated to laser scanning data are given in (Vosselman, Gorte, Sithole, and Rabbani 2004) and (Geibel and Stilla 2000). Most often region growing from a seed point is applied (Vosselman, Gorte, Sithole, and Rabbani 2004) where the features used as similarity measure are

- height difference for airborne laser scanning data,
- normal vector similarity, or
- distance to a plane.

Differences and similarity may either be measured from the seed point to a currently investigated point, or from the previously accepted segment point to its new neighbors. The latter strategy allows to grow over bent surfaces, the first one not. These region growing approaches generally deliver smooth (gently curved) or planar (flat) regions.

The watershed transform is used to segment digital surface models, not point clouds, by a notably different approach. In forestry it is one standard method to extract the single trees from a canopy model. While most general purpose approaches are preformed on the point cloud, Vögtle and Steinle (2004) and Rottensteiner, Trinder, Clode, and Kubik (2005), for example, apply 2.5D techniques on gridded versions of the original data. This is only applicable for ALS data and reduces the range of extractable structures. Operating on the point cloud enables also the extraction of vertical planes or planes stacked on top of each other, thus the full 3D content of the data.

Clustering performs the grouping of point sets not in object space, but in a feature space. The features used may be an estimated normal vector for each point, a local roughness measure, the intensity measure, etc. The connectivity in object space is realized by adding the coordinates of the points as elements of the feature vector. Such approaches have been presented for laser point clouds by, e.g., Filin and Pfeifer (2006) and Melzer (2007).

The normal vector, a frequently used feature, is often estimated by computing an orthogonal regression plane. In this eigenvector/eigenvalue approach all three eigenvalues can be used to classify points as belonging to a surface, a volumetric distribution of points, a single point or a linear feature (Medioni, Lee, and Tang 2000). In (Belton and Lichti 2006) also the recognition of surface boundaries is discussed.

Voting schemes such as the Hough transform are hardly applied on large data sets. Their disadvantage is that connectivity is not considered. Such approaches are more typically used, if some organization of the entire point cloud into smaller entities has already been performed. Rabbani and van den Heuvel (2005), e.g., first apply segmentation based region growing, and then use a Hough transform to detect and reconstruct cylinders in the individual segments. von Hansen, Michaelsen, and Thonnessen (2006) apply the RANSAC algorithm (Fischler and Boller 1982) for detecting planes. In order to overcome the problem of connectivity, they first divide the space into larger 3D cells and apply RANSAC plane detection to the point cloud within the cell. Then a grouping step connects similar planes of neighboring cells.

There is a number of strategies to *reduce the volume* of the data. Modeling itself, especially model reconstruction with the help of analytical surfaces, can be seen as a means to reduce the data volume, and by fitting surfaces also a means of reducing noise. The same holds for the interpolation of a digital surface model (DSM) or a DTM by qualified interpolation methods that consider the stochastic properties of the data. Methods to decimate dense point clouds and reduce noise are given in (Pauly, Gross, and Kobbelt 2002). An overview on decimation of polygonal meshes is given in (Heckbert and Garland 1997).

Close range scanning systems based on the phase shift measurement principle are capable of producing very dense point clouds, e.g. 5 points per cm^2. The footprints of the laser beam on the object surface are then overlapping. It is therefore justified to reduce the volume of the data and also reduce the noise in the data in one step. According to the authors view there is currently a lack of studies that investigate these possibilities considering the properties of laser scanning data (next to noise e.g. measurement position, or missing points) and not treating the measurements as a set of discrete points.

5 DTM DETERMINATION FROM ALS DATA

During the ALS data acquisition process no interpretation or classification of the determined echoes, which were reflected from different objects, is performed. However, for the generation of a DTM the classification of the ALS data into terrain and off-terrain points is essential. This separation, which is important for other applications (e.g. vegetation and power line mapping), is often also entitled as "filtering".

In the past, many different solutions for the filtering of the ALS data were published (cf. Sithole and Vosselman (2004)). On one hand these methods can be classified by the input data they use (one type of methods uses rasterized ALS data while others use the original ALS point cloud) whereas on the other hand they can be grouped by the different concepts they use in order to classify the data. One group of algorithms are the morphological filters (e.g. Vosselman (2000)), which use a structure element, describing admissible height differences as a function of the horizontal distance. Another group are the progressive densification methods (Axelsson 2000; von Hansen and Vögtle 1999). They start with a rough approximation of the DTM with initial terrain points (typically the lowest point within a certain grid cell) and iteratively densify the DTM by the evaluation of a set of rules (e.g. maximal distance to the DTM approximation, angle criteria, etc.). The third group of filter methods work surface based (Kraus and Pfeifer 1998; Elmqvist, Jungert, Lantz, Persson, and Söderman 2001). They use a surface model that iteratively approaches the DTM calculated based on the entire point set by adapting the influence of the individual input points. Finally, recently a set of segmentation based methods were published (e.g. Sithole and Vosselman (2005) and Tóvari and Pfeifer (2005)). In the first step, these methods segment the ALS data with a local neighborhood analysis and subsequently classify the segments by different strategies. Most of the existing methods do not consider further input data (e.g. ortho photos) and only analyze the geometric relation between neighbored ALS points. A comparison of the performance of different methods can be found in (Sithole and Vosselman 2004).

Doneus and Briese (2006) studied the advanced possibilities for DTM generation using full-waveform ALS data. They used the echo width, which was determined with the help of a Gaussian decomposition of the full-waveform (FWF) signal for each echo (Wagner, Ullrich, Ducic, Melzer, and Studnicka 2006). The potential of this further information for the elimination of low vegetation could be demonstrated. With the help of a pre-filter step that eliminates echoes with a higher echo width a significant improvement of the DTM could be achieved. However, up to now it is not studied in detail how (and if) the additional FWF information can be used for advanced modeling tasks.

6 SUMMARY

In this paper an overview on data acquisition and the first processing steps was given for airborne and terrestrial laser scanning. There is a small number of standard products, e.g. the DTM, that are produced routinely and efficiently. In order to increase automation for other applications, further development of the first processing steps, especially registration, segmentation, and error/outlier removal, is necessary. For calibration, geometric and physical aspects will have to be considered simultaneously. Also the application-specific approaches are still matter of research, e.g. building reconstruction. The hardware development in the recent years has been fast, considering for example the increase in pulse repetition rate. However, the success rate in object reconstruction did not grow linearly with it. Therefore, most research effort will have to be spend in these application specific fields.

REFERENCES

IAPRS= International Archives of Photogrammetry and Remote Sensing

Conf. on O3D= Conference on Optical 3-D Measurement Techniques

3rdTech, 2007. www.3rdtech.com. Homepage of the company 3rdTech, accessed: June 2007.

Abmayr, T., Dalton, G., Hines, D., Liu, R., Härtl, F., Hirzinger, G., and Fröhlich, C., 2005. Standardization and visualization of 2.5d scanning data and color information by inverse mapping. In: Gruen and Kahmen (Eds.), *7th Conf. on O3D*, Vienna, Austria, pp. 164–173.

Ahokas, E., Kaartinen, H., and Hyyppä, J., 2003. A quality assessment of airborne laser scanner data. In: *IAPRS, XXXIV, 3/W13*, Dresden, Germany.

Ahokas, E., Kaasalainen, S., Hyyppä, J., and Suomalainen, J., 2006. Calibration of the Optech ALTM 3100 laser scanner intensity data using brightness targets. In: *IAPRS, XXXVI, 1*, Paris, France.

Al-Manasir, K. and Fraser, C., 2006. Registration of terrestrial laser scanner data using imagery. *The Photogrammetric Record 21*(115), 255–268.

Axelsson, P., 2000. DEM generation from laser scanner data using adaptive TIN models. In: *IAPRS, XXXIII, B4*, Amsterdam, Netherlands, pp. 111–118.

Behan, Maas, and Vosselman, 2000. Steps towards quality improvement of airborne laser scanner data. In: *Proceedings of the 26th annual conference of the Remote Sensing Society*, Leicester, UK.

Belton, D. and Lichti, D., 2006. Classification and segmentation of terrestrial laserscanner point clouds using local variance information. In: *IAPRS, XXXVI, 5*, Dresden, Germany.

Beraldin, J.-A., El-Hakim, S., and Blais, F., 2007. Traceable 3d imaging metrology: evaluation of 3d digitizing techniques and commercial 3d systems/scanners in a dedicated metrology laboratory. In: *8th Conf. on O3D*, Zurich, Switzerland.

Besl, P. and McKay, N., 1992. A method for registration of 3D shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence 14*(2), 239 – 256.

Blais, F., 2004. Review of 20 years of range sensor development. *Journal of Electronic Imaging 13*(1), 231–240.

Böhm, J. and Becker, S., 2007. Automatic marker-free registration of terrestrial laser scans using reflectance features. In: *8th Conf. on O3D*, Zurich, Switzerland.

Bollweg, A. and de Lange, R., 2003. Wat ruist er door het struikgewas. Technical Report AGI-GAR-2003-22 (in Dutch), Adviesdienst Geo-Informatie en ICT, Rijkswaterstaat, The Netherlands.

Brenner, C., Dold, C., and Ripperda, N., 2007. Coarse orientation of terrestrial laser scans in urban environments. *ISPRS Journal of Photogrammetry and Remote Sensing*. Accepted for publication.

Breuckmann, B., Rein, H., Pfeifer, J., and Mutsch, J., 2007. Acceptance test of topometric 3d-scanners: experiences with the guideline vdi/vde 2634. In: *8th Conf. on O3D*, Zurich, Switzerland.

Burman, H., 2000. Adjustment of laserscanner data for correction of orientation errors. In: *IAPRS, XXXIII, B3/1*, Amsterdam, The Netherlands, pp. 125–132.

Burman, H., 2002. Laser strip adjustment for data calibration and verification. In: *IAPRS, XXXIV, 3*, Graz, Austria, pp. 67–72.

Callidus, 2007. www.trimble.com. Homepage of the company CALLIDUS precision systems GmbH, accessed: June 2007.

Crombaghs, M., Brügelmann, R., and de Min, E., 2000. On the adjustment of overlapping strips of laseraltimeter height data. In: *IAPRS, XXXIII, 3A*, Amsterdam, Netherlands, pp. 230–237.

Csanyi, N. and Toth, C., 2007. Improvement of lidar data accuracy using lidar-specific ground targets. *Photogrammetric Engineering & Remote Sensing 73*(4), 385–396.

Diamond Airborne Sensing, 2007. www.diamond-air.at. Homepage of the company Diamond Aircraft, accessed: August 2007, in German.

Dold, C. and Brenner, C., 2006. Registration of terrestrial laser scanning data using planar patches and image data. In: *IAPRS, XXXVI, 5*, Dresden, Germany, pp. 78–83.

Doneus, M. and Briese, C., 2006. Digital terrain modelling for archaeological interpretation within forested areas using full-waveform laserscanning. In: *The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST*, Zypern.

Ellum, C. and El Sheimy, N., 2006. New strategies for integrating photogrammetric and GNSS data. In: *IAPRS, XXXVI/5*, Dresden, Germany, pp. 103–108.

Elmqvist, M., Jungert, E., Lantz, F., Persson, A., and Söderman, U., 2001. Terrain modelling and analysis using laser scanner data. In: *IAPRS, XXXIV, 3/W4*, Annapolis, MD, USA.

Faro, 2007. www.faro.com. Homepage of the company FARO Technologies, Inc., accessed: June 2007.

Filin, S., 2002. Surface clustering from airborne laser scanning data. In: *IAPRS, XXXII, 3A*, Graz, Austria, pp. 119–124.

Filin, S., 2003. Recovery of systematic biases in laser altimetry data using natural surfaces. *Photogrammetric Engineering & Remote Sensing 69*(11), 1235–1242.

Filin, S. and Pfeifer, N., 2005. Neighborhood systems for airborne laser data. *Photogrammetric Engineering & Remote Sensing 71*(6), 743–755.

Filin, S. and Pfeifer, N., 2006. Segmentation of airborne laser scanning data using a slope adaptive neighborhood. *ISPRS Journal of Photogrammetry and Remote Sensing 60*(2), 71–80.

Finnegan, D. C., Krabill, W., Lichvar, R. W., Ericsson, M. P., Frederick, E., Manizade, S., Yungel, J., Sonntag, J., and Swift, R., 2005. Using NASA‘s Airborne Topographic Mapper IV to Quantify Geomorphic Change in Arid Southwestern Stream Systems. In: *AGU Fall Meeting Abstracts*.

Fischler, M. A. and Boller, R. C., 1982. Random sample consensus: A paradigm for model fitting with applications to image analysis and automated cartography. *Communications of the ACM 24*(6), 381–395.

Fli-Map, 2007. www.flimap.nl. Homepage of FLI-MAP, accessed: August 2007.

Flood, M. and Gutelius, B., 1997. Commercial implications of topographic terrain mapping using scanning airborne laser radar. *Photogrammetric Engineering & Remote Sensing 63*, 327–365.

Fox, C. S., Accetta, J. S., and Shumaker, D. L., 1993. *Active Electro-Optical Systems*, Volume 6 of *The infrared and electro-optical systems handbook*. SPIE Optical Engineering Press.

Geibel, R. and Stilla, U., 2000. Segmentation of laser altimetry data for building reconstruction : different procedures and comparison. In: *IAPRS, XXXIII, B3*, Amsterdam, the Netherlands, pp. 326–334.

GIM, 2007. www.gim-international.com/productsurvey. Product surveys of GIM international, accessed: August 2007.

Godin, Rioux, Beraldin, Levoy, Cournoyer, and Blais, 2001. An assessment of laser range measurement on marble surfaces. In: *5th Conf. on O3D*, Vienna, Austria.

Hanke, K., Grussenmeyer, P., Grimm-Pitzinger, A., and Weinold, T., 2006. First experiences with the trimble gx scanner. In: *IAPRS, XXXVI, 5*, Dresden, Germany.

Heckbert, P. S. and Garland, M., 1997. Survey of polygonal surface simplification algorithms. Technical report, School of Computer Science, Carnegie Mellon University, Pittsburgh, PA. Technical Report.

Hesse, C., Neuner, H., and Kutterer, H., 2005. Statistical analysis of kinematic lasers scans. In: *7th Conf. on O3D*, Vienna, Austria, pp. 103–112.

Hodgson, M. E. and Bresnahan, P., 2004. Accuracy of airborne lidar-derived elevation: Empirical assessment and error budget. *Photogrammetric Engineering & Remote Sensing 70*(3), 331–339.

Höfle, B. and Pfeifer, N., 2007. Correction of laser scanning intensity data: Data and model-driven approaches. *ISPRS Journal of Photogrammetry and Remote Sensing*. Accepted for publication.

Hoover, Jean-Baptiste, Jiang, Flynn, Bunke, Goldgof, Bowyer, Eggert, Fitzgibbon, and Fisher, 1996. An experimental comparison of range image segmentation algorithms. *IEEE Transactions on Pattern Analysis and Machine Intelligence 18*(7), 673–689.

Hopkinson, D., Chasmer, L., Zsigovics, G., Creed, I., Sitar, M., Treitz, P., and Maher, R., 2004. Errors in lidar ground elevation and wetland vegetation height estimates. In: *IAPRS, XXXVI, 8/W2*, Freiburg, Germany.

Horn, B., 1987. Closed-form solution of absolute orientation using unit quaternions. *Journal of the Opical Socienty of America A 4*, 629–642.

Hug, C. and Wehr, A., 1997. Detecting and identifying topographic objects in imaging laser altimetry data. In: *IAPRS, XXXII, 4/W2*, pp. 16–29.

Hyyppä, J., Hyyppä, H., Litkey, P., Yu, X., Haggren, H., Roennholm, P., Pyysalo, U., Pitkaenen, J., and Maltamo, M., 2004. Algorithms and methods of airborne laser-scanning for forest measurements. In: *IAPRS, XXXVI, 8/W2*, Freiburg, Germany.

I-SiTE, 2007. www.isite3d.com. Homepage of the company I-SiTE Pty Ltd, accessed: June 2007.

Jelalian, A. V., 1992. *Laser Radar Systems*. Artech House, Boston.

Jutzi, B. and Stilla, U., 2003a. Analysis of laser pulses for gaining surface features of urban objects. In: *2nd GRSS/ISPRS Joint Workshop on Remote Sensing and data fusion on urban areas. URBAN 2003, IEEE*, pp. 13–17.

Jutzi, B. and Stilla, U., 2003b. Laser pulses analysis for reconstruction and classification of urban objects. In: *IAPRS, XXXIV, 3/W8*, Munich, Germany, pp. 151–156.

Kager, H., 2004. Discrepancies between overlapping laser scanning strips - simultaneous fitting of aerial laser scanner strips. In: *IAPRS, XXXV, B/1*, Istanbul, Turkey, pp. 555–560.

Karimi, H. A. and Hammad, A., 2004. *Telegeoinformatics: location-based services and computing*. CRC Press, Boca Raton.

Katzenbeisser, R., 2003. Technical note on: Echo detection. TopoSys GmbH, Germany.

Kilian, J., Haala, N., and Englich, M., 1996. Capture and evaluation of airborne laser scanner data. In: *IAPRS, XXXI, B3*, Vienna, Austria, pp. 383–388.

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

Kraus, K. and Pfeifer, N., 2001. Advanced DTM generation from LIDAR data. In: *IAPRS, XXXIV, 3/W4*, Annapolis, MD, USA, pp. 23–30.

Latypov, D., 2005. Effects of laser beam alignment tolerance on lidar accuracy. *ISPRS Journal of Photogrammetry and Remote Sensing 59*(6), 361–368.

Leica, 2007. www.leica-geosystems.com. Homepage of the company Leica Geosystems, accessed: August 2007.

Lichti, D., 2007. Error modelling, calibration and analysis of an amcw terrestrial laser scanner system. *ISPRS Journal of Photogrammetry and Remote Sensing 61*(5), 307–324.

Lichti, D., Gordon, S., and Tipdecho, T., 2005. Error models and propagation in directly georeferenced terrestrial laser scanner networks. *Journal of Surveying Engineering 131*(4), 135–142.

Lin, 1997. Waveform sampling lidar applications in complex terrain. *International Journal of Remote Sensing 18*(10).

Lindenberger, 1989. Test results of laser profiling for topographic terrain survey. Technical Report 13, Institute of Photogrammetry, University of Stuttgart.

Lindenberger, J., 1993. *Laser-Profilmessungen zur topographischen Geländeaufnahme*. Ph. D. thesis, University Stuttgart, Institute of Photogrammetry.

Lohr, U. and Eibert, 1995. The toposys laser scanner-system. In: Fritsch and Hobbie (Eds.), *Photogrammetric Week*.

Lowe, D. G., 2004. Distinctive image features from scale-invariant keypoints. *International Journal of Computer Vision 60*(2), 91–110.

Medioni, G., Lee, M.-S., and Tang, C.-K., 2000. *A computational framework for segmentation and grouping*. Elsevier, Amsterdam.

Melzer, T., 2007. The mean shift algorithm for clustering point clouds. *Journal of Applied Geodesy*. Accepted for publication.

Naesset, E., 1997. Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing 52*(2), 49–56.

Optech, 2007. www.optech.ca. Homepage of the company Optech, accessed: June 2007.

Oude Elberink, S. and Crombaghs, M., 2004. Laseraltimetrie voor de hoogtemetingen van de kwelders Waddenzee. Technical Report AGI-GAP-2003-50 (in Dutch), Adviesdienst Geo-Informatie en ICT, Rijkswaterstaat, The Netherlands.

Parian, J. A. and Gruen, A., 2005. Integrated laser scanner and intensity image calibration and accuracy assessment. In: *IAPRS, XXXVI, 3/W19*, Enschede, the Netherlands, pp. 18–23.

Pauly, M., Gross, M., and Kobbelt, L., 2002. Efficient simplification of point-sampled surfaces. In: *Proceedings of the conference on Visualization '02*, Boston, Massachusetts, pp. 163–170. IEEE Computer Society.

Pfeifer, N., Dorninger, P., Haring, A., and Fan, H., 2007. Investigating terrestrial laser scanning intensity data: Quality and functional relations. In: *8th Conf. on O3D*, Zurich, Switzerland.

Pfeifer, N., Gorte, B., and Oude Elberink, S., 2004. Influences of vegetation on laser altimetry – analysis and correction approaches. In: *IAPRS, XXXVI, 8/W2*, Freiburg, Germany, pp. 283–287.

POB, 2007. www.pobonline.com. Product surveys of Point of Beginning, accessed: August 2007.

Rabbani, T., Dijkman, S., van den Heuvel, F., and Vosselman, G., 2007. An integrated approach for modelling and global registration of point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing 61*, 355–370.

Rabbani, T. and van den Heuvel, F., 2005. Efficient hough transform for automatic detection of cylinders in point clouds. In: *IAPRS, XXXVI, 3/W19*, Enschede, the Netherlands, pp. 60–65.

Reed and Lynch, 1996. Near field airborne remote sensing using a laser mapping system on electric transmission line corridor surveys and capacity analyses. In: *International Airborne Remote Sensing Conference and Exhibition – Technology, Measurement & Analysis*, San Francisco, USA.

Reshetyuk, Y., 2006. Calibration of terrestrial laser scanners for the purposes of geodetic engineering. In: *3rd IAG Symposium on Geodesy for Geotechnical and Structural Engineering and 12th FIG Symposium on Deformation Measurements*, Baden, Austria.

Riegl, 2007. www.riegl.com. Homepage of the company RIEGL Laser Measurement Systems GmbH, accessed: August 2007.

Ries, C., Kager, H., and Stadler, P., 2002. High-quality geo-referencing of GPS/IMU-supported multi-spectral airborne scanner data - experiences and results. In: *IAPRS, XXXIV/3*, Graz, Austria, pp. 222–226.

Ritchie and Pachepsky, 1998. Seasonal changes in fractal landscape surface roughness estimted from airborne laser altimetry data. *International Journal of Remote Sensing 19*(13).

Rottensteiner, F., Trinder, J., Clode, S., and Kubik, K., 2005. Automated delineation of roof planes from lidar data. In: *IAPRS, XXXVI, 3/W19*, Enschede, the Netherlands.

Rueger, J., 1990. *Electronic Distance Measurement: an introduction* (3 ed.). Springer-Verlag, Heidelberg, Germany.

Rusinkiewicz, S. and Levoy, M., 2001. Efficient variants of the icp algorithm. In: *Third International Conference on 3-D Digital Imaging and Modeling (3DIM '01)*, Los Alamitos, CA, USA, pp. 145.

Schmitz, Wuebbena, Bagge, and Kruck, 2001. Benefit of rigorous modelling of gps in combined at/gps/imu-bundle block adjustment. In: *OEEPE Workshop*, Hannover, Germany.

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

Sithole, G. and Vosselman, G., 2005. Filtering of airborne laser scanner data based on segmented point clouds. In: *IAPRS, XXXVI, 3/W19*, Enschede, The Netherlands, pp. 66–71.

Skaloud, J., 2006. Reliability of direct georeferencing phase 0 – an overview of current approaches and possiblities. In: *EuroSDR Official Publication 51*, pp. 143–168.

Skaloud, J. and Lichti, D., 2006. Rigorous approach to boresight self-calibration in airborne laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing 61*(1), 47–59.

Sotoodeh, S., 2006. Outlier detection in laserscanner point clouds. In: *IAPRS, XXXVI, 5*, Dresden, Germany.

TopEye, 2007. www.blomasa.com. Homepage of the BLOM GROUP, accessed: Augsut 2007.

TopoSys, 2007. www.toposys.com. Homepage of the company TopoSys GmbH, accessed: June 2007.

Tóvari, D. and Pfeifer, N., 2005. Segmentation based robust interpolation - a new approach to laser data filtering. In: *IAPRS, XXXVI, 3/W19*, Enschede, The Netherlands, pp. 79–84.

Trimble, 2007. www.trimble.com/. Homepage of the company Trimble, accessed: June 2007.

Valanis, A. and Tsakiri, M., 2004. Automatic target identification for laser scanners. In: *Proceedings of XXth ISPRS Congress*, Istanbul, Turkey.

Vögtle, T. and Steinle, 2004. Detection and recognition of changes in building geometry derived from multitemporal laserscanning data. In: *IAPRS, XXXV*, Istanbul, Turkey.

von Hansen, W., Michaelsen, E., and Thonnessen, U., 2006. Cluster analysis and priority sorting in huge point clouds for building reconstruction. In: *18th International Conference on Pattern Recognition (ICPR'06)*, pp. 23–26.

von Hansen, W. and Vögtle, T., 1999. Extraktion der Geländeoberfläche aus flugzeuggetragenen Laserscanner–Aufnahmen. *Photogrammetrie Fernerkundung Geoinformation 4*, 229–236.

Vosselman, G., 2000. Slope based filtering of laser altimetry data. In: *IAPRS, XXXIII, B3*, Amsterdam, Netherlands, pp. 935–942.

Vosselman, G., Gorte, B. G. H., Sithole, G., and Rabbani, T., 2004. Recognising structure in laser scanner point clouds. In: *IAPRS, XXXVI, 8/W2*, Freiburg, Germany.

Vosselman, G. and Maas, H.-G., 2001. Adjustment and filtering of raw laser altimetry data. In: *Proceedings of OEEPE Workshop on Airborne Laserscanning and Interferometric SAR for Detailed Digital Terrain Models*, Stockholm, Sweden.

Wagner, W., Ullrich, A., Ducic, V., Melzer, T., and Studnicka, N., 2006. Gaussian decomposition and calibration of a novel small-footprint full-waveform digitising airborne laser scanner. *ISPRS Journal of Photogrammetry and Remote Sensing 60*(2), 100–112.

Wagner, W., Ullrich, A., Melzer, T., Briese, C., and Kraus, K., 2004. From single-pulse to full-waveform airborne laser scanners: potential and practical challenges. In: *IAPRS, XXXV*, Istanbul, Turkey.

Wehr, A., Hemmleb, M., Thomas, M., and Maierhofer, C., 2007. Moisture detection on building surfaces by multi-spectral laser scanning. In: *8th Conf. on O3D*, Zurich, Switzerland.

Wehr, A., Kleusberg, A., and Schiele, O., 2006. CW-laser-scanning state-of-the-art at INS and future multispectral sensors. In: L. Gruendig and O. Altan (Eds.), *Turkish-German Joint Geodetic Days "Geodesy and Geoinformation in the Service of our Daily Life"*, Berlin, Germany.

Wehr, A. and Lohr, U., 1999. Airborne laser scanning an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing 54*(2-3), 68–82.

Zoller+Fröhlich, 2007. www.zofre.de. Homepage of the company Zoller+Fröhlich GmbH, accessed: June 2007.

Zwally, H., Schutz, B., Abdalati, Abshire, Bentley, Brenner, Bufton, Dezio, Hancock, Harding, Herring, Minster, Quinn, Palm, Spinhirne, and Thomas, 2002. Icesat's laser measurements of polar ice, atmosphere, ocean, and land. *Journal of Geodynamics 34*(3), 405–445.