УДК 681.7.055:621.375.826

Norbert Pfeifer, Christian Briese
Vienna University of Technology
Institute of Photogrammetry and Remote Sensing, Austria

LASER SCANNING – PRINCIPLES AND APPLICATIONS

SUMMARY

In this overview paper the principles of laser scanning systems are presented. This includes a survey of different range measurement principles as well as different mechanisms for the deflection of the emitted laser beam. Furthermore, the usage of the laser scanning (LS) principle at different platforms (airborne (ALS), terrestrial (TLS), satellite) is discussed. Additionally, typical sensor parameters of currently commercially available sensor systems are presented. Furthermore, the technique of full-waveform LS is introduced and georeferencing of ALS data for improved precision is presented. The usage of LS data in different applications will be presented in an overview.

ZUSAMMENFASSUNG

Dieser Überblicksartikel präsentiert die Grundprinzipien des Laserscannings und beinhaltet neben einer Übersicht über die unterschiedlichen Entfernungsmessprinzipen auch einen Überblick über die verschieden Strahlablenkmechanismen. Weiters wird auf die Verwendung des Laserscanning Prinzips auf unterschiedlichen Plattformen (Flugzeuggetragenes (Airborne) Laserscanning (ALS), Terrestrisches Laserscanning (TLS)) eingegangen und es werden typische Sensorparameter von im Moment kommerziell verfügbaren Systemen zusammengefasst. Der Artikel beinhaltet außerdem eine Vorstellung des full-waveform Laserscannings und geht auch auf die Thematik der Georeferenzierung der ALS und TLS Daten ein. Am Ende des Artikels folgt ein Überblick über unterschiedliche Anwendungsgebiete des Laserscannings.

АННОТАЦИЯ

В статье представлены принципы работы систем лазерного сканирования. Дается краткий обзор различных методов измерения расстояний, а также устройств для отклонения излучаемого лазерного луча. Кроме того, обсуждаются принципы использования лазерного сканирования на различных платформах (бортовой, наземной и спутниковой). Приведены также стандартные параметры современных, промышленно выпускаемых сенсоров. Описывается методика двухволнового лазерного сканирования и геопространственной привязки данных воздушного лазерного сканирования улучшенной точности. Рассмотрены различные области применения данных лазерного сканирования.

Key words: Laser scanning, Range Measurement, LiDAR

1. INTRODUCTION

Automated restitution methods for object acquisition have gained more and more importance in the last years. Next to automatic image matching, laser scanning, often also referred to as LiDAR (light detection and ranging), has revolutionized 3D data acquisition for both, topographic as well as close range objects. In contrast to the "classical" manual data acquisition techniques, like terrestrial surveying and analytical photogrammetry, which require a manual interpretation in order to derive a representation of the sensed objects, these new automatic recording methods allow an automated dense sampling of the object surface within a short time.

Laser scanning is a prosperous data acquisition method with rapid development since the mid 1990ies. It is suitable for measurement volumes below $1m^3$ up to areas of hundreds and thousands of km^2. In this sense it falls well within the realm of photogrammetry.

Photographic images record passive solar or artificial radiation backscattered by objects in the camera's field of view. The backscatter strength is typically resolved i), spatially, by pixels in the image plane, ii) chromatically, by recording in different wavelength bands, and iii) radiometrically, by quantizing the photo current with typically eight to twelve Bit. Laser scanning, as it will be detailed later on, achieves the spatial resolution by scanning the instantaneous field of view with the help of mechanical devices, e.g. a moving mirror, over the entire field of view. Concerning the chromatic aspect the differences are larger. The backscatter is recorded for one wavelength only, i.e., monochromatically. Additionally, not passive radiation is used for the measurement, but the backscatter of laser energy emitted by the sensor system itself. The most notable difference is, however, that the time lag between emission of a laser beam and detection of its backscattered echo is measured. With the group velocity of the light, the light speed in the atmosphere, the time difference can be transformed to the range between emitter and detector. Both, photographs and the recorded echoes of laser beams, are impaired – to a small extent only – by ambient light, i.e. energy not originating from the location of the specific sensed objects but stray light. Photographs record texture and colour, laser scanning measures primarily ranges but also monochromatic reflectance. In both cases, however, data is acquired area-wise in a systematic manner. Recording of electromagnetic radiation, by a map (ping) that generates an image of object space, is the basis for both. In such an image, measurements can be performed automatically or manually.

This paper will first discuss the different range measurement principles used in laser scanning. This will be augmented by an overview of beam deflection mechanisms. Typical parameters of currently available systems are listed as well. The next section is devoted to the exterior orientation of the laser scanner device. Finally, a number of applications for both, airborne and terrestrial laser scanning systems are presented including data processing aspects.

The authors are well aware, that overview papers on laser scanning have been written before (Wehr and Lohr, 1999a), that this topic is covered in photogrammetric text books (Kraus, 2004), and that journal editions are devoted to that subject (Wehr and Lohr, 1999b). The rapid development on the one hand, and the integrated overview on both, airborne and terrestrial laser scanning, on the other hand, allow the attempt to give a broad, yet concise overview on this interesting technique.

2. LASER SCANNING PRINCIPLES

As defined by Böhler and Marbs (2002), a laser scanner uses laser light to measure distances from the sensor to the object in a systematic pattern. The distance measurement aspect, i.e. the ranging, relies on laser light for performing that measurement (Sec. 2.1). The range measurement themselves are acquired in a pattern by deflecting the strongly collimated laser energy, i.e. the beam, in different directions (Sec. 2,2).

2.1 Laser Range Finding

Different principles can be used to measure the distance between sensor system and target. They differ in precision but all have their justification for a certain range envelope. The largest ranges can be probed using the pulse round trip time measurement principle, obtaining cm-accuracy. Shorter distances, e.g. up to 100m, can be measured faster and more accurate with the phased based measurement technique. Shorter distances, e.g. up to 2m, can be measured with even higher precision, e.g. accuracy better than ±1mm, with triangulation. A concise overview on range measurements is given in Rueger (1990). Laser RADAR (radio detection and ranging) is extensively treated in Jelalian (1991). The different ranging principles will be detailed in the following with “pulse round trip” first, also including aspects applying to all laser ranging principles.

Pulse round trip time

For pulse round trip measurements a pulse of laser energy is emitted, typically using a solid state or semi-conductor laser. This pulse has typically a duration of a few nanoseconds, most often specified for the FWHM (full width half maximum) of the pulse). A pulse duration of 5ns corresponds to a length of 1.5m, as the speed of light is approximately $3 \cdot 10^8 \mathrm{ms}^{-1}$. Often the pulse is assumed to have Gaussian shape, which is more realistic than a rectangular pulse shape (see Figure 1, middle). The pulse is not only distributed in time, but also in space perpendicular to the propagation direction. Again, the energy distribution is often assumed to be of circular symmetric Gaussian type, and the beam diameter is given by those point where the energy drops to $1/e^2$ (or 1/e, depending on the definition in use) of the maximum energy. However, elliptic Gaussian and more irregular energy distributions have been remarked (Abshire, 2005), whereas Jutzi and Stilla (2006) report experiments where the lateral energy distribution corresponds more to a pill box function, i.e. a circular symmetric energy distribution with a step edge from maximum to zero energy. The beam diameter expands with distance from the sensor, and for larger distances from the emitter, the diameter is given as $\gamma \cdot r$, where r is the range and γ the so-called beam divergence. Values of γ cannot be made arbitrarily small due to limits caused by the diffraction of light (Young, 2000).

The emitted beam travels through the atmosphere and interacts with objects along its path. Reflection and absorption at atoms, molecules and aerosol occurs and detecting their backscatter gives rise to laser remote sensing of the atmosphere (Weitkamp, 2006), which will not be treated here. For applications in photogrammetry the interaction with targets as natural and man-made surfaces is of interest. The energy package can be absorbed or reflected. If it is reflected it can be reflected specular, i.e. mirror-like, or diffuse, e.g. as a Lambertian reflector, or in a mixture of all (Rees, 2001). The backscattered energy that travels the same path backwards, from the reflecting surface to the sensor system, is detected by a system comprising a narrow optical filter and an avalange photo diode. Upon emission of the beam a time counter is started and it is stopped upon receiving the echo (Figure 1, left). If the time interval is Δt, and the average group velocity of light along the path from sensor to object is c_g, the range

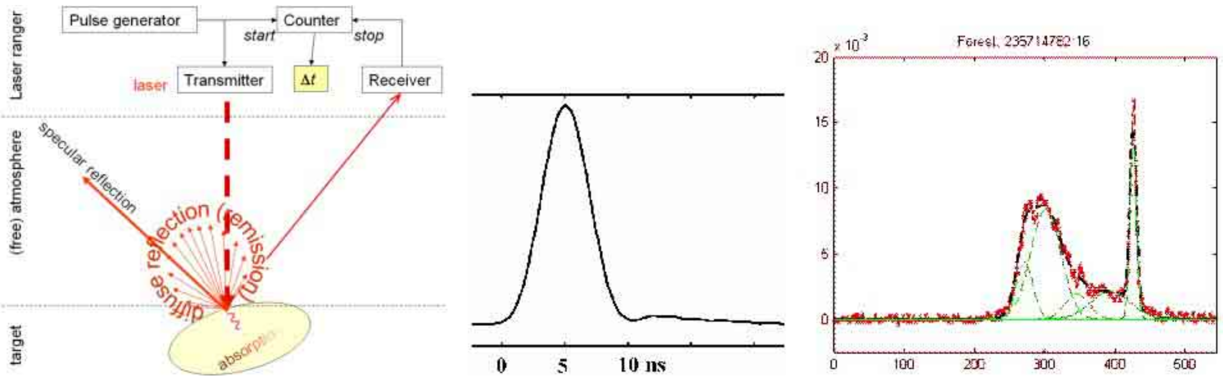

Figure 1 – Left: Principle of a pulse laser ranger. Middle: Shape of a pulse emitted by a Riegl LMS-Q560 laser scanner, from Wagner et al (2006). Right: Backscattered and recorded echo of a laser pulse emitted over a forest by GLAS (Geoscience Laser Altimeter System on board the satellite ICESat), from Van Duong et al (2006). The horizontal axis in both images shows nanoseconds.

$$r = c_g \cdot \Delta t / 2.$$

The strength of the backscatter may be recorded as well, resulting in the so-called "intensity"-value which is given as a digital number. However, typically it is proportional to, or at least growing with, the maximum or average power of the backscatter.

It is not necessarily the case that the entire beam is scattered back from one surface only. In vegetation, e.g., but also at building edges, etc., parts of the energy are reflected earlier, giving rise to the first echo. In vegetation this occurs typically at the tree crown. Parts of the energy can be reflected at intermediate heights, so-called, 2nd, 3rd, etc. echo, and the last energy packet received at the detector is called "last echo". In airborne operation the last echo does not necessarily correspond to the ground, not even over vegetation, as all the energy may be backscattered before reaching the ground. In open areas only one echo is detected, at the edges of bridges, two echoes can be detected, and detection of first, last and intermediate echoes can occur in vegetation. In order to separate these echoes, their spatial distance must be larger than the pulse width. A theoretical lower limit is given by half the pulse length, corresponding to the factor 1/2 given before.

The number of pulses emitted per second, the pulse repetition rate (PRR), is currently 200000 for airborne operation, i.e. PRR=200kHz, and about a factor ten lower for terrestrial operation. With higher pulse rates the emitted energy is lower, setting an upper bound to the maximum range to be measured. Most systems have an additional maximum range under which they can operate, which is given by $c_g/(2 \cdot \mathrm{PRR})$, i.e. only one pulse may travel through the air at once. Not all systems advertised fall under that restriction however.

So far, discrete return systems have been described. From the returning echoes ranges are extracted and stored. Advanced systems record the waveform of the returning echo, i.e. the time-dependent variation of signal power (Figure 1, right, Van Duong et al, 2006). With these full waveform systems it is possible to extract more information. Firstly, different echo detection algorithms can be used to analyze the signal (Jutzi and Stilla, 2005) in post-processing. It may be possible to dissolve two echoes which are closer together than half the pulse length but applying algorithms which are more powerful than electronic analysis. Additionally, the cross section of each target, i.e. each surface generating an echo, can be computed (Wagner et al, 2006). The cross section is basically a product of target reflectivity and spatial extent. It is the highest level of information that can be extracted from the echo without additional assumption on the target (e.g. Lambertian scattering characteristics).

The ranging accuracy depends primarily on the time measurement accuracy and the accuracy of detecting the backscattered echo. Under favourable circumstances cm-precision can be achieved, but for distances larger than 1km ranging precision is rather in the order of a few centimetre. Increase in precision can be achieved by repeating a measurement a number of times. Increases in range and precision can be achieved by increasing the emitted power, as the signal to noise ratio raises. However, systematic errors prevent reaching arbitrarily high precision with this technique. In airborne operation the laser scanners can range up to three or even five kilometres. In experiments performed by NASA (Bufton, 1989) ranging from 20km height were conducted successfully. Currently ICESat is orbiting around earth, performing nadir-looking range measurements to the earth surface. Terrestrial systems have typically lower maximum ranges, also because of eye-safety issues.

The “intensity” values recorded by laser scanning measurement have hardly been used so far. They are subject to many influences such as spreading loss, surface roughness, object reflectivity, and atmospheric attenuation. Therefore, they have been used for visualization purposes mainly (Figure 2). Normalization of these measurements is described in Wagner et al (2006) and Höfle and Pfeifer (2007). The expectation is that these normalized values are suitable for classification purposes.

Figure 2 – Example of one (part of an) airborne laser scanning strip showing the recorded intensity values. Data courtesy of EuroSDR.

Phase shift measurement

Higher precision, in the domain of millimetres, and higher measurement rates, can be obtained applying the phase shift measurement principle. A c/w (continuous wave) laser is used as the carrier for a signal modulated onto it, typically using amplitude modulation. The phase of the emitted and the received signal are compared. The relation between phase difference, Δφ given in radians, and the one-way range is:

$$r = \Delta\varphi/(2\cdot\pi)\cdot\lambda/2 + \lambda/2\cdot n,$$

where λ is the wavelength in meter and n is the unknown number of full wavelengths between the sensor system and the reflecting object surface. Choosing, e.g., λ=100m, means that there is a unique measurement range of 50m. All measurements to objects further away will be folded into the first 50m interval. The precision of the measurement is in the order of one percent of the phase and can even be better. With the values from above this would result in a measurement precision of ±50cm. This problem can be solved by using more than one modulation wavelength, i.e. two or three wavelengths (Figure 3). Then, the longest wavelength defines the uniqueness range and the shortest wavelength defines the precision that can be obtained.

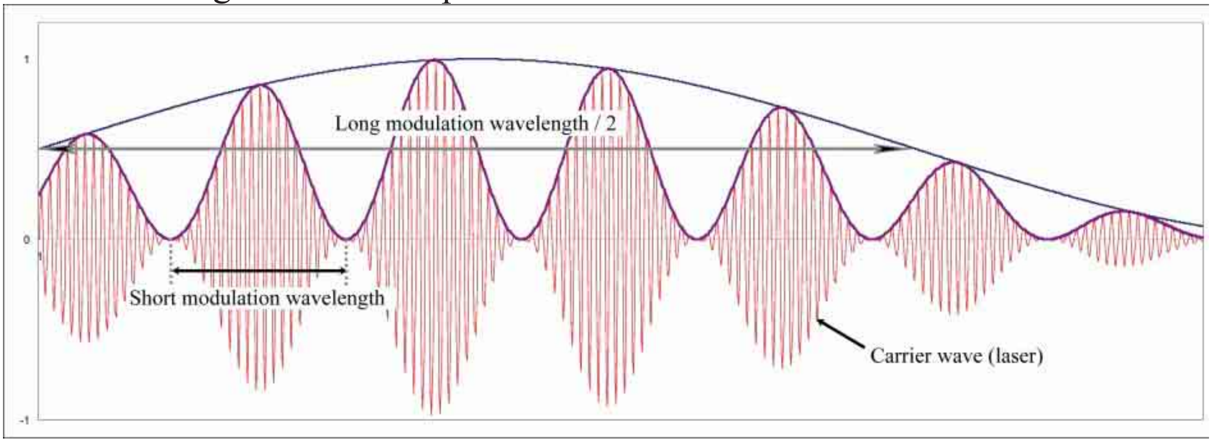

Figure 3 – Schematic drawing of two modulation wavelengths and carrier wave for phase-based laser ranging.

Due to the range limitation this measurement system is primarily of interest for terrestrial laser scanners, but in (Hug and Wehr, 1997) also the usage in airborne operation has been demonstrated. Current systems offer a measurement rate of 500kHz and more. Precision is in the order of ±1mm. The differences in terrestrial scanners between pulse round trip time scanners and phase based difference measurement scanners are therefore: higher range for "pulse round trip" and higher measurement speeds and better precision for "phase based" laser scanners. With phase based ranging always one return is measured, contrary to pulse round trip ranging. If a beam, due to its diameter, illuminates to spatially distinct objects, the returning signal is a superimposition of both, continuous wave, echoes. The range reading will therefore be in between the ranges to the nearer and the farther object.

Triangulation

To obtain even higher precision with laser scanning, range is not determined directly, but via angle measurements. In a triangulating laser scanner, the laser energy is widened in order to form a plane, rather than a beam. With the help of a rotating mirror, this plane is swept through object space. For one position of the plane, i.e. one angle of the mirror, the intersection of this plane with the surfaces in object space results in one curve, or multiple curves. The object space is, at the same time, imaged through a lens onto an image plane. The image covers the entire scene, but only the curve is of interest. It can be extracted, e.g., by computing the difference image of two images. The first image is the scene without the laser plane. The second image contains the "laser light" curves. The curves in the image plane form a bundle of rays, connecting the map of the curves with the projection centre. The intersection of this bundle with the plane of laser energy yields the position of the points in object space.

This method of scanning is restricted in depth, because the quality of the intersection decreases with range. The basis, i.e. the distance from the emitter to the camera, cannot be made too big for practical reasons. Therefore, this type of scanners is restricted to ranges of one or a few meters. The precision is typically better than ±1mm. The method described measures not one point at a time, but a sequence of points along the "laser light" curves on the objects of interest. In a few seconds the entire field of view can be scanned. The number of points depends, among other factors, on the resolution of the camera. With standard VGA resolution this results in approximately 250000 points per scan.

2.2 Scanning

In pulse round trip and phase based ranging only one point is measured per shot, excluding the possibility of multiple returns for the time being. The laser beam is therefore scanned over the field of view. Different scanning mechanisms are in use for this (Figure 4).

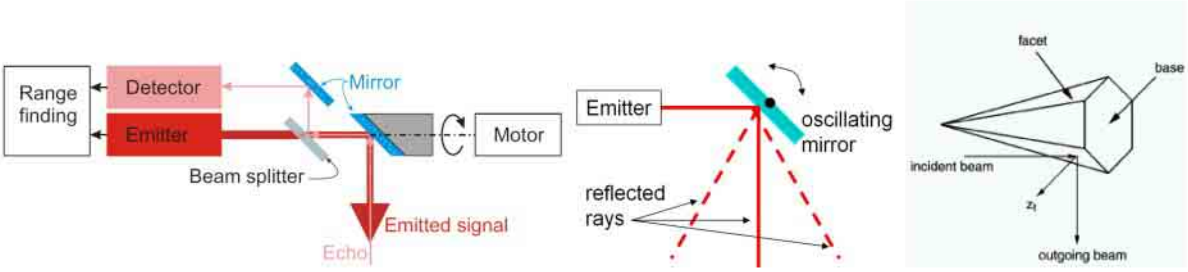

Figure 4 – Scanning principles (selection). Left: rotating mirror, middle: oscillating mirror, right (from Lapytov, 2005): multi-faceted mirror.

One possibility is to use a rotating mirror which is inclined 45° to the beam cast onto the mirror. The beam is deflected by 90° into different directions depending on the current mirror angle. One complete rotation of the mirror results in a deflection of the beam into 360° bundle of rays in the plane perpendicular to the emitted laser beam. A multi faceted mirror can be used to deflect the laser beam into a smaller angular interval. Different construction principles are possible. A pyramid mirror can be used, where the pyramid axis is parallel to the emitted laser beam. Another option is to use a regular prism, the side facets being the mirrors, where the prism axis is orthogonal to the emitted beam. These scanners produce a point pattern that results in a line of points when the laser is shot at a plane. This line is traversed always from the same side.

An oscillating mirror also scans a restricted angular field. If the turning points can be controlled by some means, it has the advantage, that the field of view can be adapted to application requirements. On the other hand, compared to a rotating mirror, the mirror always has to be accelerated and stopped at the turning points. Such a scanner produces a zig-zag pattern.

A special system is the so-called fiber scanner (TopoSys, 2007). The laser is shot onto a nutating mirror, and rotation of the mirror and firing of the pulses is timed in such a way, that each reflection is “caught” by a small optic, guiding the laser into a fibre that is then bent so that the bundle of (128) fibres is equally distributed over the angular field of view.

The above principles deflect the laser beam within one plane. Using a nutating mirror, i.e. a mirror that has a surface normal different from 45° to the incoming laser beam, results in a cone pattern of reflected rays.

Typically, not only a one-dimensional scan is desired, which can be achieved by applying one of the principles described above. In order to realize a two-dimensional scan two methods can be used. First, two moving mirrors can be used. For terrestrial laser scanning this results in so-called window scanners, e.g. with a field of view of 40° by 40°. Secondly, one moving mirror can be coupled with a movement of the platform. In airborne laser scanning this is realized by the forward motion of the aircraft. The same applies to the scanning from a moving car or boat. In static terrestrial laser scanning this can be realized by rotating the scan head, resulting in so-called panoramic scanners, with a field of view of 360° by e.g. 80°. If the rotation of the scan head is coupled with a rotating mirror that scans into all directions within a plane (first principle described), the scanners are called hemispherical.

The orientation of the mirror can be measured by angle encoders. The measurement precision is typically chosen to fit to the ranging precision for the typical ranges acquired with the respective laser scanner.

2.3 Current Systems

Technology in laser scanning, airborne and terrestrial is developing fast. It is therefore not suitable to describe specific scanners of different vendors, as at the moment of printing the article, the information may be outdated already. Therefore, rather some average performance figures shall be given for different laser scanners measuring the range directly[1]. The values given are oriented at the best product of the different vendors. The market for triangulating scanners is even bigger and their performance characteristics are limited to the statements made above.

Airborne laser scanners use almost solely the round trip time measurement for ranging (Riegl, 2007, Optech, 2007, Leica, 2007, TopEye, 2007, TopoSys, 2007). One exception is the research system ScaLARS, which applies the phase difference measurement (Hug and Wehr, 1997). The PRR of current “top end” devices is 100kHz to 200kHz with a ranging precision of a few cm, up to one decimetre. The operational flying height above ground 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. Lower flying heights provide higher point densities and smaller footprints, i.e. beam diameter at ground height. Larger flying heights result in bigger area coverage, but especially the lateral errors grows linearly with flying height (provided the same IMU is used). Operation from a helicopter is suitable for following a linear feature, e.g. a power line, or flying adapted to terrain height. Helicopters are generally used for lower flying heights. Mainly two laser wavelengths are in use: 1.06µm and 1.5µm. The maximum field of view in airborne laser scanning, measured perpendicular to the forward movement of the aircraft, is depending on the scanner used and reaches from ±7° to ±30°.

Terrestrial laser scanners use the round trip time measurements (Riegl, 2007, Leica, 2007, Trimble, 2007, Optech, 2007, Callidus, 2007, I-SiTE, 2007) and the phase based ranging (Zoller+Fröhlich, 2007, Faro, 2007, 3rdTech, 2007). Round trip time ranging scanners are suited better for outdoor operation where longer ranges have to be measured. Correspondingly, the scanning principle applied most often is the panoramic scanner. 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. The PRR is typically 10kHz and less, and precision lies between ±5mm and ±2cm. Scanners applying the phase based ranging are typically hemispherical scanners. They are well suited for indoor usage and outdoor environments with a larger number of objects (e.g. piping installations, inner city areas), restricting

---

[1] The vendor list given in this article is not necessarily complete. No quality on judgement is associated with naming or omitting a specific laser scanner vendor.

the view. Therefore, not many possibilities are given to measure points beyond the uniqueness range. The PRR is typically above 100kHz, and precision is ±2mm or better.

For terrestrial scanners issues as eye-safety, power consumption, environmental conditions, and weight are of importance.

Laser ranging from satellite is currently performed by one satellite, NASA's ICESat (Zwally et al, 2002). It circles the earth in a distance of 600km. Data is performed profile-wise along the orbit, i.e. no scanning is performed. Along the profile every 175m at ground level a measurement is made. The footprint diameter is 70m. The spacing of the profiles at the equator is 15km, and with an inclination of 94° the satellite has a near polar orbit. One of the main purposes of that satellite mission is to assess the changes of the polar ice caps, but topographic applications have also been reported, e.g. forest assessment in Siberia (Ranson et al, 2004) and landcover classification (Van Duong et al, 2006).

3. ORIENTATION OF LASER SCANNING DEVICES

A laser scanner measures a point cloud by determining range and direction (orientation of the mirror) to reflecting surfaces. This point cloud is therefore acquired in the coordinate system of the sensor itself. To either transform the measurements from two standpoints into the same coordinate system or transform the measurements to a superior, e.g. state plane, coordinate system, a congruency transformation needs to be determined. In the airborne case, direct geo-referencing has to be applied, it will be treated first. In the terrestrial case typically a two step procedure is taken. First the scans from different stand points are transformed into one system, which is then transformed into a superior coordinate system.

3.1 Airborne Laser Scanning

Collection of point clouds from airborne platforms requires always that the path of the platform, i.e. its position and angular attitude, are observed continuously. With a PRR of 100kHz, 100000 range and scanner angle measurements are made per second, and for each one the sensor coordinate system has its own exterior orientation. For increasing accuracy some form of ground control is necessary, leading to the methods of strip adjustment.

Data in airborne laser scanning is acquired strip wise. A strip length of 20km is not uncommon, but the strip length cannot be made arbitrarily long due to drift errors in the IMU, which are corrected after flight manoeuvres. Wider areas are acquired by placing strips next to each other with an overlap to avoid gaps. Larger overlaps can be favourable to increase accuracy in strip adjustment (see below) or to increase the point density (e.g. by a strip overlap of 50%).

Laser scanning from a ground based or water based moving platform is similar to airborne laser scanning with the exception that the laser scanning is not looking primarily vertical and that data acquisition rather follows the allowed routes (e.g., streets) than systematically scanning the project area.

Direct Georeferencing

The most common equipment for direct georeferencing is a combination of the GNSS (global navigation satellite system) receiver and an inertial measurement unit (IMU), building together the POS (position and orientation system). Typically, a GPS antenna is mounted on top of the aircraft and the IMU is rigidly mounted to the sensor platform. The vector from the GPS antenna phase center to the laser firing point, or more precisely the point of refelction at the mirror, is called the GPS offset or level arm. It has to be measured after installing a laser scanner in the aircraft, most often by tacheometry. GPS is used for two purposes. In real time mode it is used to tell the pilot the deviation from the planned flight plan. It additionally records the satellite signals for subsequent differential post-processing. In combination with a terrestrial GPS reference station, which should not be further than 30 to 50km from the aircraft, the flight path is reconstructed. The measurement rate of GPS receivers is in the range of 1Hz to 10Hz, which is less than the PRR by a factor of 10000 or more. Airplanes typically fly with a speed of e.g. 60ms^{-1}, helicopters somewhat slower. The intermediate positions of the sensor along the flight path, but also the angular attitude are determined by the IMU with its accelerometers and gyros. Measurement frequency of the IMU is in the range of 200Hz up to 2kHz. The observations of exterior orientation are joined in a Kalman filter and the flight path can be determined with an accuracy of ±5 to 10cm under good conditions. The constant rotation angles from the IMU to the laser scanner body frame, the so-called IMU misalignment is determined by performing a calibration flight. Such a calibration flight may be used to improve the GPS offset vector, too.

The mathematical model, relating the primary measurements of the laser scanner, i.e. range r and scan angle α, with the time-dependent exterior orientation of the sensor system, expressed by the position of the antenna phase centre (x_0, y_0, z_0) and the sensor attitude angles ω, φ, and κ, to the ground point (x, y, z) is

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} + \mathbf{R}_{\omega\varphi\kappa} \left(\mathbf{t} + \mathbf{R}_{\mathrm{m}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ -r \end{pmatrix} \right)$$

In the above equation $\mathbf{t}$ is the GPS antenna offset and $\mathbf{R}_{\mathrm{m}}$ is the IMU misalignment. The rotation angles are summarized in the matrix $\mathbf{R}_{\omega\varphi\kappa}$ accounting for the rotation of the body frame to the global frame. All measurement acquired by the multi sensor system have to be synchronized, which is possible with the GPS time signal.

Strip Adjustment

Higher precision can be achieved by applying the so-called method of strip adjustment. It is motivated by observing that neighboring points recorded by the scanner may have a very high precision relative to each other. The planarity of a set of points on a flat concrete surface, e.g., may be as low as ±2cm. The absolute precision, however, is still in the range of one or two decimetres. Another motivation originates in computing digital surface models from each strip separately and then determining the difference model in the overlap of two strips. Errors in planimetry become visible in slanted terrain and especially at edges, e.g. ridges in roofs or railroad embankments. Strip adjustment also becomes necessary, if the GPS offset vector or the IMU misalignment is not known to a sufficient precision, leading to on-the-job calibration as known from aerial photogrammetric image orientation. In general, strip adjustment can be seen as a method of removing systematic errors apparent in the data.

There are two methods for strip adjustment. An overview is given in (Pfeifer, 2005). One is data driven and does not consider the properties of the sensor system. The systematic errors are removed by shifting and titling the strips or by adding correction polynomials (or other functions) to each coordinate direction. The systematic errors are either measured manually or automatically in the overlapping areas. Additionally, control patches, analogous to control points in bundle block adjustment of images, can be used to improve the orientation of the entire block of strips. While effective to some extent, the disadvantage of this kind of strip adjustment is that new errors may be introduced contradicting the physically possible errors. The polynomial model may not always be able to account for the special deformations caused by misalignments in the sensor itself. The other method of strip adjustment is exploiting the sensor model. It resides on the equation given above, which relates the ground point coordinates to measurements of the laser scanner and the exterior orientation. At flat surfaces in the overlap, e.g. a building roof, the points from either strip must lie in the same plane (Figure 5). The parameters of this plane equation become therefore unknowns in the strip adjustment, too. Such a tie patch is analogous to a tie point in bundle block adjustment of images. Methods for model driven strip adjustment have been presented by Burman (2002), Filin (2003), and Kager (2004).

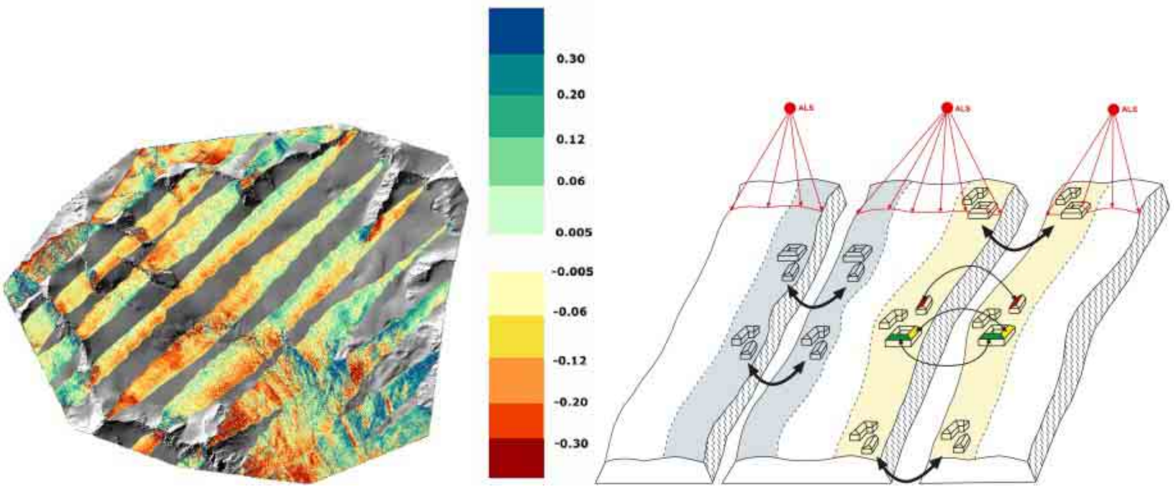

Figure 5 – Left: The background shows airborne laser data acquired over a glacier. In the overlaps of adjacent strips the height differences of the strips are shown. Dark red and blue tones refer to differences larger than 30cm. Right, principle of airborne laser scanning strip adjustment based on tie patches (Kager, 2004).

3.2 Terrestrial Laser Scanning

As mentioned before, terrestrial laser scanners are either so-called window scanners, having a field of view similar to a conventional area camera, or panoramic scanners. Normally, one scan is not enough to collect data covering the entire object of interest. If the scanner is placed inside, occlusions prevent seeing all details from one stand point. Scanning the outside of an object requires more standpoints to scan the object from all sides. For measuring one point on the object surface, three observations are made, namely the range r and two angles α, the horizontal angle and β, the angle in the vertical. In the sensor coordinate system the coordinates (x, y, z) of the point are obtained by a conversion from the spherical to the Cartesian coordinate system.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = r \begin{pmatrix} \cos\alpha\cos\beta \\ \sin\alpha\cos\beta \\ \sin\beta \end{pmatrix}$$

If only the object itself is of interest, it is sufficient to determine the relative orientation of the 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 this is also called georeferencing.

Relative Orientation, Registration

Two different methods for computing the relative orientation between two laser scans can be applied. One is similar to relative orientation of images where tie points are used. As laser scanners do not measure distinct points, i.e. intersection of geometric or radiometric edges directly, but scan the surface irrespective of the location of features, points have to be extracted first. The second method does not require identical points and performs the orientation of two scans, given approximate values of sufficient quality, entirely automatically. From these algorithms the term registration was coined which is now used synonymously with relative orientation. Also the terms (co-)alignment and consolidation are in use, but the authors discourage their use. If two scans are given, the slave scan is transformed onto the master scan by a congruency or Euclidean transform, i.e. a shift and a rotation.

Extraction of distinct points becomes especially simple, if artificial targets are placed in the scene. Typically spheres of a bright material, cylinders of retro-reflective material, of flat targets either with two black and two white rectangular fields or with circles with good contrast are distributed. The point cloud of these points needs to be picked manually, and fine measurement can be performed automatically, e.g. by a robust sphere adjustment to a given set of points, possibly containing outliers. Alternatively to artificial targets, also natural targets may be used. At the intersection of three planes a distinct point may be computed, but it is more straightforward to use patches, especially planar patches, for the computation of the transformation parameters. A method for automatic finding of these patches and computation of transformation parameters has been presented by Rabbani et al (2007).

If three pairs of points are picked in either scan, the transformation parameters can be determined. Using more points increases the redundancy, reliability, and avoids extrapolation, if they are placed accordingly. For the computation of the transformation parameters closed-form methods as those suggested by Horn (1987) should be used, because they do not require the determination of approximate values. If planar patches are used, obtaining approximate values can be split to first computing rotation parameters and then the shift.

Placing or targets can be impossible, especially if the object is not accessible, additionally it can become time consuming. As an alternative methods like ICP (iterative closest point) can be used. It has been suggested by Besl and McKay (1992) and variants are studied in (Rusinkiewicz and Levoy, 2001). The algorithm requires that the slave point cloud, i.e. the data set to be transformed, is oriented relatively approximately with the master point cloud. For each point (or a suitably selected subset) of the slave point cloud the closest point in the master point cloud is identified. Therefore, pairs of corresponding points, one from the slave, and the other from the master are available. Then the transformation parameters (shift vector and rotations) are determined, so that the distance between corresponding point pairs after the transformation is minimal. More precisely, the sum of distance squares is minimized. This process is iterated, i.e. new correspondences are searched and the transformation parameters are updated. The convergence rate is not very high, and therefore different variants have been studied (see above).

Absolute Orientation, Georeferencing

In order to transform one or multiple scans, generally one point cloud, into a superior coordinate system control points are required. These control points can either be distributed in the scene or the coordinates of a laser scanner stand point may be observed, e.g. by centering over a known point or by mounting a GPS 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. 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.

4. APPLICATIONS

So far, data acquisition and transformation into one coordinate system has been described. The next step is generating a model from the point cloud. This model can then be applied for different purposes. The simplest model is the point cloud itself. It can be used for measuring distances and angles by clicking onto – more or less – distinct points. Another very simple model of retrieving information from the point cloud is stochastic modelling. Statistic figures, e.g. percentiles of height, etc., are correlated with ground observations. Most other models generate a surface from the point cloud, e.g. by rasterization, or generating a mesh, most often a triangulation from the point cloud. For regular objects primitive instancing (i.e., fitting of planes, cylinders, spheres, …) is used, leading to boundary representation (B-Rep) models, and finally surface reconstruction can be performed by modelling with free form surfaces. This article, however, will not concentrate on the generation of models themselves, but rather proceed to the applications directly.

4.1 Airborne Laser Scanning

Airborne laser scanning is used routinely in order to acquire digital terrain models (DTM). First, however, the digital surface model (DSM) will be discussed. When interpolating the entire point cloud acquired with airborne laser scanning, a so-called DSM is obtained. In open areas it runs along the ground, it runs over house roofs, and in the vegetation is continuously "jumps" up and down, i.e. from the ground to the tree canopies, depending on where the points were measured. If data acquisition was performed in the leaf-off season, more ground points are recorded, but also during full development of the tree crowns gaps in the canopy allow recording of ground points, albeit less frequently. Using either only the first echoes or only the last echoes increases or diminishes the outline of houses, respectively. Similarly the DSM will show more of the vegetation canopy or the ground in wooded areas. Such a DSM is strongly influenced by many factors of the observed scene. Wheat for example, has a penetration rate from almost 100% to almost 0%, depending on its growing state. Additionally, the viewing angle causes artefacts in the DSM. A house roof facing away from the scanner shades a ground area where no ground points can be recorded.

In order to obtain only ground points, so-called filtering algorithms are applied. They perform a classification of the measured points into ground points and off-terrain points. Filtering can, however, also be applied to the DSM, i.e. a rasterization of the point cloud. An overview on filter algorithms is given in Kobler et al (2007), and an experimental comparison of filter algorithms has been performed by Sithole and Vosselman (2004).

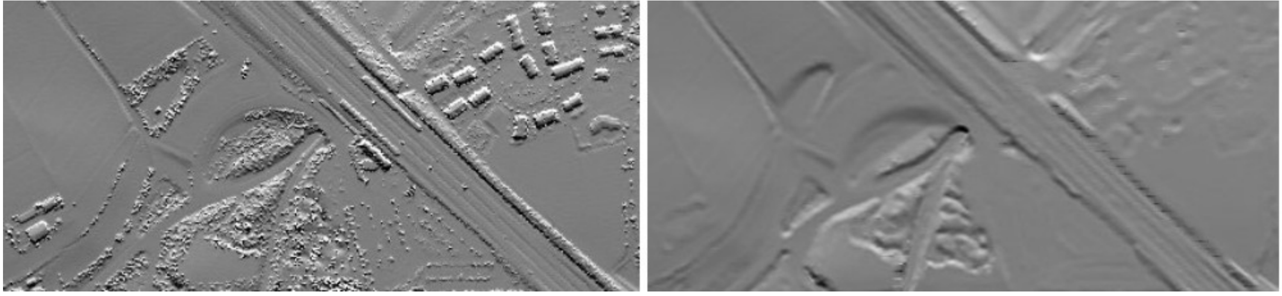

Figure 6 – Image of DSM (left) and DTM (right).

The difference from a DTM to a DSM is a so-called normalized digital surface models (nDSM). It shows above ground elevations, i.e. nDSM = DSM-DTM. Such an nDSM is often used for building detection. Many algorithms proceed by extracting objects from the nDSM and classifying those into low objects (by a height threshold), vegetation (by a roughness measure) and buildings. An overview on building detection algorithms is given in Pfeifer et al (2007). In order to reconstruct the shape of buildings, primarily their roof form, locating the building is the first step. If not performed with building detection from the airborne laser scanning data, this is done with the help of cadastral maps. An experimental comparison of building reconstruction algorithms is given in Hyyppä et al (2005).

In forestry airborne laser scanning is used for acquiring stand characteristics and for single tree detection. This allows monitoring of forest growth. An detailed overview on applications and algorithms of laser scanning data in forestry is given by Hyyppä et al (2004).

Mapping of corridors, i.e. highways, rail roads, power lines, etc. can be performed efficiently with airborne laser scanning. Often the precise location of power lines is not known and therefore measured, but also safety distances (e.g. closeness of vegetation) can be checked.

4.2 Terrestrial Laser Scanning

The field of applications for terrestrial laser scanning is very diverse. Therefore, only a limited number of applications will be mentioned.

To acquire a city model, including additionally the roof forms the geometry of the facades, terrestrial laser scanning is an interesting option. Typically, imagery is acquired as well, so that the geometric model can be textured. In documentation cultural heritage laser scanning is applied not only in research, but also in practice, ranging from small artifacts with a few centimetres diameter, to statues and monuments with a height of one or a few meters, up to entire buildings and castles. As the precision and measurement volume requirements are very diverse, not one laser scanner alone can be used to cover all applications in cultural heritage. Figure 7 shows an example of a historic room in Schönbrunn castle, Austria, which was acquired by a scanner with a pulsed laser scanner (Riegl LMS-Q420i (Riegl, 2007)). The texture was acquired with a Canon Eos1Ds digital camera mounted on top of the scanner.

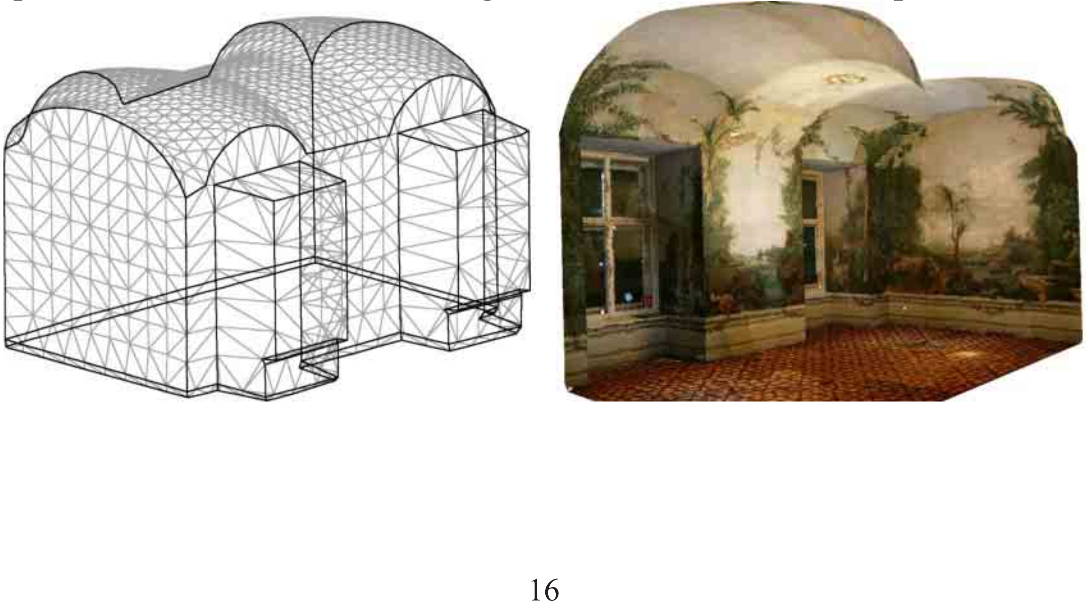

Figure 7 – Left: Boundary representation (black) and triangulated surfaces (grey) of an indoor room; Right: VRML visualisation of the textured model (Dorninger and Briese, 2005).

Applications of terrestrial laser scanning in engineering projects is also investigated, but in the case of high precision requirements not used routinely in practice yet. Scainoi at al (2006) have shown that deformation of large dams (approx. 100m) can be monitored with precision close to 1cm, if a sufficient number of control points measured tacheometrically is placed on the object. This allows monitoring deformation surface wise, but on the other hand it shows that georeferencing and systematic errors still have effects in the order of centimetre, if very long ranges need to be measured. Developments are continuing in that field, and with advanced instruments and mathematical models laser scanning will also be able to fulfil these higher precision and reliability requirements in near time.

5. CONCLUSIONS

This paper has summarized the technology of laser scanning, i.e. the different range measurement principles and scanning mechanisms. In this part, no separation between airborne and terrestrial laser scanning was made. With scanning from mobile platforms, on the one hand, and terrestrial scanning over very large distances, the differences are indeed decreasing. Additionally, direct georeferencing, at least approximately, is also a very interesting option for static terrestrial devices, as it allows speeding up subsequent steps, especially relative orientation.

The number of laser scanning devices, which can be utilized for applications in geodesy and photogrammetric, is about ten. Notable differences in the instruments for airborne as well as terrestrial scanners can be found. These differences largely reflect different range, accuracy, and measurement speed requirements for different applications.

For airborne laser scanning rigorous strip adjustment, based on a mathematical model of the sensor, is used in commercial projects with high precision requirements. For terrestrial laser scanning rigorous calibration is necessary too in order to improve the geometric quality of the laser scanning point cloud.

Concerning applications of laser scanning a short overview, by no means comprehensive, was given. Laser scanning can play an important role in many photogrammetric tasks. The authors expect that we will see in future integrated sensor systems, possibly integrated devices, capable of recording range and colour information simultaneously. This means that photogrammetrists will have to extend their mathematical concepts for optimally using synergies in both data sources.

REFERENCES

1. 3RDTECH, 2007. www.3rdtech.com.
2. Abshire et al, 2005. Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On-orbit measurement performance. Geophysical research letters, 32.
3. Besl and McKay, 1992. A Method for Registration of 3-D Shapes. Transactions of Pattern Analysis and Machine Intelligence, 14.
4. Registration of Range Images.
5. Böhler and Marbs, 2002. 3D scanning instruments. International Workshop on Scanning for Cultural Heritage Recording, Corfu, Greece.
6. Bufton, 1989. Laser Altimetry Measurements from Aircraft and Spacecraft. Proceedings of the IEEE, 77.
7. Burman, 2002. Laser Strip Adjustment for Data Calibration and Verification. International Archives of Photogrammetry and Remote Sensing, Vol. 34/3, Graz, Austria.
8. Callidus, 2007. www.callidus.de.
9. Dorninger and Briese, 2005. Advanced Geometric Modelling of Historical Rooms. XXth International CIPA Symposium, Torino, Italy.
10. Faro, 2007. www.faro.com.
11. Filin, 2003. Recovery of systematic biases in laser altimetry data using natural surfaces. Photogrammetric Engineering & Remote Sensing, 69.
12. Höfle and Pfeifer, 2007. Correction of laser scanning intensity data: data and model-driven approaches and applications. ISPRS Journal of Photogrammetry and Remote Sensing, under review.
13. Horn, 1987. Closed-form solution of absolute orientation using unit quaternions. Journal of the Optical Society of America A, 4.
14. Hug and Wehr, 1997. Detecting and identifying topographic objects in mapping laser altimeter data. Int. Archives of Photogrammetry & Remote Sensing, Vol 32/3-4W2, Haifa, Israel.
15. Hyyppä et al, 2004. Algorithms and Methods of Airborne Laser-Scanning for Forest Measurements. International Archives of Photogrammetry and Remote Sensing, Vol. 36/8W2, Freiburg, Germany.
16. Hyyppä et al, 2005. Accuracy of 3D city models: EuroSDR comparison. International Archives of Photogrammetry and Remote Sensing, Vol. 36/3W19, Enschede, the Netherlands.
17. I-SiTE, 2007. www.maptek.com.
18. Jelalian, 1991. Laser Radar Systems. Artech House, Boston.
19. Jutzi and Stilla, 2005. Waveform processing of laser pulses for reconstruction of surfaces in urban areas. Proceedings of 3rd International Symposium: Remote sensing and data fusion on urban areas, URBAN 2005. International Archives of Photogrammetry and Remote Sensing Vol 36/8-W27.
20. Jutzi and Stilla, 2006. Range determination with waveform recording laser systems using a Wiener Filter. ISPRS Journal of Photogrammetry and Remote Sensing, 61.
21. Kager, 2004. Discrepancies Between Overlapping Laser Scanning Strips- Simultaneous Fitting of Aerial Laser Scanner Strips. International Archives of Photogrammetry and Remote Sensing, Vol. 35, Istanbul, Turkey.
22. Kobler et al, 2007. Repetitive interpolation: A robust algorithm for DTM generation from Aerial Laser Scanner Data in forested terrain. Remote Sensing of Environment, accepted for publication.
23. Kraus, 2004. Photogrammetrie, 7th ed. Walter de Gruyter, Berlin. An English translation of the 7th edition is in preparation.
24. Lapytov, 2005. Effects of laser beam alignment tolerance on lidar accuracy. ISPRS Journal of Photogrammetry and Remote Sensing, 59.
25. Leica, 2007. www.leica-geosystems.com.
26. Optech, 2007. www.optech.ca.
27. Pfeifer, 2005. Airborne Laser Scanning Strip Adjustment and Automation of Tie Surface Measurement. Boletim de Ciências Geodésicas, 11.

28. Pfeifer, Rutzinger, Rottensteiner, Hollaus, Mücke, 2007. Extraction of building footprints from airborne laser scanning: Comparison and validation techniques. Proceedings of IEEE workshop Urban Remote Sensing, Paris, France.

29. Rabbani, Dijkman, van den Heuvel, Vosselman, 2007. An integrated approach for modelling and global registration of point clouds. ISPRS Journal of Photogrammetry and Remote Sensing, 61.

30. Ranson, Sun, Kovacs, and Kharuk, 2004. Landcover attributes from ICESat GLAS data in central Siberia. International Geoscience and Remote Sensing Symposium, Anchorage, Alaska.

31. Riegl, 2007. www.riegl.com.

32. Rees, 2001. Physical principles of remote sensing. 2nd ed. Cambridge University Press, Cambridge.

33. Rueger, 1990. Electronic Distance Measurement, 3rd ed. Springer, Berlin.

34. Rusinkiewicz and Levoy, 2001. Efficient Variante of the ICP Algorithm. Proceedings of the Third International Conference on 3D Digital Imaging and Modeling (3DIM).

35. Sithole and Vosselman, 2004. Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds. ISPRS Journal of Photogrammetry and Remote Sensing, 59.

36. TopEye, 2007. www.topeye.com.

37. TopoSys, 2007. www.toposys.de.

38. Trimble, 2007. www.trimble.com.

39. Van Duong, Pfeifer, Lindenbergh, 2006. Full waveform analysis: ICESat data for land cover classification. International Archives of Photogrammetry and Remote Sensing, Vol. 36/7.

40. Wagner, Ullrich, Ducic, Melzer, Studnicka, 2006. Gaussian decomposition and calibration of a novel small-footprint full-waveform digitising airborne laser scanner. ISPRS Journal of Photogrammetry and Remote Sensing, 60.

41. Wehr and Lohr, 1999a. Airborne laser scanning - an introduction and overview. ISPRS Journal of Photogrammetry & Remote Sensing, 54.

42. Wehr and Lohr, editors, 1999b. Theme Issue: Airborne Laserscanning. ISPRS Journal of Photogrammetry & Remote Sensing, 54.

43. Weitkamp, 2005. Lidar: Range-Resolved Optical Remote Sensing of the Atmosphere, Springer, Berlin.

44. Young, 2000. Optics and Lasers. 5th ed. Springer, Berlin.

45. Zoller+Fröhlich, 2007. www.zf-laser.com.

46. Zwally et al, 2002: ICESat's laser measurements of polar ice, atmosphere, ocean, and land. Journal of Geodynamics, 34.

BIOGRAPHICAL NOTES

Norbert Pfeifer studied surveying at the Vienna University of Technology where he also obtained his Ph.D. in 2002 (with honours). After a three years period as assistant professor in the Netherlands, at Delft University of Technology at the Delft Institute of Earth Observation and Space systems he joined alp-S, Centre for Natural Hazard Management, in Innsbruck, Austria. Since 2006 Norbert Pfeifer is Professor in Photogrammetry at the Vienna University of Technology. His main research interests are laser scanning, covering the physical aspects of data acquisition, the mathematical aspects of data processing, and finally the application of the generated models in various disciplines. More generally, topographic and 3D modeling as well as digital photogrammetry are his research topics. Norbert Pfeifer published articles in the peer reviewed journals like ISPRS Journal of Photogrammetry and Remote Sensing, Remote Sensing of Environment, and Photogrammetric Engineering & Remote Sensing.

He is on the board of scientific conferences (Optical 3D Measurement Techniques) and journals (Journal of Applied Geodesy). Together with Derek Lichti he is chairing the ISPRS (International Society of Photogrammetry and Remote Sensing) working group V/3, Terrestrial Laser Scanning.

Christian Briese studied surveying at the Vienna University of Technology where he also obtained his Ph.D. in 2004 (with honours). In 2005 he received the Ressel Prize of the Vienna University of Technology. Since 2001 Christian Briese is research assistant at the Institute of Photogrammetry and Remore Sensing (I.P.F.) of the Vienna University of Technology and since 2004 he collaborates in the Christian Doppler Laboratory "Spatial Data from Laser Scanning and Remote Sensing" of the Vienna University of Technology. His main research interests are laser scanning, covering the whole data acquisition process up to the generation of final geometric models. More generally, topographic and 3D modelling as well as photogrammetry are his research topics. Christian Briese published several articles in conferences and journals and is reviewer of the journals "ISPRS Journal of Photogrammetry and Remote Sensing" and "Photogrammetric Engineering & Remote Sensing".

CONTACTS

Norbert Pfeifer
e-mail: np@ipf.tuwien.ac.at
Telefon: +43 1 58001 12219
Vienna University of Technology
Institute of Photogrammetry and Remote Sensing – I.P.F.
Gusshausstrasse 27-29/E122
A-1040 Vienna, Austria

Christian Briese
e-mail: cb@ipf.tuwien.ac.at
Telefon: +43 1 58001 12211
Vienna University of Technology
Institute of Photogrammetry and Remote Sensing – I.P.F.
Christian Doppler Laboratory "Spatial Data from Laser Scanning and Remote Sensing"
Gusshausstrasse 27-29/E122
A-1040 Vienna, Austria