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METHODS AND RESULTS OF HIGH PRECISION AIRBORNE LASER PROFILING

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1. Introduction

The integration of new sensors in an aircraft enables a new approach for topographic terrain survey and the evaluation of digital terrain models. As an example airborne laser profiling will be presented in this paper. The main advantages of this method is the high precision data capture in a fully automatical and digital manner. Airborne laser profiling can be the method of first choice in quite a number of applications where conventional (photogrammetric or terrestrial) techniques fail, where they are too expensive or not fast enough. Compared with further recently proposed airborne sensors (e.g. microwave sensors) airborne laser profiling is distinguished by the high accuracy of its results. Some areas where this method is especially suited and where its application has already been demonstrated will be mentioned:

- Forest areas
  where no sight to the ground is available in the aerial photographs, and where terrestrial surveying is too expensive.

- Coastline and wetland control
  where the poor texture in the aerial photographs and the unfavorable geometrical conditions (strip adjustment along the sea side) cause difficulties by the photogrammetrical evaluation.

- Opencast exploitation of mineral sources
  where the result of the surveying shall be submitted to the digital data base within short time (e.g. a few hours).

- Tracing of streets, railroads, pipelines, electrical power lines
  where a digital terrain model is necessary only along the planned line.

The following chapter 2 describes the realization of the airborne laser profiling system and raises some of the involved problems. The main part of this paper presents in the chapters 4 and 5 some experiences and results of a test project. This test was carried out in summer 1989 in the Harz, a highland in central Germany covered by forests (cf. description in chapter 3). The project was planned and treated by a special research project at the Photogrammetric Institute of Stuttgart University with collaboration and support by the survey department (topographic division) of the state of Niedersachsen. The main investigations are summarized in chapter 4 concerning the analysis of the laser measurements in forest areas, expressed by the reflectance and penetration. The analysis of the accuracy of the laser point coordinates follows in chapter 5.

2. Realization of an airborne laser profiling system

The principle of airborne laser profiling is explained by figure 1. The main components are installed in an aircraft. The central instrument is the laser rangefinder measuring the distance to the ground. The coordinates of the laser points on the ground can be computed in a terrestrial reference system, if the complete orientation - that is the position and the attitude - of the laser beam is known. The realization of the airborne laser profiling system has to cope with a couple of tasks, which will be sketched out in a few keywords. The system components mentioned in the following refer to the experimental system with which the test flights were carried out. The system was installed in the Dornier Do 128 of the Institute of Flight Guidance and Control of the Technical University of Braunschweig.

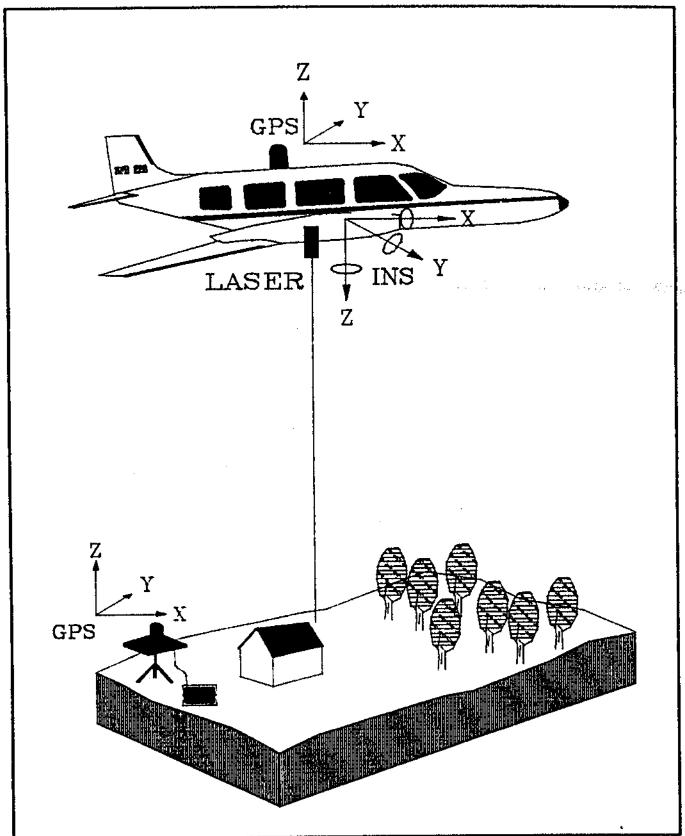

Fig. 1 Principle of Airborne Laser Profiling

- Airborne laser rangefinding

The laser rangefinder has to measure the range between the aircraft and the ground without retro-reflectors. The applied instruments are based on pulsed Nd-YAG or GaAs laser sources emitting light in the near infra-red. Thus, the laser beam is not able to penetrate any solid material (in contrast to microwave range-finding). Speaking about penetration while flying over a forest area means that the laser rangefinder utilizes the gaps in the tree foliages to measure to the ground level of the forest. In doing so, the laser receives multiple signal returns from one emitted laser pulse, when parts of the laser energy is reflected at the tree foliage whereas other parts are penetrating to the ground. The airborne laser rangefinder must be able to discriminate the multiple returns and select the last return for the distance measurement referring to the signal reflected on the ground. Nevertheless, in very dense vegetation the laser beam is not able to penetrate to the ground level. Then the last signal return is located anywhere in the tree foliage. The typical appearance of a laser profile is demonstrated by the example in figure 2.

Several rangefinders are available by a few manufacturers which are specially suited for airborne laser rangefinding. The main difference of these instruments is their maximum range of operation; maximum ranges up to 10km are realized. For the test flight described in chapter 3 the laser rangefinder Model 501SA from Optech Inc. Ontario was applied. Its maximum range is 500m depending on the reflectivity of the ground materials and weather conditions. The diameter of the laser beam is 0.75m by the mean flying height of 300m. The accuracy of the single laser distance in airborne operation has empirically been determined to be 0.08m. In the aircraft the rangefinder was operated with a 33Hz measuring rate only, although up to 2kHz are possible. The density of the measured points along the profile was 1.8m accordingly.

- Sensor orientation

Up to now the sensor orientation was the most severe problem in the realization of any new airborne surveying system. For that reason the first experiments on laser profiling since the early 1970s were not successful, because of the poor accuracy of the sensor orientation and the high costs for the involved efforts. Only since positioning by the NAVSTAR Global Positioning System (GPS) became applicable for high precision kinematic positioning in an aircraft, the complete sensor orientation can be solved by the combination of an inertial navigation platform (INS) and GPS for attitude and position determination.

For the realized system the attitude of the aircraft was determined by an INS Honeywell Lasernav. The aircraft positions are calculated post mission by relative kinematic positioning using GPS phase observations. The position of the aircraft GPS-antenna is determined in reference to a second stationary GPS-antenna on a known reference point. Two GPS receivers Sercel TR5S-B were applied for the test flights. These receivers are qualified for airborne positioning because of their measuring rate (every 0.6 sec) and their high quality and reliability. There were never problems with cycle slips during the test flights.

- System integration

The main system components laser rangefinder, GPS for positioning and INS for attitude determination are integrated to an airborne laser profiling system. Therefore the measurements of theses instruments are controlled by a synchronized process and the measured data are sampled and registered in a common data format. These tasks are executed by a central on-board computer.

- Aircraft navigation

As the profiling system samples the points only along the profile, the coverage of the terrain is obtained by a number of parallel profiles. The required density of the profiles depends on the roughness of the terrain and the desired accuracy of the DTM. Airborne laser profiling make high demands on the navigation of the aircraft, which can be fulfilled only by a high precision navigation system. Nowadays several systems based on real-time differential GPS navigation are commercially available.

The programming of the on-board computer and the aircraft navigation was realized for the test flights by the Institute of Flight Guidance and Control.

- System calibration

The system calibration is a process where each instrument is calibrated for itself and the relations between the instruments are determined with reference to the terrain coordinate system. The calibration of a system consisting of three independent instruments is a demanding task which cannot be solved completely under stationary conditions. Some calibration parameters must be determined indirectly, through in-flight calibration by measuring additional topographic control points. The method can be compared with self-calibration in aerial-triangulation.

- Data evaluation and computation of the laser points

The data evaluation consists of the pre-processing the data of the instruments (e.g. calculation the GPS positions out of the phase observations), the synchronization of the data (e.g. the interpolation of the GPS positions to the laser registrations) and the computation of the coordinates of the laser points. These coordinates are transformed in the state reference coordinate system.

- Analysis of the laser points and derivation of a DTM

The main task of the point analysis is the separation of the topographically utilizable laser points on the ground from the laser points referring to topographically not-relevant objects like buildings or vegetation. The large number of measured points requires clearly an automatical procedure by sophisticated computer programs. The utilizable laser points are introduced into a database for the derivation of a digital terrain model (DTM).

Figure 2 gives an example of the analysis of the laser profiles. The first plot shows the originally measured laser points in a coniferous forest. The result of the analysis is the computed ground profile represented by the additional points in the second plot below.

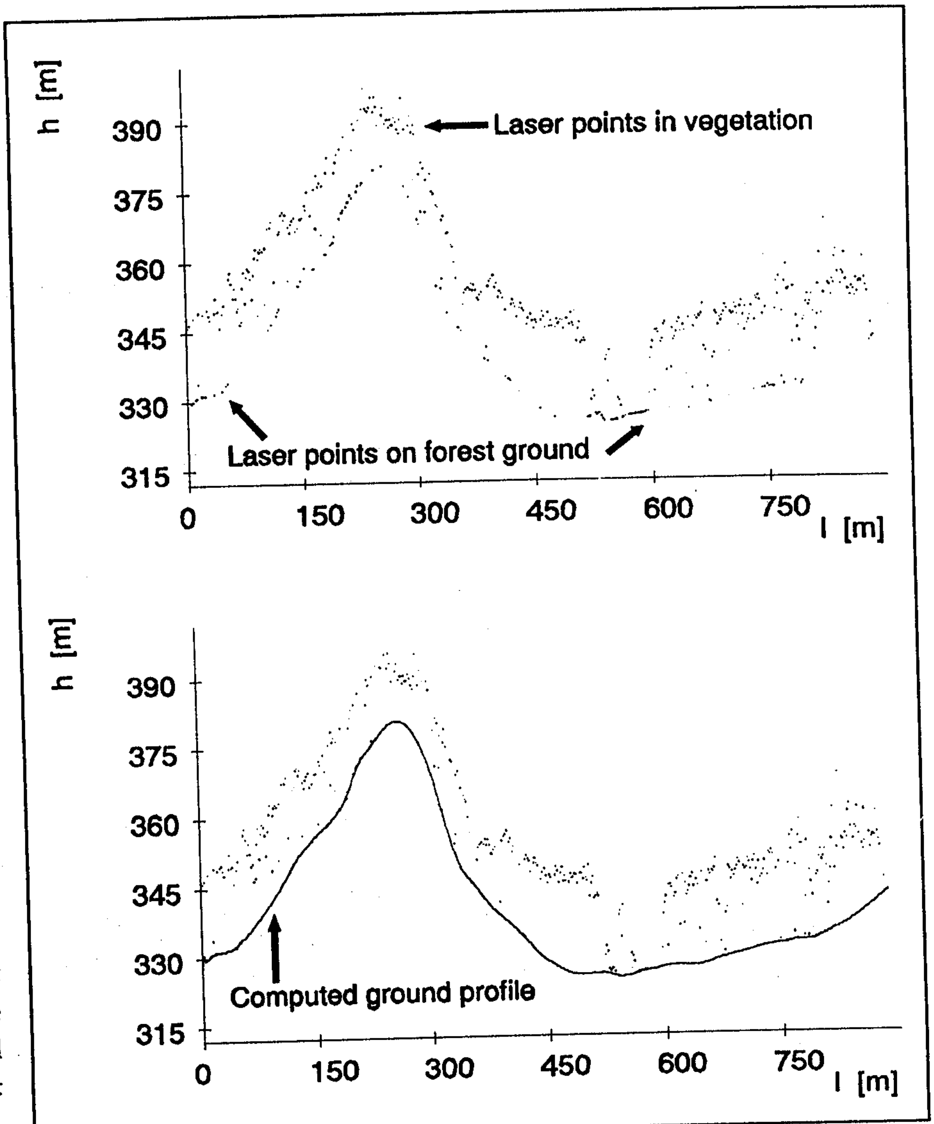

Fig 2. Original measured laser profile (above)
Ground profile after profile analysis (below)

The automatic system calibration, computation and analysis of the laser points is solved by powerful software developed at the Institute of Photogrammetry at Stuttgart University.

3. Airborne laser profiling test project Harz 1989

In the following some results of the project Harz will be presented. The practical interest at this project is the application of airborne laser profiling for the topographic terrain survey in forest areas, where photogrammetric means fail and terrestrial surveying is too expensive. The scientific interest was concentrated on:

- the system integration and calibration,
- application of the developed software under nearly practical conditions,
- investigation of the laser reflectance and penetration in forest areas,
- analysis of the accuracy of the laser point coordinates,
- analysis of the DTM derived from laser points.

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Some items of the test area are summarized in table 1. The terrain can be divided in three characteristic parts. In the western part we find a smooth ridge covered by trees. There the mean terrain slope is about 15%. The central area is open and nearly flat terrain with agricultural areas, two villages (Badenhausen and Windhausen), a railway line and a federal highway. The eastern part covers the wooded ascent to the Harz mountains. As an example figure 3 presents a laser profile, which gives an impression of the type of terrain.

It was intended to cover the whole area by laser profiles with a distance of 50m. Unfortunately after 5 profiles thunderstorm caused a break and the bad weather conditions did not allow to complete the flying program in the following days.

Date of flight	August 24th and 25th 1989
Location	in the highlands of the Harz near Osterode
Size of the test area	12 km in west-east direction 1 km in north-south direction
Height above sea level	from 140 m to 500 m
Ground cover	51% agricultural area 27% coniferous forest 17% deciduous forest 5% urban area
Flight plan August 24th August 25th	 10 profiles with 100m distance 5 profiles with 100m distance, shifted by 50m to profiles of the first day
Number of points August 24th August 25th	 66 019 laser points 32 261 laser points

Tab. 1 Airborne laser profiling project Harz 1989

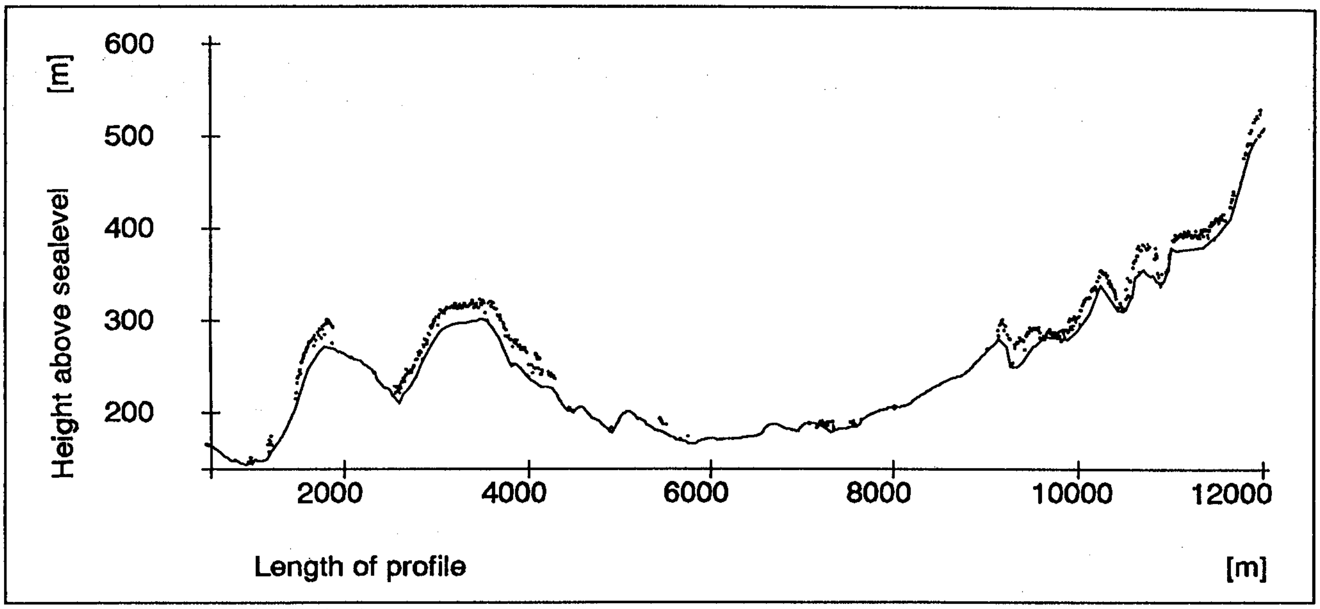

Fig. 3 Laser profile from the Harz project

4. Analysis of the laser measurements

4.1 Reflectance

In this context we understand with the term reflectance the percentage with regard of the emitted laser pulses where the distance could be successfully measured, i.e. where enough energy was reflected from the ground surface to trigger a measurement. In the Harz project for more than 98% of the emitted pulses the distance could be measured. This high success rate has also been obtained in earlier tests on various kinds of object surfaces (cf. Lindenberger 1989). Thus, concerning the reflectance, there are practically no restrictions for topographic terrain survey by airborne laser profiling.

4.2 Penetration

The penetration of laser pulses in forest areas is the capability to measure the points directly on the ground level of the forest. It is of prime interest concerning the application of airborne laser profiling for practical projects. The penetration rate gives the number of laser points referring to the ground surface in relation to all measured profile points.

In table 2 the results of the Harz project are summarized and roughly classified according to the two main forest types. With 35% in coniferous forest the penetration rate is obvious higher than in deciduous forests (24.7%). We have to consider that the flight was carried out in August under the most unfavorable conditions concerning the dense foliage of the trees. A comparative test presented by Krabill et al. (1984) with flights in summer and winter showed that the penetration rate in deciduous forest increases from 21% in summer to 68% in winter.

Forest	Total number of measured points	Points measured on the ground	Penetration rate
Coniferous	8 684	3 043	35.0 %
Deciduous	5 365	1 327	24.7 %

Tab. 2 Penetration in forest areas

Figure 4 shows a part of a laser profile, with coniferous forest in the left part and deciduous forest in the right part. In the coniferous part the ground points are very regularly distributed, about every third measured point is on the ground surface. However, in the deciduous forest the ground points are concentrated in a few locations, with more or less large gaps between the points. This example illustrates that the average penetration rate alone does not give, in each case, a quality criterion for the laser measurements in forest areas. In addition, the distribution of the ground points must be regarded. In order to obtain a better distribution of the ground points in deciduous forests we recommend airborne laser profiling in winter time. In addition the measurement rate - 33Hz at the Harz flights resp. a point every 1.8m along the profile - should be increased at least three times (100 Hz).

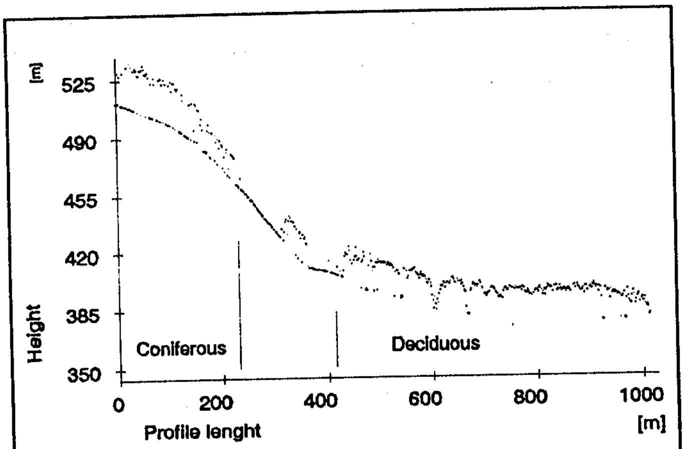

Fig. 4 Penetration in coniferous and deciduous forest

5. Analysis of the accuracy of the laser points

In this chapter we determine the height accuracy of the airborne laser profiling system. The object of the analysis is the vertical component of the laser point coordinates, resp. the terrain heights. The accuracy is estimated by independent photogrammetric and tacheometric check measurements of identical points. Thus, the horizontal coordinates are held fix and the terrain heights are compared with the result of the laser profiling. Systematic errors can be detected by the mean of the height differences, whereas from the standard deviation of the differences the bias-free accuracy of the system can be estimated.

5.1 Photogrammetric check

For the independent photogrammetric check measurements aerial photographs at scale 1:12500 and with 60% forward overlap were made available by the survey department of the state of Niedersachsen. An accuracy of σ_z=0.19m (0.1‰h) can be assumed to be achieved by measurements of not-signalized terrain points in these photographs.

Differences of terrain heights: Airborne laser profiling - photogrammetric check measurement	Number of check measurements	Mean of differences	Standard deviation of differences
1) All measured check points	16 916	-0.01 m	0.27 m
2) Without differences > 0.75m	16 716	-0.02 m	0.24 m
3) Agricultural areas	15 055	-0.03 m	0.24 m
4) Forest areas	1 661	0.05 m	0.27 m
5) Western part mean terrain slope 15%	4 769	-0.09 m	0.26 m
6) Central part mean terrain slope 7%	11 353	0.00 m	0.23 m
7) Eastern part mean terrain slope 28%	1 443	0.03 m	0.25 m
8) Eastern part Flight direction from east to west	963	0.05 m	0.25 m
9) Eastern part Flight direction from west to east	480	-0.01 m	0.25 m

Tab. 3 Photogrammetric control measurements of terrain heights

Table 3 lists the mean and the standard deviation of the height differences under several aspects. In the first line the mean and the standard deviation is computed out of all 16916 measured check points. In the second line 200 points (<1.2%) are eliminated from the data set which are considered gross errors with differences >0.75m. The mean of the differences (-0.02m) indicates that the laser points are practically free of systematic errors. Taking in consideration the accuracy of the photogrammetric check measurements, the height accuracy of the airborne laser profiling system is estimated to σ_z=0.15m. In this case the terrain survey by the airborne laser profiling system is more accurate than the photogrammetric check measurements.

In the following lines 3) to 9) of table 3 the height differences are analyzed in order to detect some systematic errors of the laser system, indicated by dependencies of the mean. In the lines 3) and 4) the points are classified according to the ground cover - open agricultural areas or forest areas. For the lines 5), 6) and 7) the points are grouped by their location in one of the characteristic terrain parts. The final classification in the lines 8) and 9) considers the flight direction. Possible systematic errors should be detected primarily in the steep ascent in the eastern part of the terrain. As the mean of the differences shows practically no dependency, we arrive at the conclusion that the laser points are free of bias. The calibration of the airborne laser profiling system evidently has compensated all possible systematic effects.

5.2 Tacheometric check

In addition to the photogrammetric check measurements some laser points were tacheometrically checked by the survey department of Niedersachsen. The verification, that the laser point refers in fact to the ground surface and not to low vegetation cover, is the special advantage of the terrestrial checks, but the involved effort is excessive compared with photogrammetric checks. For that reason the number of checked points is far lower and the points are located in two regions only. Table 4 summarizes the results of this check.

Differences of terrain heights: Airborne laser profiling - tacheometric check measurement	Number of check measurements	Mean of the differences	Standard deviation of the differences
1) Agricultural areas	121	0.00 m	0.14 m
2) Forest areas (total)	111	0.23 m	0.30 m
3) - with ground vegetation	50	0.07 m	0.19 m
4) - without ground vegetation	61	0.41 m	0.33 m

Tab. 4 Tacheometric control measurements of terrain heights

The agricultural area - first line in table 4 - is located in the flat central part of the test area. The 121 check points were measured within two laser profiles. The horizontal coordinates could be set out with an accuracy of 0.03m. The mean and the standard deviation of the differences confirm the results of the photogrammetric check. Thus, the high accuracy of airborne laser profiling is proven by two independent methods.

The second region is in a forest area in the eastern part, the steep ascent to the Harz. From 5 laser profiles 111 points were measured. The mean of the differences of 0.23m (cf. line 2) is clearly higher than all other results mentioned earlier. The further analysis of these points showed that at 61 points the forest ground was covered with a low and dense vegetation (fern, high standing grass, brushwood). The comparison of the means of the differences in line 3) (0.07m without vegetation) with line 4) (0.41m with vegetation) makes evident the influence of low vegetation. We point out that this influence was not detected from the large number of photogrammetric check measurements. To cope with low vegetation in forest areas we re-affirm the recommendation to use winter flights and a higher laser measuring rate.

5.3 Conclusions

The large number of photogrammetrical and tacheometrical check measurements enables a reliable determination of the accuracy of airborne laser profiling. The check measurements verified a mean height accuracy of 0.15m. This accuracy comprises the precision of:

- airborne laser rangefinding
- positioning by GPS
- attitude determination by INS
- modelling of the flight path (i.e. interpolation of GPS positions)
- system calibration.

The terrain heights out of airborne laser profiling has been proved to be free of systematic errors. Only low and dense vegetation in forests caused problems by the identification of the ground surface. We have to keep in mind that the test flight was carried out under the most unfavorable conditions in August with the maximum state of vegetation. The high accuracy qualifies airborne laser profiling, amongst photogrammetry and tacheometry, as a method for high precision topographic terrain survey.

The derivation of a digital terrain model is not described in this paper. The factor influencing the accuracy of a DTM is primarily the distance between the profiles specified in dependence on the terrain morphology. Against that the height accuracy of the profile points is of minor importance.

References

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Abstract

The paper introduces an airborne laser profiling system for topographic terrain survey. The system consists of a special laser rangefinder applicable to airborne operation, GPS for positioning and an INS for attitude determination. The advantages of airborne laser profiling are the capability to penetrate the tree canopy in forest areas and the fully digital data capture and evaluation. In a number of regions where conventional methods fail, are too expensive or not fast enough, airborne laser profiling will be successfully applied.

The second part of the paper presents results of an experimental test flight in the Harz. The results confirm the high accuracy of airborne laser profiling. A vertical point accuracy of 0.15m has been verified by photogrammetric and terrestrial check measurements. Thus, airborne laser profiling has proven its capability for high precision topographic terrain survey.

METHODEN UND ERGEBNISSE HOCHGENAUER LASER-PROFILBEFLIEGUNGEN

Zusammenfassung

Der Aufsatz stellt die Laser-Profilmessung als ein neues Verfahren zur topographischen Geländeaufnahme vor. Dabei werden vom Flugzeug aus mit einem speziellen Laser-Entfernungsmesser reflektorlos die Distanzen zur Erdoberfläche gemessen. Die Orientierung des Laserstrahls bezüglich eines erdfesten Bezugssystems, die zur Berechnung der Koordinaten der Laserpunkte benötigt wird, wird durch die Positionsbestimmung mittels GPS und einem inertialen Navigationssystem zur Neigungsbestimmung direkt gemessen.

Zu den wesentlichen Eigenschaften der Laser-Profilmessung zählen die Fähigkeit in Waldgebieten die Messungen direkt an der Oberfläche des Waldbodens vornehmen zu können, die vollständig digitale Datenerfassung und die vollautomatische Auswertung der Meßdaten. Die Anwendung dieser Methode bietet sich in Gebieten an, in denen die konventionellen photogrammetrischen oder terrestrischen Verfahren Schwierigkeiten haben, wie z.B. in Waldgebieten, Gebirgslagen, eis- und schneebedeckten Flächen, Küsten- und Wattgebieten, zur schnellen Kontrolle der Ausbeutung von Bodenschätzen, oder zur Trassierung von Straßen, Eisenbahnen, Pipelines, Stromleitungen.

Im zweiten Teil des Aufsatzes werden Ergebnisse eines im Sommer 1989 durchgeführten Testflugs im Harz vorgestellt. Aus einer großen Zahl von photogrammetrischen und terrestrischen Kontrollmessungen konnte eine sichere Schätzung der aus Laser-Profilmessungen abgeleiteten Geländehöhen erfolgen. Die durchschnittliche Höhengenauigkeit von 0.15m zeigt, daß mit der Laser-Profilmessung ein hohes Genauigkeitsniveau erreicht wird. Damit reiht sich die Laser-Profilmessung neben der Tachymetrie und Photogrammetrie unter die hochgenauen Methoden der topographischen Geländeaufnahme ein.

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