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TEST RESULTS OF LASER PROFILING FOR TOPOGRAPHIC TERRAIN SURVEY

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1. INTRODUCTION

The topographic terrain survey for mapping and digital terrain models is an expensive task, in spite of all developments in the field of data capture. The photogrammetric method solves this task in a most accurate and economic manner. However, these methods fail in areas covered by large forests. Then additional terrestrial measurements are necessary, usualy done by costly and time consumptive tacheometry. Recently several study groups in Canada and the United States are investigating the potential of airborne laser profiling as a new method for topographic terrain survey. A series of papers report the high accuracy level of airborne laser rangefinders and their capability of penetrating tree foliage (e.g. Krabill et al. 1984, Moreau and Jeudy 1986). These advantages linked together with the capability of on-line data capture without the necessity of human measurements make airborne laser profiling a most interesting method for topographic terrain survey.

Laser rangefinders for airborne use, being in production nowadays, are restricted for profiling along the flight path, whereas scanning lasers, covering an area to both sides of the path, are under construction. Despite these circumstances, which require more costs for flying, airborne laser profiling will be an economic method for several applications. These applications are not restricted to topographic mapping in forest areas. Laser profiling can be a first choice method for projects where photogrammetric measurements are difficult or very expensive (e.g. the coast-line control) and for time critical tasks when a digital terrain model should be evaluated immediately after the flight. Besides, some special hydrological and geological applications are described in literature (e.g. Hoge et al. 1980, Jackson et al. 1988).

Investigation of new methods for digital terrain data capture is the topic of a special research project at Stuttgart University. In sommer 1988 airborne laser profiling test flights were realized by the Institute of Photogrammetry at Stuttgart University in collaboration with the Institute for Flight Guidance and Control at the Technical University of Braunschweig, the Landesvermessungsamt of the state of Baden-Württemberg, the Meetkundige Dienst of Rijkswaterstaat in Delft and the Rheinische Braunkohlenwerke AG in Cologne.

Chapter 2 and 3 of this paper describe the main system components and their specific features. The subject of chapter 4 is the processing of the measurements and the derivation of coordinates for the laser-points. After that, some results of the test flights will be presented. Chapter 8 deals with the processing of the measured data in order to derive a digital elevation model.

2. AIRBORNE LASER RANGEFINDERS

For our tests we leased the laser rangefinder Model 501 SX from the producing firm Optech Inc., Canada. Some specifications of this type are compiled in table 1. The maximum range of this model is restricted to 500 m but other types with ranges up to 10 km are available too. Airborne laser rangefinders are capable to measure distances by reflection to virtually any remote surface without the necessity of special targets or retro-reflectors. The laser emits a beam of near infrared light from a pulsed semiconductor diode. The reflected energy from natural targets is variing from 10% - 30% for sand, 30% - 50% for vegetation to 50% - 80% for ice and snow (Optech 1987). The maximum range is dependend on the target reflectance as well as from weather conditions. A range registration of 0.0 m indicates a failure. This occurs in either of three cases : the target is too narrow or too far away or no reflections are received from the target surface (e.g. on smooth water surfaces).

The capability of the laser beam to penetrate the tree canopy for receiving ground reflections is one of the main advantages of laser profiling for topographic applications. As the emitted laser beam has a wavelength near the visible light, it is not able to permeate through the foliage of a tree like microwaves, but the energy of the laser penetrates a tree canopy through the gaps in the foliage. Thereby several returns of the emitted laser pulse will be

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Table 1 : Specifications of the airborne laser rangefinder Optech Model 501 SX

Wavelength	904 nm
Optical power	150 W in a 15 ns wide pulse
Beam divergence	2.5 mR
Range	10 - 500 m assuming target reflectance of 20% and clear weather conditions
Resolution	0.1 m
Accuracy	0.2 m
Measurement rate	1, 10 or 100 Hz by internal trigger any rate up to 2000 Hz by external trigger
Target discrimination	Distance reading computed from : first, last or last minus first return pulse
Data output	parallel binary (20 Bits) or asynchronous serial (ASCII) or analog
Size of sensor	260 mm * 180 mm * 120 mm
Size of control unit	260 mm * 190 mm * 150 mm
Weight of sensor	3 kg
Weight of control unit	3 kg

received as parts of the energy are reflected along the penetration of the light through the vegetation cover. The rangefinder is able to discriminate these returns. The registration of the first or the last return or the difference of them is selectable by the user. As for topographic applications only the ground reflections are of interest, the last return pulse will be selected and recorded.

3. HARDWARE COMPONENTS OF AN AIRBORNE LASER PROFILING SYSTEM

An airborne laser profiling system (ALPS) consists of a series of measuring, computing and recording devices which provide the necessary information for the derivation of the topographically relevant digital terrain data. The problem is to determine the position of the laser beam target point on the ground in a 3-dimensional coordinate space. Various solutions are possible, of which some realized system configurations are described in literature (e.g. Chapman et al. 1988). In the following the main system components of our realized ALPS will be presented briefly, except for the previously described laser rangefinder. Figure 1 gives an overview of the system.

All instruments were installed on board of the Dornier Do 28 aircraft of the Institute of Flight Guidance and Control. The measured data are sampled by the on-board computer of type PDP 11/73 and recorded on a high density magnetic tape. As the sampling frequency of the computer was fixed to 23 Hz and the planned velocity of the aircraft was about 50 m/s, the expected distance of the laser points within the profile is about 2.2 m.

3.1 Positioning by Global Positioning System (GPS)

A GPS receiver is able to determine the position of his antenna in a 3-dimensional geodetic coordinate system. GPS will be applied in two ways: for the calculation of the laser rangefinder positions and for the navigation of the aircraft along the desired flight path. As the precision of kinematic positioning using only one GPS receiver is about 20 m in the best case (Wells et al. 1986), which is far too low, the differential GPS mode was applied by utilizing a second GPS receiver on ground. Thus, as demonstrated by Frieß (1989), an accuracy of a few centimeter can be expected for the kinematic positioning in an aircraft .

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As for the navigation of the aircraft high accurate positions are required in real-time, the data of the stationary GPS receiver were transmitted by telemetry to the aircraft for a joint processing on-board. The Institute for Flight Guidance and Control developed a display indicating the pilot the actual offset of the aircraft from the planned flight path. The high accuracy potential of this kind of navigation can be demonstrated by the standard deviation of 15 m from staight lines obtained at the Gammertingen test flights. For the future a further increase of the navigation accuracy is expected when the results of the real-time differential GPS will be directly control the auto-pilot of the aircraft.

From the applied Sercel GPS receivers TR5SB the aircraft positions can be obtained every 0.6 seconds. This rate would be too low for positioning every laser spot so that an interpolation becomes necessary.

3.2 Attitude data from the Inertial Navigation System (INS)

Most realizations of ALPS use the INS for the determination of attitude and position. Because of the manifold systematic errors from non-modeled physical effects, an external control of the INS becomes undispensable. For that reason these ALPS realizations are operating in helicopters where the necessary zero-velocity updates are feasible every few minutes. A more sophisticated solution is the combined processing of GPS and INS data in a joint adjustment.

The INS in our ALPS is primarily required for the attitude measurements which are necessary for a high accurate determination of the laser beam orientation. The gyroscopically fixed platform Delco Carrousel 4 measures the attitude angles of the aircraft. A cheaper solution of the attitude determination is available : the INS becomes dispensable if the roll and pitch angles are directly measured by sensors implemented in the laser-system.

3.3 Visual control by a spotting camera

A camera, its axis parallel aligned to the laser beam, records permanently the surrounding of the laser profile. The measured laser-points can be examined in the pictures and the orientation of the laser beam can be checked at significant points in the laser-profiles assigned definitely to characteristic terrain features or man-made structures.

For the testflights a Rollei single-photo camera with picture size 6 x 6 cm^2 was used. The reason for this choice was the desirable stereoscopic evaluation by photogrammetric means. However, we made the experience that this kind of camera is impractical for use in an ALPS. The large number of incurred photographs cannot economically be evaluated and the necessity of the human interference contradicts the principle of a fully automatic system. For these reasons video-cameras or fully digital camera systems are recommended. Then an immediately link to computer-controlled processing becomes feasible.

4. PROCESSING OF ALPS MEASUREMENTS

The coordinates of the laser target points are calculated from the measurements of the GPS receivers, the INS platform and the laser rangefinder. This chapter deals with the calculation of the laser point coordinates out of the measurements, whereas in a second step these laser points are prepared for input in a digital terrain database (cf. chapter 8).

4.1 Pre-processing

The pre-processing of the raw measured data achieves the compilation of a consistent data set with a common time reference. This comprises the calculation of the GPS antenna positions from the sampled pseudo-ranges and phase measurements. Then the GPS positions obtained at each 0.6 seconds are interpolated to the 23 Hz frequency of the INS and laser registrations. Besides, the registrations of all instruments are inspected and obvious gross errors are removed (e.g. laser recordings with range 0.0 m).

4.2 Coordinate systems

The measurements of the ALPS instruments are related to different coordinate systems. The following explanations refer to the schematic sketch in figure 2, where the three coordinate systems of the ALPS are introduced :

1. The aircraft-fixed coordinate system defined by the main body-axis of the aircraft is moving along the flight path. This system plays a central part as with regard to it the locations of the instruments have fixed coordinates during all aircraft movements, except for deformations of the aircraft body during the flight.
2. The stationary GPS-receiver on the ground is the origin of a topocentric horizontal coordinate system in which the GPS measurements are evaluated. The positions $[X,Y,Z]_A{}^T$ of the on-board GPS-antenna are transformed into this system.
3. The attitudes (Roll,Pitch,Yaw) from the INS are defined as the angles between the aircraft-fixed system and the inertial coordinate system. The inertial coordinate system is defined by the local horizon at the starting point of the aircraft, where the INS is aligned.

4.3 Calibration and datum transformations

The different locations of the ALPS instruments within the aircraft and the three coordinate systems to which the measurements are related require some transformations. The parameters describing the calibration and the datum transformations are constant during the flight and must be determined in a calibration process. The most important parameters are :

1. The antenna offset vector $[dx,dy,dz]^T$ describing the different locations of the laser rangefinder and the GPS antenna in the aircraft-fixed system.
2. The laser-alignment angles (droll,dpitch) describing the angles between the axis of the laser rangefinder and the aircraft-fixed coordinate system. The laser rangefinder is mounted with a pitch angle of about 5 degrees so that the laser will point vertical to the ground during the flight.
3. The rotation angles (da,db,dc) representing the orientation between the inertial and the topocentric coordinate systems defined by INS and GPS.

Further calibration parameters (e.g. a scale factor and a constant for the laser ranges) are not yet considered in our tests.

4.4 Computation of laser target points

The coordinates of the laser target points are calculated in the topocentric coordinate system considering the above mentioned calibration parameters by the following equation :

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_L = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_A + R(da,db,dc) \cdot R^T(Roll,Pitch,Yaw) \cdot \left(R(droll,dpitch,0) \cdot \begin{bmatrix} 0 \\ 0 \\ S_L \end{bmatrix} - \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} \right)$$

$[X,Y,Z]_L^T$	Laser target point in topocentric system
$[X,Y,Z]_A^T$	Position of the GPS antenna in topocentric system
$[0,0,S_L]^T$	Measured laser range
$(Roll,Pitch,Yaw)$	Measured attitudes by INS
$[dx,dy,dz]^T$	Antenna offset vector in aircraft-fixed system
(da,db,dc)	Rotation of inertial system against topocentric system
$(droll,dpitch)$	Laser alignement angle
$R(...)$	denotes the Euler rotation matrix

4.5 Transformation in the state coordinate system

The coordinates of the laser-points are required in the state coordinate system rather than in WGS 84 or the related topocentric system. For that reason the transformation parameters between these systems are necessary (7 parameter transformation with 3 translation parameters, 3 rotation parameters and 1 scale factor). As these parameters are in general unknown, they can locally determined by GPS measurements at points which coordinates are known in the state system. At least the coordinates of 3 points are required in both systems.

For the test Gammertingen 11 bench-marks around the test area were determined in the WGS 84 and in the state coordinate system. As in the state system the plane coordinates and the heights above sea-level are separated, some assumptions about the geoid-undulations have been made using the quasi-geoid proposed by Lelgemann et al. (1982). An accuracy of the transformation of 0.05 m was achieved in the test area.

5. ALPS TEST GAMMERTINGEN

5.1 Description of the test area

The aim of this test was to investigate the capabilities of ALPS for topographic mapping especially in regions covered by forests. The test area Gammertingen was selected in collaboration with the Landesvermessungsamt of the state of Baden-Württemberg. The test area is situated near the village Gammertingen about 80 km south of Stuttgart. The landscape in the area ranges from deep valleys to nearly smooth tableland. A profile is plotted in figure 5. Table 2 summarizes some characteristics of the test area.

Table 2 : Characteristics of the test-area Gammertingen

Location	appr. 80 km south of Stuttgart
Size	6.0 km in west-east direction 2.4 km in north-south direction
Height above sea level	from 640 m to 805 m
Distance between the profiles	100 m in the northern part 50 m in the southern part
Total number of flown profiles	40 in longitudinal direction 4 in cross direction
Total number of measured laser points	78 060 points
Accuracy of the aircraft navigation	15.1 m standard deviation from straight lines
Average distance of all measured laser points within the profiles	2.9 m

The success of the test-flights was affected by the bad constellation of the GPS satellites caused by satellite 9 which was put out of action in August 1988. For that reason only in two short windows GPS measurements could be carried out. As the first GPS observation-window was required for the determination of the starting position of the aircraft, only about 90 minutes for the test flights were available on each day. The whole test area was flown during 3 days on 18th, 19th and 24th of August 1988. In figure 3 the flying path including the turns outside the test area are plotted. Despite very clear weather conditions during the testflights, the rangefinder did not reach the maximum range of 500 m. Signals were seldom received at flying heights above 400 m.

5.2 Ground-cover and reflectance

Within the selected area manifold ground covers are found. Typical for this region are the agriculture fields surrounded by bushes and low trees. On the other hand there are forests with coniferous and deciduous trees as well. All measured laser-points were classified according to 6 ground-cover classes by a human operator inspecting all profiles in an analytical plotter. A more detailed classification especially desired for the different kinds of forests could not be derived from the available aerial photographs. In table 3 the results of the classification is presented. In the column (2) the number of laser points with received reflection are listed, while the column (4) gives the number of the points where the laser received no reflection. The percentage values in column (3) present the contribution of each class to the total ground-cover. The reflectance, defined as the perecentage value of the received points against the total number of emitted points, is listed in column (5) for each class.

Table 3 : Ground-cover and reflectance in Gammertingen

Total number of recorded laser points	78 060	100.0 %
Number of points with received reflection	70 463	90.3 %
Points without reflection	7 597	9.7 %

(1) Ground-cover class	(2) Points with reflection n	(3) $n/\sum$ n	(4) Points without reflection m	(5) Reflectance $n/(n+m)$
Agricultural areas	38 877	55.2 %	805	98.0 %
Young and low coniferous forest	13 342	18.9 %	2 995	81.7 %
Old and high coniferous forest	8 146	11.6 %	1 813	81.8 %
Low deciduous trees and bushes	3 592	5.1 %	569	86.3 %
Old and high deciduous forest	5 957	8.5 %	1 015	85.4 %
Urban areas and waters	549	0.7 %	400	57.9 %

5.3 Penetration rates

A question of main interest is the penetration of the laser beam through the tree foliage. The penetration rate is the percentage value of the ground reflections versus the total number of received reflections. From other investigations (Krabill et al. 1984) is known that in forest areas the penetration rate varies greatly between 10% and 68% depending on coniferous or deciduous tree types and on winter or summer foliage.

In our investigations the decision whether a measured laser reflection refers to a ground point or a foliage point was done automatically by a computer program (cf. chapter 8.1); the human operator inspected the results only for reliability.

The penetration rates of the high deciduous and coniferous forests are given in figure 4. In addition to these results the rates in young and low forests were calculated. For the young coniferous forests a penetration rate of 30.3 % and for the low deciduous trees and bushes a penetration rate of 43.8 % was obtained. These high rates in the low and very dense forests seem to be not very reliable because from inspections in the terrain no penetration in these forests was expected. The high rates produced by the algorithm indicate some problems of the identification of the real ground points in low and dense forests, but that problem occurs for the automatic process as well as for an human operator.A further figure carried out from the laser-test flight Hambach should be anticipated here. In the coniferous forests at the periphery of the mine a penetration rate of 21 % was reached. Consequently every 5th measured point can be further used for terrain modelling.

As the test flights were realized in summer under the most unfavourable vegetation conditions, a low penetration rate in deciduous trees was expected. The obtained rate could be increased to about 50 % on winter conditions (Krabill et al. 1984). With the low measurment frequency of only 23 Hz, in some parts of the laser profiles no or too few ground reflections were obtained. For that reason a ten-times higher frequency, at least, is desired for future tests. The dependency of the penetration rate on several possible parameters like the laser energy or the pulse frequency must be the subject of further investigations.

6. FURTHER ALPS-TEST FLIGHTS

On September 7th, 1988 two further test flights could be realized. In contrast to the Gammertingen test where the investigation of the capabilities of ALPS for the derivation of DEM in forest areas were of main interest, here the investigation of the laser reflections on different kinds of surfaces were the aim of the tests. For that reason these test flights were not planned to cover a whole area but only some selected profiles were flown.

6.1 Hambach

The Rheinische Braunkohlewerke AG is running the Hambach opencast mine for the exploitation of lignite. The mine is located in the lignite revier of West-Germany to the west of Cologne. The bulk of the exploited materials and of the overburden layers must be determined by continuous control measurements. This is mainly done by periodical photogrammetric flights. The measurement and evaluation of the aerial triangulation and ensuing derivation of digital terrain models is a time critical task as the results of the volume determination are directly used for the control of the further exploitation by the bucket-wheel excavators. The capability of fully digital terrain data capture and the automatic evaluation qualifies ALPS for this application. The ALPS tests therefore met great interest at Rheinbraun.

A 10 km long profile along the whole Hambach mine was selected for a four-times repeated flight. The colour spectrum of the essential materials in the Hambach mine are variing from bright colored sand and gravel to the dark lignite. The terrain height within the profile varies from 230 m above sealevel to -103 m under sealevel within a distance of about 1 km. This extreme height difference were a great challenge for the pilot of the aircraft, especially as some light haze in the mine reduced the maximum range of the laser rangefinder to about 350 m. For this kind of application a more powerful laser is recommended.

An important result is that the laser rangefinder received reflections from all types of the materials in the mine. One exception must be mentioned : no reflections were received over the smooth water surface of a sewage purification plant in the periphery of the mine.

6.2 Rotterdam

A third test flight was carried out at the Netherlands Channel-coast near Rotterdam. To control the coast-line every year profiles in cross direction to the coast-line are measured by the responsible authorities. This control measurements by terrestrial as well as photogrammetric means are expensive because of the involved difficulties. For this reason the Meetkundige Dienst van Rijkswaterstaat is looking for new possibilities to cope with these tasks. As the ALPS could be one potential solution the behaviour of the laser over the sea and over beach and wetland areas was investigated.

Within the 1 hour flight a profile of 10 km length, along the beach and back on the wetland and some loops over the sea including also some sandbanks were flown. The test took place outside of a GPS-window so that the positions are determined roughly from the INS only. This is sufficient for the classification of the laser points.

It is one of the most promising results of this test that reflections could be received from each kind of ground surface even in areas being expected to be difficult for the laser like the sandbanks and the open sea. The reflectance of all 40000 measured points within the test area is analysed. At 29540 points (= 73.9 percent) a laser reflection was recorded. A closer inspection of the failures shows a relation of the attitude of the aircraft with the reflectance of the laser. In the sharp turns over the sea roll angles to a maximum of 30 degrees took place. Within the range of 5.0 degrees roll angle 64.7 percent of the points with received reflection are recorded while 80.5 percent of the failures are outside this range. Concerning all points within 5 degrees rolling a reflection rate of 94.9 percent is obtained. The analysis of the reflectance in dependence on the attitude also indicates a limiting factor for scanning lasersystems.

The results of this test confirm the information given by the manufactorer that the reflectance on water strongly depends on the roughness of the water-surface. The laser worked excellent in the presence of waves whilst from the smooth inland waters no reflection could be received.

7. ACCURACY INVESTIGATIONS

The accuracy investigations are focused on two aspects : the estimation of the range measurement accuracy of the laser rangefinder and the analysis of the absolute accuracy of the laser-point coordinates. The measurement accuracy can be estimated from the measured laser-ranges or from the Z-coordinates of the derived laser-points, if a smooth flight path and a mainly vertical orientation of the laser beam can be assumed. In contrast to that, the absolute accuracy of the laser-points is examined by independent photogrammetric or terrestrial measurements. In this case the accuracy and the calibration of the whole system is checked.

7.1 Measurement accuracy of the laser rangefinder

The accuracy of the laser measurements has been estimated by analysing flat parts of terrain profiles. When we assume that the terrain can be approximated by a linear regression then the deviations from the fitted straight line are interpreted as the measurement noise. The results presented here are obtained by a more sophisticated way: the terrain profiles are modelled by stochastic processes and the measurement accuracy is estimated by variance-component estimation technique (Lindenberger 1987).

Table 4 : Estimation of the accuracy of the measured laser ranges

Analysed profile in the region	Estimated standard deviation of measurement noise
Meadow in Gammertingen	0.07 m
Ground surface of Hambach mine	0.14 m
Wetland near Rotterdam	0.07 m

The flat meadow in the valley near Gammertingen is excellently suited for such investigations. Table 4 shows the estimated accuracies in this region together with the results of selected profiles from the Hambach and Rotterdam test-flights. From the Hambach flight a part of a profile at the ground surface of the mine was selected. This profile is not as smooth as the others because of the deep traces of the bucket-wheel-excavators. The profile from Rotterdam is a very flat part over the wetland. In contrast to the other regions the original measured laser-distances and not the derived terrain heights are analysed here. The figures demonstrate the high accuracy potential of the laser rangefinder. With this results we can proceed on the assumption that the measurement accuracy of the laser rangefinder is fairly within the limits of 0.2 m indicated by the manufacturer.

7.2 Absolute accuracy of the laser-points

The flights from Gammertingen only were intended for a accurate analysis, as the geodetic datum for the transformation of the GPS coordinates in Hambach are determined in an approximative manner and the positions from Rotterdam are from less accurate INS measurements. However, it became obvious already during the flights in Gammertingen that the desired accuracy of positioning could not be reached because of the bad satellite constellation. In addition, the low elevation angles of the satellites (partially less than 10 degrees) caused some loss of lock to the satellites when the GPS antenna at the top of the aircraft came into the shadow of the aircraft wing during a turning circle. This happened although the pilot attempted to turn without rolling the plane. The loss of the satellite contact causes an ambiguity of the GPS-phase measurements. Then the subsequent positions are evaluated from the less accurate pseudo-range measurement. Therefore, precise absolute positions of the profiles are not possible.

Photogrammetric control measurements of complete profiles demonstrated a high accordance of the laser profiles to details in the terrain. However, the laser profiles were shifted against the terrain coordinates. The coordinate shifts could be measured at definitely identified terrain features. These so-called topographic checkpoints can be details of buildings, brooks or isolated trees. Along the flight path a shift-component of about 40 m with alternating sign according to the flight direction was observed. The shift across the flight path was about 1 m and in height about 5 m. Assuming the shifts being essentially constant within one profile, the orientation of each profile can be improved by the measurements at the check-points. In this way the laser profiles were processed for the derivation of the DEM (cf. chapter 8.3).

The most cruical error component pointing along the flight direction is mainly forced by two effects. The calibration of the laser beam alignment was done only roughly in the hangar due to the pressure of time. The second effect is originated by a time delay caused by the processing and recording of the GPS-signal. The receiver requires in the order of 0.4 sec until the signal is physically available at the output and can be recorded (Jacob 1989). During this time the position of the aircraft is moving about 20 m producing an systematic error in the coordinate along the flight direction. This effect is characteristic for the realized ALPS and is not considered at the actual status of the evaluation. In addition to that, the interface between the GPS-receiver clock and the computer-clock caused some typical synchronization errors.

8. DERIVATION OF A DIGITAL ELEVATION MODEL

The derivation of a digital elevation model (DEM) will be the final product of a ALPS mission. However, this was not the aim of our test flights in summer 1988 where primarily the system components of the ALPS were tested. Nevertheless, some aspects of data processing for the derivation of a DEM shall be outlined.

8.1 Processing of wooded areas

In wooded areas a cluster of reflections from the tree foliage and the ground-surface are obtained, even when only the last returns of the laser pulses are recorded. As for further evaluations only the ground profile is of interest, the ground reflections must be separated from the reflections in the trees. Figure 6a shows a part of a profile from a coniferous forest in Hambach with all recorded measurements. The clusters of reflections are clearly visible. By the way, the tree heights cannot be determined reliably from the data when recording the last laser returns only.

An automatical separation of the ground points can be obtained by calculating the envelope of the clusters. The proposed algorithm is based on morphological operations which are primary developed for digital image analysis (Haralick et al. 1987). With the operations OPEN and CLOSE the top and the bottom envelope of the reflection cluster are extracted. All laser points lying on the bottom envelope within a chosen bandwidth are selected for the ground profile.

The comparison of the ground profiles selected by a human operator with the results of the automatic algorithm demonstrates a reliable separation of the ground and foliage reflections. In some regions, especially when impenetrable brushwood covers the ground surface, the algorithm as well as the human viewer fail by identifying foliage points wrongly as ground points. In such cases further information is required.

8.2 Filtering of laser profiles

The preparation of the laser profiles for their input in a digital terrain database includes the filtering of the measurements. The filter process improves the quality of the results in a considerable way. Application of terrain profile analysis (e.g. Lindenberger 1987) is recommended. The main effect is the elimination of the observation noise. With an adequate algorithm outliers in the laser profiles can be detected and rejected.

8.3 Reduction of laser profiles

The distribution of the laser points with their high density along the profile is disadvantageous for the derivation of a DEM. If the ratio of the distance of the profiles to the points within the profiles is too large the derived DEM will become inaccurate and not representing the real terrain. For this reason the number of laser points must be reduced. This reduction can be done again by a digital terrain analysis. Then the characteristic terrain features are retained.

Some figures from the Gammertingen test shall be presented. The average density of the points within the profiles is about 2.9 m. After the selection of the ground points in the forest areas the average density in the whole area is reduced to 4.2 m. As this density is far too high a reduction factor 5 was chosen. After the reduction with retaining the characteristic points an average density of 14.8 m was obtained. Figure 6b shows the profile of figure 6a after processing.

8.4 Calculation of the DEM

In the southern part of the test-area with 50 m distance between the profiles a DEM was calculated from the filtered and reduced ground points. In this area the total number of measured laser points is 52702, thereof 29086 points are selected as ground points. After the reduction 9580 points are retained which are the input for the DEM derivation with SCOP. Figure 7 shows the derived contour map in the scale 1:25000.

9. CONCLUSIONS

The laser rangefinder fulfilled all expectations except for the maximum available range and exceeded the expectations concerning the range measurement accuracy and the reflectance on various kinds of ground surface. Some questions like the dependance of the penetration rate in forests on the emitted laser-energy and the pulse rate remain open and will be the subject of further investigations.

In contrast to the excellent performance of the laser rangefinder the integration of the ALPS hardware-components including the calibration of the instruments represents a more difficult problem. This problem has to do with the fact that the leased laser rangefinder was available only for a few weeks where only a limited number of test could be carried out. The necessity of visual control became evident for the measurement of check-points, the identification of peculiar laser points and the classification of the ground surface. The installed single photo camera will be replaced by a video-camera. Future test flights will consider the gained experience for a improved system design.

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ABSTRACT

Airborne laser-profiling provides a new approach to the topographic terrain data-capture. In addition to a laser-rangefinder the airborne laser profiling system (ALPS) comprises a GPS receiver and a inertial navigation system for the orientation of the laser beam. A main advantage of the ALPS is its capability to penetrate the tree canopy, so that the ground surface can be measured in forest areas. Costly and time intensive manual measurements are superseded by the fully digital data capture and evaluation.

In summer 1988 test flights in three regions have been realized. The evaluation of the tests was mainly focused on the analysis of the laser reflections at various kinds of natural surfaces, the determination of the penetration rates in forests and the estimation of the accuracy of the measurements.

VERSUCHSERGEBNISSE VON LASER-PROFILMESSUNGEN ZUR TOPOGRAPHISCHEN GELÄNDEAUFNAHME

ZUSAMMENFASSUNG

Laser-Profilmessungen sind ein neues Verfahren zur topographischen Geländeaufnahme. Vom Flugzeug aus werden mit einem Laser-Abtastsystem Geländeprofile gemessen. Dabei besitzt der Laser die Fähigkeit, in Waldgebieten direkt die Waldbodenoberfläche zu messen. Ein Laser-Abtastsystem besteht im wesentlichen aus einem Laserdistanzmesser zur reflektorlosen Messung der Strecke zur Erdoberfläche, einem GPS Empfänger und einem Inertialsystem zur Orientierung des Laserstrahls. Kosten- und zeitintensive manuelle Messungen sind durch die vollständig digitale Datenerfassung und Auswertung entbehrlich.

Im Sommer 1988 wurden in drei Testgebieten mehrere Versuchsflüge durchgeführt. Die Auswertung dieser Flüge konzentrierte sich auf die Untersuchung des Reflexionsverhaltens des Laser an verschiedenen natürlichen Oberflächen, die Bestimmung der Durchdringungsraten in Waldgebieten und die Schätzung der Meßgenauigkeit des Laser-Profilsystems.

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Figure 1 : The airborne laser profiling system ALPS for topographic terrain survey

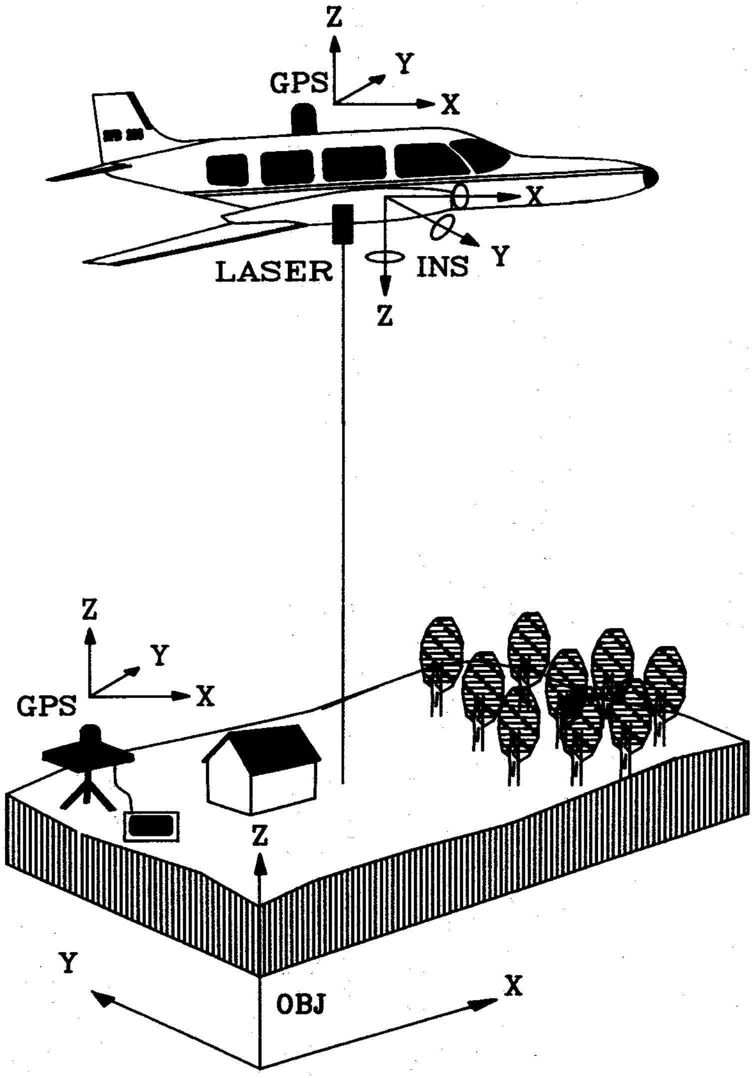


Figure 2 : Schematic sketch of the coordinate systems and measurement elements of the ALPS

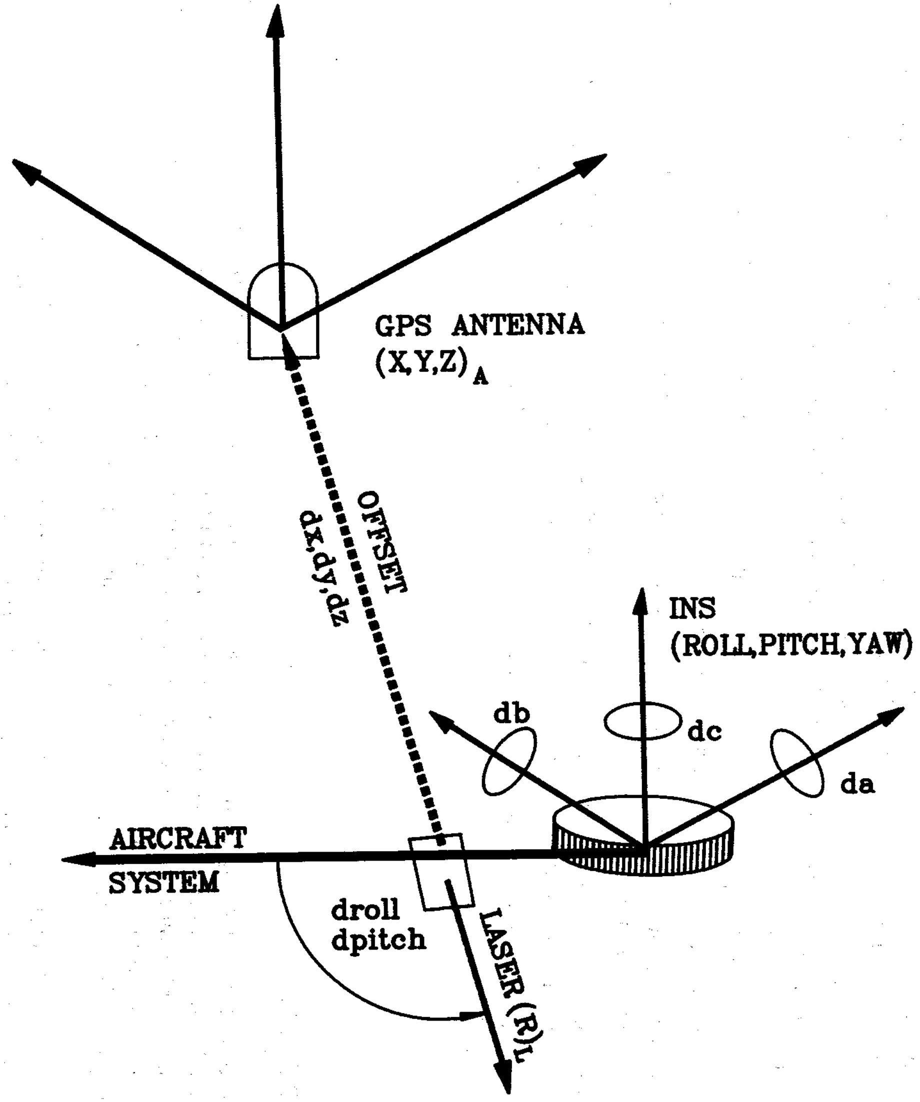


Figure 3 : Flight path of the ALPS-test Gammertingen

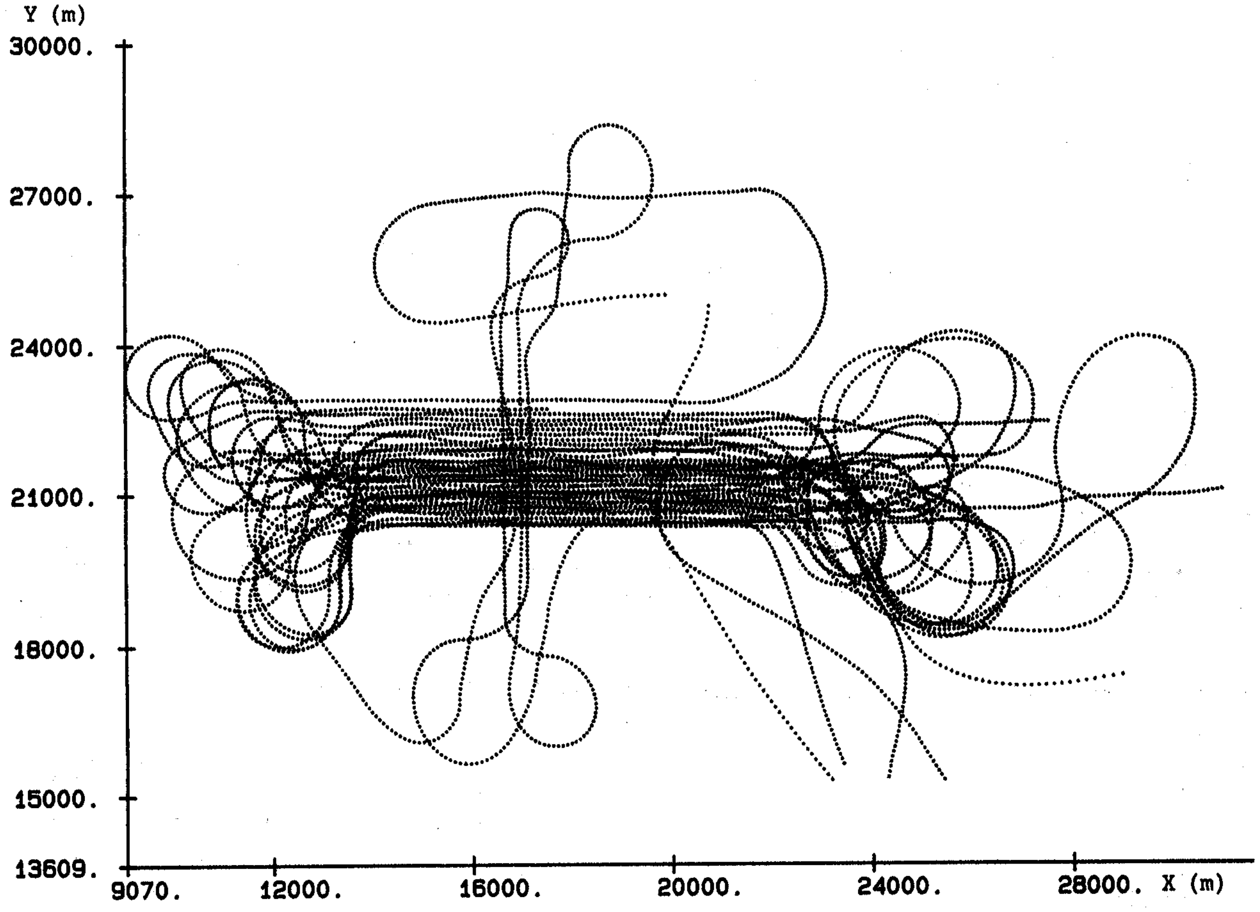


Figure 4 : Penetration rates in forests

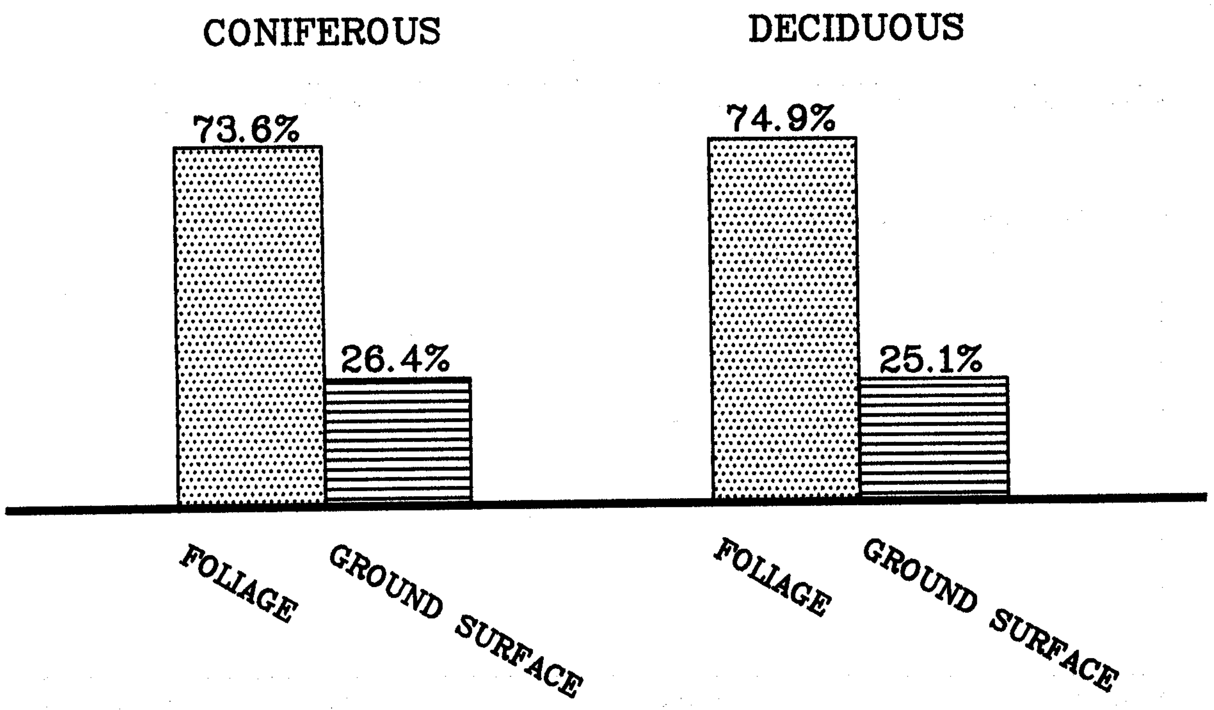


Figure 5 : Example of a profile from Gammertingen

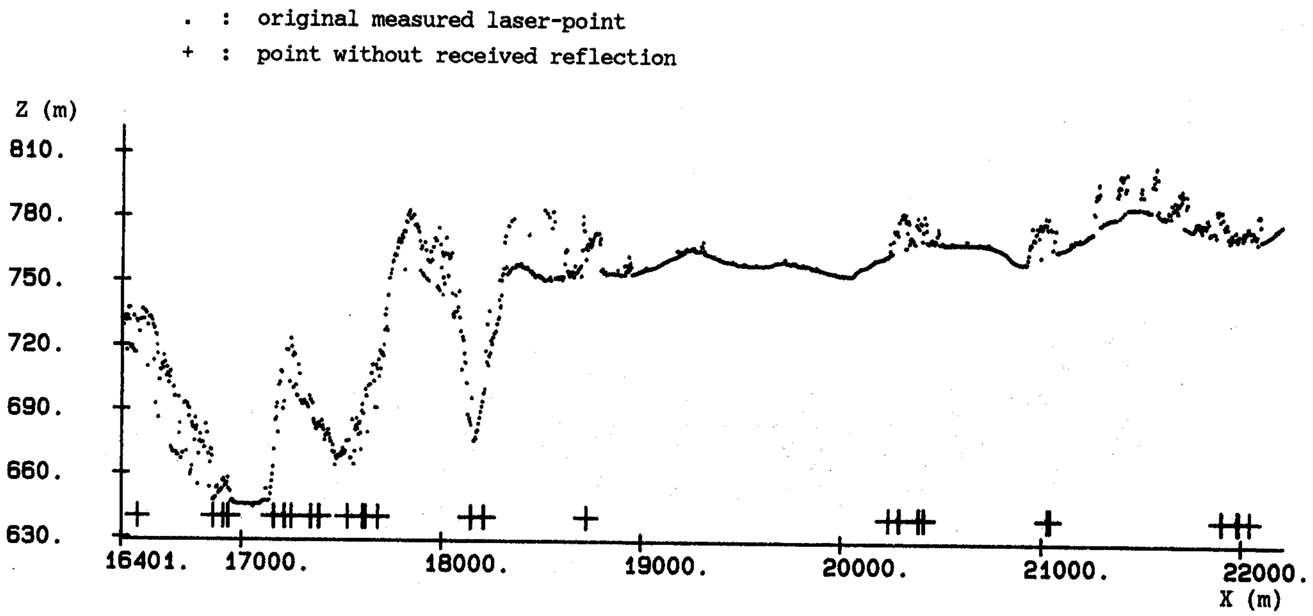


Figure 6a : Measured laser-points in a coniferous forest from Hambach flight

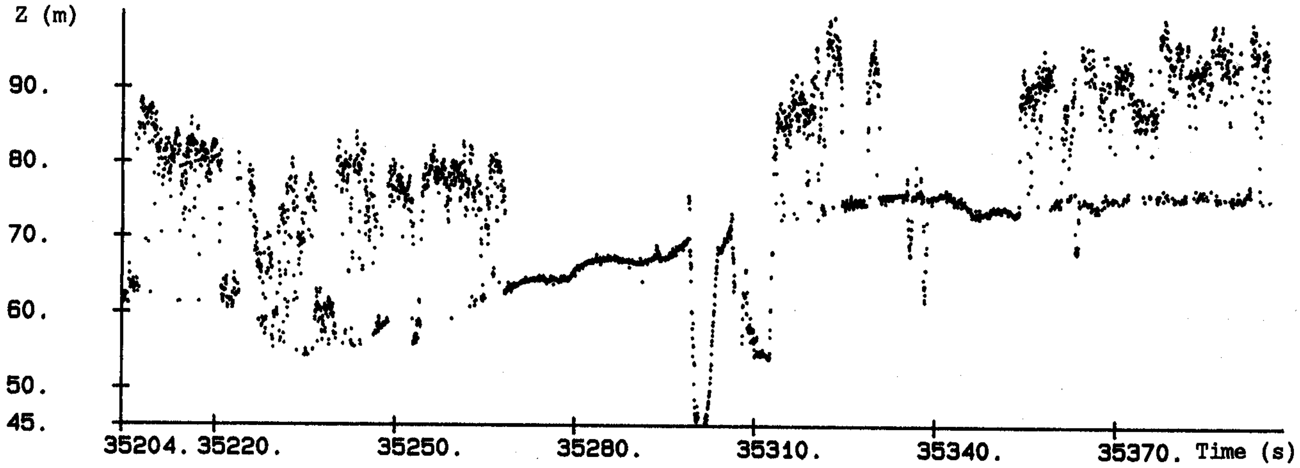
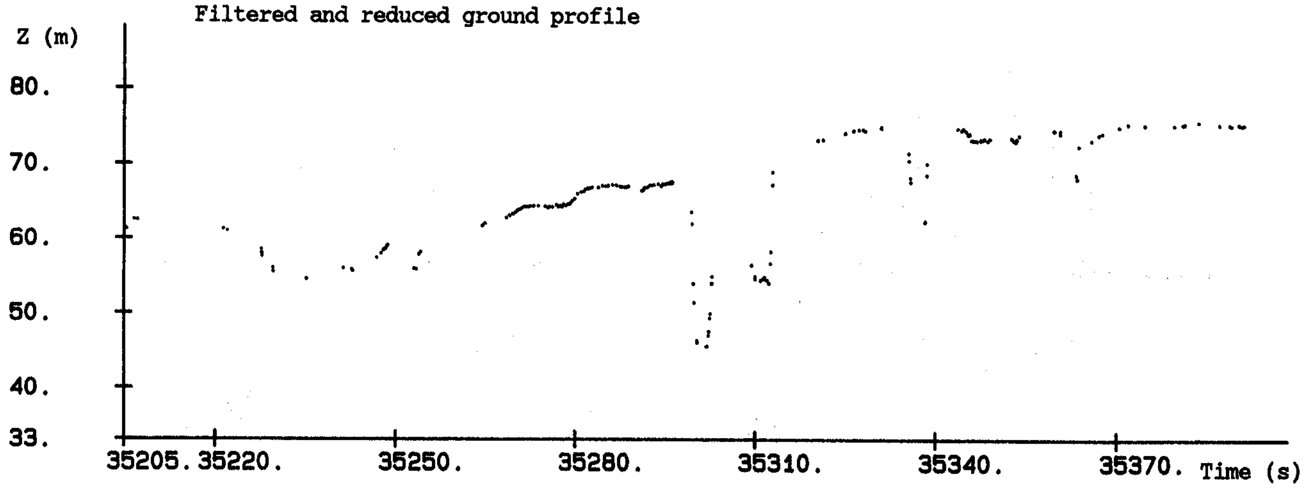


Figure 6b : Same profile after processing
Filtered and reduced ground profile



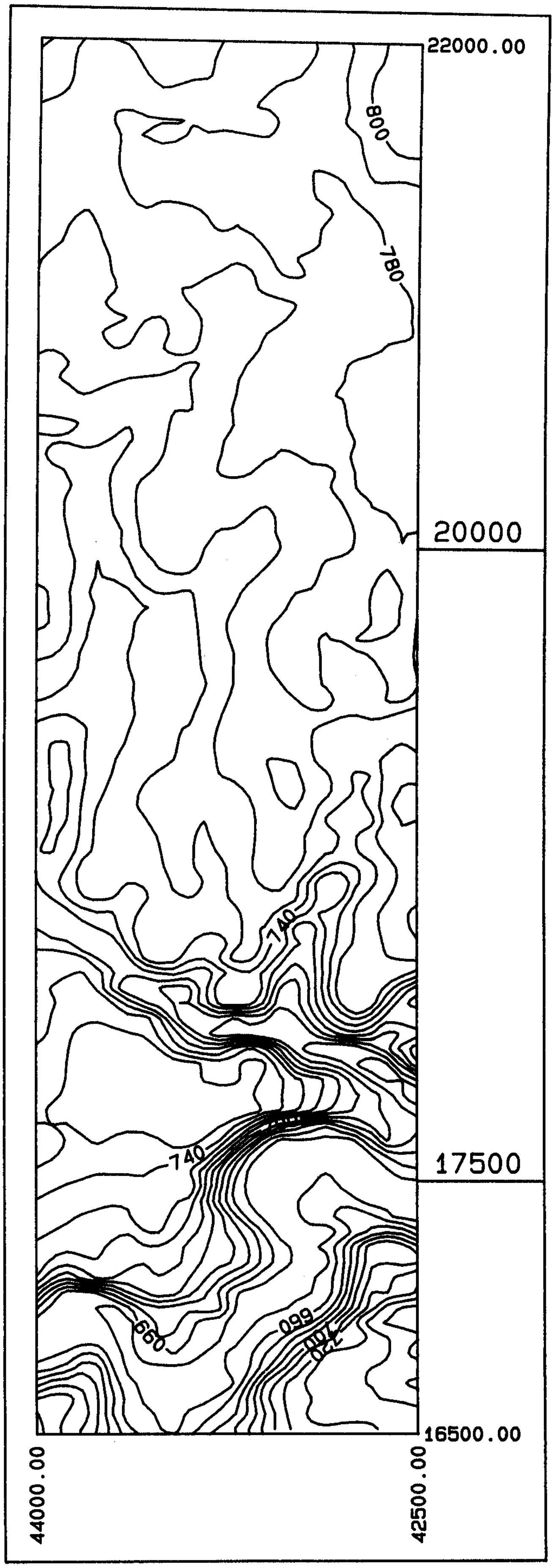


Figure 7 : Contour map from Gammertingen test-area
Digital elevation model computed from ALPS measurements
Scale 1 : 25 000