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Calibrating an Airborne Laser Profiling System

Height measurements with a near infrared airborne laser profiling system gave results that are equal to and in some cases better than measurements made by conventional photogrammetric and ground survey methods.

Abstract: *Tests were carried out with a near infrared laser profiling system to determine its capabilities in measuring terrain and tree height variations by remote means. The laser, combined with an inertial navigation system and a photogrammetric camera, was flown over the Canadian NRC Photogrammetric test site near Sudbury, Ontario, and over plantation forests at the Petawawa National Forestry Institute, and the laser heights were then compared with those determined photogrammetrically and from ground surveys. Using data from independent flights, mean height differences between the airborne laser and the photogrammetric method were found to be between 1 and 24 cm with corresponding standard deviations of 61 to 90 cm. 95 percent of all laser data was within 1.80 m of the height determined by conventional photogrammetry. The laser data is more variable in relation to ground survey data and, depending on the vegetation density, the laser produces a trace of part of the vegetation canopy. The comparison in sparsely vegetated terrain was found to be good, giving mean values that differed by 18 cm and standard deviations that differed by 16 cm.*

Introduction

Laser technology is finding exciting new applications in airborne remote sensing, and successful uses of the laser techniques have been reported in bathymetry (Hoge *et al.*, 1980; O'Neil, 1980; Calder and Penny, 1980), atmospheric pollution measurements (Sharp, 1982), terrain height measurements (Krabill *et al.*, 1980), and tree height measurements (Arp *et al.*, 1982). This type of technology is of interest to terrain scientists because airborne profiling systems can provide digital terrain information quickly and accurately, and in a form suitable for direct input into digital terrain models (DTM's) and geographic information systems.

Published results on calibration and accuracies of such systems are few and it is the aim of this paper to

- Provide calibration results of a near infrared laser profiling system;
- Compare laser determined height measurements

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with those obtained by means of conventional photogrammetry; and
- Compare laser measurements with survey data of ground profiles.

Ground surveyors have used laser surveying instruments for a number of years, but the use of such systems in the airborne mode only started in the late 1970's. The most obvious applications are in terrain mapping and in tree inventory work over large and inaccessible areas, where conventional surveys cannot provide adequate data because of time and cost constraints. The laser systems are capable of producing accurate distance measurements, and it appears that the main constraint in the use of such instruments in the air is not the laser itself but the accuracy in determining the aircraft attitude and position during the flight (Link and Collins, 1981).

DESCRIPTION OF AIRBORNE LASER SYSTEM

The airborne system used in this research consists of four separate components: a laser, a photogrammetric camera, an inertial navigation system, and an airborne data acquisition system. Because of a lack of a suitable micro-data acquisition system, the Canada Centre for Remote Sensing ADAS System in a DC-3 aircraft was used. It should, however, be noted that the same results can be obtained more cheaply using a small aircraft and microcomputer system (McDonough *et al.*, 1980; Jepsky, 1983).

Airborne Laser. A low power gallium-arsenide laser profiling system built by Associated Controls and Communication Inc. (ACCI) was used for this project. The instrument operates at 904-nm wavelength, and has a pulse rate of 2000 pps and a peak output of 80 Watts. It is a prototype laser described in part by Mamon *et al.* (1976) and Jepsky (1981) and was modified for our research by Davis Engineering Ltd., Ottawa. The return pulse is detected by a silicon avalanche photodetector and amplified for distribution to time interval and peak amplitude processing. Return pulse time is established using a half amplitude detected circuit which issues a stop command to a fast interval counter. Amplitude is measured with a sample and hold circuit synchronized to the firing cycle.

Inertial Navigation System. The Inertial Navigation System (INS) used in this experiment is a Litton LTN-51 System which was modified to provide greater attitude resolution data than the normal production systems. A special connector was built so that the test port could be continuously monitored in order to acquire the working parameters of the LTN-51 at 50-millisecond intervals. This was necessary because the normal data output of the LTN-51 was of limited accuracy and had a very low update rate. These modifications are only of historic interest now because the LTN-51 is no longer in production and newer systems available provide more timely and accurate data in digital format and on the standard ARINC busses (Gibson *et al.*, 1981).

A special hardware mount was constructed to enable a rigid connection between the LTN-51, the photogrammetric camera, and the laser in order to have a common reference axis.

Photogrammetric Camera. A Wild RC-10 camera (focal length 151.99 mm) was mounted on the same platform as the laser to provide ground coverage and to facilitate the determination of the actual flight path and laser footprint position. Provisions were made to measure both the camera exposure time (INS accuracy) and the pulsed laser signal so that the laser signal corresponding to the image focal center could readily be identified.

Airborne Data Acquisition System. The CCRS-Airborne Data Acquisition System (ADAS) was used and an overview of the system is provided in Figure 1. This system is not entirely adequate for the type of data generated by the laser. ADAS accepts only 100 pulses per second (pps) while the laser produces 2000 pps. Interface modifications made by Davis Engineering Ltd. allowed data recordings at 2.5-ms intervals. This means that only every fifth laser pulse was recorded. For our tests this proved to be adequate, but in very dense forests a higher data acquisition rate might be needed for sufficient penetration of the forest canopy.

CALIBRATION TESTS

Laser footprint measurements and boresighting tests were carried out both on the ground and in the air. The airborne tests took place at the Canadian NRC Photogrammetric Test Site near Sudbury, Ontario and over plantation forests at the Petawawa National Forestry Institute in Chalk River, Ontario. The NRC test site is the most intensively surveyed area in Canada and, because it is covered with very sparse vegetation, was found to be excellent for laser tests.

Laser Footprint Measurements. The size of the laser beam on the ground is a function of distance to the target. To measure the footprint, the laser was leveled horizontally on the ground and a pegboard grid (2.5-cm rectangular grid, painted flat black) was placed at a distance of 290 m. Retro-

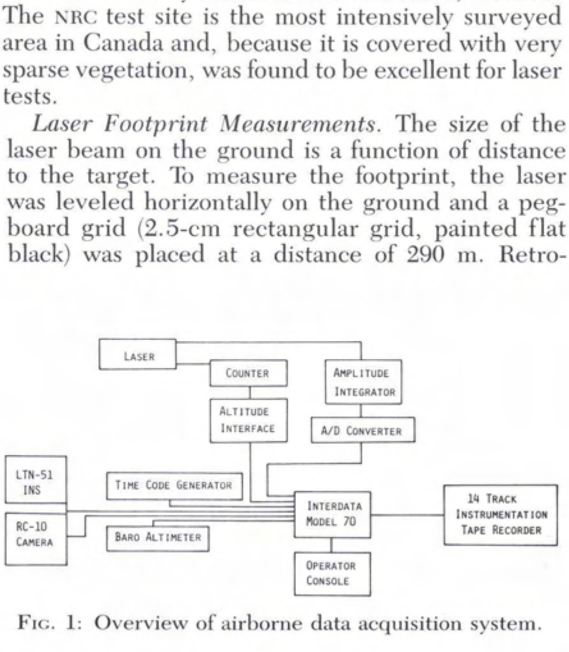

FIG. 1: Overview of airborne data acquisition system.

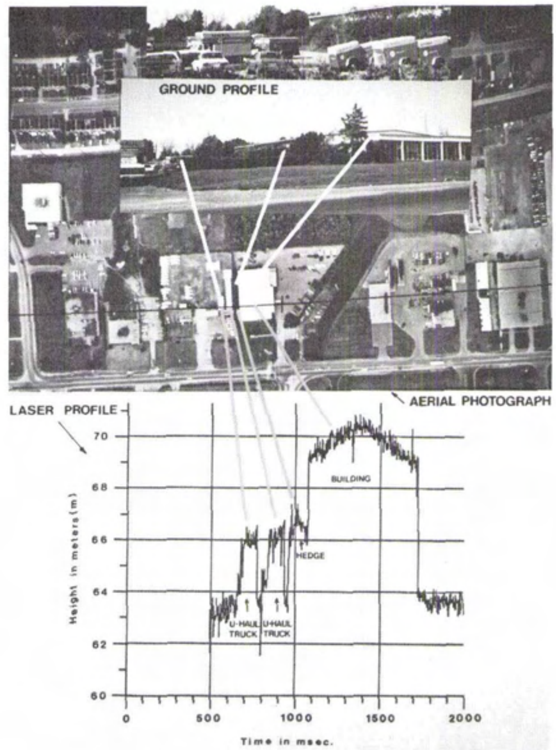

FIG. 2. Laser trace along flightline.

reflective targets (small bicycle reflectors) were used on the grid to seek the footprint. Return beam strength was measured by an oscilloscope connected to a buffer video output. To avoid saturation of the receiver, the receiving lens was partially masked. Relative amplitude was mapped on a grid corresponding to the target placement. The beam is best characterized as a 50-cm diameter circle at the half-power points, with a flat top (ripple <20 percent) and steep drop-off beyond the circle (response is <10 percent beyond 70 cm). These measurements were made using a target masked off to expose 0.6 cm in the pertinent direction of grid movement. Indirect measurements over known targets (tubular structure of an overhead sign on a freeway) also confirmed that subjects of approximately 50-cm size are recorded (Schreier and Lougheed, 1983).

Boresight Measurements. A number of tests were carried out to determine the position of the laser spot relative to the photogrammetric camera. Using time exposure photography during night flights over selected targets proved to be unsuccessful because of low ground reflectivity at 904 nm, low sensitivity of the #2424 IR film at 904 nm, and because the average power of the laser is apparently too low for such tests. Calculation of boresights was attempted but was judged inadequate, and indirect boresighting tests were carried out over known targets.

Targets such as the U-Haul trucks illustrated in Figure 2 were clearly identified from the air with the laser trace. However, the only reliable indirect boresighting test is one in which the target is captured at the photo focal center. Successful results were obtained during a Petawawa flight where the focal center in one image occurred immediately to the right of the canopy of a single tree in a meadow. The recorded laser frequency during that flight was 6.7 pulses per one metre on the ground. The labeled laser pulse which coincides with the exposure time occurred three pulses after the tree canopy, or approximately 45 cm to the right of the tree. Given the accuracy in determining the focal point on the photo and considering the 50-cm diameter footprint of the laser, it is evident that the boresight was adequate for our research.

Positioning of Laser Spot. The position of each laser spot on the ground was determined by first correcting the position data from the INS and then converting the laser range data to the local photogrammetric reference frame and adding it to the aircraft position. In previous projects vertical control for the aircraft and camera have been obtained through a combination of barometric pressure and vertical acceleration data corrected for off-set and drift error by means of photogrammetric control in post flight processing. Unfortunately, in this test the barometric pressure was not properly recorded so the vertical control for the laser data processing was derived entirely from the camera station data provided from the photogrammetric resections. Because the photogrammetry was acquired at approximately 3-second intervals, it was reasonable to fit a smooth curve through the camera station elevation and to use those data in place of the normally derived data.

Photogrammetric resections of each photograph were performed by Integrated Resources Photography Ltd. (IRP) to determine the aircraft position at each camera firing time. These data were then used to correct the position data from the INS. A cubic spline was used to compute the INS position errors using the camera stations as reference points. This enabled the errors between the camera stations to be interpolated so that the INS position could be corrected at every laser firing time. Then all that was necessary was to compute the location of the laser spot on the ground, given the aircraft position and attitude and the laser slant range. This calculation is given by the following vector equation:

$$\begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix} = \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} + \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ -r \end{bmatrix}$$

where $(X_G, Y_G, Z_G)^T$ is the computed ground location of the laser spot in UTM coordinates; $(X_A, Y_A, Z_A)^T$ is the aircraft position; the matrix with elements (a_{ij}) is the direction cosine matrix computed using the measured roll, pitch, and heading angles; and $(\epsilon_x, \epsilon_y, \text{ and } -r)^T$ is the measured slant range data from the laser, with ϵ_x and ϵ_y being range proportional components due to misalignment of the laser and camera axes.

Because the laser is rigidly mounted to the aircraft frame, the laser measurement is made in the aircraft coordinate reference frame and the laser measurements were then transformed into the local UTM coordinates; hence, the requirement for the direction cosine matrix.

The changes in the Easting and Northing position of the laser spot due to aircraft attitude changes are given in Figures 3 and 4. At a flying height of approximately 300-m above ground level, the laser spot may easily move by as much as 30 m in 10 seconds with respect to the aircraft. If the profiler is to be used for accurate measurements over rough terrain, it is essential that the aircraft attitude be taken into account when computing the track of the profile.

Figure 5 illustrates how the height calculations of a profile may be affected by aircraft attitude changes. The changes in height have much smaller magnitudes than the changes in position; however, it may be seen that uncompensated attitude changes could result in height errors of almost 1 m. This is several times as large as the measured errors of the laser range data. At a flying height of 1000 m, the changes would be over three times as great as those portrayed in Figures 3 through 5, and the potential height accuracy of a profiler would be severely degraded if the attitude corrections were omitted.

An alternative to using the inertial system for measuring the attitude would be to place the laser on a stabilized platform; however, there are still accuracy, platform stability, and cost trade offs to consider.

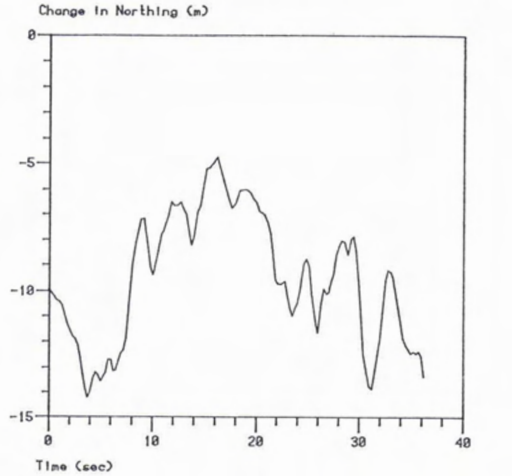

FIG. 4: Changes in Northings of laser spot in relation to aircraft position.

COMPARISON BETWEEN LASER AND PHOTOGRAMMETRY

Using the Canadian NRC ground survey control data, height variations were determined photogrammetrically using aerial triangulation of analog restitution with a Wild A-10 autograph plotter. More than 600 measurements were made at or near the laser footprint path in each of three independent flight lines, and the laser points that showed the closest match with the photogrammetric points in both Northing and Easting position were then selected for height comparisons.

Similarly, height variations were measured photogrammetrically along one flight line and the corresponding laser points at right angles to the flight line were then selected for height comparisons. This

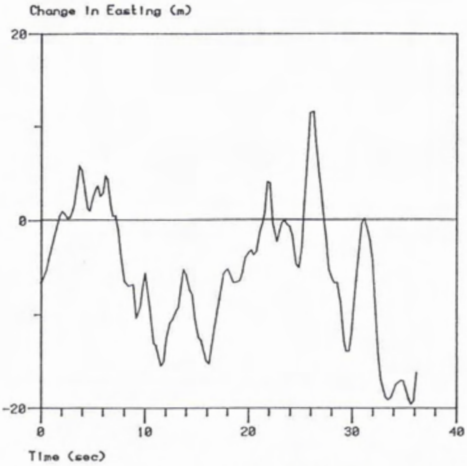

FIG. 3: Changes in Eastings of laser spot in relation to aircraft position.

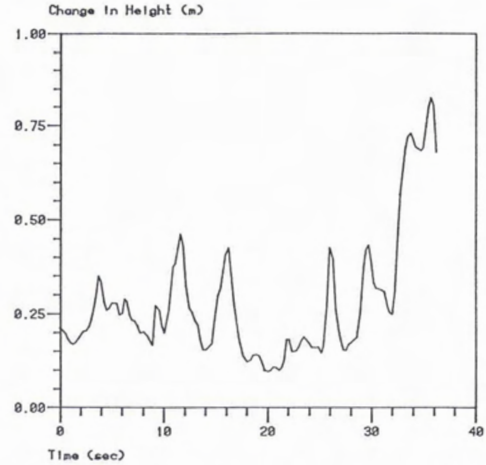

FIG. 5: Effect of aircraft attitude changes on height measurements.

indicated the potential height error obtained between the laser and photogrammetry without the use of INS (uncorrected position).

COMPARISON BETWEEN LASER AND GROUND SURVEYS

Tests were carried out to compare ground surveyed micro-profiles with those derived by means of the laser profiling system. Two 90-m transects were chosen in the Petawawa test area, one on a sparsely vegetated sandy surface and one on a grass and fern covered surface. The laser signal is scattered by the vegetation and only relates to the actual ground conditions in areas where bare soil is exposed and where vegetation cover is sparse. We thus expect the laser profile to be offset by the height of the continuous vegetation cover.

The main problem is matching the initial starting point of the ground survey with the laser. Without a clear visible target, this point cannot be transferred from the photo to the ground within a 15-cm accuracy, which is equal to the distance between two consecutive laser points. We believe that we can locate the ground position within 1 m, and this means that the laser starting point can be one of six possible laser points. This error can be reduced by a fine adjustment once the laser and ground profile are matched.

The laser measurements were made for every 15-cm distance along the flight line, and with a 50-cm size footprint it is evident that every fourth laser measurement occurred on an entirely new surface. For this study we averaged four laser readings to represent the actual terrain height over a 60-cm horizontal distance. The laser values were then compared with the ground survey data at 60-cm intervals.

RESULTS

LASER ACCURACY IN RELATION TO PHOTOGRAMMETRY

Using the airborne data corrected for attitude position changes with INS, it was possible to match 323, 646, and 632 laser points with those determined by means of photogrammetry for the three test flights near Sudbury. An example of the computer generated data for flight line 1 is provided in Figure 6, and the summary of all data is reproduced in Table 1. It is evident from these results that the two methods produce height measurements which are closely related and which produced an overall mean difference of 11 cm. Considering the potential error inherent in both methods, the match is excellent. Using flight line 2 data, height deviations between the two methods displayed in Figure 7 reveal that large deviations occur at sporadic intervals, and

COMP#	EASTING		NORTHING		HEIGHT		DELTA			
	Photo	Laser	Photo	Laser	Photo	Laser	East	North	Height	Dist
172	4106.43	4106.65	5114.53	5114.91	253.78	253.30	-0.22	-0.38	0.48	-0.08
173	4108.28	4109.44	5114.09	5113.59	253.80	253.93	-1.16	0.50	-0.13	-1.16
174	4113.43	4112.32	5112.53	5113.23	253.95	253.63	1.11	-0.70	0.32	1.30
175	4115.23	4114.92	5112.03	5111.88	256.38	256.97	0.31	0.15	-0.59	0.36
176	4117.45	4117.81	5111.34	5110.31	255.15	255.48	-0.36	1.03	-0.33	-0.47
177	4119.11	4119.05	5110.87	5111.30	254.01	254.38	0.06	-0.43	-0.37	0.21
178	4121.66	4120.78	5110.61	5109.98	253.87	253.97	0.88	0.63	-0.10	0.83
179	4121.66	4123.66	5110.61	5108.75	253.87	253.89	-2.00	1.86	-0.02	-2.22
180	4126.20	4126.56	5109.39	5108.50	253.74	253.63	-0.36	0.89	0.11	-0.44
181	4130.62	4129.50	5108.35	5107.51	253.62	253.55	1.12	0.84	0.07	1.02
182	4133.22	4132.44	5107.64	5107.55	253.52	252.81	0.78	0.09	0.71	0.83
183	4137.45	4138.16	5106.64	5106.77	253.47	253.57	-0.71	-0.13	-0.10	-0.60
184	4142.13	4141.08	5105.48	5105.98	253.37	253.18	1.05	-0.50	0.19	1.19
185	4147.72	4146.83	5104.07	5105.23	253.44	253.30	0.89	-1.16	0.14	1.15
186	4149.83	4149.62	5103.55	5105.17	253.40	253.38	0.21	-1.62	0.02	0.57
187	4154.47	4152.46	5102.41	5104.24	253.41	253.43	2.01	-1.83	-0.02	2.38
188	4154.47	4155.26	5102.41	5104.16	253.41	253.59	-0.79	-1.75	-0.18	-0.39
189	4158.22	4158.03	5101.54	5102.92	253.39	253.48	0.19	-1.38	-0.09	0.51
190	4162.34	4160.80	5100.45	5101.83	253.44	253.65	1.54	-1.38	-0.21	1.84
191	4163.70	4163.55	5100.19	5101.55	253.42	253.42	0.15	-1.36	0.0	0.46
192	4165.35	4166.29	5099.63	5100.14	253.16	253.01	-0.94	-0.51	0.15	-0.75
193	4168.66	4169.02	5098.91	5099.84	253.42	252.71	-0.36	-0.93	0.71	-0.11
194	4171.85	4171.73	5098.08	5098.51	253.43	253.06	0.12	-0.43	0.37	0.27
195	4174.57	4174.38	5097.49	5097.92	253.39	253.46	0.19	-0.43	-0.07	0.34
196	4176.97	4177.12	5096.81	5096.49	253.49	253.24	-0.15	0.32	0.25	-0.14
197	4180.69	4179.88	5095.84	5096.26	253.36	253.00	0.81	-0.42	0.36	0.95
198	4182.13	4182.55	5095.50	5094.80	253.40	253.11	-0.42	0.70	0.29	-0.46
199	4185.90	4185.28	5094.70	5094.53	253.44	253.20	0.62	0.17	0.24	0.65
200	4188.75	4188.01	5093.95	5093.35	253.47	253.58	0.74	0.60	-0.11	0.69
201	4192.63	4190.77	5092.87	5093.05	253.47	253.44	1.86	-0.18	0.03	1.93
202	4192.63	4193.53	5092.87	5091.71	253.47	253.43	-0.90	1.16	0.04	-1.02
203	4196.33	4196.34	5092.02	5091.59	253.65	253.41	-0.01	0.43	0.24	-0.02
204	4199.60	4199.15	5091.33	5090.33	253.58	253.69	0.45	1.00	-0.11	0.33
205	4200.25	4201.99	5091.09	5090.22	253.58	253.63	-1.74	0.87	-0.05	-1.79
206	4205.38	4204.90	5089.83	5089.22	253.72	253.55	0.48	0.61	0.17	0.43
207	4210.00	4207.78	5088.72	5089.19	253.73	253.55	2.22	-0.47	0.18	2.34
208	4210.00	4210.67	5088.72	5088.20	253.73	253.82	-0.67	0.52	-0.09	-0.69
209	4214.78	4213.55	5087.43	5088.29	253.87	253.77	1.23	-0.86	0.10	1.44
210	4214.78	4216.37	5087.43	5087.12	253.87	253.90	-1.59	0.31	-0.03	-1.55
211	4219.19	4219.23	5086.38	5086.96	253.94	253.61	-0.04	-0.58	0.33	0.14
212	4225.44	4224.83	5084.81	5085.52	254.12	254.16	0.61	-0.71	-0.04	0.80
213	4227.62	4227.61	5084.26	5084.27	254.09	254.35	0.01	-0.01	-0.26	0.08
214	4231.13	4230.42	5083.61	5083.00	254.17	254.15	0.71	0.61	0.02	0.65
215	4233.66	4233.16	5082.93	5082.71	254.23	254.53	0.50	0.22	-0.30	0.53
216	4236.28	4235.94	5082.26	5081.36	254.36	254.27	0.34	0.90	0.09	0.23
217	4239.30	4238.66	5081.47	5080.96	254.54	254.44	0.64	0.51	0.10	0.61
218	4243.56	4241.33	5080.38	5079.48	254.64	254.41	2.23	0.90	0.23	2.10
219	4243.56	4243.99	5080.38	5079.09	254.64	255.21	-0.43	1.29	-0.57	-0.59
220	4247.59	4246.71	5079.50	5077.68	254.83	254.85	0.88	1.82	-0.02	0.59
221	4249.82	4249.34	5078.96	5077.18	255.19	255.32	0.48	1.78	-0.13	0.21
222	4252.47	4252.01	5078.28	5075.95	255.69	255.85	0.46	2.33	-0.16	0.08
223	4254.05	4254.64	5077.93	5075.79	256.07	256.87	-0.59	2.14	-0.80	-0.91
224	4257.67	4257.36	5075.96	5074.62	256.72	257.34	0.31	2.34	-0.62	-0.06
225	4263.57	4262.83	5075.58	5073.68	258.10	258.67	0.74	1.90	-0.57	0.44
226	4264.92	4265.61	5075.27	5073.81	258.70	259.58	-0.69	1.46	-0.88	-0.89
227	4267.95	4268.40	5074.57	5073.97	260.08	260.53	-0.45	0.60	-0.45	-0.49
228	4270.95	4271.15	5073.81	5073.13	261.70	262.20	-0.20	0.68	-0.50	-0.26

FIG. 6: Example of height comparison between laser and photogrammetric method (line 1).

TABLE 1. SUMMARY RESULTS OF COMPARISON BETWEEN LASER AND PHOTOGRAMMETRIC METHOD

	Flight 1	Flight 2	Flight 3
$\bar{x}$ Δ Height (m)	−0.05	−0.24	0.01
SD Δ Height (m)	0.61	0.64	0.90
Min Δ Height (m)	−2.90	−3.80	−4.72
Max Δ Height (m)	2.85	2.46	5.44
$\bar{x}$ Δ Easting (m)	0.02	−0.01	−0.62
$\bar{x}$ Δ Northing (m)	0.35	−0.45	−0.36
Number of Corresponding Points Used for Comparison	323	646	632

TABLE 2. COMPARISON OF LASER/PHOTOGRAMMETRIC HEIGHT WITH AND WITHOUT THE USE OF THE INERTIAL NAVIGATION SYSTEM (INS)

	Using Corrected Position With INS	Using Uncorrected Position Without INS
$\bar{x}$ height (m)	−0.24	−0.49
SD height (m)	0.64	1.12
Min height (m)	−3.80	−3.90
Max height (m)	2.46	1.75
Corresponding points used	646	477
Mean distance from flight line (m)		2.60
SD distance from flight line (m)		3.34
Maximum distance from flight line (m)		15.31

these can be in part attributed to interference by vegetation. A few small trees occur in several places along the flight line. Depending on density, the laser will include the vegetation canopy in the height measurement, while photogrammetry excludes the vegetation cover as much as possible in height measurements. The remaining differences are most likely caused by inaccuracies inherent in the photogrammetric method such as film shrinkage, uncertainties in the relative orientation of the stereo models, and operator pointing accuracies, as well as the position determinations of the laser footprint. The use of the laser without the attitude data from the inertial navigation system is also of interest and, as shown in Table 2, a comparison was made in one flight line between the laser height variations and the photogrammetric measurements along the flight line uncorrected for changes in attitude of the aircraft. The mean height difference between the two methods is approximately twice as large, and in the worst case the laser footprint is some 15.31 m from the flight line. Although the overall differences are still relatively small, this will not be the case in steeply sloping terrain, and it is recommended that one use INS corrections in order to obtain the best height accuracies from the laser.

From the photogrammetric test, it is clearly evident that the laser profiling system is as reliable as conventional photogrammetric techniques and under optimum flying conditions probably surpasses photogrammetric measurements.

We believe that the use of an older inertial navigation system (LITTON-51) did not seriously affect the outcome of the results, with the possible exception that the proper use of the vertical positioning data might have improved the match between laser and photogrammetric data between photo stations. Also, small increases in accuracy are anticipated with the use of new inertial navigation systems.

LASER ACCURACY IN RELATION TO GROUND SURVEYS

The two micro-profiles surveyed on the ground were matched up with the airborne laser profile and, as can be seen in Figures 8 and 9, the laser profiles are significantly more variable than the ground survey profiles. A fairly good overall match was obtained for the sandy profile (Figure 8) which showed a mean height difference between the laser and ground survey data of 18 cm (SD △ height, −16 cm, Max △ height, 63 cm, Min △ height, −53 cm). The laser profile from the grass/fern covered profile

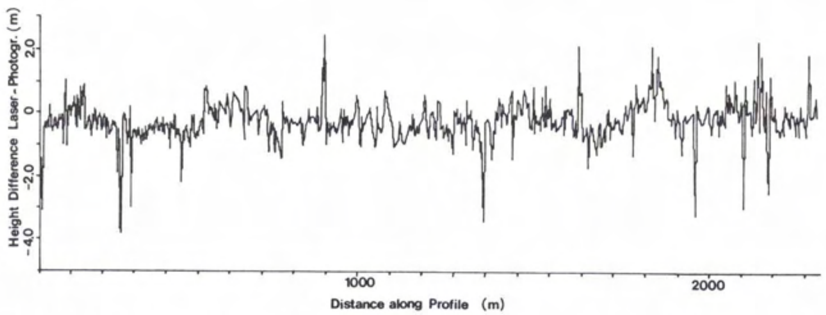

Fig. 7: Difference between laser and photogrammetrically determined height (flight line 2).

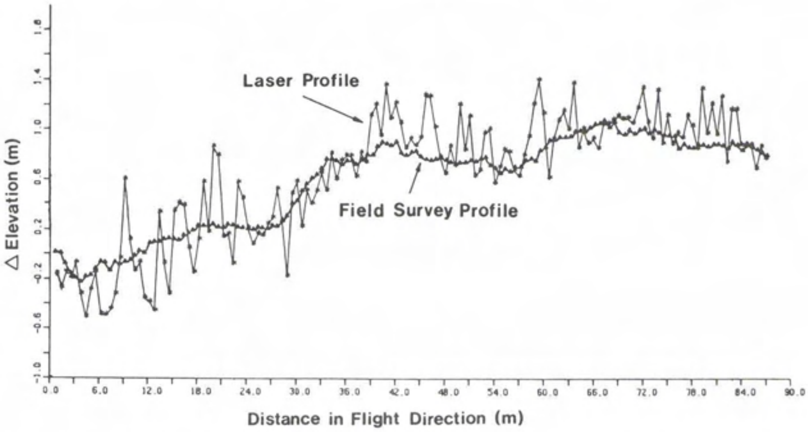

FIG. 8: Comparison between laser and ground profile (sparsely vegetated sandy surface).

is consistently higher than the survey profile (Figure 9). The mean difference between the laser and survey data was 33 cm (SD Δ height, 23 cm, Max Δ height, +114 cm, Min Δ height, −63 cm) and is attributed to the vegetation canopy which is traced by the laser system. The vegetation cover thus has a significant influence on the laser measurements, but at the same time it appears readily possible to measure vegetation height by subtracting the actual ground levels from the vegetation canopy, and this promises to be useful for tree height measurements in forestry.

CONCLUSIONS

Based on the results presented in this paper, the following conclusions can be made:

- Airborne laser height measurements compared favorably with those obtained by means of conventional photogrammetry. Mean differences between the two methods were less than 24 cm, and 95 percent of all laser points occurred within 1.80 m of those determined by means of photogrammetry.
- The aircraft positioning and the determination of the exact laser footprint position are critical in obtaining precise measurements. The use of an inertial navigation system is thus essential, particularly in steeply sloping terrain.
- Comparison between ground surveys and laser data revealed that the laser profile is more noisy than the field surveyed profile, and vegetation such as fern-grass ground cover results in an off-set between the laser and the ground profiles that is equivalent to the vegetation canopy height. Over sparsely covered surfaces the overall height comparisons were good, giving mean height differences of 18 cm and a difference in standard deviation of 16 cm.
- Finally, it has been shown that the laser profiling system produces height measurements on the same order of accuracy as conventional methods. The laser method, however, has the advantage of producing the data more efficiently and in a form for direct input into DTM's and geographic information systems.

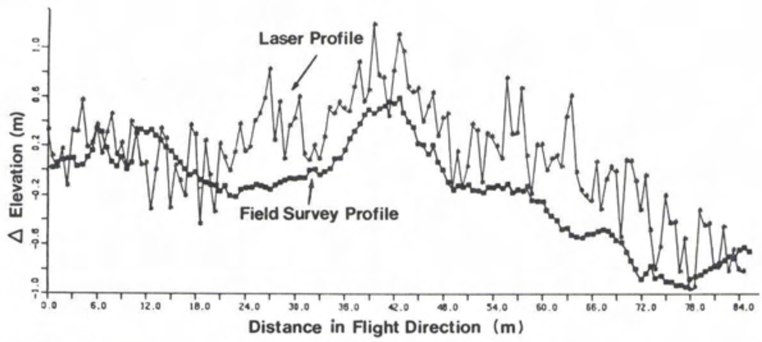

FIG. 9: Comparison between laser and ground profile (grass and fern covered surface).

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