High Altitude Laser Ranging Over Rugged Terrain

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ABSTRACT: A laser ranger can, in principle, be used as an auxiliary system with aerial photogrammetry. It can also be used as a profiler for mapping, with photogrammetry playing a role in determining the instrument's position and orientation. Laser ranger measurements from aircraft to ground were combined with high altitude aerial photography in the Rocky Mountains west of Calgary. Estimates of the range from camera stations to ground by laser and photogrammetry initially differed considerably, but compensation for laser beam misalignment drastically reduced the discrepancy. When the laser measurements were combined with measurements of instrument position and orientation by an inertial system between camera stations, analysis showed that the combined system can give a terrain elevation profile with accuracy of a few decimetres or a few metres, depending on the terrain type, vegetation, and slope, provided that the laser alignment is known and photogrammetry using ground control is used to update the inertial system at each end of the profile.

SINCE THE LASER WAS INVENTED, instruments have been developed which use a laser beam to determine the distance from the laser source to a given target by measuring the time taken by a light pulse to travel from instrument to target and back. These instruments are used in surveying and mapping under the general name of laser rangers. When installed in aircraft, they can be used together with aerial photogrammetry (Jepsky, 1986).

In one such application, a laser ranger serves an auxiliary purpose in photogrammetric triangulation and mapping. The latter processes involve the determination of coordinates of points in a ground coordinate system from the coordinates of corresponding points in photographic images. Usually the transformation from image to ground coordinates is determined by identifying and measuring certain image points which correspond to surveyed control points on the ground. A certain minimum number of control points is needed for the photogrammetric orientation; this number varies depending on whether one is analyzing a single photo/model or a block of photos/models.

If this ground control is inadequate, then to some extent it can be replaced by information on the camera's position and orientation. This information can be provided by auxiliary positioning systems. The use of such information was foreseen over a decade ago by Zarzycki (1972), Blais (1976), and others.

In some circumstances, photogrammetry may be unsuitable for mapping. This may be the case over areas which exhibit few distinctive features, such as snowfields, sand desert, and grassland, where it is difficult to uniquely match pairs of points in the two images required to form the stereomodel. In these conditions, a laser profiler can function well as a terrain profiler. The coordinates of the target point on the ground can be found if one knows the position and orientation of the instrument, plus the range that it measures. Position and orientation can be provided by an inertial positioning system, but such a system requires frequent updating.

Such mapping systems have already been used in certain situations. Jepsky (1986) describes typical laser profiler systems and their applications. Schreier *et al.* (1984) describe experiments in Ontario in which 95 percent of the laser elevations agree with those from conventional photogrammetry within 1.8m, using aircraft-mounted equipment at a flying height of 300m, while Moreau and Jeudy (1986) report acceptable results for a laser profiler survey by helicopter.

Additionally, photogrammetry can be used to provide the updates if the nature of the terrain and availability of control points permit its use at some points on the flight line. In this situation, photogrammetry plays the auxiliary role in its integration with another system. Similar information on the instrument's position and orientation is desirable for other airborne mapping systems such as multispectral scanners.

Any auxiliary information must, of course, be of adequate quality if its use is to result in an improvement in the accuracy of photogrammetric mapping or triangulation. The purpose of the experiment described here was to evaluate the accuracy and precision of the output of a laser ranger by comparing this output, as determined experimentally, with the equivalent values computed by "traditional" photogrammetry using ground control. This analysis uses data obtained under the extreme conditions of a high-flying aircraft over very rugged terrain. Such conditions will generally maximize the effects of any errors that are present.

More specifically, comparisons are made between the ranges measured by the laser ranger at the camera stations and the corresponding ranges measured by photogrammetry. In addition, a few detailed terrain elevation profiles between camera stations are examined, with a view to determining the equipment preparation and observational procedure that will give the highest accuracy.

EXPERIMENTAL CONDITIONS AND DATA SOURCES

In this investigation, photogrammetry using ground control is used to estimate the distances that are measured by the laser ranger. The photogrammetric estimates are compared with the actual measurements. If the discrepancies between them are less than the errors normally present in the photogrammetry, then it can be assumed that the ranger measurements will be acceptable as input to the photogrammetric adjustment, and as an acceptable alternative to profiling by photogrammetry.

In the summer of 1983, aerial photography was carried out in the Kananaskis area west of Calgary, Alberta. This is an area of rugged terrain near the eastern edge of the Rocky Mountains, including peaks, valleys, and lakes, in which there exists a control network of high quality. The project was a cooperative one, involving The University of Calgary, the Canada Centre for

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Remote Sensing (CCRS) Department of Energy, Mines and Resources (EMR), Alberta Forestry, Lands and Wildlife, the Directorate of Cartography (Department of National Defence), the Surveys and Mapping Branch of the Province of British Columbia, and the Canada Centre for Mapping of EMR. Flying height was about 9800 m and terrain elevation was between 1300 m and 3350 m above sea level. Data were acquired by CCRS, using a Falcon 20 jet aircraft. A Wild RC-10 camera, with lens of focal length 153.30 mm and image size 230 by 230 mm, was used, and the flight pattern comprised five lines of length 70 km oriented north-south, and five lines of length 25 km oriented east-west, flown at a velocity of 200 m/s. The spacing between camera stations was about 2.3 km. Endlap and sidelap were 80 percent and 60 percent, respectively, giving a high redundancy of measurement from multiple overlap and a base-to-height ratio smaller than normal.

While the aerial photography was being taken, the camera position and orientation were recorded continuously by a combination of two inertial systems, a Litton LTN-051 navigation system of the local level type, mounted about 3 m from the camera, and a Honeywell 478H intertial reference unit of the strapdown type, which was attached directly to the camera.

Also, for much of the observation period, the aircraft's height above ground was recorded by a laser altimeter. The laser equipment was attached not to the camera but directly to the airframe, about one metre from the camera. A Neodymium-Yag laser of 100 mw peak power, with a pulse repetition rate of 20 pulses per second and a range greater than 10 km was used (Gibson, 1986). It had a resolution of one nanosecond in timing, equivalent to 15 cm in range, and, at the flying height typical for this experiment, the spread of the laser beam produced a circular spot of 300 micrometres in diameter on the image, or 15 m on the ground. More details of the equipment used are given by Thyer (1987).

Photogrammetric image measurements were originally made in the spring of 1985, on a Wild STK-1 stereocomparator, with some measurements repeated in the autumn of 1985. The SPACE-M method of independent model block adjustment (Blais, 1979) was applied, to both the set of five N-S lines and the set of five E-W lines, using ground control only.

For the purpose of this study, the relevant parts of the adjustment outputs were the coordinates of the perspective centers and of certain points on the ground. Processing of the auxiliary data, including determination of the camera positions and orientations from the inertial systems, was done by CCRS, who then forwarded the processed data to The University of Calgary.

Two data sets supplied by CCRS are relevant to this investigation. One comprised ten sections corresponding to the different flight lines, and included the time, the UTM (*N*, *E*, and *H*) coordinates of the camera, in addition to the roll, pitch, and heading angles, as determined by the inertial system. In most cases, the laser range for each camera station or perspective center was available. The other data set comprised detailed terrain profiles for the first five flight lines, as produced by the auxiliary systems. Gibson (1986) gives further details of the processing used in preparing these data sets.

ACCURACY OF THE PHOTOGRAMMETRY

As photogrammetry is being used as a standard of comparison for the accuracy of the laser data, its own accuracy and precision should be borne in mind when interpreting the results. In particular, a given set of photogrammetric data does not uniquely determine the coordinates of a set of points in object space. These coordinates depend also on factors such as the type of adjustment, amount and distribution of ground control, statistical weights, constraints that may be applied, and the size of the adjustment block. Therefore, the values of coordinates from several different adjustments, and their mutual consistency, should be considered.

The first five flight lines were processed three times by the SPACE-M independent model block adjustment, using photogrammetric data from the first set of measurements for the spring of 1985, then using the remeasured data obtained in the autumn of 1985. Two adjustments were made using this later data set, including and excluding the constraint that waterline points on a lakeshore should be at the same height.

The laser ranges are particularly related to two sets of points in the output of the SPACE-M adjustment. One set consists of the perspective centers (PCs), and the other set comprises the points on the ground corresponding to the principal points of the images. Such a point can be referred to as the quasi-nadir point (QNP) or the ground principal point (GPP); it corresponds to the nadir point if the principal axis is perfectly vertical. The length of the line from a QNP to its PC should correspond to the range measured by the laser.

The SPACE-M adjustment is primarily intended for topographic mapping at the best possible accuracy, and for such applications the PCs are of secondary importance. Though they are normally used in the adjustment process, some of them may be rejected from this process if they are associated with large residuals and if their rejection improves the fit of points on the ground. Apart from points at the end of a flight line, the SPACE-M output gives two estimates of the position of each PC, one from each of the two models in which it appears, and hence the "best estimate" of the PCs position is the weighted mean of these two estimates.

A basic statistical analysis was made on the difference between the two estimates of position, to give an indication of their reliability. The distance between the two estimated positions was calculated, together with its horizontal and vertical components, and for each of these quantities the RMS and maximum values were computed. For each of the three adjustments, the analysis was applied to data sets including and excluding adjustments outliers. The results are summarized in Table 1, and more details can be found in Thyer (1987).

In general, when outliers were excluded, the discrepancy was typically 5 m in the horizontal and 1 m in the vertical, but occasionally two or three times as great. These values are consistent with the generally accepted height accuracy expected from photogrammetry, namely 0.01 to 0.03 percent of flying height. Inclusion of rejected points roughly doubled these values (see Table 1).

EVALUATION OF LASER RANGES AT CAMERA STATIONS

When the laser is mounted close to the camera and its beam is assumed to be parallel to the camera principal axis, the photogrammetric estimate of the laser range is the length of the vector from PC to QNP, computed from coordinates by the three-

TABLE 1. DISCREPANCIES BETWEEN PC POSITION ESTIMATES FROM SPACE-M (METRES) FOR BOTH SITUATIONS: OUTLIERS INCLUDED AND EXCLUDED

	All Points		Exc. Outliers	
Total Distance	RMS	MAX	RMS	MAX
Old Data	10.4	38.7	5.6	14.1
New Data w/Lakes	12.3	65.9	6.0	13.6
New Data wo/Lakes	9.4	47.8	5.3	12.0

	All Points		Exc. Outliers	
Vertical Distance	RMS	MAX	RMS	MAX
Old Data	2.0	9.9	0.9	2.3
New Data w/Lakes	1.9	13.5	0.8	2.3
New Data wo/Lakes	1.6	10.6	0.7	1.7

dimensional version of Pythagoras' theorem, and using the mean when there are two estimates of PC position. When its values from this experiment were compared with the values measured by the laser, agreement was unacceptably bad. The discrepancies had RMS values between 65 m and 90 m on the five flight lines; they were sometimes as great as 180 m, and roughly equally divided into positive and negative values, so that the mean was small compared with the random variation. The following reasons for the large discrepancies were considered:

- the laser ranger is intrinsically subject to random errors;
- the range is being deduced from the wrong part of the return pulse;
- when the ground surface is very irregular, with obstacles such as trees and boulders present, it is possible that the laser gives the range to the treetops, and the photogrammetry the range to the ground, or vice-versa;
- the laser reading is not correctly synchronized with the photography; or
- the laser is not correctly aligned with the camera and, therefore, the two ranges are not being measured to the same ground point.

The last reason was investigated first, as a matter of convenience. The laser range was compared with the photogrammetric range from the PC to other ground points near the QNP, and it was found that the discrepancy between range estimates from laser and photogrammetry were least for a certain image point slightly displaced from the principal point. This indicated an alignment error. Details of the processes used for checking the laser alignment are given by Thyer (1987).

Misalignment of the laser beam thus appeared to be the main cause of the large discrepancies in range estimates, and results from the foregoing test suggest that discrepancies are reduced to an RMS value of less than 7 m when the misalignment is corrected. This is nearly double the variability in the range measurements that was found between different photogrammetric adjustments, as reported in the previous section.

LASER PROFILING

During this experiment, the laser ranger was run continuously in the N-S flight lines, taking about 20 readings per second. The inertial system was also run continuously, giving position coordinates and orientation angles for the camera. Its post-mission updates were now provided by photogrammetry at the camera stations, and it was assumed that, between consecutive camera stations, the position coordinates and orientation angles were subject to a fixed bias plus a constant drift. Assuming that the laser was physically close to, aligned with, and fixed with respect to the camera, then its position and orientation could be determined for each pulse. From this information and the measured range, the location of each laser spot on the ground was found. CCRS performed this analysis, and provided a data file with the time and E, N, and H coordinates for each laser spot.

First, some sections of laser profiles over lakes were studied. After a correction for laser misalignment was made, the water profile was found to be essentially a straight line with superimposed noise having an RMS amplitude of about 0.1 m. Next, profiles over land were examined.

Greater discrepancies between laser and photogrammetric ranges should be expected over land than over water for the following reasons:

- Land surface is generally less smooth; the height of the ground, or of other objects intercepted by the laser beam, could vary considerably within the area of the laser spot (footprint). This is especially true in forest, where the laser echo could be partly from the treetops and partly from the ground, depending on the density of the forest, and where the photogrammetrist has the choice of measuring ground or treetop elevations. Indeed, Corten (1984) points out (p. 68) that a laser beam can penetrate between trees when there is up to 99 percent canopy, though the amount of penetration would depend on the width of the laser beam and the size of the openings. He also indicates (p. 55) that a laser airborne profile recorder can measure tree heights if it can distinguish the parts of the return pulse that are reflected from ground and treetops.
- On sloping ground, different parts of the laser spot are at different elevations and, therefore, at different ranges. Further, an error in the assumed alignment of the laser beam could mean that the laser beam is actually directed at a different point from what one expects, so that the laser measurement and photogrammetric measurement are actually being made at different ground points which have different elevations.

For analysis, five sections of flight line were chosen, each corresponding to the region between the two perspective centers of a photogrammetric model. Each section contained about 500 laser readings, spaced about 10 m apart over a distance of about 5 km. For each section, the location of each laser spot on the ground had been found by the method described above.

Because the laser beam was within 3° of the vertical, any discrepancy in photogrammetric and laser range estimates would differ from the corresponding discrepancy in elevation estimates by less than 0.14 percent. Also, an error in the laser range would cause a corresponding error less than 6 percent as great in the horizontal position of the laser spot. For instance, if the beam was tilted 3°, an error of 10 m in the laser range would result in an error of only 0.5 m in the horizontal coordinate of the laser spot, which is much less than the size of the spot itself.

Bearing these points in mind, the photogrammetric model was set up on a Wild ACl analytical stereo plotter, using the control point coordinates from the same adjustment as was used to update the inertial system. (Use of values from a different adjustment might have resulted in the laser and photogrammetric measurements being made at different points.) Elevations were then measured at the E and N coordinates given in the laser profile.

At this point there still remained some slight effect of misalignment. It was found that the profiles from laser and photogrammetry matched best if one was shifted slightly relative to the other.

Further, elevations were measured at points 12 m to each side of the laser spot, perpendicular to the flight line, to allow computation of terrain slope, defined as the tangent of the angle of slope, by a finite difference method. The type of terrain cover at each point in the profile was also noted and coded on a nine-point scale, as listed in Table 2.

One aim of this analysis was to determine whether the difference between the two height estimates depended on the terrain cover and slope and, if so, how. Therefore, two of the profile sections, referred to as W and X, were chosen to include varied vegetation and little relief, and two, labeled Y and Z, to include high relief with little vegetation. A nine-point scale for slope categories was devised too, as shown in Table 3.

In each section, the shift for correct matching was performed, the data file was prepared, and then, for each combination of terrain type and slope, the mean, standard deviation, and RMS values were calculated for the discrepancy between the two estimates of elevation. The results are shown in Tables 4 to 7. Also, Figures 1 to 4 present graphs of the terrain slope, height

TABLE 2. NINE-POINT SCALE FOR TERRAIN COVER TYPE

1	Open	5	Open Timber
2	Rock	6	Medium Timber
3	Brush	7	Thicker Timber
4	Scattered Timber	8	Thick Timber
		9	Shade and/or Bad Photogrammetry

TABLE 3. NINE-POINT SCALE FOR VALUES OF TERRAIN SLOPE (Slope = Tangent of Slope Angle)

1	< 0.25	6	1.25 to 1.49
2	0.25 to 0.49	7	1.50 to 1.74
3	0.50 to 0.74	8	1.75 to 1.99
4	0.75 to 0.99	9	> 1.99
5	1.00 to 1.24		

TABLE 4. SECTION W: DISCREPANCIES IN METRES BETWEEN LASER RANGES AND PHOTOGRAMMETRIC RANGES FOR VARIOUS SLOPE CATEGORIES AND TERRAIN TYPES (LEFT COLUMN).
For each terrain type,
the first line gives the sample size,
the second line gives the mean discrepancy,
the third line gives the standard deviation, and
the fourth line gives the RMS discrepancy.

	Slope Category				
	1	2	3	4	All
1	173	3	1	2	179
	−2.17	4.80	8.12	13.59	−1.82
	3.56	5.24	0.00	12.70	4.31
	4.17	7.11	8.12	18.60	4.68
2	2	0	0	0	2
	−1.96	0.00	0.00	0.00	−1.96
	1.07	0.00	0.00	0.00	1.07
	2.23	0.00	0.00	0.00	2.23
3	58	0	0	0	58
	−0.70	0.00	0.00	0.00	−0.70
	2.96	0.00	0.00	0.00	2.96
	3.04	0.00	0.00	0.00	3.04
4	42	6	0	0	48
	1.04	0.39	0.00	0.00	0.96
	4.36	3.22	0.00	0.00	4.24
	4.48	3.24	0.00	0.00	4.35
5	83	6	0	0	89
	4.70	8.52	0.00	0.00	4.96
	5.26	5.06	0.00	0.00	5.33
	7.05	9.91	0.00	0.00	7.28
6	20	0	0	0	20
	4.98	0.00	0.00	0.00	4.98
	4.89	0.00	0.00	0.00	4.89
	6.97	0.00	0.00	0.00	6.97
8	18	0	0	0	18
	6.63	0.00	0.00	0.00	6.63
	6.96	0.00	0.00	0.00	6.96
	9.61	0.00	0.00	0.00	9.61
All	396	15	1	2	414
	0.59	4.53	8.12	13.59	0.81
	5.28	5.76	0.00	12.70	5.49
	5.31	7.32	8.12	18.60	5.55

difference, and terrain type as functions of position along the profile.

Even though Section W is of gentle relief, Figure 1 suggests that terrain slope effects cannot be ignored; the only difference greater than 20 m clearly occurs at a point where there is a short and steep slope. However, such a spike does not occur at previous records with steep slope. This situation suggests that there could still be some laser alignment error. A short interval of steep slope in Section X also corresponds to a large difference.

Turning to the problem of terrain cover, Figure 2 shows that there are several short intervals of open terrain, which in some cases correspond to roads through the forest. These often occur with negative values of the difference, whereas the neighboring

TABLE 5. SECTION X: DISCREPANCIES IN METRES BETWEEN LASER RANGES AND PHOTOGRAMMETRIC RANGES FOR VARIOUS SLOPE CATEGORIES AND TERRAIN TYPES (LEFT COLUMN).
For each terrain type,
the first line gives the sample size,
the second line gives the mean discrepancy,
the third line gives the standard deviation, and
the fourth line gives the RMS discrepancy.

	Slope Category					
	1	2	3	4	5	All
1	31	2	0	1	0	34
	0.38	9.46	0.00	23.47	0.00	1.60
	7.92	3.75	0.00	0.00	0.00	8.78
	7.93	10.18	0.00	23.47	0.00	8.92
3	31	0	0	0	0	31
	−1.80	0.00	0.00	0.00	0.00	−1.80
	2.90	0.00	0.00	0.00	0.00	2.90
	3.41	0.00	0.00	0.00	0.00	3.41
5	116	9	0	4	1	130
	5.96	4.53	0.00	14.26	17.14	6.20
	6.02	1.36	0.00	1.62	0.00	5.98
	8.48	4.73	0.00	14.35	17.14	8.62
6	95	1	0	0	0	96
	12.84	−0.54	0.00	0.00	0.00	12.70
	6.69	0.00	0.00	0.00	0.00	6.79
	14.47	0.54	0.00	0.00	0.00	14.40
7	3	0	0	0	0	3
	8.43	0.00	0.00	0.00	0.00	8.43
	1.44	0.00	0.00	0.00	0.00	1.44
	8.55	0.00	0.00	0.00	0.00	8.55
8	154	15	5	0	1	175
	0.73	5.27	11.50	0.00	10.86	1.48
	4.23	4.67	2.15	0.00	0.00	4.78
	4.29	7.04	11.70	0.00	10.86	5.00
All	430	27	5	5	2	469
	4.66	5.12	11.50	16.10	14.00	4.92
	7.51	4.06	2.15	3.96	3.14	7.43
	8.84	6.53	11.70	16.58	14.35	8.91

forest gives positive values. It can be seen from Tables 4 and 5 that, on the whole, there are negative differences for open terrain, but progressively higher differences for thicker forest. Indeed, for Section W, the correlation coefficient between elevation difference and terrain type number is equal to 0.528. This relation may be explained by the fact that the photogrammetric heights were estimates of the ground elevation, while the laser beam may have been partly reflected from the treetops.

Sections Y and Z cover terrain with little vegetation but much relief. Indeed, in parts of Section Y, the relief is so rugged that parts of the profile are in image shadow, and the photogrammetric elevation there can only be estimated. Such points should have been classified under Terrain Type 9 (bad photogrammetry), but by an oversight they were classified in Type 1 (open ground), to which they also belonged. Because of this need for estimation, there occur some exceptionally large (in magnitude) values of the difference in Section Y, and rejection of points in the image shadow would now involve either repeating the photogrammetric measurements or using a purely arbitrary criterion for their rejection.

In spite of this problem, some conclusions can be drawn. The RMS values of difference generally increase as slope increases, and approximately in direct proportion to the slope value. In the case of Section Z, they are nearly 5 m times the slope value, which is what one would expect with an uncertainty of 5 m in the laser spot position. More details on the analysis results can be found in Thyer (1987).

TABLE 6. SECTION Y: DISCREPANCIES IN METRES BETWEEN LASER RANGES AND PHOTOGRAMMETRIC RANGES FOR VARIOUS SLOPE CATEGORIES AND TERRAIN TYPES (LEFT COLUMN).

For each terrain type,
the first line gives the sample size,
the second line gives the mean discrepancy,
the third line gives the standard deviation, and
the fourth line gives the RMS discrepancy.

	Slope Category									
	1	2	3	4	5	6	7	8	9	All
1	21	42	99	99	44	14	7	16	8	350
	−1.21	−5.12	−4.59	−6.97	−4.85	−3.93	−31.51	−21.96	27.84	−5.72
	6.14	9.69	12.76	9.96	14.36	9.50	49.48	32.01	20.75	16.62
	6.26	10.96	13.56	12.16	15.16	10.28	58.66	38.81	34.72	17.58
2	0	3	14	21	16	9	6	13	33	115
	0.00	0.46	−7.74	1.99	5.19	5.97	−4.10	13.77	−13.61	−1.94
	0.00	20.00	8.92	23.80	21.26	20.72	21.49	21.90	74.10	44.27
	0.00	20.01	11.81	23.89	21.89	21.56	21.87	25.87	75.34	44.32
5	14	9	1	0	0	0	0	0	0	24
	−1.94	6.70	6.54	0.00	0.00	0.00	0.00	0.00	0.00	1.65
	5.13	2.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.95
	5.49	7.08	6.54	0.00	0.00	0.00	0.00	0.00	0.00	6.17
All	35	54	114	120	60	23	13	29	41	489
	−1.50	−2.84	−4.88	−5.40	−2.17	−0.06	−18.86	−5.94	−5.52	−4.47
	5.77	10.77	12.38	13.88	17.08	15.69	41.45	33.11	69.09	25.78
	5.96	11.13	13.31	14.89	17.21	15.69	45.54	33.63	69.31	26.17

TABLE 7. SECTION Z: DISCREPANCIES IN METRES BETWEEN LASER RANGES AND PHOTOGRAMMETRIC RANGES FOR VARIOUS SLOPE CATEGORIES AND TERRAIN TYPES (LEFT COLUMN).

For each terrain type,
the first line gives the sample size,
the second line gives the mean discrepancy,
the third line gives the standard deviation, and
the fourth line gives the RMS discrepancy.

	Slope Category									
	1	2	3	4	5	6	7	8	9	All
1	1	31	82	75	16	7	11	3	3	229
	−1.50	1.47	1.86	2.70	1.67	7.73	3.91	0.59	5.43	2.36
	0.00	2.75	1.84	2.18	4.21	6.70	9.73	8.80	8.58	3.80
	1.50	3.12	2.62	3.48	4.53	10.23	10.49	8.82	10.15	4.47
3	1	60	89	1	0	0	0	0	0	151
	−0.27	1.79	2.44	2.41	0.00	0.00	0.00	0.00	0.00	2.16
	0.00	1.51	1.97	0.00	0.00	0.00	0.00	0.00	0.00	1.83
	0.27	2.34	3.14	2.41	0.00	0.00	0.00	0.00	0.00	2.83
5	0	17	26	2	0	0	0	0	0	45
	0.00	1.45	3.37	6.18	0.00	0.00	0.00	0.00	0.00	2.77
	0.00	2.44	3.42	2.34	0.00	0.00	0.00	0.00	0.00	3.26
	0.00	2.84	4.80	6.61	0.00	0.00	0.00	0.00	0.00	4.28
6	0	15	24	4	0	0	0	0	0	43
	0.00	3.86	7.11	9.64	0.00	0.00	0.00	0.00	0.00	6.21
	0.00	2.42	2.35	0.76	0.00	0.00	0.00	0.00	0.00	2.94
	0.00	4.56	7.49	9.67	0.00	0.00	0.00	0.00	0.00	6.87
All	2	123	221	82	16	7	11	3	3	468
	−0.89	1.91	2.84	3.12	1.67	7.73	3.91	0.59	5.43	2.69
	0.62	2.26	2.69	2.64	4.21	6.70	9.73	8.80	8.58	3.35
	1.08	2.96	3.91	4.09	4.53	10.23	10.49	8.82	10.15	4.30

CONCLUSIONS AND RECOMMENDATIONS

From the foregoing analyses, it appears that the main sources of inaccuracy in the use of a laser ranger are outside the instrument itself. Profiling over lakes indicated that the noise in the range measurements was only about 10 cm.

Discrepancies between photogrammetric and laser ranges were far greater. Misalignment of the laser beam proved to be a major problem which can be largely eliminated. The tests on laser misalignment implied that, with the laser misalignment corrected for, the RMS discrepancy between ranges is over 6 m, and of this, only 2 m or less can be accounted for by the uncertainty in the height of the PC, according to Table 1.

As long as the laser spot is of a finite size, some uncertainty in range is unavoidable on sloping terrain, and this uncertainty is proportional to the slope, and also to the diameter of the laser

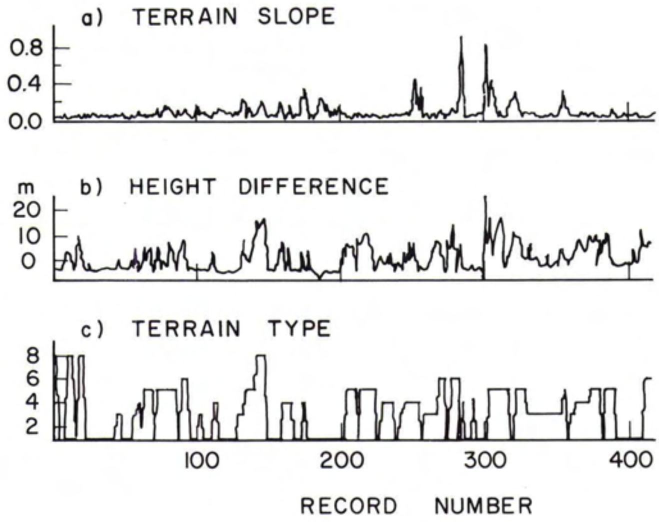

FIG. 1. Characteristics of terrain profile Section W

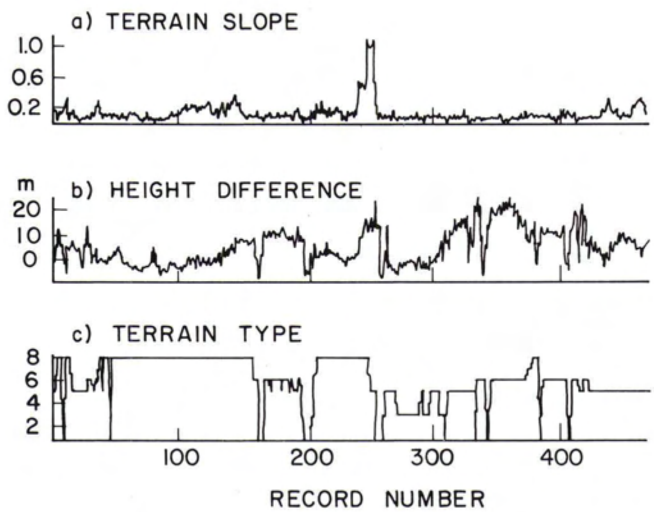

FIG. 2. Characteristics of terrain profile Section X

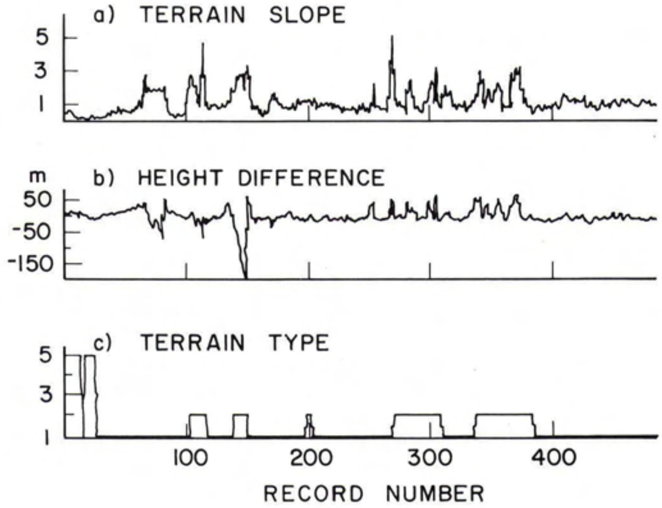

FIG. 3. Characteristics of terrain profile Section Y

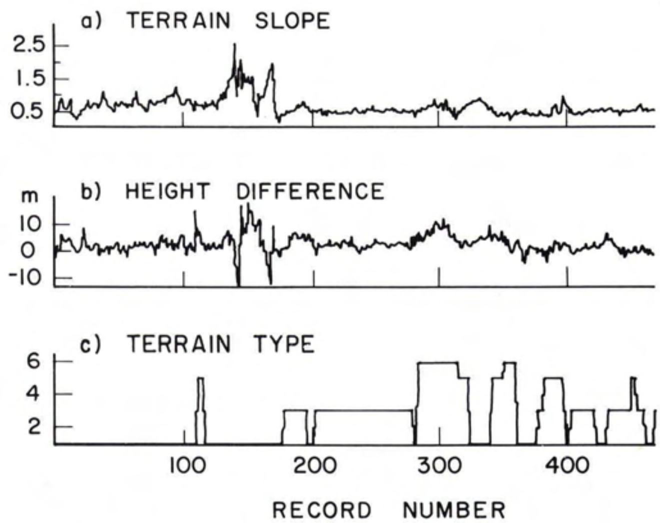

FIG. 4. Characteristics of terrain profile Section Z

spot, which itself is proportional to the range. The dependence on terrain cover is more complex. Graphs such as those in Figures 1 and 2 strongly suggest that error in the distance to the ground depends on the vegetation cover, probably because the laser measures the range to the canopy.

For both research and operational use, it is essential to know the laser misalignment accurately. It can be determined by either of the methods described previously, *viz.* photogrammetry involving several images such that terrain near the laser spot gives a good random sample of slope steepness and orientation relative to the camera, or night photography over a homogeneous dark area (e.g., a lake). The latter method ensures that the laser spot is the only features on the image, or is otherwise clearly distinguishable. If the laser is mounted separately from the camera, the crab-angle must be measured also, including during calibration.

Laser ranges may be able to play a role in photogrammetric adjustment, provided that the aforementioned ground effect can be determined within 1 or 2 metres. Even then, if there is a possibility that the laser spot location in a photographic image may include some non-uniform ground cover, such as open ground and isolated trees, the reliability is much reduced.

Under reliable conditions, the range could be used as direct input to a bundle adjustment because photographs comprise the basic photogrammetric unit. In an independent-model block adjustment, at the independent-model stage where each model has its own scale, it may be possible to use the ratio of the laser ranges from the two PCs to control deformation within the model. At the absolute orientation stage, the range may be useful in scaling a model to the block.

The use of the laser ranger in profiling is more promising. Here, good updates of the inertial system are essential, and accuracy may be improved by using more sophisticated modeling of errors between updates, as outlined by Schwarz (1983), together with more modern equipment. For a high-flying aircraft, updating can be achieved by photogrammetry using ground control at the ends of the flight lines, but then the locations of the profiles are restricted by the locations of ground control.

GPS satellite positioning will probably be adequate for updating the aircraft position at sometime in the future, when the full constellation of satellites is in use. However, it does not directly give a complete update of the orientation. If the updating problem could be solved, and the effects of terrain cover, vegetation, and slope were more thoroughly investigated, then laser profiling from high-flying aircraft would have the potential of giving terrain elevations to accuracy of a few decimetres over smooth surface and topography.

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BOOK REVIEW

Remote Sensing of Shelf Sea Hydrodynamics (Proceedings of the 15th International Liege Colloquium on Ocean Hydrodynamics). Jacques C. J. Nihoul (editor). Elsevier Science Publishing Company, Inc., 52 Vanderbilt Ave., New York, N.Y. 10017. xii + 354 pages, 206 illustrations, hardcover, 1984. $100.

THIS BOOK presents the proceedings of the 15th annual Liege Colloquium on Ocean Hydrodynamics. As is appropriate to the ongoing format of the Liege colloquia, the volume is centered on the application of remotely sensed information to the analysis of hydrodynamic processes, rather than on the methods of obtaining the information. As is also appropriate to any such volume, the major emphasis is on the importance of the synoptic overview provided by remote sensing to the future development of ocean science. The book is comprised of 18 sections representing individual presentations; I have attempted to review them here by lumping them into several appropriate categories.

The presentation by Nihoul provides a natural introduction by pointing out the areas in which remote sensing data will assist in the future development of theoretical models of ocean circulation. Just such a model is presented by Loth and Crepon, who describe a numerical model of western Mediterranean circulation. This paper seems out of place in the volume in that it makes little use of remotely sensed data, but this basically proves Nihoul's point by showing the types of information that are missing when model development and operation depend on sparse data sets. A related article by Muralikrishna discusses the potential importance of remote sensing information to modeling of near-coastal processes and to the establishment of information databases. Of special concern here is the conflict between the spatial scale of nearshore processes and the available resolution of satellite-based sensors.

Through a combination of number of presentations and overall clarity of the discussions, the major thrust of the volume seems to revolve around the application of visible-band (especially Coastal Zone Color Scanner (CZCS)) and infrared techniques. Gower leads off the volume by providing an overview of CZCS techniques, which revolve around using optical variations in water properties caused by differences in phytoplankton concentrations to delineate variations in physical processes and water masses. Later in the volume, Pingree discusses application of this technique to the study of details of current structure and frontal information on the European shelf. Lin, Borstad, and Gower shift the focus a little by concentrating on the fact that sensing of the phytoplankton itself is a major ability and goal of the CZCS technique. This topic diverges from the goal of discussing physical processes, but is nevertheless of interest because of its direct impact in the assessment of ocean productivity. Yentsch closes the volume by turning the focus back to physical processes. He sets the stage for the future by discussing the various scales involved in ocean modeling and by pointing out the correspondences between physical processes and changes in phytoplankton concentrations that will have to be understood in order to make the art of colorimetry a truly quantitative science.

CZCS has certainly provided us with some of the most stunning visual images of ocean processes available to date. It thus occupies an important niche in large-scale oceanography, and is well represented in this volume. In contrast, the most successful of techniques at the scale of ocean surface processes (namely, radar sensing of currents and surface wave properties) are less well represented. SAR, SLAR, and related radar based techniques have shown great promise in a range of applications, from sensing the surface wave climate to sensing internal waves, fronts, and currents through the distortion that these features