Airborne Laser Profile Data for Measuring Ephemeral Gully Erosion

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ABSTRACT: Soil erosion, which leads to a decrease in soil productivity and a degradation of water quality, is a major problem on at least one-third of our nation's cropland. Better information is needed on the extent and severity of erosion, especially information on gully erosion. The feasibility of using airborne laser measurements of surface heights as a method for providing information on ephemeral gully erosion was investigated. Laser profile data were obtained over control fields with both artificial and natural gullies and recorded at 4000 pulses per second at a nominal aircraft speed of 25 metres per second and altitudes of 50 and 100 metres. A moving average filter was used to remove random noise and surface microroughness effects. Analysis of the data from the artificial and natural gully fields clearly indicated the location and cross section of gullies as small as 50 cm wide and 15 cm deep. These results demonstrated the feasibility of the approach because the tested conditions were what would be considered very small gullies.

INTRODUCTION

SOIL EROSION is a major problem on at least one-third of our nation's cropland. This has led to a decrease in soil productivity and to a degradation of water quality across the nation. Better information is needed on the extent and severity of erosion, especially on gully erosion (National Research Council, 1986).

The Soil Conservation Service (SCS) of the USDA has identified two types of gully erosion as major problems. Ephemeral cropland gully erosion is caused by concentrated flow and often results in substantial loss of soil. These ephemeral gullies are erased with each tillage operation but tend to reoccur in the same area of a field each year. The other type of gully results from repeated runoff and is not obscured by tillage operations. This type of gully is large enough that it can interrupt farming operations and require major efforts to control.

Ephemeral gullies can be identified and measured through extensive field survey; however, this is impractical on a national basis. A technique is needed to efficiently detect and monitor such gullies. Information is also needed on the soil loss resulting from these features. Finally, this information is necessary to assist in the planning, design, and application of control practices that can economically prevent, control, or heal these gullies.

Remote sensing has the potential for efficiently collecting repetitive and spatially distributed data. Some success has been achieved in monitoring gully development using controlled stereo photography (Welch *et al.*, 1984; Spomer and Mahurin, 1984; Thomas *et al.*, 1986). However, this approach requires site visits and surveys. Most of the work utilizing airborne laser profiling over large areas at larger scales than those involved in ephemeral gullies has involved topographic mapping (Link *et al.*, 1982; Krabill *et al.*, 1984).

Airborne laser measurements of soil surface heights were investigated in this study as a means of potentially identifying and measuring gully erosion. Potential advantages of this technology are its ability to (1) collect data sets in a period of a few minutes that would require a much longer time frame for a ground survey team, (2) collect more complete data with a greater density and repetitiveness than would be possible with a ground survey, (3) acquire data from areas that are essentially inaccessible to ground crews, and (4) collect data in a digital form that is immediately ready for computer analyses of surface heights.

Laser profiling technology has been used for measuring and mapping topographic features (Link *et al.*, 1982); however, it has not been tested for features with the dimensional characteristics of ephemeral gullies, as small as 15 cm deep and 50 cm wide. In the first phase of the investigation, the feasibility of the technology for the application was established. An airborne laser profile system was used to collect soil surface height measurements over controlled, tilled fields. Airborne and ground observations were compared for both natural and artificially created gullies to determine the system capabilities. The emphasis in these studies was on the detection of the gullies.

EXPERIMENT DESCRIPTION

An airborne laser profiler was flown over four fields with natural and artificially created gullies. These flights were conducted at two altitudes, 50 and 100 m.

CONTROL FIELDS

Concurrent with the aircraft flights, several ground level photographs of the surface conditions and gullies were obtained on each field. All photos were made using a gridded board as a scaled background for quantifying the shape and microroughness. These photographs were later enlarged and the surface profile was electronically digitized. Figure 2 was produced from the digitized data.

A 115-m by 215-m area located on the USDA Beltsville Agricultural Research Center was selected for these studies. The area is relatively level and consists of mostly loamy sand soil (70 percent sand and 7 percent clay). The area was divided into four fields in the east-west direction as shown in Figure 1. The treatments in each were as follows:

(1) *Artificial gullies spaced 1.5 m apart.* These gullies were created with a tomato-bedder and had a typical profile on the flight date as illustrated in Figure 2A (15 cm deep and 50 cm wide).

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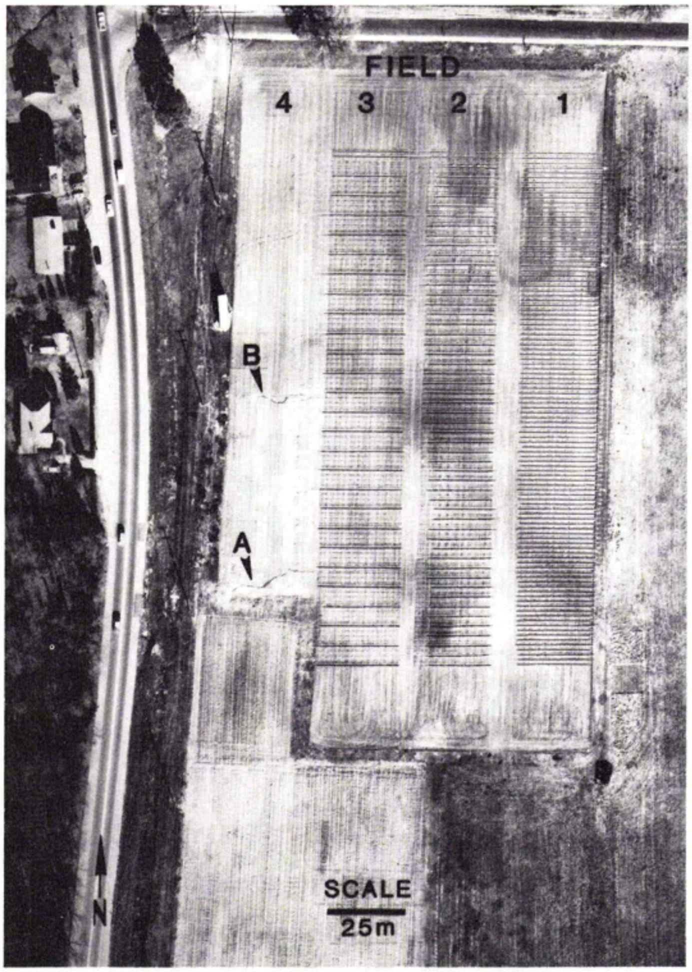

FIG. 1. Black and white aerial photograph of the control fields; numbers are at top of photo. Natural gullies are indicated by A and B.

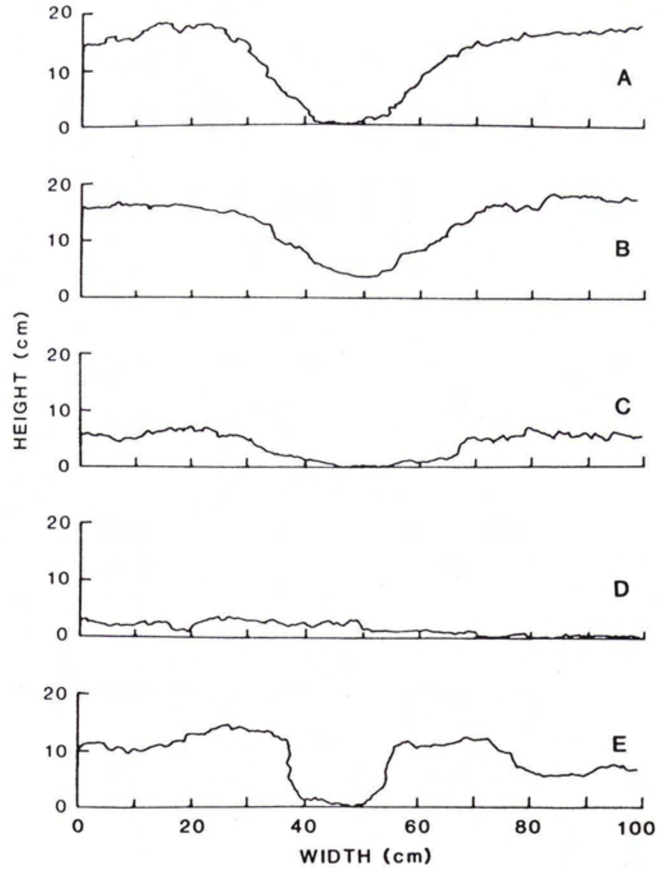

FIG. 2. Surface profiles from digitized ground photography: (A) artificial gully field 1, (B) artificial gully field 3, (C) tire track, (D) control field 4, and (E) gully B in field 4. Horizontal scale in cm.

(2) *Artificial gullies spaced 3 m apart.* These gullies were created with a middle buster plow and had a typical profile on the flight date as illustrated in Figure 2B.
(3) *Artificial gullies spaced 6 m apart and similar to section 2 above.* Both fields 2 and 3 had tire tracks between the artificial gullies. Figure 2C illustrates the profile of a tire track on the flight date.
(4) *Smooth surface field.* Figure 2D illustrates the microroughness of this field on the flight date.

The gullies in fields 1, 2, and 3 were 25 m long. A 3 m buffer was left between fields 1 and 2 and fields 2 and 3. As shown in Figure 1, field 4 was shorter than the others.

All of the fields were prepared on 17 and 18 November 1986, when the fields were wet. This resulted in a moderate amount of microroughness after tillage. However, the actual aircraft flights did not occur until 6 December 1986. During the interim period, a significant amount of rainfall (9.2 cm) occurred. This resulted in a reduction in the microroughness and soil consolidation.

Another result of the rainfall on the fields was that natural gullies were created on field 4 at points A and B indicated in Figure 1. Although the cross-sections of these natural gullies varied across the field, they were on the same order of magnitude as the artificial gullies. Figure 2E shows a typical cross-section in gully B.

AIRBORNE LASER PROFILES AND AIRCRAFT SYSTEMS

A PRAM III digital airborne laser profiler (Jepsky, 1986), operating in the near infrared, was installed on a Fairchild-Hiller Heli-Porter aircraft. This instrument sends and receives signals at 903 nanometres. Data were collected and recorded at 4000 pulses per second at altitudes of 50 and 100 m over each of the four fields. The nominal divergence of the sensor is 1.3 milliradians. At an altitude of 50 m, the ground resolution diameter is 6.5 cm and at 100 m it is 13 cm. Additional details on the laser system are listed in Table 1.

Aircraft speed was approximately 25 m/sec. At this speed and a data rate of 4000 pulses per second, the data point centers are 0.6 cm apart. The product received was a tape of distance from

TABLE 1. SPECIFICATIONS FOR PRAM III LASER SYSTEM.

General	
Pulse rate	4000 pulses/second
Design accuracy	15 cm (single pulse)
Recording accuracy	nearest 12.5 cm
Measurement density	0.625 cm at 25 m/sec
Transmitter	
Laser type	Gallium arsenide injection diode
Pulse width	10 nanoseconds
Peak power	70 watts (nominal)
Rise time	<7 nanoseconds
Wavelength	904 nanometres (infrared)
Beam divergence	1.0 milliradian
Receiver	
Field of view	1.3 milliradians
Wavelength	904 nanometres
Bandpass	20 nanometres
Detector	Silicon avalanche photodiode

the aircraft with a range resolution of 12.5 cm. Because there were no absolute positional corrections applied to the data, comparisons over long time intervals are not valid. However, relative comparisons over short time periods, less than one second (<25 m), are probably acceptable at this stage of the analysis. To further reduce potential errors due to aircraft drift and general surface slope, a linear regression was applied to the data. The residual values, predicted minus observed, were then used in analysis. All graphs used in this report express the deviation of a point from the mean distance from the airplane for a particular strip of data. Stereo photography was also obtained over each flightline for ground location purposes.

RESULTS AND DISCUSSION

Data segments for analysis were selected using the aerial photography. The raw data for the control section of field 4 at 100 m altitude is shown in Figure 3A. Each symbol represents one data point in distance from the aircraft. A great deal of data are collected by the instrument and, if there was no variation, the data would appear as a solid line at one distance value. However, there is variation which is related to microroughness (clods), small ridges caused by field preparation (rills), instrument error, aircraft positioning, and the discrete range resolution of the instrument. The result of these variations is a scatter of data points at discrete levels. The most likely distance from the aircraft at a point along the flightline will be that with the highest concentration of data points or darkest level of Figure 3A. To make the data more meaningful, they were transformed using the regression correction described previously to a zero mean and slope. Therefore, the remaining figures use the deviations of the measurements from this zero reference line, which will be called surface height.

In developing a system to locate and measure gullies, we needed to normalize the data so that the gullies become a dominant feature. A simple approach to the problem is the use of a moving average filter (Davis, 1973; McCuen and Snyder, 1986). In this approach a series of measurements is averaged and the resulting value is assigned to the midpoint. Using this approach, random variations due to instrument errors and range resolution are averaged out. Figure 3B is the result of applying a 21-point moving average filter to the raw data, after the regression correction. This is equivalent to averaging the results over a total distance of 25 cm. Averaging more points results in a smoother function; however, averaging too many points results in masking significant features, i.e., gullies.

Figure 3C is the result of applying a 201-point moving average filter to the same data. The pattern is much smoother. However, the area it averages over is more than a metre long.

Selecting an optimal filter is a complex problem. As pointed out by Davis (1973) and McCuen and Snyder (1986), the development of the optimal filter depends on very specific aspects of the problem and a careful analysis of the data. Although further analysis may be warranted in the future, we decided to simplify the analysis by considering only a uniform weighting in the filter. A set of data was selected from the control section of field 4 at both 50-and 100-m altitudes. These data were analyzed statistically and visually to determine an acceptable level of filtering.

Statistical analysis was based on the standard deviation of the filtered data over the control section of field 4 which consisted of 1800 data points. The standard deviation using unfiltered data represents one extreme. The other limit would be zero if all 1800 points were used in the filter; it would merely reproduce the average value. Results for filters utilizing up to 61 data points are shown in Figure 4 for the two flight altitudes.

Before discussing Figure 4, it should be noted that the data segments selected for the two altitudes were not over the same location on the ground; therefore, comparisons of absolute values are not possible. However, the patterns can be compared.

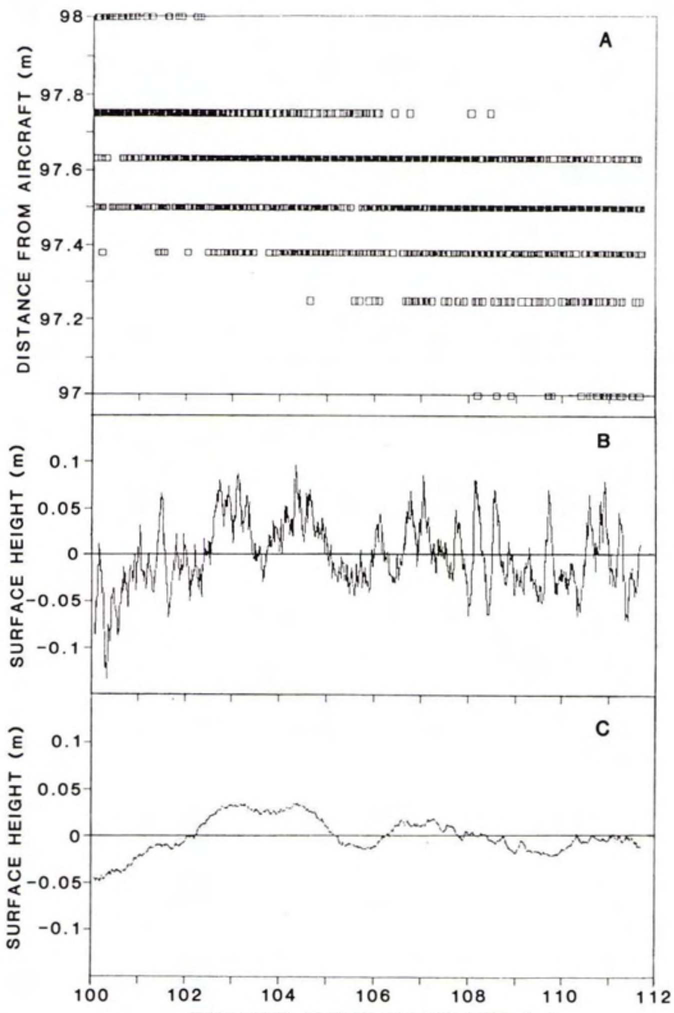

FIG. 3. Field 4 100 m altitude control section laser data: (A) raw data, (B) 21-point moving average data, and (C) 61-point moving average data.

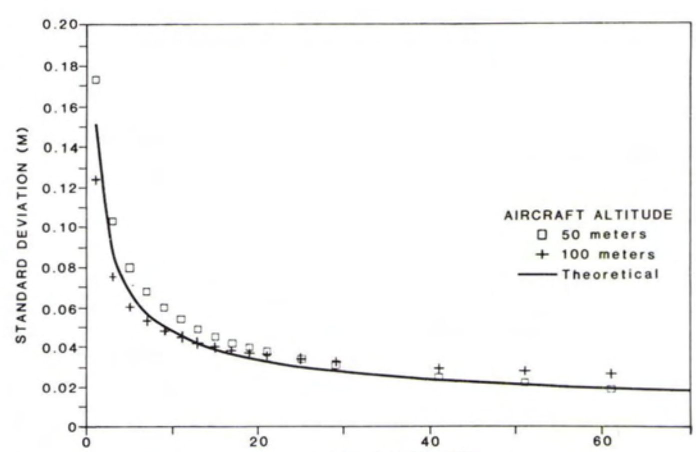

FIG. 4. Standard deviation of laser profile data versus the number of points used in computing the moving average for the control sections of field 4.

The standard deviations for the unfiltered data were 0.173 m at 50 m altitude and 0.124 m at 100 m altitude. The manufacturer's reported accuracy under controlled conditions is 0.15 m for this system for a single pulse. For 64 point averages, the manufacturer states that the tested accuracy is 0.02 m. We observed standard deviations of 0.019 and 0.027 m for the 50- and 100-m altitudes, respectively, utilizing a 61-point filter. Obviously, the system is performing within expected bounds based on these results.

The pattern exhibited by the data in Figure 4 is very similar to that which would be predicted for the standard deviation as a function of sample size if the data are normally distributed.

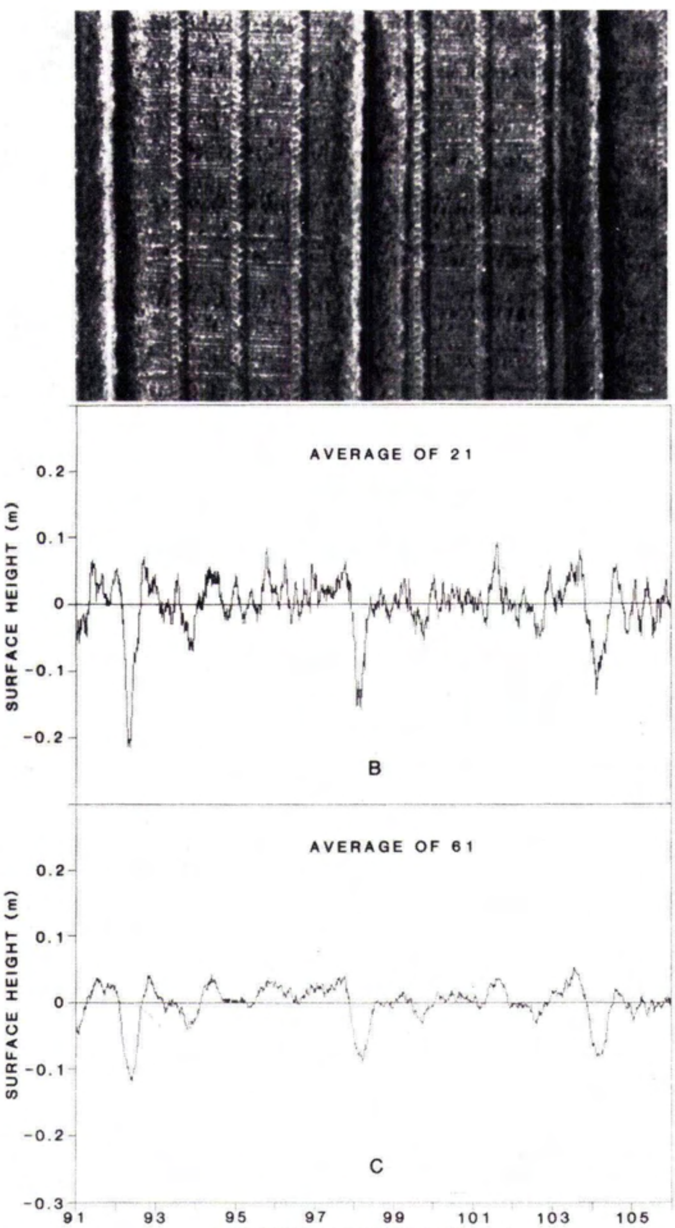

FIG. 5. Field 3 100-m altitude laser data artificial gullies 6 m apart: (A) aerial photography, (B) 21-point moving average data, and (C) 61-point moving average data.

This particular characteristic indicates that the variability due to the error sources described above is randomly distributed.

For both altitudes, the standard error decreases as the number of points averaged increases. The rate of reduction decreases as the number of points increases. Selecting a cutoff for when the decrease becomes insignificant is not straightforward. Obviously, more than three points should be averaged; however, how many more? One criterion that could be used is the expected variations in the surface heights due to tillage operations (as opposed to gullies) that we wish to ignore. Based upon values presented by Zobeck and Onstad (1987), these can range up to 5 cm. If 5 cm is considered a tolerable standard deviation associated with microroughness, (i.e., if we are not interested in variations less than this) the number of samples that should be averaged can be selected. Based upon this criterion, Figure 4, and visual inspection of typical data sets, we selected a moving average of 21 points for both altitudes.

The standard error of estimate curves (Figure 4) for the two altitudes are not very different when 21 or more samples are averaged; the standard deviation for 100 m altitude is a little smaller. One reason why the values for the different altitudes converge is that the resolutions converge as the number of points averaged increases. The ground resolutions for 21 samples are approximately 0.2 m at 50 m altitude and 0.25 m at 100 m altitude. Using a 21-point moving average, data from field 3 collected at a 100-m altitude can be used to illustrate the experimental results. Figure 5A is a photo of the field with gullies 6 m apart; Figure 5B is the result of applying the moving average filter to the regression corrected (normalized zero slope) data. The gullies are evident in the data, especially when viewed in conjunction with the scaled photograph. Dimensions of the gullies in this particular section range from 0.15 to 0.2 m in depth and from 0.5 to 0.7 m in width. It appears that the depth might be more important in detection than the width because this feature is easier to recognize.

If we were primarily interested in detection, a longer average could be used that would further enhance the differences between the gullies and the other sources of variation in the measurement. Figure 5C shows the results of applying a 61-point moving average filter. The gullies are much more obvious. Of course, the dimensions are not correct, especially the depth. However, once the gullies are detected, the data could be reprocessed to extract the dimensions. Other features such as the tire tracks could also be inferred.

Analyses utilizing other data sets produced similar results. However, detection of gully features in field 1, 1.5-m apart gullies, was complicated by their proximity to each other. This resulted in problems when longer filters were applied.

Tests using the artificial gullies are useful because the conditions were known and nominally uniform. However, the locations of the gullies were known and this certainly made interpretation easier. A better test was possible using the natural gullies that developed in sections of field 4. In general these were shallower and narrower than the artifical gullies and the features varied widely cross track. Exact dimensions under a flightline can only be inferred through the limited ground samples and the aerial photography.

Figure 6 shows an enlargement of an aerial photograph and the laser data, 21 points averaged, over a gully cross-section B in field 4. In this case the gully is detectable at a point 113 m along the flightline. The laser response is distinct from the background for a gully less than 0.15 m deep, which was shallower than the artifical gullies. However, results of analysis of other cross sections were not as obvious as this case. The shallower depth of the natural gullies is believed to cause the problem. It appears that, in order to distinguish the gullies from background variations and other uncorrected sources of error, they must be at least 0.15 m deep.

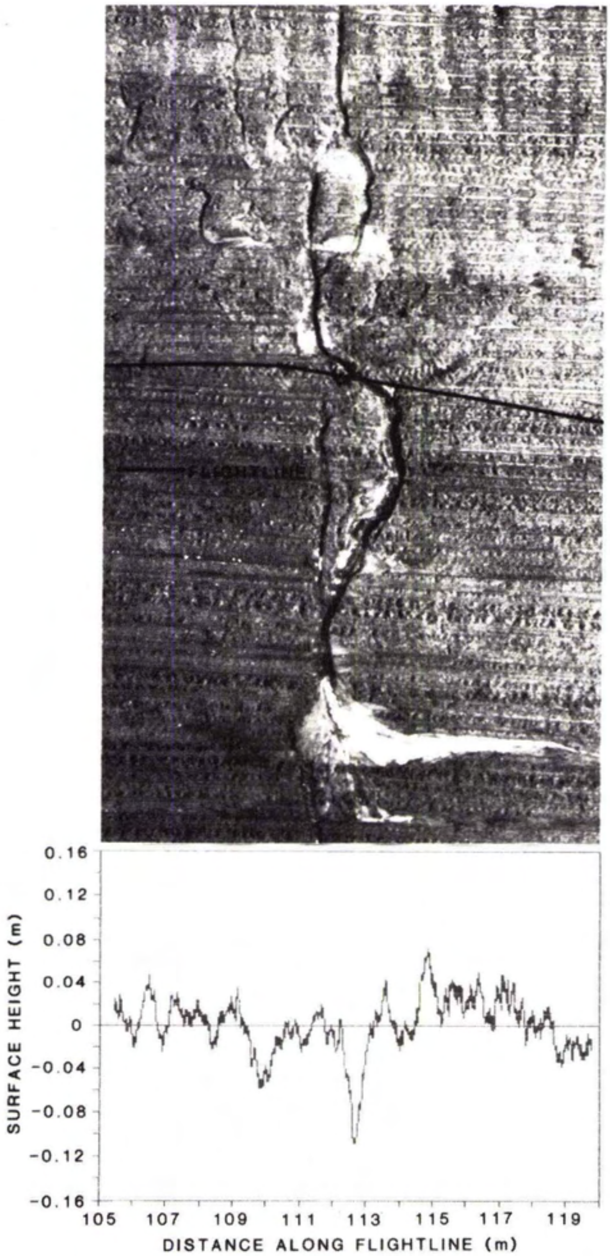

FIG. 6. Natural gully B in field 4 from 50 m altitutde: (A) aerial photograph, and (B) 61-point moving average data. Both figures have the same horizontal scale.

SUMMARY

The objective of this investigation was to determine the feasibility of using airborne laser profiling to detect ephemeral gullies. Results obtained over fields with artificial and natural gullies indicate that, at altitudes between 50 and 100 m and relatively slow aircraft speeds, this is possible. The conditions tested, a nominal gully width of 0.5 m and depths of 0.15 m, are realistic minimum conditions. Actual field gullies could be larger. Considering the resolution of the sensor and the gully characteristics, the quality of the result was better than expected.

Additional work on a detection algorithm is needed. The moving average filter used in these studies was the simplest solution to removing data noise due to the sensor and microroughness. The use of more sophisticated filters and problem-specific weighting functions could yield better data for detection purposes. Also, more sophisticated statistical analysis procedures could be used in developing the averaging scheme.

Beyond gully detection, the next step is the measurement of gully dimensions and the use of these data for estimating soil erosion over a field. Such experiments are currently being planned.

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