Airborne laser-scanning
A comparison with terrestrial surveying and photogrammetry

Abstract:

The acquisition of topographical data can be done by terrestrial surveying (tachymetry), photogrammetry or airborne laser-scanning. This paper outlines the two conventional methods and describes the measurement scheme of laser-scanning. Importance is attached to a complete coverage of the topography instead of pinpointing prominent elements or structures.

A comparison of the three methods outlining their advantages and disadvantages for specific applications completes the paper.

1 Introduction

Recent years have witnessed growing use of laser-scanning for the acquisition of digital terrain models. Yet it seems there is little knowledge or perhaps awareness of the special attributes this measuring system holds.

Terms such as accuracy, DTM or DSM, keep giving rise to misconceptions. What is looked for is an elevation model which represents the entire topography as accurately as possible, what is demanded though is often the accuracy of single points.

In the following, therefore, the attempt is made to describe the characteristics of various methods and to compare them with the performance of laser-scanning. The conventional methods are only outlined as they may be assumed to be generally known.

2 Terrestrial surveying

In contradistinction to the laser-scanning method, terrestrial surveying can determine individual points with a very high accuracy (accuracies of millimeters possible). With modern electronic surveying instruments this is promoted by combining multiple measurements to form one measurement with a very wide confidence band.

As a rule those points the surveyor individually considers being important are recorded in such spot measurement systems, generally with the acquisition of significant single points or edges (KAHMEN 1993). In the main, ground points are captured in the process, trees are determined in part only by one spot measurement (possibly with one attribute: treetop diameter).

The individual measurements are generally reproducible at any time and hence can also be checked at a later date. However, the points determined with high accuracy by such a method permit information on non-covered areas between the points to only a very limited, comparative degree of accuracy. Since, however, regard is paid to topographically relevant points during recording, it is generally possible to linearly interpolate intermediate points to a first approximation.

Yet a larger, dense and wide-area acquisition of points (over several hectares) is not economically viable. Terrestrial surveying will maintain its importance in the cadastral sector where the laser-scanning method is not suitable. The high-accuracy surveying of buildings by laser- scanning could play only a supportive role in this area.

3 Photogrammetry

In comparison with terrestrial surveying, photogrammetry is better suited when the acquisition of area-wide topographical points with economically efficient input of time and resources is sought after.

In photogrammetric surveying, the accuracy depends primarily on the flight altitude and on the focal length of the camera (KRAUS 1994), (KKVA 2000). Use of smaller focal lengths enhances the height accuracy which can be attained. At the digital evaluation, the resolution with which the aerial image is scanned plays an important part (digital cameras: resolution when the picture is taken).

For the normal case of photogrammetric compilation with two images, the following formula applies for the attainable height accuracy (KRAUS 1994):

$$\sigma_z = m_b * Z / B * \sigma_{P\xi}$$

m_b: Image scale figure
Z: Flying height above ground
B: Photo base
$\sigma_{P\xi}$: Parallax measuring accuracy

In all considerations it is important in photogrammetric point determination to distinguish between signalized points and "natural terrain points". Usually attainable accuracies for signalized points in a bundle block adjustment are (KRAUS 1994):

Position: $\sigma_{xy(sig)} = \pm m_b * 3\mu m$
Height: $\sigma_{z(sig)} = \pm m_b * (0.03 ‰ – 0.04 ‰) * c$
c: Camera constant

Given an image scale of 1:5000 and a camera constant of 15.3 cm, the following values can be reached:

$\sigma_{xy(sig)} \approx \pm 1.5$ cm
$\sigma_{z(sig)} \approx \pm 3$ cm

For natural terrain points, a definition uncertainty is added.

Position: $\sigma_{xy(max)} = \sqrt{\sigma^2_{xy(sig)} + \sigma^2_{xy(def)}}$

Height: $\sigma_{z(max)} = \sqrt{\sigma^2_{z(sig)} + \sigma^2_{z(def)}}$

Approximation values for the definition uncertainty in natural terrain points can be noted from (KRAUS 1994):

	Position [cm] $\sigma_{xy(def)}$	Height [cm] $\sigma_{z(def)}$
House and fence corners	7 – 12	8 – 15
Manhole covers:	4 – 6	1 – 3
Field corners:	20 – 100	10 – 20
Bushes, trees:	20 – 100	20 – 100

With this method very good accuracies can be achieved, if one presupposes correspondingly good, high-contrast structures of the topography in the aerial images.

However, the above particulars always relate to corner points requiring a commensurate contrast to the ambient field (textured terrain). In a homogeneously dense and area-wide (raster-like) survey of terrain this condition is not met everywhere and hence cannot be fulfilled in all cases. Photogrammetric evaluation is based on a passive measuring method, i.e. measurements in shadowy areas are associated directly with the accuracy they can reach.

Depending on the measuring point density in the evaluation, more accurate area-wide information on the terrain can be derived. A homogeneous, area-wide coverage is attained, for instance with the SCOP software. This software interpolates between measured points to create a homogeneous transition between the individual areal elements – break lines are the exception if they are declared as such.

An automatic method for photogrammetric mass point acquisition is, for example, the approach of an automatic area correlation in digital images, based on the LSM – Least Squares Matching approach. However, this method is appropriate only in well-textured and open terrain (without woodland and buildings) (KRAUS 2000).

As already mentioned, the accuracies which can be achieved with this method depend greatly on the structure and contrast of the surface in the aerial images. It is seldom the case that the accuracies of the “best case”, which may be specified for an evaluation, apply to all measurements within an area. The results of such a “best case” may not be taken as the basis for indicating the accuracy of derived, areal information for the entire model. It becomes difficult, and in some cases impossible, to guarantee a high and constant accuracy for each individual measurement in areas of mud flats, sandy beaches or meadows.

4 Laser Scanning

4.1 Principle

The distance to the ground, or rather to a reflecting object, is determined by a sensor in the aircraft using a pulsed laser (fig. 1). If the beam direction and position of the sensor are known, the coordinates of the reflecting object can be calculated.

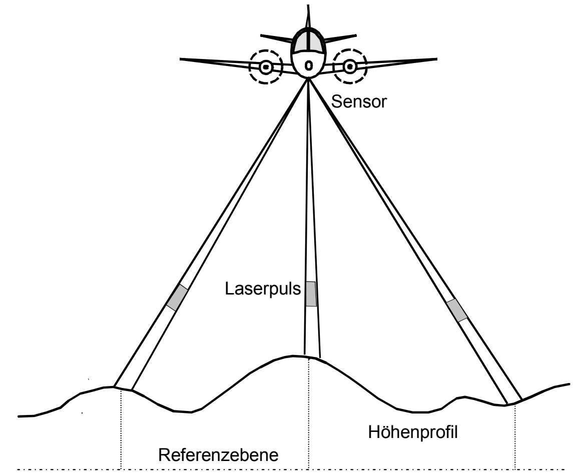

Fig. 1: Principle of measurement

The beam direction is changed from pulse to pulse by a respective apparatus and is influenced by the aircraft movement. A strip of terrain under the aircraft is surveyed through the lateral deflection of the laser beam and the movement of the aircraft. Area-wide surveying of large territories is carried out with a series of neighboring strips.

The current position of the sensor is primarily determined by the continuous forward movement of the aircraft, but is also affected by gusts and thermal current or air pockets. The measuring errors in distance, position and direction will not be discussed further in this article. On the one hand these errors can be combated by appropriate flight parameters (very good GPS) and adequate sensor design, and on the other hand their causes and effects are set out in a series of publications (SCHENK 2001-a, SCHENK 2001-b, KATZENBEISSER 2003-a).

4.2 Area coverage

In a flight strip the entire area is covered. The distribution of the measuring points and their spacing depends substantially on the scanner system used, the flight altitude and the scan angle. In general, distinction must be made between four different scan patterns (figs. 2 and 3).

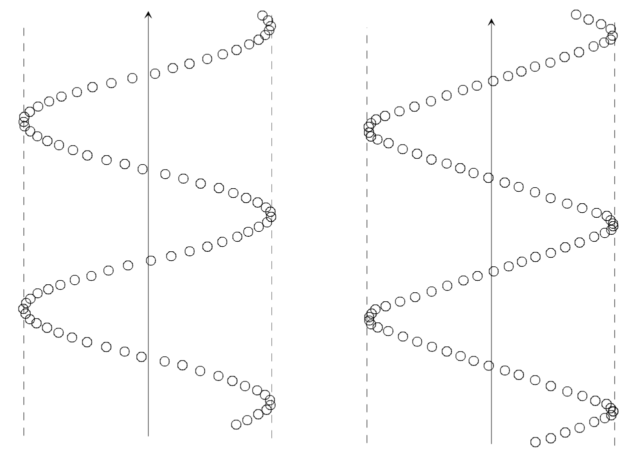
Fig. 2: Swiveling mirror pattern

In the case of a swiveling mirror the beam is deflected between two extreme positions, forming a sinusoidal or sawtooth pattern depending on the type of control. In the case of the sine, the distance between points along the scan line is very large in the center and very small at the edge. Data from the edge area is not usable due to angle errors. In the case of the sawtooth, the distance between points along the scan line is largely constant, narrower distances are encountered only in the extreme edge area. The distance along the flight direction depends on the scan frequency and flight speed and can be changed on a wide scale.

The laser beam is deflected linearly from one side of the strip to the other by a rotating polygon mirror (fig 3 left). No measured values can be collected at the corners of the polygon. The size of these not usable areas varies with the detailed design.

In the fiber scanner, the laser beam is aligned by the orientation of the individual fibers. The measuring spacing is constant in accordance with the fiber arrangement. The laser pulse rate is used fully for measurement. Fig. 3 shows on the right the resulting scan pattern superimposed with a very slight oscillation for filling the measurement gaps otherwise forming between the fibers.

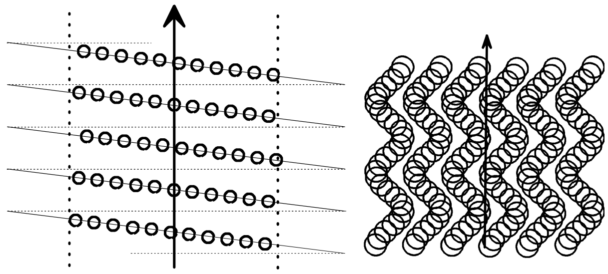

Fig. 3: Polygon and fiber scanner

4.3 Reliability

In a distance measurement by an EDM the requirement of a multiple measurement is normally made. The measuring duration or number of measurements is oriented to the "quality" of the reflector. The less the reflecting object (reflector, house wall, tree trunk, etc.) is known, the longer the measuring duration has to be.

It follows from the continuous movement of the aircraft and the changing beam deflection that each distance measurement is unique. It cannot be verified or improved by multiple measurements. The reliability of a single measurement with a scanning laser is hence significantly less than that of a measurement with EDM. The reliability of an elevation model hence has to be attained by other means. As with EDM, an ensemble has to be found permitting dependable information. This can be accomplished by very dense measurements where it may be assumed that hardly any differences in height have occurred in the immediate vicinity. The selection of the ensemble has to be made dynamically and be adapted to the respective conditions.

Another possibility is used by TopoSys. In the flight direction the areas illuminated by the laser beam overlap greatly due to the high scan rate (fig. 3). Even in dynamic terrain, no significantly different results can occur between two successive measurements, provided there are no abrupt changes in height (road – roof edge). With a suitable plausibility check of adjacent measurements, a higher reliability of the measurements is therefore attained.

4.4 Accuracy

Positional accuracy data for single measurements is often called for, this mostly meaning the accuracy of the positional and directional definition of the sensor. It is overlooked here that a laser beam is not infinitely narrow and that it widens as distance increases (beam divergence).

It is generally assumed that the energy distribution in the laser beam follows a Gaussian distribution curve (fig. 4, schematic, standardized normal distribution). Two indications are customary for the beam diameter. In optics $\varphi = 1/e^2$ is used, while the ISO standard for laser safety takes $\varphi = 1/e$. The radius becomes $r = 2\sigma$ or $r = \sqrt{2}\sigma$.

The position of a reflecting object is always assigned to the beam center. An object in the laser beam reflects as much energy as corresponds to its position in the beam. An object with high reflectivity outside the nominal beam diameter can create a detectable echo, while an object with low reflectivity can be detected only in the inner area. It follows from this that the position of objects with low reflectivity is documented with greater accuracy than such with high reflectivity.

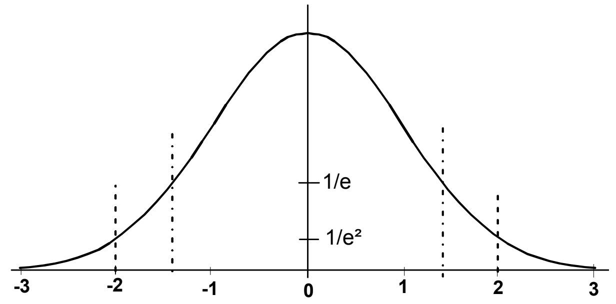

Fig. 4: Beam diameter

However, a low reflectivity also brings about lower signal strength of the echo, with the result that in many sensors the measuring accuracy decreases or the measuring noise substantially increases (KATZENBEISSER 2003-b).

Fig. 5 is a standardized representation depicting the signal strength of an echo from areas of equal size. The echoes shown in red on the right become weaker as the distance from the beam center increases. The same applies to the echoes shown in blue on the left, where the reflecting areas have only 1/10 of the reflectivity of the red ones.

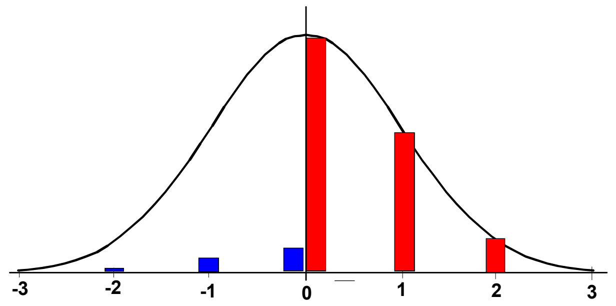

Fig. 5: Echo strength

4.5 Object accuracy

How well or how accurately do the multitude of single measurements describe a terrain or objects? The single measurements are more or less randomly distributed over a strip. In a homogeneous terrain, the measuring distance or distribution of the measurements is of subordinate importance. If, however, objects such as trenches, embankments, roof ridges are to be recorded, then corresponding demands have to be made on distribution and measurement spacing.

Fig. 6 shows a building and the measured values randomly distributed over it, as are to be expected in the frequently required measuring density of 1 point per 4 m². The open circles represent ground elevations and the red circles roof elevations. Plenty of interpretation is possible on the basis of these eight higher-level measured values. Fig. 7 shows one possibility.

If one assume that the basic form has to be a rectangle, buildings can be inserted in almost any orientation. Here two possibilities of rectangles are shown; a small one oriented to the roof elevations

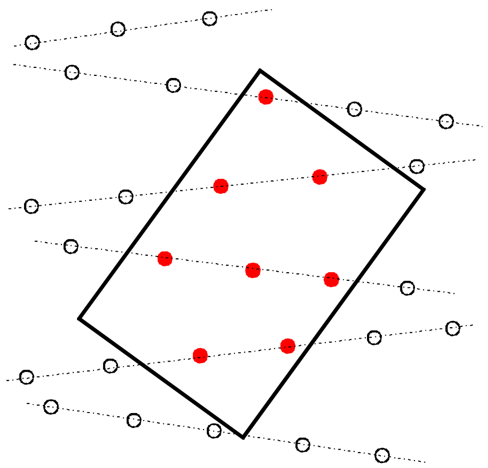
Fig. 6: Distribution of measuring points over a building

and a large one oriented to the ground elevations (fig. 7).

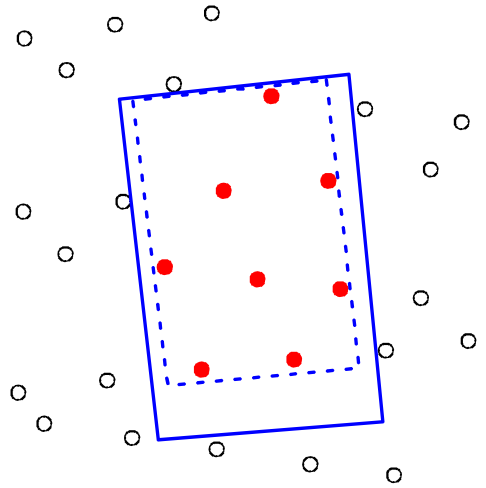
Fig. 7: Surmised building

Here reference is made to an old rule applied by interpreters of aerial photographs. Even though one did not talk about pixels 70 years ago, the following applies to the minimum object size in the image

- discover 3 – 5 pixels
- recognize 20 – 40 pixels
- describe 100 – 200 pixels

where

- discover means: something is there
- recognize means: rough differentiation – tree, vehicle, tent
- describe means: classification into automobile, truck, etc.

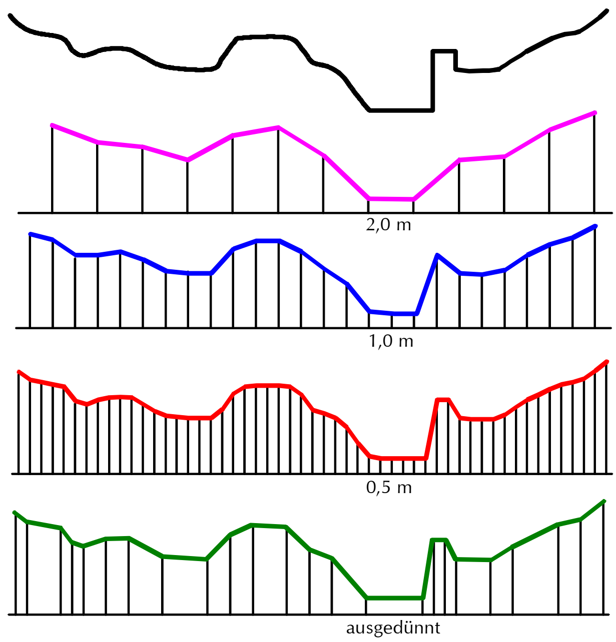

Fig. 8: Contours and measuring width

There is also a similar problem for terrain structures. Fig. 8 shows the problem in principle, simplified to a two-dimensional view.

The black line shows a 25.0 m long terrain contour with an embankment 2.5 m wide, a river bed and a retaining wall. If the contour is scanned with a step size of 2.0 m, the lilac contour is formed, with 1.0 m step size the blue contour, and with 0.5 m the red contour. The lilac contour shows neither the embankment nor the retaining wall. In the blue contour the embankment can at least be seen, for the retaining wall one needs to know the place. On the other hand, the red contour gives a very good rendering of the terrain with all the objects. If the red profile is thinned, the green contour is obtained having about the same number of sample points than at 1.0m steps but describing the terrain more precisely.

Here again a very old rule applies: If a signal is scanned with equidistant increments, the step width must be less than half the smallest form one wishes to recognize. In electrical engineering this requirement is known as Shannon’s theorem and has been used for over 50 years. In the example of Fig. 8 this signifies the following: If one wants to recognize the 1.0 m wide retaining wall, the sampling distance must not be larger than 0.5 m. What has been explained here in simplified form, applies analogously in 3D. If the measurement spacing becomes too large, then detailed structures will be lost.

4.6 Multiple echoes

Every reflecting surface impinged by the laser reflects a part and thus generates a possibly detectable echo.

Fig. 9 shows the general principle for a laser measurement. In the case of the house two echoes are formed, one from the roof and one from the ground next to it. In the case of the pine tree, four echoes from the branches and one from the ground are shown.

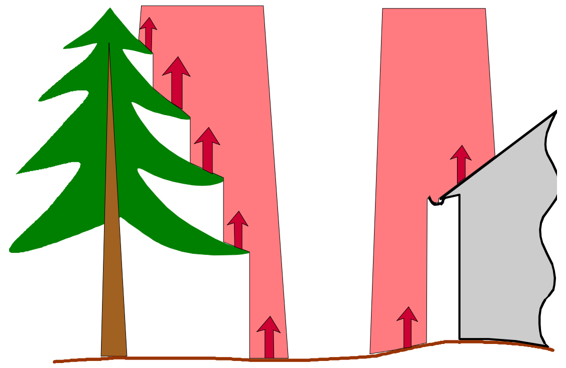

Fig. 9: Multiple echoes

In practice, the five echoes of the pine tree are usually not present. To be able to detect separate echoes, reflecting areas must be at a minimum distance which depends on the respective sensor used and ranges at present from 0.8 m to 6.0 m. If the lower branch is only 2.5 m above the ground, then with almost all sensors the last echo originates from the branch and not from the ground. With the TopoSys sensor the minimum distance is just under 1.0 m. In the vast majority of cases it is sufficient to measure and evaluate the First Echo (FE) and Last Echo (LE) (KATZENBEISSER 2003-2).

For the most part a surface model is generated from FE data, while the LE data provide the basis for a terrain model. In addition to these two models, a series of other very application-specific models can be generated (LÖFFLER 2003). By way of example, a tree without foliage is surveyable in the FE data, yet it disappears almost entirely in the LE, as in the optical image.

4.7 Intensity

The last 2 years have seen intensity images coming under increasing demand. The idea behind this is that further information can be derived from the strength of the echo signal.

In remote sensing with passive sensors, the reflectance of an imaged area in multiple spectral regions is used to draw conclusions on the nature or classification of this area.

A transfer of this modus operandi to laser-scanning is admissible to only a very limited degree, because the area is illuminated by the laser and the size of the illuminated area is rarely known (KATZENBEISSER 2003-c).

The reflectance value is to some extent significant only if and when just one echo is detected over open flat areas.

4.8 Applications

In connection with digital elevation models one currently talks of a digital terrain model (DTM) and a digital surface model (DSM). The DTM relates to a model of the ground surface bearing neither vegetation nor buildings. There is not as yet any clear definition for the DSM. It is mostly understood as the surface of a wood (treetops) or the roofs of buildings. If power lines are routed above the roofs, then the power supply provider looks for both the power line and the roof, the height of the terrain is of little concern to him at this point.

There are similar problems with the DTM. For high water simulation, the hydraulic engineer needs all potential obstructions and hence looks for all elevated objects, while relatively small drainage channels are of no interest to him. For groundwater simulations, however, the hydraulic engineer looks for all the channels as they can have a considerable impact on the water table. Banked up dirt roads are of negligible interest for his task.

A reliable basic elevation model therefore has to have a high density of measuring points to provide a sound basis for the diverse tasks of a municipality, for instance. At the same time, the data volume has to be reduced for the respective application in such a way as to be optimally matched and processable with standard software.

5 Advantages and disadvantages of the individual measuring methods

5.1 Terrestrial surveying

Accuracy: ~ millimeter range (position and height)

Advantages:

1. Measurements are repeatable
2. Extremely accurate spot measurement of surfaces / single point surveying
3. Highly efficient distribution of points in surveying the topography

Disadvantages:

1 Relatively elaborate measurements
2 Impracticable to survey mass points
3 Subject selection of relevant points in the terrain

5.2 Photogrammetry

Accuracy: ± 10 cm – 100 cm (position and height)

Advantages:

1. Image of the topography exists
2. Efficient, extensive survey of the topography
3. Acquisition of prominent terrain lines / break lines

Disadvantages:

1. Passive measuring method (requires good lightning conditions)
2. Accuracy of the measuring points varies within the model
3. Precondition of recognizable textures in the aerial photograph
4. Object reconstruction with min. 2 beams
5. Elaborate control point signalizing

5.3 Laser Scanning

At a measuring distance of 1000 m, a laser beam accuracy of < 20 cm can be assumed. The positional accuracy of objects as a whole additionally depends on the density of measuring points and the beam divergence.

Accuracy: ± 15 cm height and < 0.2 m position

Advantages:

1. Uniform, dense acquisition of points
2. Area-wide, representative information
3. Active measuring method
4. Point acquisition even if there is no structure
5. Object reconstruction with only one beam
6. No expensive evaluating equipment required
7. With dense acquisition, special evaluations of the data are possible at any later time
8. Multi-echo measurements often survey ground points under the vegetation

Disadvantages:

1. "Only" acquisition of height data and no structure elements (prominent terrain points)
2. Sophisticated flight planning, depending on terrain relief
3. Without additional processing the outcome is a surface model but not a terrain model
4. There is no visual image of the topography but a shaded relief image

Parts taken from: (KRAUS 2000, KRAUS 2001, KRAUS 1994, KKVA 2000).

6 Summary and Outlook

Reckoning from the first paid commissions for the acquisition of elevation models with airborne laser-scanning, this method is just 8 years "old". Even in our present-day fast-moving times, this is still a very infant stage.

Within these years airborne laser-scanning has developed into a very efficient tool and still has very high potential for development. Many applications – formerly thwarted by reason of costs – become affordable and hence viable by virtue of this measuring method.

At the same time, there are a large number of tasks in which conventional surveying cannot be replaced by airborne laser-scanning.

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