Prospectus on Airborne Laser Mapping Systems

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The state of the art of operating airborne laser mapping systems is summarized; also summarized are the results of field experiments conducted to evaluate system performance capabilities. The projected capabilities of systems currently under development and projected for operational testing in the near future are contrasted to the capabilities established for the operating systems. Current constraints on improving performance are identified and discussed with respect to individual system components (i.e., lasers, data recording and processing systems, positioning systems, and information display systems). A prospectus on the performance of future laser mapping systems is provided for specific technology advances.

Accurate measurements of terrain surface geometry are a common requirement for most engineering and environmental studies. Elevation, slope aspect and magnitude, relief, valley and stream cross sections, and underwater topography are basic inputs for analyses of a multitude of natural phenomena. Historically, these data have been collected on the ground or, when possible, by photogrammetry. The invention of the laser has been the most significant recent advancement in measurement technology. Ground-survey techniques have adopted laser technology, and as early as the mid-1960s lasers were placed in aircraft to examine their potential for airborne terrain (1,2) and bathymetric (3) mapping. Increased attention has been given to the airborne laser system, and the technique has emerged as a powerful new tool for terrain mapping (4-8), bathymetry (9-11), and water quality (12,13) applications.

The objectives of this paper are to summarize the current state of the art in airborne laser mapping systems, identify constraints on improving system performance, and project the impact of emerging technology on the potential performance of future systems. The state of the art and the prospectus on the future of laser and positioning systems are also discussed. A summary of current application capabilities and the potential impact of new and emerging technology on application capabilities is provided.

STATE OF THE ART

Laser Systems

The overland surveying capability of laser ranging systems has been recognized for some time, and a number of systems have demonstrated this capability with varying degrees of success. Notable among the most recently reported works are (a) the results of the Australian WREMAPS I systems (6) and the improved WREMAPS II systems (7); (b) the airborne oceanographic lidar (AOL) operated by the National Aeronautics and Space Administration (NASA) Wallops Flight Center (5); (c) a laser profiling system developed by the Avco Everett Corporation (14); and (d) a laser profiling system--the laser airborne profile recorder (APR)--used in South America (8). The Australian systems and the laser APR have provided topographic information for remote areas.

Considerable variation exists in the transmitter, optical, and recording components of the various terrain mapping systems. The wavelength of the laser transmitter is not critical for most terrain mapping applications, especially for low-altitude mapping. The WREMAPS I system uses a continuous wave (CW) argon ion laser at 488 nm, and the APR system uses a CW helium neon laser at 632.8 nm. The Avco and WREMAPS II systems use pulsed-frequency, doubled Nd:YAG lasers at 532 nm, whereas the AOL is equipped with a 337.1-nm pulsed nitrogen laser. The CW laser systems gauge the vertical distance between the aircraft and the ground by measuring phase delay between the transmitted and received signals. The pulsed laser system measures slant range between the aircraft and the ground by recording the time difference between the transmitted and received laser pulses. The APR system records the analog laser return data on a strip-chart recorder. The remaining systems record computer-compatible digital data.

All of these terrain mapping lidar systems report data acquisition in a profiling mode. However, the AOL acquires detailed data in a scanning mode. Scanning necessarily requires a high laser repetition rate, which limits the candidate lasers that can be used. The AOL produces a conical scan pattern along a 30° swath beneath the aircraft.

A number of airborne laser systems can also gather hydrographic data in relatively shallow coastal waters: (a) the Australian WRELADS II system (15); (b) the Canadian MKII lidar bathymeter (16); and (c) the NASA AOL system (9,10,17). Both the Australian WRELADS II system and the AOL can provide scanning data along a 30° swath beneath the aircraft at sampling rates of 156 and 400 pulses per second (PPS), respectively. The Canadian MKII system produces a profile record at a 10-PPS sampling rate. The Canadian lidar bathymeter is flown as an auxiliary component to a photogrammetric surveying system and the lidar record provides vertical reference points for later photogrammetric analysis. The Australian system provides complete survey data independently. The NASA AOL system is essentially a flying lidar laboratory that has terrain mapping, hydrography, and laser fluorosensing applications. The flexibility in the design of the AOL allows rapid change of lasers as well as modification of transmitter and receiver components. The Naval Oceanographic Research and Development Activity (NORDA) is currently developing the hydrographic airborne laser sounder (HALS) (18), which is to be used as an operational system.

Hydrography presents a number of obstacles not encountered in terrain mapping applications. The absorption characteristics of water restricts the laser transmitter to the blue-green spectral region; thus a relatively few candidate lasers can be used. The AOL hydrographic tests flown with an Avco C-5000 nitrogen laser filled with neon gas yielded a relatively low power 10-ns laser pulse at a 540.1-nm wavelength; however, the power requirements for an operational lidar preclude use of this type of laser. The Canadian, Australian, and HALS systems use frequency doubled Nd:YAG lasers at an emission wavelength of 532.1 nm. The 0.8- to 10-Mw peak power outputs of the YAG lasers from these various systems, coupled with a relatively narrow 5- to 7-ns pulse width, are adequate for performing airborne hydrography. The major problem with YAG lasers is in obtaining sufficient pulse repetition rates necessary for most hydrographic applications. The HALS system will be equipped with a 400-PPS YAG laser developed recently by Avco. The Australians have bypassed this problem by using two separate YAG lasers on an alternating-pulse basis. Additional candidate lasers are addressed later in this paper.

The digitization and recording of information from each laser pulse are essential components of

Table 1. Summary of available positioning systems.

Measurement Technique	Displacement	Velocity	Acceleration
Electromagnetic			
Optical	Laser ranging; optical trackers; tracking photographs	NA	NA
Microwave	Radar; active DME	Doppler navigators (Singer Kearfoot SKK-1000)	NA
Radio	Active DME; range receiver	Satellite doppler systems; TRANSIT; GPS	NA
Mechanical			
Inertial	NA	NA	Accelerometers; gyros
Barometric	Pressure; transducer	Rate of change	NA

Notes: NA = not applicable.
DME = distance measurement equipment.

both terrain mapping and bathymetry lidar systems. All bathymetry lidar systems record temporally resolved backscattered waveforms. The existing terrain mapping systems vary considerably in this regard. Some systems, such as the AOL, record the entire waveform, whereas other systems, which are essentially laser profilers, record only the slant range between the aircraft and the initial laser target. These laser profilers depend on a high laser pulse repetition frequency (PRF) and occasional direct penetration through vegetative cover to determine the ground.

Positioning Systems

Laser systems are capable of making extremely accurate distance measurements. Interpretations of the measurements require accurate information on the position and orientation of the laser at the time of the measurement. The absolute accuracy obtainable by virtually all existing laser mapping systems is constrained by the associated position measurements, not by the laser measurements.

Positioning systems can be classified into two broad categories: electromagnetic (EM) or mechanical. Electromagnetic systems use optical, microwave, or radio frequency energy to measure displacement, velocity, or acceleration. Mechanical systems rely on physical phenomena and can be further subdivided into inertial and barometric types. The data in Table 1 provide a general summary of the different types of positioning systems that have some potential for use in airborne laser mapping applications.

Electromagnetic systems that use displacement for positioning can operate in three geometric configurations. The EM systems and other major systems are briefly discussed in this section.

EM-Optical

EM-optical positioning systems use laser systems for measuring either distance (range) or angular displacement. Three-range systems are possible that provide range measurements from three reference ground stations to the aircraft. Because laser systems provide both accurate range and angle measurements, these systems commonly rely on a single-range measurement coupled with two angle measurements. The EM-optical systems provide about the best resolution (0.01 to 0.02 m) and accuracy (about 0.30 m) of all positioning systems.

EM-Microwave

EM-microwave positioning systems use both displacement and velocity techniques. Those systems that use displacement have either range-range-range or range-angle-angle geometric configurations, whereas those systems that use velocity are primarily doppler navigation systems. The doppler-determined velocity is integrated to determine displacement for the actual position determination.

Basic doppler navigation systems usually have three components: the doppler radar, a compass, and a computer. The doppler radar provides ground speed and drift information; the compass provides a heading reference; and the computer processes this basic information into position and guidance data. Although such systems are extremely valuable for aircraft navigation, they would not provide adequate absolute positioning data for many laser mapping applications.

Virtually all of the microwave displacement systems use a transmitter or receiver on the aircraft and three or more ground reference stations with active transponders. Such systems are commonly used for x-y or horizontal positioning applications. The resolution for microwave displacement systems is approximately 0.1 m (horizontal), and accuracy is roughly 1 to 2 m. The systems are advertised as being capable of determining positions of moving aircraft out to ranges of 185 km, depending on the systems used. Position updates can be made from 2 to 10 times/sec.

EM-Radio

There are two major types of EM-radio positioning systems: those that operate on displacement measurements, and those that measure velocity through doppler techniques. The doppler techniques are primarily used with satellite-based navigation systems.

Radio-displacement positioning systems operate only in the range-range-range geometric configuration. Both the VHF (1.6 and 3.3 MHz) and UHF (450 MHz) frequency bands are used. Virtually all of these systems were developed for horizontal positioning of ships at sea or aircraft over water. It is possible to determine positions out to ranges of 400 km at night and twice as far during the day; range resolutions are approximately 1.0 m, and range accuracy is approximately 2 to 3 m. Typically, position is determined about once every 2 sec. VHF system performance over land can be degraded to about one-half that possible over water.

The TRANSIT satellite currently provides the only operational satellite doppler positioning system. This system, which was initiated in 1967, currently has five satellites in nominal polar orbits. Users determine their position by measuring the doppler shift between their receiver's very stable oscillator frequency and the received frequency from the satellite. Resolution of the TRANSIT system is approximately 200 m.

The NAVSTAR global positioning system (GPS) is a 18-satellite, worldwide radio navigation system that is intended to become operational in the late 1980s. The GPS is intended to provide continuous global coverage for an unlimited number of passive users and also provide users with details of precise position, velocity, and time (19). Accuracies obtainable are expected to be within 8 m horizontal, 10 m vertical, and 0.03 m/sec velocity (19).

Mechanical Inertial

Many aircraft rely on inertial navigation devices for determining their position with respect to destination or some other reference. Inertial positioning systems are also used in the surveying and mapping industry to accurately locate ground points over large areas. In this capacity such systems are used in both ground vehicles and aircraft (primarily helicopters). Inertial positioning systems operate on the principle of Newton's laws of motion and rely on two devices--the gyroscope and the accelerometer--to do their job. Gyroscopes provide an extremely accurate means to measure direction and angular rates of change.

Inertial positioning requires the measurement and double integration of acceleration to determine displacement with time. Usually three orthogonally mounted accelerometers are used to meet this need. Because accelerometers are sensitive to both gravitational and inertial reaction forces, changes in the gravitational component must be compensated for to achieve accurate results, especially in the vertical channel. Three orthogonal accelerometers and two, 2-degree-of-freedom gyroscopes (mounted on a stable platform and isolated from the maneuvering of the carrying vehicle) are normally the heart of an inertial positioning system (20).

Before an inertial mission, a 30- to 50-min stationary period is used to orient the system into the local level coordinate system. During the course of a mission, it is necessary to make periodic zero velocity updates (ZUPT). During ZUPT times, the difference between system velocity as output by the software and the true velocity (zero) is used to estimate future system performance. Kalman filtering is typically used in making error and correction estimates.

The accuracy of the inertial systems depends on the number and spacing of ZUPTs. When inertial systems are operated in a ground vehicle or in a helicopter under specified surveying procedures, the total horizontal distance traveled is generally accurate to within 1 part in 10,000 horizontally and 1 part in 20,000 vertically (21,22).

Mechanical-Barometric

Barometric pressure systems represent one of the oldest methods for vertical positioning of aircraft. A constant barometric pressure (isobaric) surface (assumed to be spheroid concentric with the geoid) is monitored by checking for changes in barometric pressure. When isobars are sloped with respect to the geoid, a meaningful reference for vertical aircraft motion is not represented, except over short distances.

Positioning Systems in Use

The WREMAPS II system initially used a Wild Statoscope type RST 2 as a barometric pressure altitude reference. The device has been reliable in the field and has demonstrated short-term repeatability of approximately ±1 m and long-term repeatability of ±2 m. An advanced Statoscope system has been developed that will improve height measurement repeatability to 0.5 m (7). A 70-mm strip camera is used to record the precise track followed by the laser beam.

The Avco airborne laser mapping system uses a continuous ground-based three-axis microwave positioning system to help determine the vertical and horizontal position of the aircraft. The laser altimeter and positioning system are computer controlled. Aircraft roll and pitch are determined with a two-axis vertical gyro, and a barometric pressure reference monitors additional changes in aircraft altitude. The system output is a digital tape that provides parameters for horizontal and vertical position for both the aircraft and the point of measurement.

The NASA AOL uses a Litton LTN 51 commercial inertial navigation system to acquire positioning information. The velocity output and true heading of the LTN 51 are used to compute the flight path of the aircraft. Roll and pitch parameters are obtained from the same system, and all position data are digitized for subsequent correction of the laser altimeter data. An inexpensive vertical accelerometer is used to monitor short-term vertical motions of the aircraft. When the accelerometer is coupled with the elevations of three points along a flight line, long- and short-term aircraft vertical motion can be removed from the laser data through a quadratic correction. In addition, the aircraft is equipped with a nadir-oriented, 35-mm half-frame camera and a nadir-oriented television camera with a video cassette recorder.

An APR system, as applied by TRANARG C.A., Caracas, Venezuela (8), used a Spectra Physics Geodolite 3-A laser profile system in conjunction with a Statoscope differential barometric pressure altimeter (vertical control) and a Cubic Corporation autotape microwave positioning system (horizontal control). Daily air temperature and pressure measurements were made at several ground stations to help determine changes in the isobaric surfaces. All profile lines flown were relatively short distances that began and ended over known reference points. Aerial photography was also used to help establish the reference points.

Summary of Current Application Capabilities

Terrain Surface Mapping in Open Areas

The ability to map terrain surface geometry is the simplest task for an airborne laser mapping system. The principal constraint is the ability to position the aircraft during flight. A terrain profile acquired in a joint U.S. Army Corps of Engineers Waterways Experiment Station (WES) and NASA experiment (4) that used the NASA AOL system is shown in Figure 1. Aircraft motion was removed successfully by using three known reference points and the output of a vertical accelerometer. The laser profile is compared with a reference profile obtained from low-altitude stereo photography by using standard photogrammetric techniques. The root mean square difference between the two profiles over the 1200-m distance was 27 cm. On similar flight lines that have less topographic relief, the root mean square difference was as low as 12 cm for nonforested areas.

Terrain Surface Mapping in Forested Areas

A portion of the flight lines flown in the joint WES/NASA experiment was over wooded terrain. A laser profile and a reference photogrammetric profile over both open and forested areas for "leaves-off" conditions are shown in Figure 2. The root mean square difference between the laser and reference profiles was 50 cm in the forested area. Close examination of the actual ground profile in that area indicated that much of the difference recorded was due to the inability of the photogrammetric technique to accurately depict the terrain surface in the wooded area. Preliminary analyses of "leaves-on" data for dense forests indicated that only 5 to 15 percent of the laser pulses actually penetrated the canopy, reflected from the ground, and reached the aircraft, as opposed to approximately 40 to 50 percent of the pulses under leaves-off conditions.

Figure 1. Comparison of laser and reference profile for a stream valley.

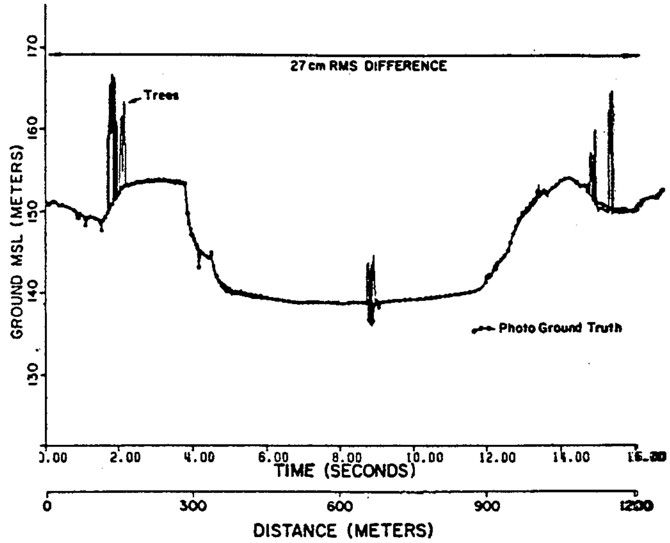
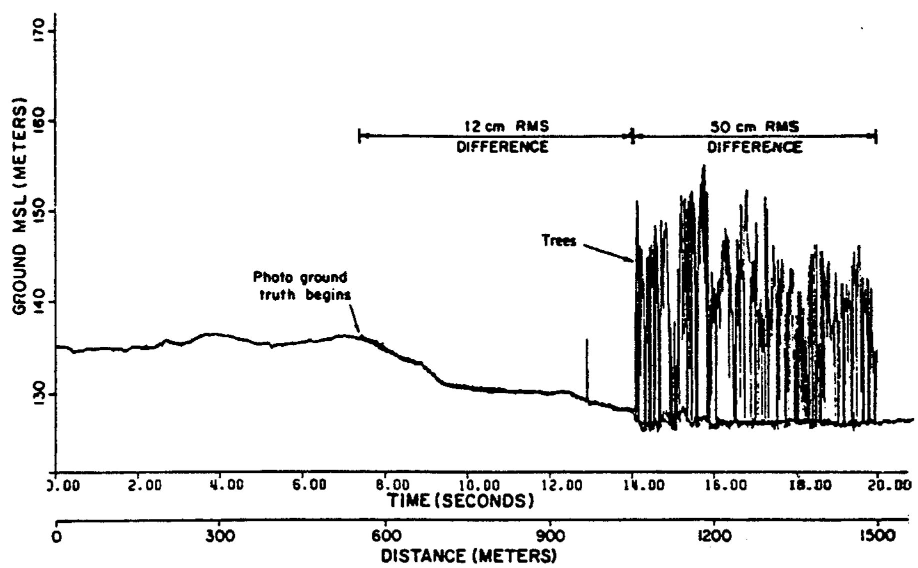


Figure 2. Comparison of laser and reference profile over open and forested areas.



A comparison of three-dimensional perspectives for photogrammetric ground truth and for the composite of two laser-scan passes over a forested (leaves-off) site is shown in Figure 3. The laser data were smoothed for easier comparison to the photogrammetric data. An independent point-by-point comparison indicated that almost 80 percent of the laser data were within 1 m of the photogrammetric data.

Bathymetry

Experiments with the NASA AOL system (9) and the Avco airborne laser mapping system (14) have indicated that the capability exists for reliably mapping bottom geometry in clear ocean water to depths of 10 or 12 m, and in slightly turbid waters to 4.6 m.

The Defense Mapping Agency and NORDA are developing an operational system called HALS. The preliminary work done with the NASA AOL system (a prototype for the HALS) resulted in the following conclusions (23):

1. The technique was able to measure water depths to within the 0.3-m root mean square accuracy standard over the set of conditions experienced;
2. Airborne laser hydrography could be performed for one-sixth the cost of conventional sonar surveys;
3. Airborne laser hydrography required only one-fifth the manpower of conventional sonar surveys; and
4. The technique offered the added potential benefits of a 100-fold increase in the number of soundings per unit area.

In a recent study with the Corps of Engineers Wilmington (North Carolina) District, the NASA AOL system was used for nearshore mapping. An example of both beach and bathymetric laser profile data is shown in Figure 4.

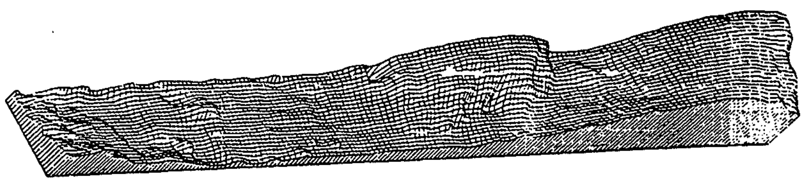
PROSPECTS FOR THE FUTURE

Laser Systems

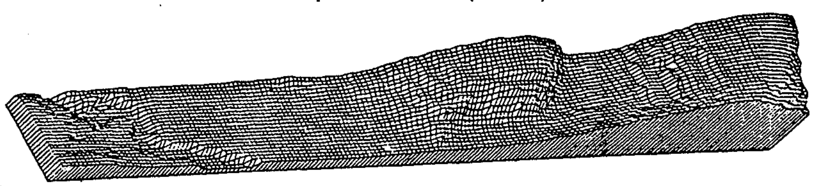
The future laser systems for a host of airborne mapping applications are almost on-line. The capability to produce subnanosecond pulses at various wavelengths will soon be the state of the art, as will be the requisite higher pulse rate frequency (PRF) and output power. Laser subsystem reliability and maintainability will follow shortly thereafter.

Development of scanning mechanisms to directly collect data in a true raster format will take place as higher PRFs and power become available, thus facilitating the subsequent data processing. Moreover, the higher PRF will increase data density to the point where repeat or overlapping passes will not be required, thus saving expensive flight time. Soon airborne laser systems will be operationally limited only by the speed of electronics for command, control, and data capture. Application of these systems is currently limited (and will be in the future) by the capability of navigation and positioning subsystems, not by the lack of measurement quality and quantity from the laser itself.

Figure 3. Comparison of laser scan and reference data for a forested area.

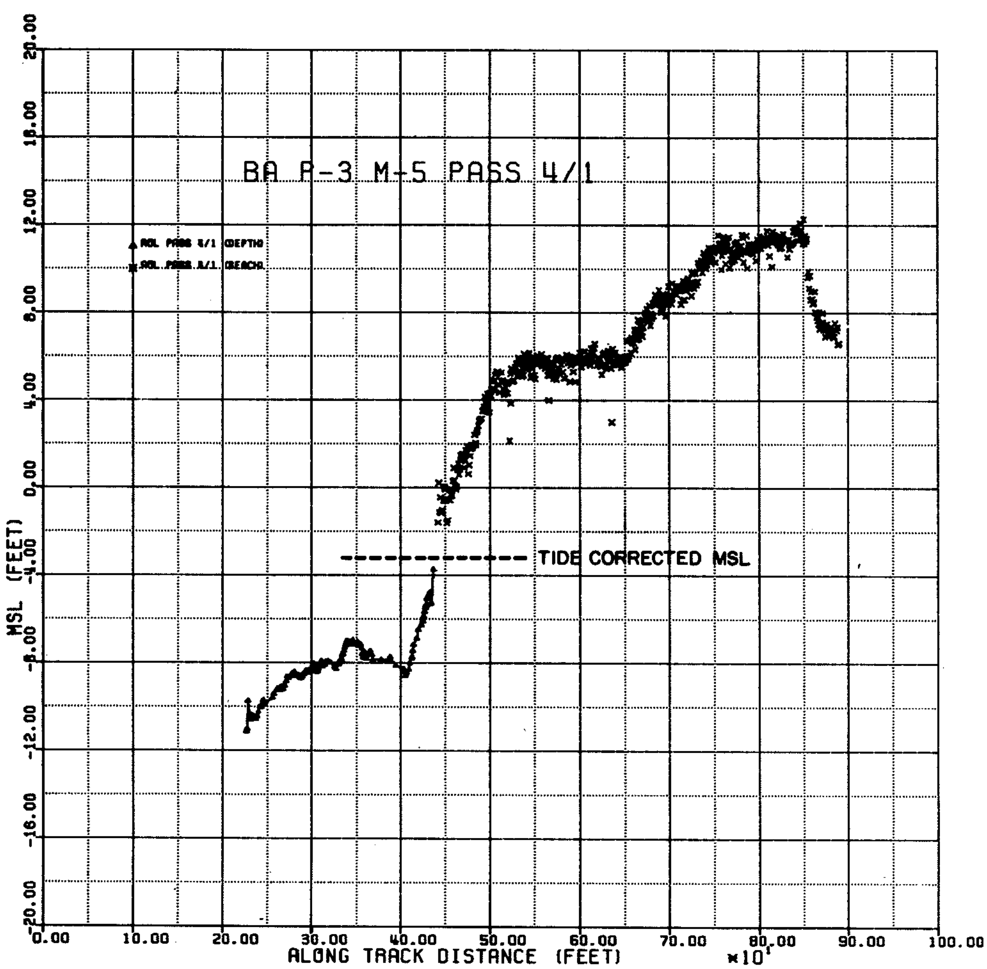


a. Composite of 2 laser scans (smoothed)



b. Photogrammetric ground truth

Figure 4. Example of laser profile data for mapping experiments near shore areas.



Positioning Systems

Many of the systems outlined in Table 1 have adequate horizontal positioning capability for many mapping applications because a vast majority of the systems were designed specifically to give information. The accuracy of vertical positioning capabilities with laser tracking devices is approximately 30 cm, and accuracy with microwave systems is 2 m. These capabilities are adequate for some applications, but marginal for others.

There are valid reasons why the more sophisticated positioning techniques have not been more widely used. Many systems (such as the range-range-range microwave and radio frequency devices) require active ground reference stations that are expensive enough to warrant manning each station to prevent loss or damage to the equipment. The laser tracking devices are extremely accurate and can operate from a single point (given the line of sight) but require a sophisticated and expensive ground platform for tracking. Inertial systems have enormous potential, but the requirement for frequent stops for ZUPT purposes is prohibitive in any aircraft except helicopters. Unfortunately, these systems are not designed specifically to meet the needs of airborne laser mapping systems.

Aside from specific accuracy requirements, the ideal positioning system for airborne laser mapping applications would require no ground reference stations. Of all the concepts currently in use or being developed, only inertial systems or the GPS could provide this capability. If ground stations are necessary, it would be beneficial if they were passive, inexpensive, and required no manpower. Future GPS capabilities are fairly well determined, and for some applications the GPS horizontal resolution will be adequate. Inertial systems that operate in helicopters may provide high accuracy over short survey lengths. Both EM-optical and EM-microwave devices have considerable potential for use with passive reflectors. Finally, combining different types of systems to generate an enhanced total capability has considerable potential for the future.

EM-Optical and Passive Ground Stations

The U.S. Geological Survey (USGS) and NASA are evaluating the use of laser tracking devices in aircraft and passive retroreflectors on the ground. The USGS investigation is in conjunction with development of their aerial profiling of terrain systems (APTS). In the APTS a sophisticated inertial navigation system will define the position of the aircraft in three coordinates, where a two-axis laser tracker will determine long-term drift errors of the inertial platform (the laser tracker data will be a substitute for the ZUPT data). Three or more retroreflectors positioned over known stations interspersed with several other reflectors will provide ground truth every 3 min. The accuracy goals for the system are 50 cm horizontal and 15 cm vertical.

The NASA Goddard Space Flight Center has been engaged in the design of a centimeter-accurate, multibeam, airborne laser ranging system (ALRS). The basic philosophy behind ALRS is to invert the usual satellite tracking laser ranging configuration by placing the ranging and pointing hardware in the aircraft and replacing the expensive ground stations with relatively low-cost retroreflectors. The ALRS will be capable of simultaneously ranging to six retroreflectors, thereby giving aircraft position to less than 1 m.

SUMMARY

The general advantages of airborne laser mapping include the ability to (a) collect data sets in a period of seconds that might otherwise require days or weeks by a ground survey team; (b) acquire data densities that are orders of magnitude greater than those feasible for ground systems; (c) acquire data in areas inaccessible to ground crews; and (d) collect data in a digital form that leads to easy and immediate computer processing. The ability to accomplish terrain surface mapping (even in forested areas) and bathymetric mapping (in reasonably clear water) has been demonstrated. Perhaps the most serious constraint to improving the performance of airborne laser mapping systems is the adaptation of improved positioning technology. Improvements in laser systems can enhance current capabilities, but not as much as improvements in positioning.

The major relevant advances in laser systems will focus on increased repetition rates and peak power levels. Increased power levels alone will not significantly enhance system performance for terrain mapping; however, significant increases in the depths at which bathymetric mapping can be accomplished could be a result of such efforts. Increased pulse rates would allow more efficient scanning by use of raster rather than conical patterns and would also enhance the ability to penetrate denser vegetation canopies.

Positioning systems are available to provide adequate horizontal control for most mapping applications. Nevertheless, most of these devices require relatively expensive active ground reference stations, which can be a manpower and cost constraint. That is not to say that such systems cannot be used cost effectively; in fact, the cost of laser surveys where such systems are used can be as much as one-third or one-half the cost of conventional survey methods. Vertical positioning for detailed surveys can be achieved over short flight paths; however, to do so requires the application of numerous methods in conjunction with considerable ground truth.

Available positioning systems have not been designed for airborne laser mapping. Techniques that use passive rather than active ground reference stations and aircraft-based optical or microwave range and doppler systems are needed to address the horizontal and vertical positioning problems over large areas.

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