Chapter 11
Airborne LIDAR Topographic Surveying

This chapter provides a general overview of the basic operating principles and theory of Airborne Light Detection and Ranging (LIDAR) systems. There are two basic types of LIDAR systems, those used for topography and those used for bathymetry. This chapter will deal mainly with topographic systems and uses. For bathymetric systems, see EM 1110-2-1003, "Hydrographic Surveying," Chapter 13, for additional information. The references listed at the end of this chapter should be used for more detailed background of all the topics covered in this chapter.

11-1. General

There are many methods/tools that can be used to collect elevation for input into an elevation model, including conventional ground surveys, photogrammetry, and remote sensing. One method/tool for collecting elevation data is LIDAR. LIDAR is an active sensory system that uses light, laser light, to measure distances. When mounted in an airborne platform (fixed wing or rotary wing), this device can rapidly measure distances between the sensor on the airborne platform (See Figure 11-1a and b) and points on the ground (or a building, tree, etc.) to collect and generate densely spaced and highly accurate elevation data. LIDAR mapping technology is capable of collecting elevation data with an accuracy of 15 cm (6 in.) and horizontal accuracies within 1/1000th of the flight height. In order to achieve these accuracies, LIDAR systems rely on the Global Positioning System (GPS) and an inertial reference system (IRS). See Figure 11-2 for concept diagram.

a. Closeup of sensor **b. Overall view of sensor**

Figure 11-1. Lidar sensor in aircraft (courtesy of Atlantic Aerial Technology)

11-2. Operating Principles

A LIDAR device mounted in an airborne platform emits fast pulses from a focused infrared laser which are beamed toward the ground across the flight path by a scanning mirror. Upon capture by a receiver unit, the reflectance from the ground, tops of vegetation, or structures are relayed to a discriminator and a time interval meter which measures the elapsed time between the transmitted and received signal. From this information, the distance separating the ground and airborne platform is determined. While in flight, the system gathers information on a massive base of scattered ground points and stores them in digital format. An interfaced Inertial Measurement Unit (IMU) records the pitch, roll, and heading of the platform. A kinematic airborne GPS system locks on to at least four navigation satellites and registers the spatial position of the aircraft. Additionally, many systems include a digital camera to capture photographic imagery of the terrain that is being scanned. Some systems have incorporated a video camera for reviewing areas collected. Figure 11-2 is a generalized schematic of a LIDAR system. The raw LIDAR data are then combined with GPS positional data to georeference the data sets. Once the flight data are recorded, appropriate software processes the data which can be displayed on the computer monitor. These data can then be edited and processed to generate surface models, elevation models, and contours.

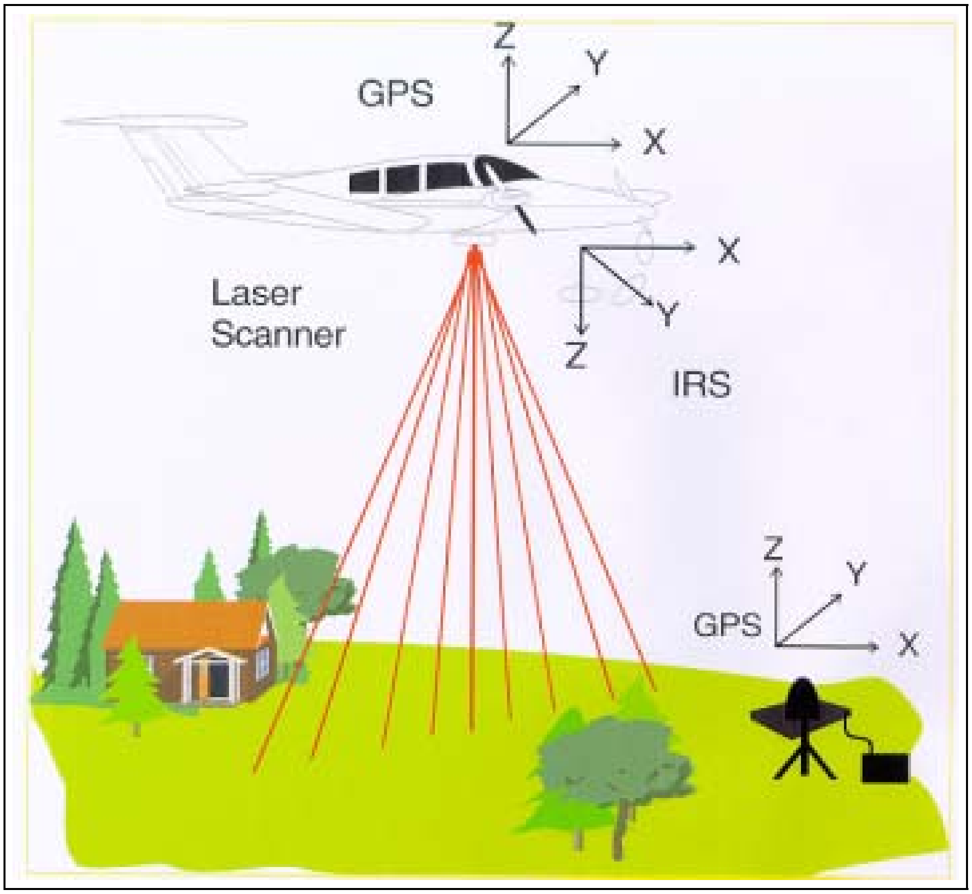


Figure 11-2. Lidar system (author unknown)

11-3. Uses of LIDAR within the Corps

LIDAR is being used for many applications within the Corps when topographic mapping, particularly those requiring elevation data, is needed. Several applications include levee profiling, dredge deposit evaluation, corridor mapping, floodplain mapping, topographic mapping of environmental or hazardous areas, and shore beach surveys, to name a few. Additional applications include large-scale Digital Elevation Models (DEM), forest management, coastal zone surveys, urban modeling, disaster response, and damage assessment.

a. Levee profiling. LIDAR systems can be used to rapidly and accurately map levee systems along rivers and waterways. Profiles and cross sections can be produced and compared to previous collected profiles and cross sections. The resulting LIDAR data sets can also be used to develop a 3-D view of the levee system identifying problems that might have otherwise been missed. The New Orleans District has used LIDAR to map sections of levee along the Mississippi River allowing them to create cross sections and identify floodwall structures near the levees and areas on the levee needing repair. They have also used the same system for planning of levee construction projects.

b. Dredge deposit evaluation. Data collection from a LIDAR system can be used to plan and monitor areas for depositing dredge material.

c. Corridor mapping. Like levee profiling, LIDAR provides an efficient and cost effective means of collecting elevation data along long corridors and linear parcels of land. The St. Louis District is using LIDAR to collect data along proposed high-speed rail corridors and rail/road crossings for accurate mapping and assessment of road grade crossings.

d. Floodplain mapping. LIDAR systems provide a cost effective means of collecting elevation data to be used in various models for floodplain modeling. Several districts have begun using LIDAR for these types of projects. The Federal Emergency Management Agency (FEMA) has also partnered with the state of North Carolina for the first statewide floodplain mapping project.

11-4. Background

The use of lasers for measuring distance have been around since the 1960s. Most surveyors are familiar with the use of laser technology in electronic distance measurement devices, either stand-alone instruments in the 1970s or on total stations in the 1980s. In the 1970s, several agencies including National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), the USGS and the Defense Mapping Agency (DMA) began developing LIDAR type sensors for measuring oceanographic and topographic properties. In the 1990's, with the development of On-The-Fly (OTF) GPS techniques, small relatively inexpensive IMU systems, and portable computing systems, it became possible to commercialize the technology and LIDAR sensors mounted in airborne platforms began to achieve more consistent and better accuracy. The number of LIDAR vendors has grown in the last 5 years from 3 in 1995 to about 50 in 2000 worldwide.

11-5. Capabilities and Limitations

a. Capabilities. LIDAR mapping systems are capable of rapid and accurate collection of topographic and elevation data without having to set out panel points or large control networks. Only one ground control station is needed within 30 km of the project/collection site. Depending on the flying height, swath width, scan angle, and scan and pulse rates, the shot spacing can range from 25 points per square meter to one point every 12 m (144 sq m). LIDAR is ideal for corridor mapping projects and can provide accurate information for shoreline/beach delineation. Laser mapping is feasible in daylight, overcast (provided that clouds are above the aircraft platform), or night time operations. Day time collection is not dependent upon adequate sun angle as is conventional aerial photography. Several vendors have developed algorithms to classify and remove vegetation to produce bare earth models of the data where some of the LIDAR data points are able to penetrate the vegetation cover.

b. Limitations. LIDAR sensors can only collect during cloud coverage if the clouds are above the height of the airborne platform. LIDAR sensors can only collect data in reasonably good weather and cannot collect data in rain, fog, mist, smoke, or snowstorms. In areas of dense vegetation coverage, the LIDAR pulses, in most cases, will not be able to penetrate through the foliage to the ground unless ample openings in the vegetation exist and the spot size of the pulse is small and densely spaced. Imagery data (digital photos or satellite imagery) are needed to perform proper vegetation classification and removal when producing bare earth models from multiple return LIDAR data.

11-6. Comparisons with Existing Technologies

a. Photogrammetry. The use of LIDAR for topographic mapping and collection of elevation data compares very well with competing technologies, such as traditional aerial photogrammetry, especially in areas where the LIDAR pulse can penetrate foliage. Not only does the data collection compare well, but the data processing of LIDAR, because it is simple X, Y, Z point data, can be more automated with minimal user interaction, unlike photogrammetric processing which requires a lot of user interaction. Table 11-1 lists the comparisons between LIDAR and traditional photogrammetry on some of their basic parameters. In many cases, photogrammetry (usually digital photography) is used in conjunction with LIDAR bare earth processing techniques.

Table 11-1
Comparison between Lidar and Photogrammetry

	LIDAR	**Photogrammetry**
Energy source	Active	Passive
Geometry	Polar	Perspective
Sensor type	Point	Frame or linear scanning
Point measurement	Direct	Indirect
Sampling	Individual points	Full area
Associated image	None or monochrome	High quality spatial and radiometric
Horizontal accuracy	2-5 times less than vertical accuracy	1/3 better than vertical
Vertical accuracy	10-15 cm (~10 cm per 1,000 m over heights of 2,500 m)	Function of flying height and focal length of camera
Flight planning	More complex due to small strips and potential data voids	Overlap and side lap need to be considered
Flight restrictions	Less impact from weather, day/night, season, cloud condition	Must fly during day and need clear sky
Production rate	Can be more automated and faster	
Budget	25%-33% of photogrammetric compilation budget	
Production	Proprietary software: processing performed by vendors, operators	Desktop software available to end-user
Limited contrast area acquisition	Can acquire data: used extensively for coastal mapping	Difficult and expensive

b. Radar technologies. LIDAR can provide higher accuracy and more detailed information about the landscape than radar technologies such as Interferometric Synthetic Aperture Radar (IFSAR). Elevation data obtained from IFSAR is collected in a side-looking mode, that is, off to one side, which can result in data voids in nonopen areas. LIDAR data are collected 10-20 deg either side of vertical to minimize data void areas and to collect direct vertical measurements to the ground or tops of features. IFSAR, however, can fly higher to obtain larger areas in shorter periods of time and is not affected by cloud cover. Current investigations are examining the benefits of combining IFSAR and LIDAR for use in enhancing the strong points of both systems.

11-7. LIDAR System Components

There are four basic components of a LIDAR system. The system includes the laser and scanning subsystem, GPS, IMU, and the operator and pilot display for flight navigation. Many systems also have an integrated digital camera to provide digital images used in bare earth modeling algorithms and feature classification procedures. Some systems have an integrated video camera to record the area scanned by the laser.

a. LIDAR sensors. The types of LIDAR sensors used for topographic applications operate in the near infrared band of the electromagnetic spectrum whereas those used for bathymetric applications operate in the blue/green band. The majority of the sensors on the market today all perform the same way in that they measure distances from the sensor to the ground or desired feature. The differences in the systems are in the power of the laser, the spread of the beam or spot size, swath angle, and the number of pulses per second transmitted. Several systems on the market today also have the capability of measuring multiple returns of each pulse sent out and the intensity of the return. Multiple returns are beneficial in areas of sparse vegetation or tree cover where the first return would hit the top of the tree and the last would penetrate down to the ground. First and last return sensors in some instances may provide bare earth models with less manual editing. See Figure 11-3 . Projects that require “bare earth” data collection should define the term “bare earth.” Employing LIDAR technology to develop bare earth models is not standardized. Care should be taken in development of a scope of work to ensure a complete understanding between all parties of the intended use of the data sets. This should include sufficient definition of terms such as bare earth and reflective surface models, etc. Typical sensor characteristics are listed in Table 11-2.

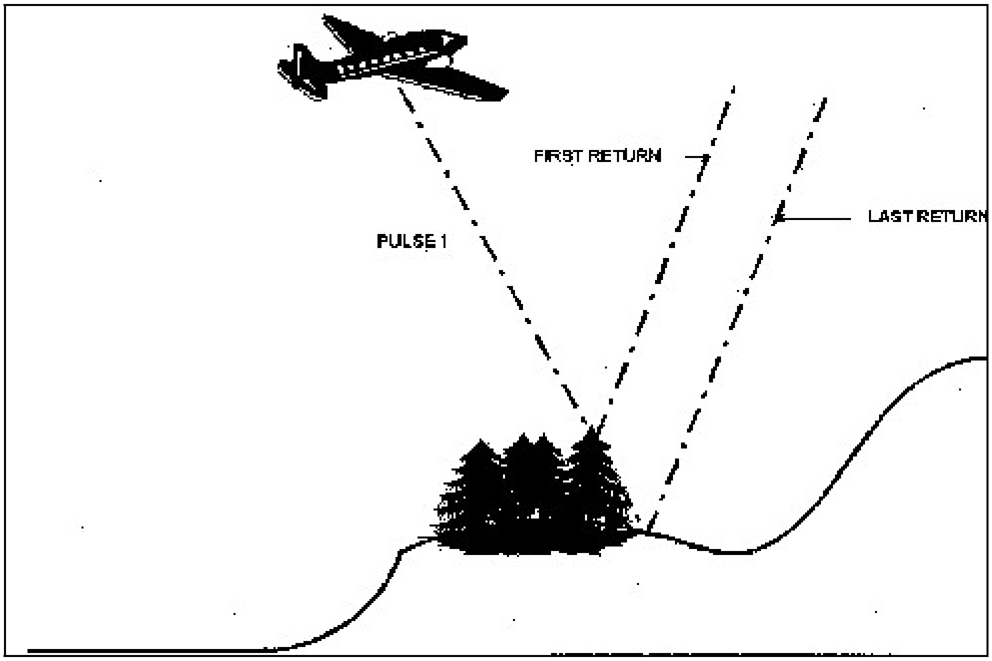


Figure 11-3. First and last return sensors (courtesy of Atlantic Aerial Technology)

Table 11-2
Typical Sensor Characteristics

Parameter	**Typical value(s)**
Vertical accuracy (cm)	15
Horizontal accuracy (m)	0.2 - 1
Flying height (m)	200 – 6,000
Scan angle (deg)	1 – 75
Scan rate (Hz)	0 – 40
Beam divergence (mrads)	0.3 – 2
Pulse rate (KHz)	05 – 33
Footprint diameter (m) from 1,000 m	0.25 – 2
Spot density (m)	0.25 – 12

b. GPS. The GPS component provides timing and positional information to the LIDAR system. The LIDAR pulses are time tagged using the time from the GPS receiver to later correlate them with the GPS solution summary. The type of GPS receiver used within the system should be capable of measuring/collecting the L1/L2 carrier phase data at a rate of 1 Hz (1 measurement per second). The same type of GPS receiver is required for ground control stations. The processing of the GPS data between the receiver onboard the aircraft and the receiver(s) on the ground control station(s) is known as On-The-Fly (OTF) Differential GPS. OTF, also referred to as Kinematic OTF or Real-Time Kinematic (RTK), allows for high-accuracy (<10-cm) 3-D positioning of a moving platform without static initialization.

c. IMU. The inertial measurement unit measures the LIDAR system orientation in roll, pitch, and heading. These values are combined with the GPS positional information and the laser range data scan values with rigorous geodetic calculations to yield the X, Y, Z of the points collected.

d. Operator and pilot displays. The operator display provides valuable information as data are being collected to the operator on the number of measurements returned, the status of the GPS satellites, IRS, and laser sensors, and the progress of the aircraft along the flight line. The pilot has a display of the aircraft along the flight line path with left/right/elevation indicators. This allows the pilot to navigate along the preprogrammed flight line.

e. Digital imagery/video. In some systems, a digital camera is used to provide an image of the areas being collected. The X,Y,Z data from the LIDAR can be overlaid on this imagery and used in the classification process. On a few systems, a down-looking video camera may also be mounted next to the laser and used to record the area scanned by the laser sensor. Time, latitude, and longitude are usually recording as part of the video display. This information is used by the operator to view the area being collected during the flight as well as used in post processing of the LIDAR data. The audio portion of the recording is used by the operator to note items or features of interest.

11-8. Planning a LIDAR Data Collection

There are several items, which need to be known when planning a project where LIDAR can be used, including when a collection should take place and requirements for ground control.

a. General. The bounding coordinates of the project area need to be known since it is critical in searching for control and setting up the flight lines to be used during the data collection. The type of area where the data collection will take place needs to be examined for amount of vegetation, trees, buildings, and other features that might impact the data collection. For example, if a bare earth elevation model is the end product, then there must be adequate spacing between the vegetation cover to allow the laser pulse to penetrate and obtain ground elevations. A bare earth DEM from LIDAR data in vegetated areas may also require a system with a higher scan rate, slower flying speed, smaller beam angle, or lower flying altitude to obtain a denser point spacing and have the laser pulses penetrate to the ground.

b. When to collect. Unlike photogrammetry, LIDAR data collection is not affected by sun angle and does not require collection to be performed in late fall or early spring for leaf-off conditions. However, it is advantageous to collect LIDAR data during leaf-off conditions in areas with dense deciduous trees, especially when the end requirements are for a bare earth DEM. Since the positioning of the LIDAR sensor relies on the GPS, specifically the kinematic solution of L1/L2 carrier phase processing, satellite ambiguity resolution must occur from data collected during times of low Position Dilution of Precision (PDOP), less than five, and with a minimum of five satellites. Most GPS postprocessing packages include mission planning software for checking PDOP and the number of satellites available for a specified time period. See EM 1110-1-1003, "NAVSTAR Global Positioning System Surveying," for more information on data collection with GPS and DGPS.

c. Ground control. The project ground control consists of the base stations, calibration control, and the project area control. All control throughout the project should be tied to a single geodetic network for consistency, blunder detection, and overall reliability. All GPS measurements should be made where the carrier phase (L1/L2) data are collected at each station and postprocessed using geodetic techniques. If orthometric heights are required as the final result, it is important that control points be used that have known North American Vertical Datum of 1988 (NAVD 88) heights for proper geoid modeling. See ETL 1110-1-183, "Using Differential GPS Positioning for Elevation Determination," for additional information on performing geoid modeling. A good source for locating high-accuracy control points in your project area is the National Geodetic Survey's (NGS) on-line data sheet search (www.ngs.noaa.gov, click on Data Sheets). Control points can be searched for in multiple ways (radial from project center, by USGS quad, bounding coordinates, …). Reconnaissance of control to be used should be done prior to data collection to make sure that control still exists and has no obstructions for satellite visibility.

(1) Base stations: These control stations must be within 30 to 40 km of the project area. In some case, the base station is set adjacent to the aircraft at takeoff and landing. The aircraft unit is initialized with the aircraft on the ground and stationary; following a brief initialization period the aircraft flies the project, then returns to the same location for a brief stationary period prior to closing the GPS session. Some vendors also collect data from two base stations to provide redundancy and backup in case one of the GPS receivers fails. By initializing the GPS ambiguities with the aircraft and base station receivers in close proximity, the ambiguity (hence GPS solution) may be carried over very long ranges. A conservative recommendation is a 50-km distance between the base station and the project site. Using a minimum of two points will also allow for processing between stations for a check on control. It is important that the control points used have the required horizontal and vertical accuracy to meet the need of the project accuracy.

(2) Calibration control: In order to make sure the LIDAR system is working properly, a calibration site may be established at or near the project site. Usually this calibration site is established at the airport where the plane begins the data collection mission. This requires additional calibration control at the airport as shown in Figure 11-4. The aircraft would fly over the airport immediately following takeoff to calibrate, or confirm calibration, of the total system.

(3) Project area control: The project area control is utilized to test the accuracy of the system and the final products. The quantity of control points is totally project dependent on the project and must consider the vegetative and terrain types in the project area. Selection of the control locations should give consideration to the fact that, in dense vegetation or steep terrain, errors in the final products may be functions of the slope or vegetative characteristics and not the LIDAR system itself.

11-9. LIDAR Data Collection

a. Calibration and quality control. Successful processing of LIDAR data normally requires both system calibration and quality control data collection. These requirements should be included in flight plan instructions to the flight crew. The following calibration and quality control requirements should be designed into each flight.

(1) Airport bidirectional and cross flight lines. A bidirectional and cross flight should be conducted over the airport for every flight using project specific parameters. The minimum critical parameters include altitude, field of view, scan and pulse rate, and aircraft speed. The results from this data set can be used to verify the accuracy of the system for the mission, and/or to make final adjustments to the calibration values used in the computations.

(2) Project cross flight lines. A cross flight line is a line that is perpendicular to and intersects the job flight lines. The primary function of the cross flight is to detect systematic errors such as a false increase in elevation of data away from nadir or line to line, detection of anomalies in individual lines, and to demonstrate the repeatability of results. It is important for these lines to cross all project flight lines. To provide the maximum information content, the cross lines should intersect the primary job lines in clear open areas with no vegetation, if possible.

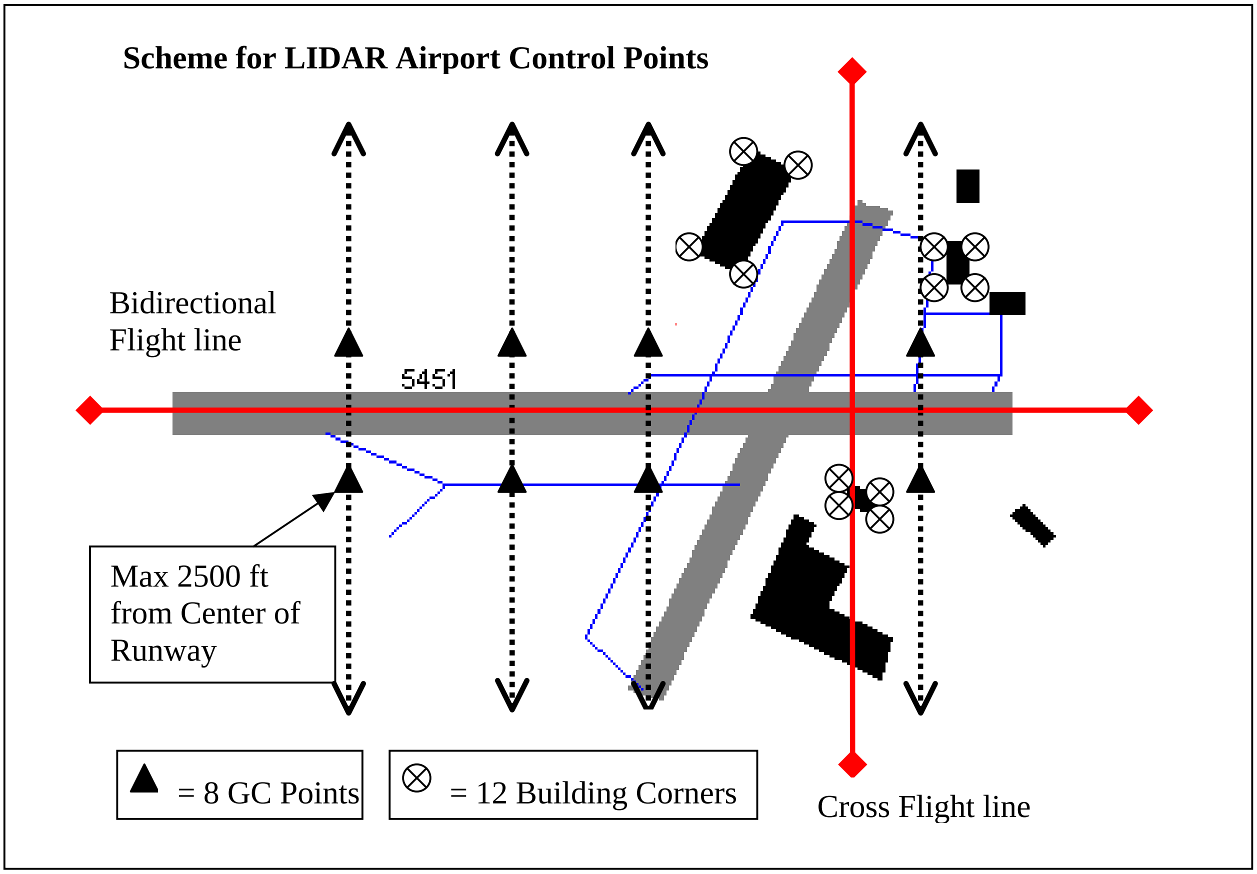


Figure 11-4. Airport calibration control scheme (courtesy of Earthdata International)

(3) Calibration site and project ground control. A series of geodetic ground control points at the airport calibration site and throughout the project are required for a complete quality control plan. Although LIDAR is very consistent between individual measurements, it is simply a two-way ranging system and is therefore susceptible to bias. To detect and correct for any bias, and as an overall quality check of the data, a series of control points should be established at the project airport as shown in Figure 11-4 and throughout the project site.

b. Base station ground control. Since positioning of the LIDAR sensor will be performed relative to the ground control stations used, proper setup and configuration of the GPS antennas and receivers is very important. This includes using tripods and tribrachs or fixed-height tripods that are calibrated and plumbed properly and receivers that are configured to collect at the same measurement rate as the receiver connected to the LIDAR sensor. GPS receiver/antennas should be set up and collecting L1/L2 carrier phase data prior to the aircraft’s entering the data collection area.

c. LIDAR collection. Once the system is configured and flight lines are established, the operator monitors the progress of the data collections to ensure data are being received back to the sensor. In almost all cases, the system operator will know if the laser is working correctly because lasers work or do not work. The operator can watch for erratic data from the IMU and the GPS to determine if those systems are working correctly. In general, flight lines are created to provide a 30-percent overlap of the previous flight line collection swath with the current lines swath. All of the LIDAR returns are GPS time-tagged to correspond with the postprocessed DGPS solution.

11-10. LIDAR Data Processing

a. Once the data are collected, the first step is to download the GPS carrier phase data from the control station and the aircraft receivers. These data are then input into the GPS postprocessing software package to compute the high-accuracy kinematic solution trajectory of the aircraft (Figure 11-5). There are several vendors that produce GPS processing software capable of this type of processing. The trajectory is then merged with the IMU data for a complete position and orientation solution. The laser ranging data are then merged, using geodetic algorithms, to the position and orientation to derive the end result, a X,Y,Z position for each pulse return measured by the sensor.

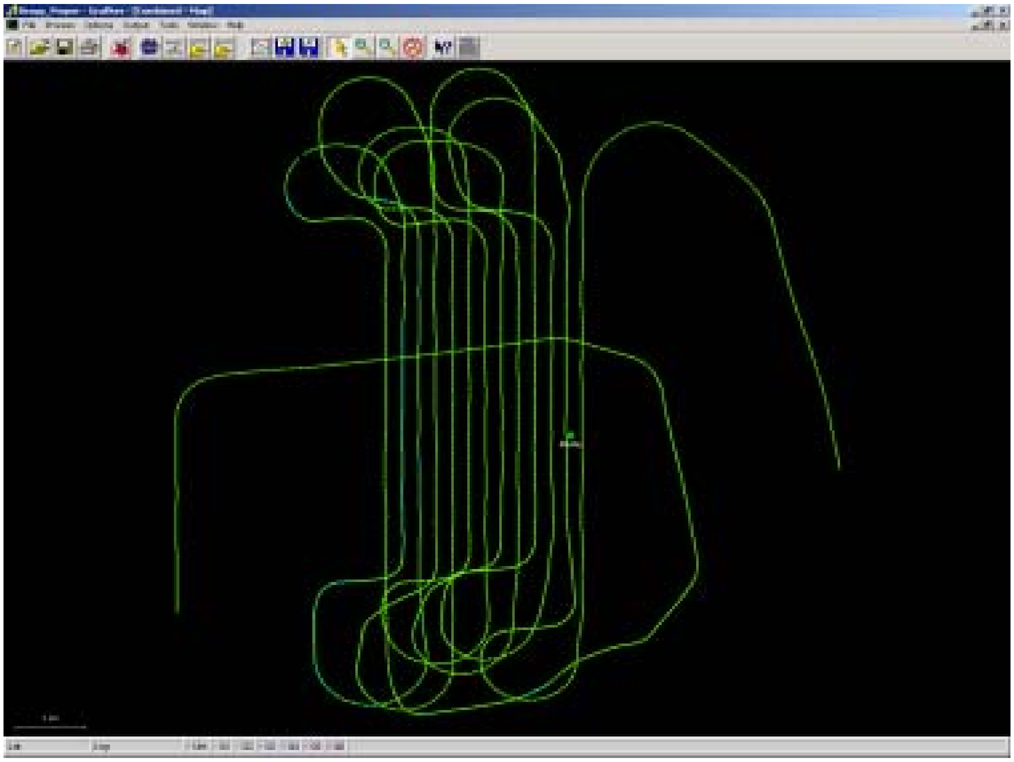


Figure 11- 5. DGPS processed trajectory of aircraft (courtesy of Rapid Terrain Visualization Program)

b. During data processing, a quality control review must examine the data for anomalies, systematic errors, or any potential horizontal or vertical bias. These anomalies could be a result of misalignment in any axis (roll, pitch, or yaw), system timing offsets, atmospheric conditions, GPS bias, or extreme spectral conditions of the natural terrain scene. Each of these anomalies can be detected with careful review and generally resolved in the data processing if required.

11-11. Results

a. Raw LIDAR data. Raw LIDAR data sets are simply a mass of X,Y,Z points for the object that the laser hits, measures, and records the distance to. The points are processed and referenced to the datum requested. See Figure 11-6.

b. Contour plots. The point data itself may or may not be of sufficient quality for a project. Often the end product required is contours of the earth surface. The accuracy requirements for the contours may require the collection of aerial imagery to assist in the collection of mass points and breaklines in the

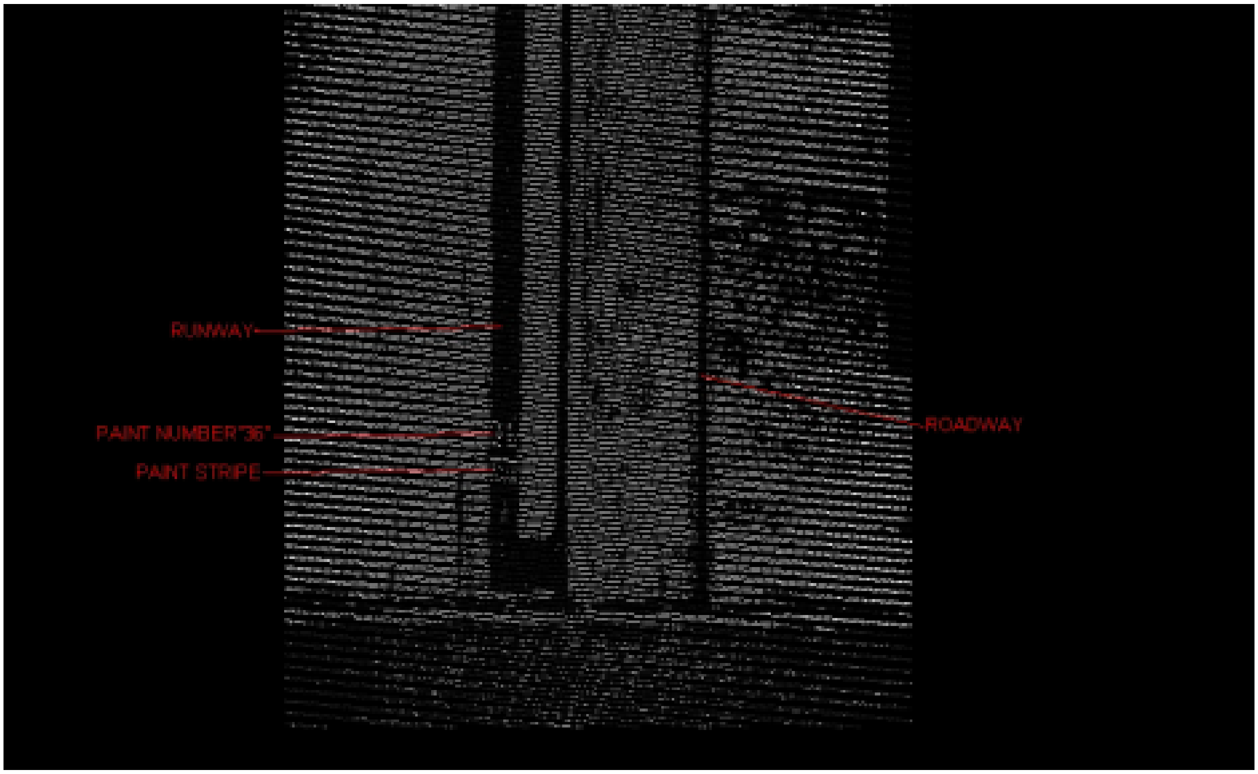


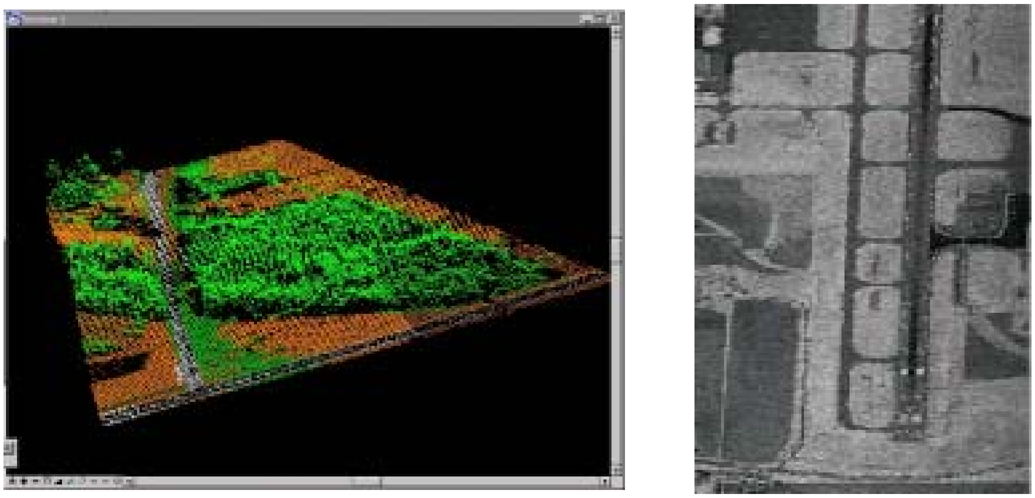
Figure 11-6. Raw LIDAR data (courtesy of Atlantic Aerial Technology)

locations required to adequately depict the character of the earth surface. Note, the sensor generally cannot see through dense vegetation or structures. In areas such as these, other tools such as ground surveys will be required to supplement LIDAR data sets and can add to the cost. When contours are required, the scope of work should state an expected accuracy according the ASPRS Standards as indicated in Chapter 2. LIDAR is simply one of the many tools that may be used to generate an elevation model. Other tools may be required in conjunction with LIDAR data to generate the type of products requested.

c. Surface modeling. These data from the sensors also may provide easy surface model generation. Surface model generation is accomplished by assigning colors or shades of gray to reflectance intensity from the sensor pulses. See Figure 11-7 a and b. Care should be taken in using surface models generated from LIDAR data sets. Note, the points utilized in the model are collected at the first or last return of the pulse. This is not necessarily to the edge of a building, ground surface, etc. A LIDAR generated surface model does not have the accuracy of an orthophoto image.

11-12. Data Classification

In order to produce an accurate contour plot of the ground elevations or to develop surface models from LIDAR data, especially in nonopen area (areas with trees, vegetation, structures, …), classification of these objects must be made in order to remove them from the final product. Most companies that provide LIDAR services have methods for performing data classification. Many of these methods are proprietary but all have the basic intention of identifying objects that are not ground features and need to be removed to develop a bald or bare earth model.



a.

b.

Figure 11-7. Surface models generated from LIDAR data (courtesy of Atlantic Aerial Technology)

11-13. Quality Control

Performing QC on projects involving LIDAR data collection can be accomplished several ways, including comparisons between ground stations, comparisons between kinematic survey solutions, and ground truth data collection.

a. Comparisons between ground stations. The use of two ground control stations can allow for processing of GPS data between both stations to check for agreement of the published coordinate values for each station. The kinematic trajectory from each station to the aircraft can be processed and compared to each other to determine if the differences are within the accuracy tolerance or not. If one control point is closer to the project site than the other, then it is expected that there will be slight differences in the two DGPS trajectory solutions.

b. Comparisons between kinematic solutions. GPS data collected on a moving platform such as an all terrain vehicle or car, across the collection area, can be postprocessed and used for comparison to the LIDAR X,Y,Z data. Several companies will collect this type of data along roads that traverse across the collection flight line and roads in the same direction of flight lines.

c. Ground truth data collection. The intensity image produced from the LIDAR collection or the image from a digital camera, if it was operated during the collection, can be used to pick areas where ground truth data collection could be collected. In areas of flat terrain or areas where detail is important it can be used as areas to collect X,Y,Z ground truth data for accessing the accuracy of the LIDAR data. Ground truth data can be collected using conventional survey techniques or DGPS techniques. Digital ortho quarter quads (DOQQ) may also be used in the ground truthing process.

11-14. Contracting Issues

a. A Contractor should provide experience in the production of the type of data required for a project. Quality control data for LIDAR projects is imperative. A Contractor should provide proof of quality of data collection for projects similar to that requested by a U.S. Army Corps of Engineers office. Quality control should include accuracy assessment of the final products and not simply the accuracy of individual point. The FEMA has a standard specification for LIDAR collection and processing. The FEMA specifications can be accessed on the FEMA web site. These specifications may be used in conjunction with or referred to in a SOW for a photogrammetric mapping project that will utilize LIDAR technology.

b. It is important for a project that might involve using LIDAR to state the accuracy of the final products in terms of DEM, Digital Terrain Model (DTM), or contours produced with the LIDAR data. For example, the accuracy should be stated in terms like "The final DTM produced will be of a quality that will meet or exceed ASPRS Class I Standards for the production of 1 foot contours." The ASPRS Standards allow for hidden (dashed contours) in areas where the ground is obscured, since data collected with LIDAR may have such areas.

c. LIDAR data collection can offer scheduling and cost advantages over labor-intensive airphoto mapping because it offers rapid data collection and fast postprocessing. Estimating the cost of LIDAR data collection is not standardized at this time. Only a few firms have the equipment and capability to collect the data, thus creating a varied market value. Cost can vary significantly based on the size, time of year, and location of a project. For some projects where elevation data are very critical, very large-scale mapping LIDAR may be cost prohibitive.

11-15. Sources of Additional Information

Several web sites exist that contain more in-depth information on LIDAR. One in particular is www.airbornelasermapping.com, which provides links to information about LIDAR, on-going research efforts, and service providers and manufacturers.