Chapter 14.
Laser Scanning Systems

14-1. Introduction

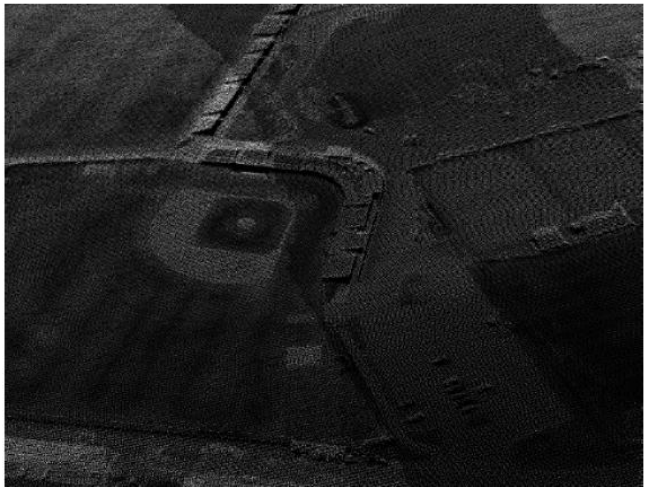

Figure 14-1. Combined aerial photography and laser scan data. (Image courtesy of Optech)

- It was not until the mid 1990s that advancements in GPS and inertial-aided navigation and georeferencing made large-scale mapping with lasers possible
- The term *laser scanning* is more appropriate for describing most of the systems used for mapping
- Laser scanning has many advantages over photogrammetry, albeit with significant tradeoffs
- For example, it is **an active system**, meaning that it provides its own energy, not relying on the sun to illuminate objects
  ⇨ This allows laser scanning to be performed at night and to avoid losing data due to sun shadows

14-1. Introduction

Figure 14-1. Combined aerial photography and laser scan data. (Image courtesy of Optech)

- ❖ Airborne laser scanning is at present less precise than airborne photogrammetric data with current systems yielding precisions in the neighborhood of 10-cm vertically and 15-cm horizontally under favorable conditions

- ❖ laser scanning does not provide the spectral information that photography does, and the data sets can be unwieldy
  - ⇨ The common practice of simultaneously acquiring both types of sensor data and fusing them to create combined data sets.

- ❖ Figure 14-1 shows aerial photography "draped" over laser scan data

14-2. Principles and Hardware

- The **main principle** behind laser mapping systems is that a laser pulse is transmitted to an object or terrain and its return signal is detected a split second later

- By accurately measuring the time delay between the transmission and return, and applying the speed of light, the distance from the scanner to the terrain or object point can be determined as shown in Eq. (14-1)

$$D = c\frac{t}{2} \qquad (14\text{-}1)$$

- t is the time between when the pulse is emitted and when the return is detected, and c is the speed of light (in the atmosphere)
  ⇨ Therefore, the basic sensor hardware for laser mapping systems is composed of a laser emitter, a laser receiver, and a timing unit

14-2. Principles and Hardware

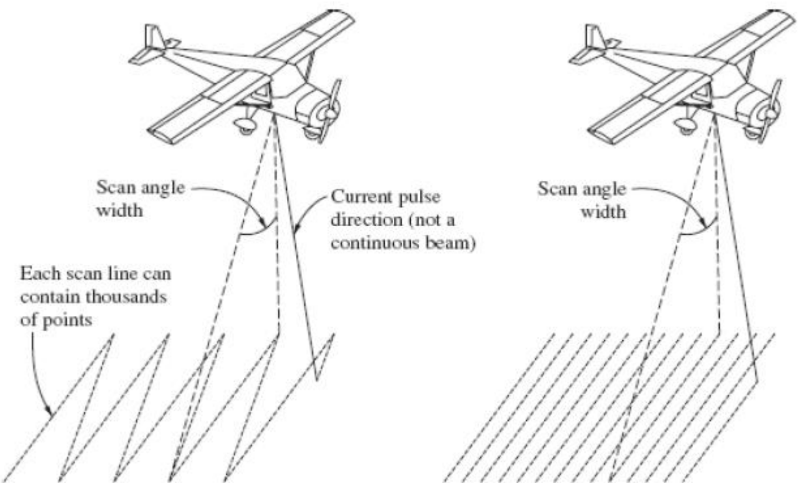

Figure 14-2. Scan pattern from an oscillating mirror laser scanning system.

- In order to cover large areas with multiple laser pulses, the direction of the laser must be changed rapidly and precisely
- Different scanning mechanisms are used to achieve this including oscillating mirrors and rotating multifaceted mirrors
- Figure 14-2 shows the point pattern from an airborne **oscillating mirror scanning system** (left), and that from a **rotating multifaceted mirror scanning system** (right)

- The zigzagging pattern generated by the oscillating mirror compared to the parallel lines from the rotating mirror
- The **oscillating mirror system** leads to smaller point spacing in the across-flight direction, and larger point spacing in the in-flight direction at the edge of the scan due to the mirror slowing down to change directions
- Some systems modify the pulse rate during acquisition to compensate for this effect

14-3. Airborne Laser Scanning

- The most common type of laser scanning is *airborne laser scanning* (ALS)
- ALS systems are composed of georeferencing hardware including an inertial measurement device and a GPS receiver
- As the aircraft travels over the survey area scanning the terrain below, the inertial navigation device periodically records the attitude angles (roll, pitch, and yaw; or omega, phi, and kappa)
- The interfaced GPS receiver is periodically recording the X, Y, Z positions of the antenna
- After the signals from the three devices are processed and combined, the laser pulses essentially define vector displacements (distances and directions) from specific points in the air, to points on the ground

14-3. Airborne Laser Scanning

(14-2)

$$\begin{pmatrix} X_A \\ Y_A \\ Z_A \end{pmatrix} = \begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} + M \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ 0 & -\sin(\alpha) & \cos(\alpha) \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ -D \end{pmatrix}$$

where:
- X_A, Y_A, Z_A are the point coordinates
- X_S, Y_S, Z_S are the scanner position
- M is the rotation matrix from the scanner to the ground system
- α is the pointing angle

❖ Equation (14-2) shows relationship between point position on the ground and the orientation and angle of the laser scanner

❖ Since the laser device can generate pulses at a very fast rate (thousands of pulses per second), the result is a dense pattern of measured X_A, Y_A, Z_A points on the terrain

Figure 14-3. Optech Orion airborne laser scanning system. (Image Courtesy of Optech)

❖ Figure 14-3 shows an ALS system with scanning and georeferencing hardware

14-3. Airborne Laser Scanning

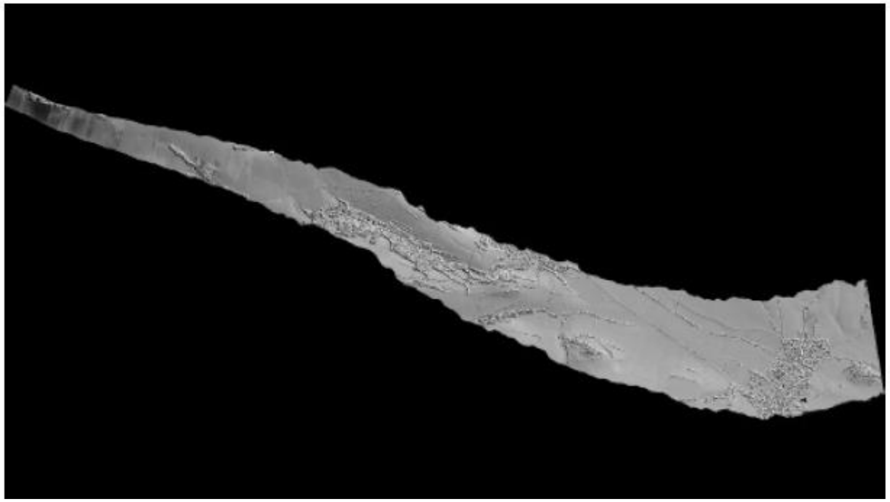

Figure 14-4. Swath pattern from an ALS system over variable terrain. (Courtesy of RIEGL USA, Inc.; http://www.rieglusa.com.)

- ALS flights are flown so that overlapping scanned *swaths* are produced for the survey area
  - ⇨ This is to ensure full coverage of the area, avoiding data gaps caused by terrain relief and to allow for calibration
- Figure 14-4 shows an ALS swath pattern illustrating the impact of terrain change on swath width
- The **swath width** is a function of the height of the scanner above terrain and the *scan angle*, the size of the angle swept by the laser
- A common procedure is to fly a few swath lines perpendicular to the other lines for use in the calibration of the scanning mirror and other hardware

14-4. Terrestrial Laser Scanning

Figure 14–5. RIEGL VZ400 terrestrial laser scanner. (Courtesy of RIEGL USA, Inc.; http://www.rieglusa.com.)

- *Terrestrial laser scanning* (TLS) is usually done using a static platform as opposed to ALS, the scanner is set up at a location and scans the survey area from this stationary position
- Since there is no movement of the platform, either the scanner's head must rotate or an additional mirror must be used to scan
- Figure 14-5 shows a terrestrial laser scanner
- TLS data is typically georeferenced by scanning targets with known datum coordinates
- The 3D coordinate transformation from the scanner system to the datum system is calculated using the target points, and is then applied to all other points in the scan
- Scans from different positions can be combined using the same process with common targets between scans

14-4. Terrestrial Laser Scanning

- TLS data may also be georeferenced by **fixing a GPS antenna to the scanner itself**
- In this case, multiple scans are combined using the method, and the positions of the antenna in the combined scanner system can be used to solve for the transformation from the combined scanner system to the datum system
  ⇨ A minimum of three scanner setups to use this method
- Another popular method for combining scans is by using **surface matching**
- The set of points for one area from one scan is compared with the points for the same area in another scan, and the relative orientation between scans is calculated based on the criteria of how well the scans "fit" together
- A common method for **surface matching** is the iterative closest point (ICP) algorithm, in which the relative orientation of two scans is iteratively updated towards a solution criterion that the sum of the distance between paired points from different scans is minimized

14-4. Terrestrial Laser Scanning

Figure 14-6. RIEGL VMX450 mobile laser mapping system. (Courtesy of RIEGL USA, Inc.; http://www.rieglusa.com.)

- Terrestrial scanning may also be collected using a mobile platform
- In this case, similar to aerial mapping, an onboard GPS receiver and inertial system must be used
- Mobile TLS combines the ability of static TLS to collect 3D data from a ground perspective with the ability of ALS to collect data over large areas in a short amount of time
- Since it uses direct georeferencing, it avoids the need for control observations
- The data from mobile TLS is generally much less accurate than static, and results are highly dependent on the visibility of satellites
- Mobile TLS is mostly used for mapping urban streets and highways; however, as more sophisticated processing is developed it is expected to be used in a wider range of applications

14-5. Laser Scan Data

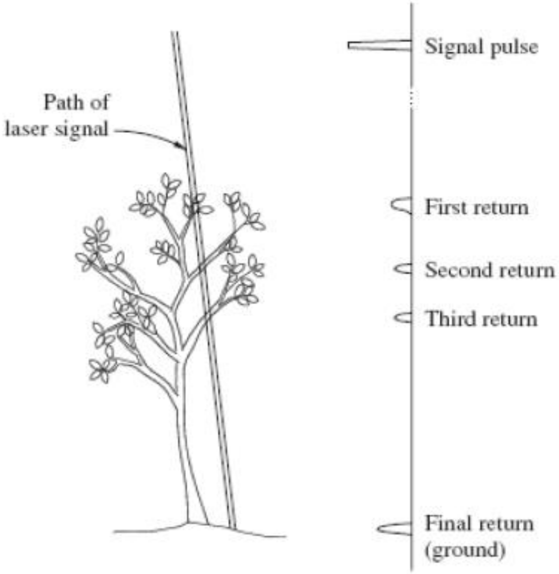

Figure 14-7. Multiple returns from a single laser pulse.

- Laser scan data consists of sets of 3D coordinates called *point clouds*
- Because of the high rate of collection, the size of these point clouds can contain millions of coordinates
- Since the laser pulse can penetrate through certain types of vegetation and other objects, each pulse may yield multiple returns

- When a pulse is emitted, a portion of it may hit leaves at the top of a tree and return to the sensor, the remaining pulse may strike a limb on the same tree and return to the sensor, and the rest of the pulse may hit the ground and reflect back to the sensor
- These multiple returns are each recorded and Figure 14-7 illustrates multiple returns from a single pulse

14-5. Laser Scan Data

❖ After the initial processing of the point cloud to determine the real-world, datum coordinates of the points, operations may be performed on the data to provide specific information sought by the user

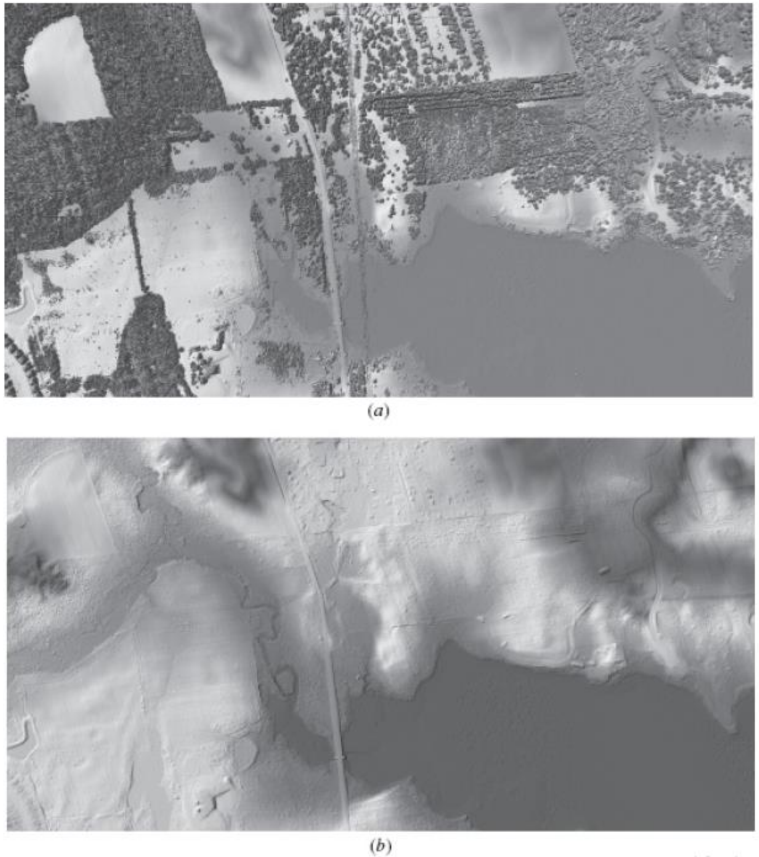

Figure 14–8. Unfiltered and filtered ALS data. (Image Courtesy of Optech.)

❖ A common procedure is to filter the data so that only last returns are used

⇨ This results in a **bare-earth DEM**, an exceptional example of the advantage of laser scanning to penetrate canopy

❖ Figure 14-8a shows before and b shows after images of a filtered point cloud

❖ The data is also commonly interpolated to create a **gridded DEM**

⇨ This DEM can be used to create contour maps and other topographic products

14-5. Laser Scan Data

- **Laser scanning systems** can be classified as either ***discrete*** or ***full-waveform*** with respect to how returns are recorded

- **Discrete sensors** record the ranges for each return, while **full waveform sensors** record a quantized waveform of the returning echo

- Using full waveform sensors allows for the extraction of extra information from the object being scanned like surface roughness, and can facilitate the filtering of terrain with short vegetation

- The major downside to full-waveform systems is the immense amount of data that is recorded

- the intensities, or the strengths of the returning signals, are usually recorded and provide even further information about the scanned object and can be used to aid in classification of the data

14-6. Error Evaluation

- ❖ The accuracy of the position of 3D points collected by ALS is most affected by the precision of the processed GPS data
- ❖ Although a nominal accuracy is associated with ALS data, the discrimination of the height of objects that are close together can be problematic due to the footprint, or laser beam diameter on the ground
- ❖ The pulse length can contribute to ambiguity in ALS data
  ⇨ An issue with getting bare earth data from areas with low vegetation
- ❖ The convolution of these returns can cause a bias in the determination of the ground (second return) height
  ⇨ The use of full waveform sensors can help alleviate this problem
- ❖ Boresight and leverarm calibrations must be found to get accurate results in ALS
- ❖ There may also be a scaling error of the angle traversed by the scanning mechanism
  ⇨ In other words, there may be errors stemming from the device that records the pointing angle of the laser beam