A Primer for Airborne Lidar

K. Clint Slatton[1,2] and William E. Carter[2]
The National Center for Airborne Laser Mapping (NCALM)
1: Electrical and Computer Engineering Department
2: Civil and Coastal Engineering Department
University of Florida
Gainesville, Florida 32611

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The essence of Airborne Laser Swath Mapping (ALSM) is the use of spatially-dense lidar (laser ranging) measurements to precisely geo-locate reflecting objects that comprise the terrain and land cover (Roth, et al., 2007), as shown in Fig. 1. If these measurements are made with sufficient accuracy and density, the set of laser reflections can be interpolated and used to infer structural properties of the terrain (e.g. topography and the location and morphology of faults and channels), of vegetation, (e.g. tree heights and crown areas), and of anthropogenic infrastructure (e.g. building heights and footprints and post-disaster damage). When intensity measurements from the laser returns are included, monochromatic spectral information can also be obtained. These structural parameters are critically important for many applications in their own right. But, when used in conjunction with physically-based geophysical, hydrologic, or ecological models, they can add value and support the improved estimation of many other important parameters for earth science applications. When acquired over large areas, these measurements and parameter estimates can also be segmented and classified to understand spatial patterns on the landscape. There are, however, six fundamental aspects of the ALSM measurement that must be well understood before one can produce “research quality” (Slatton et al., 2007) lidar data and properly analyze it for specific scientific applications.

1. Laser Emission

The type of laser, the lasing material used, and the stimulation power source determine the wavelength, repetition rate, and energy of the emitted laser pulses. For modern ALSM systems, diode-pumped, solid-state Nd:YAG, passively Q-switched, air-cooled lasers are generally used. The fundamental wavelength of Nd:YAG lasers is 1064 nm (1064×10^{-9} m), which falls in the near infrared portion of the electromagnetic spectrum. Other wavelengths can be achieved using different lasing materials and/or frequency-doubling crystals, but 1064 nm is the most common wavelength by far in ALSM systems because of the power efficiency of Nd:YAG lasers, the loss of transmit energy associated with frequency doubling, and the high sensitivity of available photodetectors in that portion of the near-infrared band.

The rate and length of the transmitted laser pulses are interrelated. For the high signal-to-noise-ratio (SNR) designs favored by most commercial ALSM systems, it is critical to maintain sufficiently high energies per transmitted pulse to ensure robust detection of the return waveform at standard altitudes of 500m to 1,500m above ground level (AGL). As a result, per pulse energies on the order of 100 μJ (100×10^{-6} J) are required. Physical limitations on the stimulated emission from the lasing material and the choice of how to implement the passive Q-switching dictate minimum pulse lengths that can be achieved given a fixed per-pulse energy design. Typical pulse durations for commercial ALSM systems are 10 ns (10×10^{-9} sec), which corresponds to a path length distance of approximately 3 m. While high laser pulse rates are desired to densely sample the terrain as the aircraft flies overhead, limitations on the power delivery rates of the pump diodes and the Q-switching also constrain the maximum pulse rates. In state-of-the-art commercial ALSM systems with pulse energies near 100 μJ and pulse lengths near 10 ns, maximum laser pulse rates are generally between 150 – 170 kHz. It should be noted however, that ranging precision generally suffers when operating near the maximum obtainable pulse rate for a given ALSM sensor.

2. Propagation from the Laser

Physical phenomena, such as aperture diffraction, extinction, dispersion, and scintillation govern the loss of energy and deterioration of the beam (mostly through spreading) for the transmitted pulses. The beam cross section is usually designed to be nominally Gaussian (TEM_{00} mode). Over the relatively short path lengths for ALSM (500 – 1500 m) through a standard atmosphere near sea level, beam attenuation is dominated by extinction. The beam would therefore remain very narrow if transmitted simply as a collimated output of the laser. But that would result in extremely high dynamic ranges in the return pulse intensities that could cause excessive range biases. To avoid this, the outgoing beam is intentionally spread out by passing it through a diverging lens. Typical half-angle beam divergences that result are around 0.3 milliradians (referenced from beam centerline to the $1/e$ intensity radius). At an AGL altitude of 600 m, that corresponds to a footprint diameter on the ground of 15 – 20 cm. While spreading the beam to obtain a more integrated intensity over the footprint is useful to a point, spreading the beam much beyond 0.8 milliradians is generally not desirable in small-footprint ALSM units because of the loss of spatial resolution suffered with the larger footprint.

3. Optical Reflection(s)

The scattering of an optical beam from an object consists of specular and Lambertian components. The specular component is highly directional and propagates in the forward scatter direction according to Snell's Law. The Lambertian component is almost isotropic, reflecting the laser light broadly over a large range of directions. A true Lambertian component results from optical scattering interactions at scales comparable to the laser wavelength. In addition, multi-directional reflections at somewhat larger scales that are still small relative to the footprint can contribute to an overall "Lambertian type" diffuse scattering of the laser light. Most natural terrain and land cover exhibit structural variation at scales comparable to or smaller than the ALSM footprint. Thus, the Lambertian component often dominates the optical reflections (exceptions include water bodies and some building roofs).

The spectral properties of each surface patch illuminated by the laser footprint determine its reflection coefficient. Sometimes the patch illuminated by a footprint is reflective enough that the directionality of the scattered light is significant. In such cases, the slope of the surface patch relative to the incident beam can have a measurable effect on the return waveform. Generally, the effects on the range measurement are minimal for well-calibrated, small-footprint, discrete-return ALSM sensors (unlike for large-footprint full-waveform lidars). However, the effect on the intensity measurements is often visible.

Diffuse media, such as vegetation canopies, can be viewed as a collection of small discrete surfaces or scatterers that reflect the laser light. The well known ability of lidar to penetrate many vegetation canopies is due to the discontinuous nature of the foliage. Small gaps in the canopy and between branches allow significant fractions of the narrow laser beam to pass through to lower levels and even to the ground. In dense natural forests of hardwood/pine mixtures and understory vegetation, roughly 10 – 20% of the laser pulses can still reach the ground. The primary effect of multiple reflections in foliage is to spread the return pulse out in time and dramatically modulate it. Whereas the transmitted pulse is uni-modal and roughly 10 ns in duration, return pulses over dense forests will in general be multi-modal and up to 100 ns or more in duration.

4. Propagation Back to the Receiver

Because most of the optical reflections on the terrain are effectively Lambertian, the reflected laser light is spread over almost all skyward directions. As a result, only a very small portion of the incident photons are reflected back toward the ALSM receiver, leading to a dramatic $1/R^2$ loss in energy, where R is the path length. This so-called “spreading loss” dominates the attenuation on the return path.

5. Signal Reception

The return pulse consists of a packet of photons whose density variations can be represented as a waveform. If the transmitted beam intercepts a single flat surface patch, the return waveform looks much like a smaller (due to the lost energy) version of the transmitted pulse. If the beam instead undergoes many scattering events (from rough or sloped terrain, building edges, and/or vegetation canopies), the return waveform will be longer and possibly multi-modal. This waveform enters the aperture of the ALSM sensor head and is focused onto a photodetector. The most commonly used type of photodetector for commercial ALSM systems is an avalanche photodiode (APD). APDs work on the principle that incident photons can excite atoms in the receiver matrix such that valence electrons become dislodged (are excited from the valance band to the conduction band). These electrons are then free to respond to the electric field placed across the detector so that they generate a measurable current. The time rate of change of this current corresponds approximately to the photon density in the return waveform. The correspondence is approximate due to the finite response times required for the electrons to move across the face of the APD.

In discrete-return ALSM units, this analog electrical signal is then passed through an analog constant fraction discriminator (CFD) circuit. In some systems (including the NCALM system), the signal is routed, according to its intensity level, to one of at least two different CFDs calibrated for low and high intensities. The CFD(s) identify a timing point on the return pulse signal by differencing the waveform with a delayed, inverted, and scaled copy. They are typically designed to trigger on the full-width-half-maximum (FWHM) point on the leading edge of the return waveform. The timing points output from the CFD are then converted to discrete time-tagged ranges.

The combination of the transmit pulse length, the closeness of reflectors in the beam’s path, the response time of the photodetector and the circuit design of the CFD, impose a lower limit on the timing resolution between successive pulses in a multi-modal return waveform. In most modern ALSM systems, this lower limit, often referred to as the “dead time” is approximately equal to the pulse length (see Fig. 2). Thus, for a 10 ns pulse length (3 m in path length), any reflection events from objects closer than about 3 m along the laser line of sight will not be resolved. When this occurs, the recorded range corresponds to that of the first (highest) object, and the second (lower) object is not observed. The dead time effect can be mitigated by either using a full-waveform digitizer or high laser pulse rates. Waveform digitizers still have an effective dead time caused by their finite range bins, but it is generally shorter (roughly 1 ns) than for discrete return ALSMs. When high horizontal resolution is the dominate requirement, however, it is advantageous to employ the higher laser pulse rates that are possible when not recording full waveforms. These high laser pulse rates (>100 kHz) can yield good sampling of vegetation vertical structure with as few as 4 returns per shot because of the numerous small gaps in the foliage.

6. Transformation to Geo-referenced Coordinates

Finally, the recorded laser ranges must be projected into a geo-referenced (Earth-fixed) reference frame, such as UTM or lat/lon in the horizontal and height above the ellipsoid in the vertical. First, the recorded scanner angle is interpolated to estimate an angle for each laser shot. Then, the position and orientation (roll, pitch, and yaw) of the aircraft are determined for each shot. This is done through a blended aircraft trajectory solution using an onboard GPS receiver and inertial measurement unit (IMU). The IMU provides high frequency (>100 Hz) estimates of orientation angles and integrated position. Because IMUs are subject to drift in their absolute position estimates, the GPS samples acquired at 1-2 Hz are used to reduce the effect of the IMU drift and improve the absolute position solution.

Multiple GPS ground stations are used to improve (differentially correct) the trajectory solution obtained from the onboard GPS/IMU. Typical random errors in the final aircraft trajectories can generally be brought down to the few centimeter level with careful calibration and good distribution of the GPS ground stations, which usually consist of both field-deployed GPS receivers and Continuously Operating Reference Stations (CORS) established by NOAA/NGS (Stone, 2006). Ionosphere-induced errors in the

GPS solutions are mitigated by employing L1 and L2 band GPS solutions. Tropospheric (water vapor) induced errors are minimized by distributing GPS ground stations over the field site, especially when the site to be mapped exhibits a large range in elevations. Finally, good mission planning and experienced field crews can collect orthogonal swaths and kinematic GPS ground truth data to be used in post-processing to minimize offsets between overlapping flight lines or elevation biases (Shrestha, et al., 2007).

Each laser return is tagged with a geo-referenced XYZ location and relative intensity value. The points are often displayed as so called "point clouds". Three dimensional (3D) precision of the geo-located laser return points can be as good as 20 – 30 cm in the horizontal and 7 – 10 cm in the vertical. The point clouds can be filtered so that the points corresponding to ground reflections are isolated and then interpolated to form bare-earth digital elevation models (DEMs).

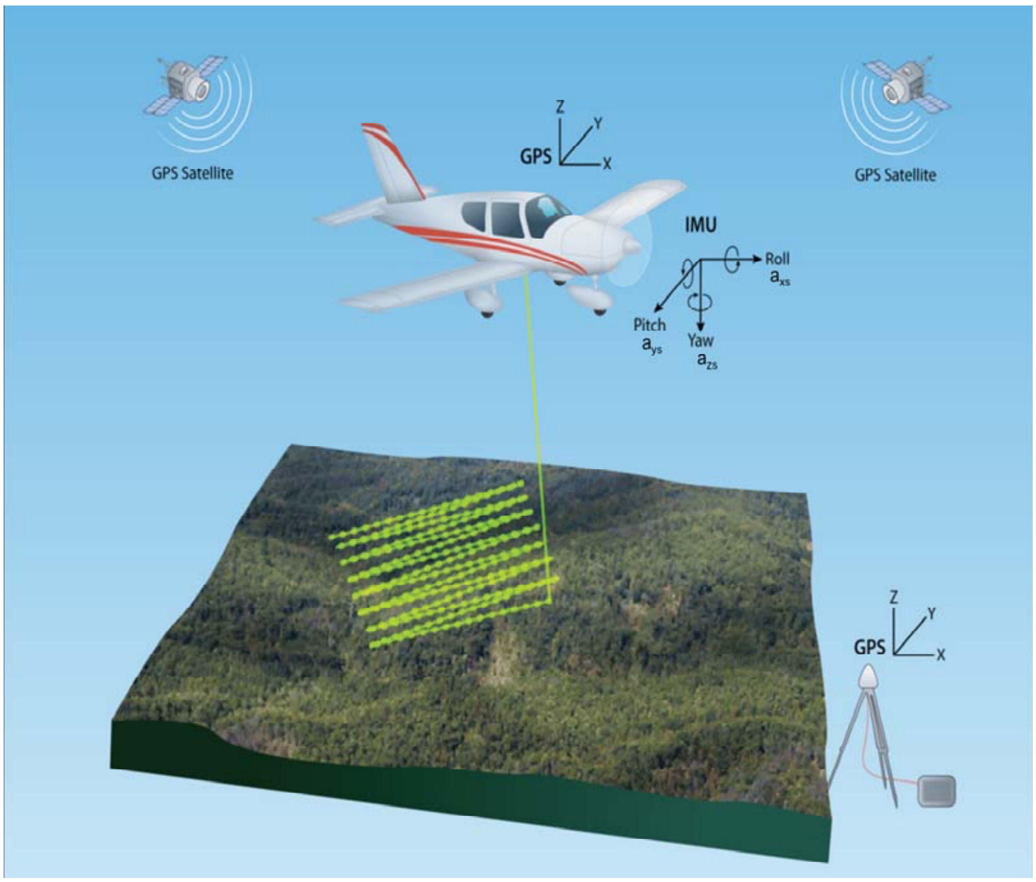

Figure 1. Schematic diagram (Carter, et al., 2007) of a small-footprint, discrete-return ALSM unit. ALSM systems are generally comprised of four major hardware components: (1) a scanning laser emitter–receiver unit, (2) differential global positioning systems (GPS receivers on the aircraft and on the ground), (3) a highly sensitive inertial measurement unit (IMU), and (4) an onboard computer for data capture and storage.

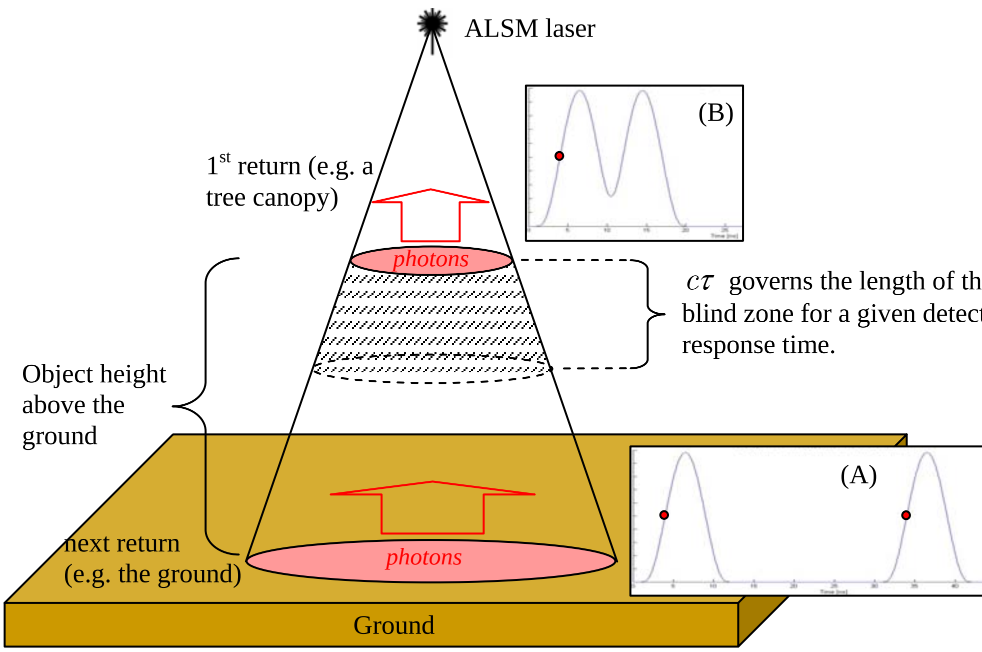

Figure 2. The “dead time” effect. Two hypothetical return pulses from a single transmitted pulse are shown. (A) The discriminator triggers on the leading edge of each pulse when they are sufficiently separated. (B) If the second return overlaps the first, the discriminator fails to detect the second return. For a 10 nanosecond pulse duration and a single-channel detector, the dead time corresponds to a distance of roughly 3 m. (Slatton, et al,. 2007).

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