LIDAR MEASUREMENT OF SNOW DEPTH: ACCURACY AND ERROR SOURCES

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ABSTRACT: Airborne laser altimetry (lidar) is a remote sensing technology that holds tremendous promise for mapping snow depth in snow hydrology and avalanche applications. In recent years lidar has seen a dramatic widening of applications in the natural sciences, resulting in technological improvements and an increase in the availability of sensors. Modern sensors allow recording of multiple pulse returns, which allows mapping of vegetation heights and surface elevations below forest canopies. Typical reported vertical accuracies are on the order of 15 cm with an average ground point spacing of 1.5 m. However many parameters in the lidar acquisition process, such as laser scan angle, laser pulse rate, and flight geometry relative to terrain gradients require consideration to ensure adequate point coverage in forested and/or mountainous terrain. Additionally, laser light interaction with the snow surface has a significant volumetric scattering component, requiring different considerations for surface height error estimation than for other earth surface materials. The penetration depth of the laser pulse (NIR wavelength of 1064 nm) is dependent primarily on grain size, liquid water content, and the angle of incidence. Using published estimates of penetration depth, we estimate radiative transfer contribution to depth measurement errors to be on the order of 1 cm. In this paper, we present a review of lidar altimetry procedures and error sources, investigate potential errors unique to snow surface remote sensing in the NIR wavelengths, and make recommendations for projects using lidar for snow depth mapping.

KEYWORDS: lidar; snow depth; remote sensing; spatial variability

1. INTRODUCTION

Airborne laser scanning (lidar) is a remote sensing tool with the ability to retrieve surface elevations at high spatial resolutions, in rough terrain and in heavily forested regions (Reutebuch *et al.*, 2003). Differencing lidar maps from two dates allows the calculation of snow depth at horizontal spatial resolutions close to 1 m, and over spatial extents compatible with basin-scale hydrologic needs (Hopkinson *et al.*, 2004; Miller *et al.*, 2003; Deems *et al.*, 2006). The spatial resolution and coverage, repeatability, and sub-canopy mapping capability of airborne lidar offer a powerful contribution to research-oriented and operational snow hydrology and avalanche science in mountain regions.

Knowledge of spatial snowpack properties in mountain regions, especially snow water equivalent (SWE) is critical for accurate assessment and forecasting of snowmelt timing (Luce *et al.*, 1998), snowmelt volume (Elder *et al.*, 1991) and avalanche hazard (Conway and Abrahamson, 1984; Birkeland *et al.*, 1995), for initialization of synoptic and global-scale weather and climate models (Liston, 1999; Groisman and Davies, 2001), and for investigations of ecologic dynamics and biogeochemical cycling (Jones, 1999; Brooks and Williams, 1999). Snowfall and wind interact with terrain and vegetation to create highly variable patterns of snow accumulation. These complex interactions produce a snow cover that is challenging to sample and model (Elder *et al.*, 1991). The seasonal snow system and its spatial distribution at multiple scales is coupled to hydrologic, atmospheric, and biologic systems through dynamic forcing of runoff characteristics, heat and energy fluxes, soil moisture distributions, and growing season duration (Jones *et al.*, 2001), greatly influencing energy, water, and biogeochemical cycling in mountain and earth surface systems.

Manual sampling of snow depth is expensive, time-consuming, potentially dangerous to field crews, and disturbs the snowpack, potentially influencing subsequent measurements. Avalanche starting zone depths and runout volumes are particularly difficult to sample, presenting an obvious need for remote sensing technologies. Further, the intervals over which snow depth can be feasibly measured are limited to spacings and extents that likely do not capture the natural variability at the slope or basin scale (Elder *et al.*, 2006). Lidar altimetry is a data acquisition tool that provides high spatial point densities over extents compatible with both avalanche research and catchment-scale hydrologic needs.

Calculation of snow depth from lidar data requires two data collections, one each for snow-free and snow-covered dates, followed by differencing the snow surface and bare-ground elevations (Hopkinson *et al.*, 2004; Miller *et al.*, 2003; Deems *et al.*, 2006). Lidar-derived digital elevation models (DEM) have been shown to have accuracies as great as ± 10 cm RMSE, even in densely forested areas (Kraus and Pfeifer, 1998; Reutebuch, *et al.*, 2003). The snow depth calculation procedure effectively involves the creation of two DEMs, plus interactions of the laser light with the snow surface. Additionally, snow depth mapping in mountain terrain involves consideration of laser scanning geometry relative to steep slopes and with the potential for dramatic variations in aircraft flying height. These factors, if not accounted for, produce the potential for large accuracy variations in lidar-based snow depth measurements.

The science of airborne lidar mapping is evolving, and the body of work concerning suitability and error sources for natural resource applications continues to grow

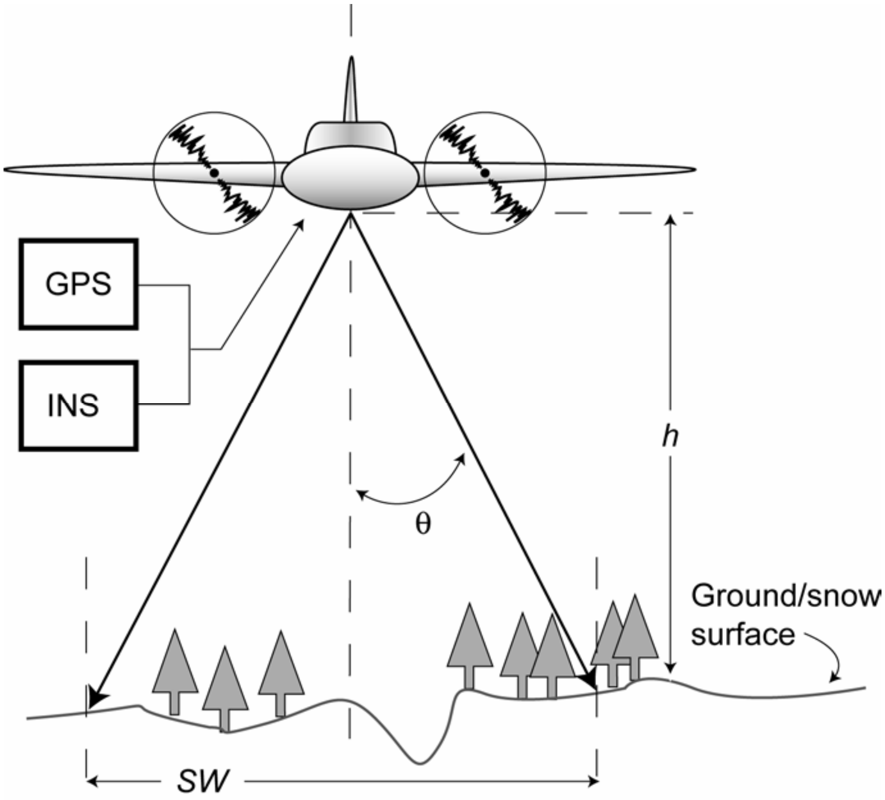

Figure 1. LiDAR system geometry: scan angle (*θ*), platform height (*h*), and swath width (*SW*) are shown. GPS and INS systems are on the platform and time-synchronized with the laser scanning system.

However, the available sensors and proprietary processing techniques are not standardized, making an understanding of each instrument, processing step, and range of potential error sources critical for successful application of airborne lidar mapping for snow science interests. This paper seeks to explore error sources and magnitudes involved in snow depth mapping using lidar, and to provide recommendations for successful employment of this powerful technology for scientific and operational snow hydrology and avalanche science needs.

2. LIDAR ALTIMETRY AND SNOW DEPTH CALCULATION TECHNIQUES

2.1 *Lidar altimetry*

Lidar is a ranging instrument, and measures target distance by calculation of the elapsed time between emitted and return laser signals. The position of the aircraft platform is established by way of Differential Global Positioning System (GPS) triangulation, and platform orientation (roll, pitch, yaw) determined via an inertial navigation system (INS) link (Figure 1). Once the platform geometry and the geometry of the scanner system are known, the time interval between laser pulse emission and return is used to determine the 3D locations of the laser point measurements. Each of these geometric components has the potential to introduce error into the final elevation measurement. Further, complex topography and multiple reflections may induce measurement errors.

The emitted laser pulse diverges as it travels away from the source. Modern sensors have divergence angles in the range of 0.3-1 mrad, which produces a ground spot radius of 0.3 to 1 m at a flying height of 1000 m (Baltsavias, 1999). The beam width allows portions of the laser spot to be reflected by several targets, resulting in multiple returns per pulse (Figure 2). Newer Lidar systems have the ability to record first, last, or several return pulses, allowing mapping of vegetation height, structure and/or understory in addition to enhancing the ability to map sub-canopy terrain. Other sensors, called 'waveform-recording' sensors (Lefsky *et al.*, 2002) offer the capability to record a time series of return intensity from each pulse. These sensors utilize a larger laser footprint (on the order of 25 m), and are most useful for studying forest canopy structure. Waveform-recording sensors, because of the large footprint, do not provide sufficient spatial resolution for snow depth mapping at the catchment scale.The spatial resolution of the point data is often quantified as the average point density per square meter, or by an average point spacing, though occasionally it is represented as the smallest elevation contour interval that can be mapped from the data. Factors influencing the spatial point density at ground level include the scan pattern, scan rate, swath width, pulse rate, and aircraft height (Baltsavias, 1999).

Several scan patterns are currently in use, and more complex scan patterns are being developed for acquisition of specific point densities or spatial coverages. The most common are parallel or Z-shaped bidirectional scans. Palmer (elliptical) scans are also in use, which provide fore and aft pointing angles in addition to the across-track directions achieved by the bidirectional scan patterns, and therefore provide more opportunities for canopy penetration. Scan angles of ± 15° are sufficient for penetration of all but the most dense conifer canopies in mountain regions (Romano, *pers. comm.*).

The scan rate is the angular velocity of the oscillating mirror that directs the outgoing laser pulse, and combines with the pulse rate to determine minimum across-track point spacing. Common scan rates are in the 30 Hz range, and are usually secondary in importance to pulse rate in determining point spacing (Wehr and Lohr, 1999).

The laser pulse rate is the primary determinant of across-track point spacing, and on older lidar systems can be a limiting factor. Newer systems can achieve pulse rates of 100 kHz, allowing for very dense laser shot patterns (Optech, Inc., 2006).

Along-track point spacing is controlled by the aircraft ground speed and the period of a single scan, with the maximum occurring coincident with the edge of the field of view. Adjacent swaths are overlapped to provide additional point density along the swath margins (Wehr and Lohr, 1999). In practice, ground speed and scan period are constrained so that the along-track spacing is consistent with the across-track spacing.

The width of the scanned swath is of primary importance for mission planning

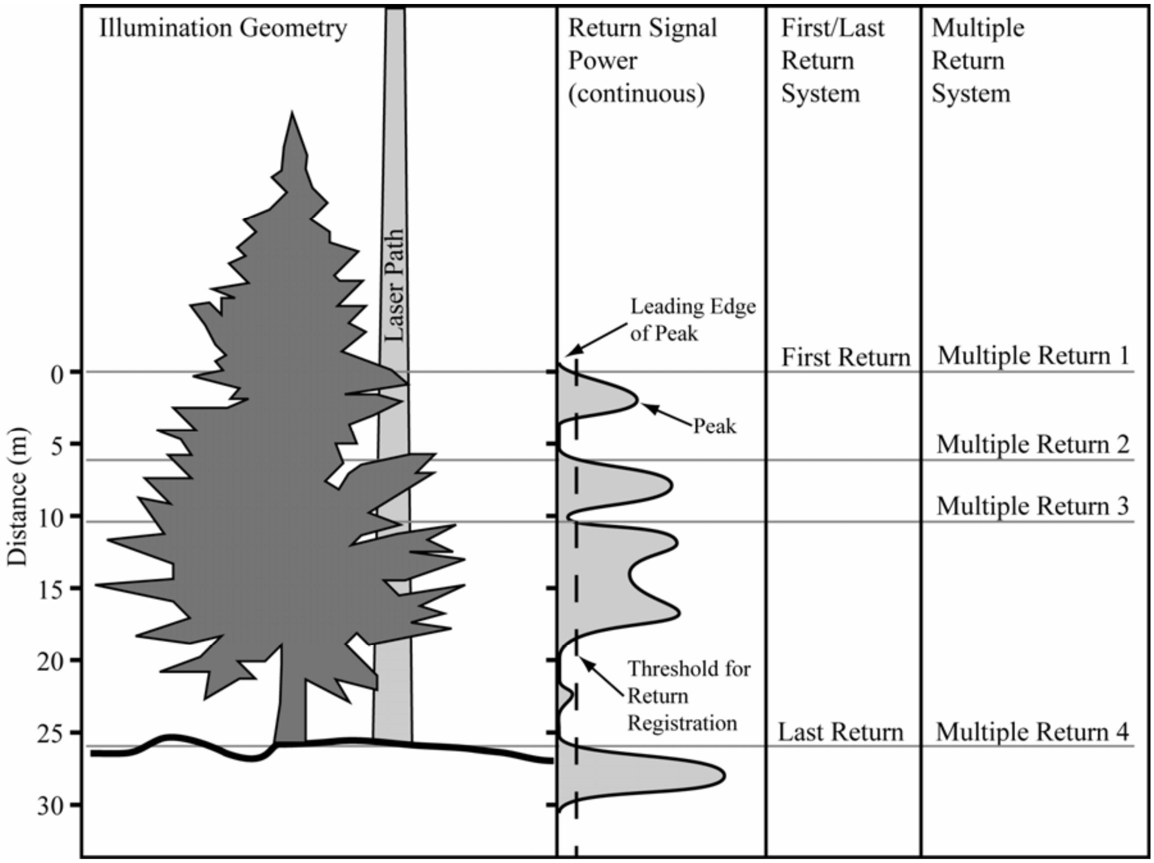

Figure 2. Laser illumination and return signal recording. Portions of the emitted laser pulse are reflected by different targets, resulting in multiple return signals for each pulse. Different LiDAR systems have different return signal recording capabilities. (*after Lefsky et al., 2002*)

purposes. Wider swaths allow greater areal coverage with fewer flight strips, and therefore can significantly decrease the data collection cost. Swath width depends primarily on the scan angle of the scanner system and the aircraft flight height. Increasing swath width via aircraft height comes at the expense of laser point spacing and/or range accuracy. At larger scan angles, the probability of canopy penetration decreases, with possible reductions in achievable ground point spacing.

The collected data, after georegistration, are represented as (x,y,z) points. The raw data must be filtered in order to ensure that all points belong to the surface of interest, i.e. the canopy, ground or snow surface. Most filtering algorithms are proprietary to laser mapping contractors, which creates a potential source of data problems that are opaque to the data user. Most filtering is done via automated algorithms that are monitored manually (Wehr and Lohr, 1999). Once the point data are filtered and a satisfactory collection of surface points has been obtained, the snow-free ground elevations can be subtracted from the snow-covered elevations to derive snow depth.

2.2 Snow Depth Calculation

Because the two datasets consist of (x,y,z) points, the likelihood of ground and snow points existing at exactly the same (x,y) location is quite small, which precludes a point-to-point subtraction. The most efficient method of subtracting the two datasets is to convert the bare-earth elevations to a grid dataset and subsequently extract the grid values below each snow surface elevation point measurement (Deems *et al.*, 2006). The creation of the grid dataset, or DEM, involves interpolation, and thus induces some error. However, due to the high spatial resolution of the point data, a simple interpolation scheme, such as inverse-distance-weighting, can be employed with minimal introduced error. Terrain with significant vertical displacements, such as cliff bands, may present challenges to DEM generation by simple interpolation, however GIS techniques, such as barrier delineation, can be used as necessary.

The grid element size should be of similar magnitude to the average point spacing of the filtered elevation point dataset in order to minimize scaling concerns and smoothing. In general, a small number of nearest neighbors should be used to interpolate each grid value, in order to minimize smoothing errors. The highest degree of smoothing will occur in areas of lower point density, such as where heavy forest cover exists.

2.3 *Integration with Other Sensors*

High-resolution orthophotography is often acquired concurrently with the lidar data, and its use during the filtering process can greatly improve data quality. The snow-covered orthophotos will also show snow drift and scour features, enabling a qualitative assessment of the final snow depth map.

In areas or seasons with partial snow coverage, snow-covered area products, such as the MODSCAG fractional snow cover maps (Painter *et al.*, 2006) could be used for mission planning.

3. ERROR SOURCES IN LIDAR MAPPING

A significant body of literature is emerging as applications for lidar technology are developed. Much work has been done to quantify errors imparted by systematic sources such as global positioning and inertial navigation systems, laser system calibration, and scanning geometry. However, as snow depth mapping application evolves, there is a need to quantify potential errors due to interactions of the laser light with the snow surface. In the following, error sources common to most laser mapping applications are reviewed. For more detail, the reader is referred to Baltsavias (1999), Wehr and Lohr (1999), and Hodgson and Bresnahan (2004). Lidar sensing of the snow cover involves the additional complication of the volumetric reflection of laser light by the near-surface snow layers.

3.1 *Positioning and Inertial Navigation Systems*

The GPS and INS systems provide positional and platform orientation data from which the location of the laser sensor can be derived, and thus the locations of the ranged ground elevations can be determined precisely (Wehr and Lohr, 1998). The GPS and INS systems must be time-rectified with the laser scanner, so that all laser range measurements are tied to the appropriate positional data.

Differentially-corrected GPS is required to achieve sub-decimeter positional accuracy, on a par with the laser range accuracy. Differential correction necessitates a nearby ground reference GPS station, usually located on a known survey or triangulation benchmark. The time series of airborne GPS locations is then corrected using the time series offsets recorded by the ground station. Error magnitudes due to GPS/INS are typically on the order of 6-8 cm.

3.2 *Flight Planning*

Flight planning is critical to mission success, minimizing cost, and data accuracy, especially in rough terrain. Terrain geometry (slope magnitude and aspect relative to the flight line) interacts with the laser scan angle to affect the laser angle of incidence at a given ground surface location. Proper flight planning will minimize the number of points collected with poor geometry.

Positional error due to terrain slope occurs via two mechanisms. First, errors in the horizontal (x,y) directions will induce an apparent error due to the uncertainty of the planimetric position of the measured elevation (Figure 3a). This effect of vertical error dependence on horizontal accuracy can cause the measured point to appear above or below the actual terrain surface due to errors perpendicular to the contour line direction (Hodgson and Bresnahan, 2004).

The second slope-induced error is due to the spreading of the laser spot on the inclined surface (Figure 3b). This effect will spread the time distribution of the returned pulse, increasing the ‘rise time’ for the return to reach the intensity threshold for return signal registration, and thus increasing the recorded range distance. For a 45° slope with a flight height of 1000 m, this ‘time-walk’ effect can

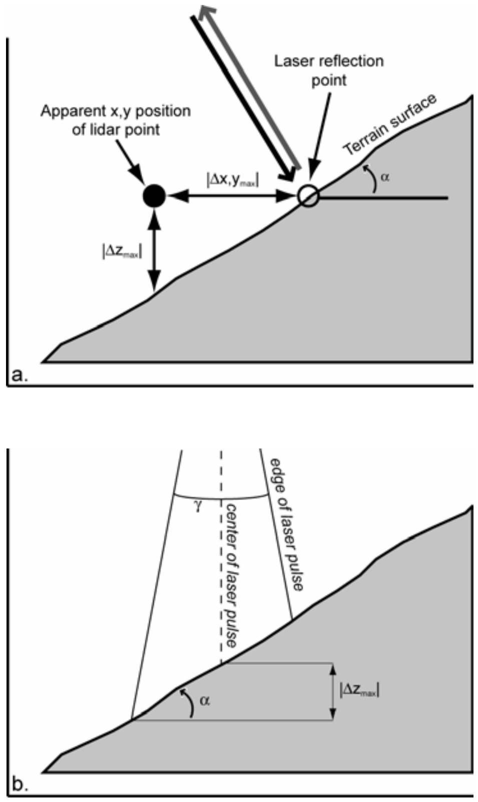

Figure 3. Errors induced by terrain slope. **a)** vertical error induced by horizontal errors (after Hodgson and Bresnahan, 2004). **b)** 'time-walk' vertical error induced by laser spot spread over inclined terrain (after Baltsavias, 1999). α = slope angle; γ = laser beam divergence; Δz_{max} = maximum elevation error; $\Delta x,y_{max}$ = maximum horizontal error.

induce a vertical error of close to 50 cm (Baltsavias, 1999). It is therefore critical that the flight planning account for areas of steep terrain by modeling the laser and terrain geometry and orienting flight lines to minimize the number of nadir laser shots on steep slopes.

3.3 Vegetation

The ability of lidar to map both forest canopy and ground surface elevations in one survey is one of the more attractive features of the technology. Accurate sub-canopy mapping is contingent on a sufficient number of laser shots reaching the ground and returning to the sensor directly. The number of successful ground hits, and therefore the final surveyed point density, decreases inversely with canopy cover density. Reutebuch *et al.* (2003) compared lidar and manually surveyed elevations in several areas with open, forested, and forested with understory cover types. They showed that the decrease in ground point density is relatively minor, with point spacings on the order of 1 point/m^2 in old growth Douglas Fir forest. The accuracy of the measured point elevations was degraded slightly by the forest or understory due to reduction in the return signal strength, but again this effect was shown to be relatively small – on the order of 10 cm.

The specific relationship between point density and canopy density is determined by the forest cover type (and therefore canopy and understory structures), the laser pulse rate, and the scan angle of the laser sensor. The effects of canopy screening are minimized by increased pulse rates and decreased scan angles. Higher pulse rates (on the order of 50 – 100 GHz) provide a larger number of laser shots per square meter and thus an increased probability of successful canopy penetration. Smaller scan angles increase the probability of canopy penetration by reducing the number of individual trees that a single laser shot must penetrate (see Figure 1). However, sub-canopy elevation mapping has been shown to be of comparable accuracy to that in open areas. Indeed, in snow-covered landscapes, the effects of understory vegetation buried in snow combined with the high reflectivity of the snow surface allow for increased accuracy compared to snow-free periods.

3.4 Post-processing

After data collection, the 'point cloud' of raw lidar return points are classified as 'terrain' or 'non-terrain' returns. This process is usually highly automated, with several steps requiring interaction from a technician. The classification can be accomplished using any number of (usually proprietary) algorithms, but commonly involves segregating terrain points through an iterative process that evaluates the deviation of individual points from a surface generated from nearby points. Classification thresholds based on these deviations are somewhat subjective, requiring manual supervision using ancillary data such as digital orthophotos or existing, lower-resolution DEMs.

Mis-classification of points can induce errors in the final elevation surface. Because the error magnitude depends on many factors, including the type of filter used, the accuracy of the measured elevation, the elevation of the vegetation above the terrain surface, and the terrain geometry, the contribution of classification errors to the overall surface accuracy will vary widely. It is clear, however, that successful application of classification algorithms is critical to the accuracy of the final elevation surface or snow depth map.

4. SNOW SURFACE INTERACTIONS

Most LIDAR acquisitions are performed with laser centered at wavelength $\lambda = 1064$ nm. At this wavelength, ice is moderately absorptive and therefore snow reflectance is most sensitive to grain size. The optical properties of ice are described by the complex refractive index, *m:*

$$m = n + ik \tag{1}$$

where n is the real part (that describes refraction) and k is the imaginary part (that describes absorption). At $\lambda = 1064$ nm, k has value of approximately 2×10^{-6}.

An understanding of the sensitivity of the transmission at this wavelength to snow grain size and snow liquid water content is important for assessment of the associated uncertainties in snow depth retrievals.

The literature on measurements and modeling of snow transmission is sparse. Beaglehole *et al.* (1998) measured the spectral transmission of solar radiation in snow in six bandpasses from 350 to 900 nm. At 900 nm, they found that the transmission of snow at 2 cm depth was 0.03 and at 4 cm depth the transmission was 0.006. Given that $k \sim 4.1 \times 10^{-7}$ at this wavelength whereas at 1064 nm it is order 10^{-6}, we can consider that the same attenuation of radiation (scattered + absorbed) comes at a shallower depth (order 1 cm). These measurements were made for fine grain snow that had a small absorbing path length but a larger optical depth for a given snow depth than the case for coarser grains.

Given the lack of measurements of transmission for varying grain sizes at this wavelength, we are compelled to make the reasonable assumption that 97% of scattering or absorption occurs in the top 1 cm of the snowpack, and therefore the overwhelming proportion of the LIDAR return from the snowpack comes from the top 1 cm. However, this assumption should be checked with further measurements given that geometric effects in the near-surface layers can contribute to non-exponential decay of radiation (Warren *et al.*, 2006).

Snow impurities will have little effect on the transmission of radiation at this wavelength given that the contrast in k for ice and impurities is relatively small and the proportion of ice is vastly greater than most impurity concentrations (Warren, 1982). Liquid water content should have a similar effect as a coarsening of grain size, whereby the optical depth of the snowpack decreases (increasing transmission) but the absorbing path length increases (decreasing transmission). Therefore, given the bounding measurements discussed above, in these cases we estimate that 97% of attenuation occurs in the top 1 cm of the snowpack.

These measurements and discussion strongly suggest that the LIDAR scattered signal at 1064 nm wavelength will come from the top 1 cm of the snowpack, independent of snow physical properties. Therefore, the sensitivity of the scattering depth is below that of the sensitivities of the technique to surface roughness, spatial variation, temporal location mismatches, and scanning geometry.

5. RECOMMENDATIONS FOR LIDAR SNOW SURVEYS IN MOUNTAINOUS AREAS

Much of the potential for error in surface elevation measurement exists in the geometric relationships between the aircraft dynamics, the scanning system, and the irregular ground surface. Careful flight planning is critical to minimizing these errors. Lidar contractors use flight planning models to constrain many of the laser geometry parameters, but we recommend that investigators seeking lidar acquisitions be proactive and involved in both the mission planning and post-processing operations.

For snow depth mapping in mountainous, forested terrain, high laser pulse rates (~ 50 kHz) and scan angles on the order of ±15° each side are desired to minimize slope-induced errors and to maximize canopy penetration and thereby maximize ground/snow surface point densities. Flight lines require careful planning so that laser shot/slope angle geometry remain favorable – i.e. obtuse, down-slope shots are minimized. In very complex terrain, significant swath overlap may be required to ensure that the planned point spacing is achieved.

Flight planning requirements for complex mountain terrain, especially the potential for complicated flight lines, are likely to significantly increase flight time and data acquisition costs over survey criteria that are adequate for flat, unvegetated sites. However, to fully utilize the accuracy and spatial resolution potentials of lidar technology, maximum accuracy should be the goal.

Current cost for lidar acquisition is prohibitive for many operational and research budgets. Some cost-saving measures, such as coincident data collection or flight dates for nearby projects, may be available and can significantly decrease aircraft flight time. Further, demand for lidar data is growing, and more lidar survey units are in operation; data collection costs are dropping, and are likely to decrease significantly in the near future.

6. CONCLUSIONS

Airborne lidar surveying is seeing increased attention as a data source for high-resolution terrain mapping. Repeat surveys that include one snow-free collection and one or more snow-covered collections allow the calculation of snow depth over sizeable geographic areas with 1-2 m horizontal spacing and decimeter-scale vertical accuracy. Data resolution and accuracy of this scale provides numerous advantages over manual survey or larger-footprint sensors.

Lidar surveying is an evolving field, with rapid advances in technology and processing techniques. The availability of lidar contractors and high-quality scanners and processing routines has increased significantly in recent years. Lidar snow depth surveying has been shown to have tremendous potential for snow hydrology and avalanche science applications, and is sure to have a significant impact on spatial snow science in the years to come.

7. ACKNOWLEDGEMENTS

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