EVALUATION OF SMALL-FOOTPRINT FULL-WAVEFORM AIRBORNE LIDAR INSTRUMENT REQUIREMENTS USING DIRSIG SIMULATIONS OF FORESTS

Keith Krause

Battelle Memorial Institute, NEON Program, Boulder, CO 80301

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ABSTRACT

The National Ecological Observatory Network (NEON) Airborne Observation Platform (AOP) provides long-term, quantitative information on land use, vegetation structure and canopy chemistry over the NEON sites. AOP flies a suite of integrated remote sensing instruments consisting of a hyperspectral imager, a waveform lidar, and a color digital camera. Small-footprint full-waveform airborne lidar provides an enhanced capability beyond discrete return lidar for capturing and characterizing canopy structure. Due to high data rates/volumes, a common practice is to truncate waveforms. Very little research exists to determine how much data should be saved. In this study, simulations are run in Rochester Institute of Technology's DIRSIG software. The resulting output waveforms are analyzed to assess three lidar system requirements: the total number of bins with a detected signal, the number of segments, and the max number of bins in a single segment. Recommendations for the values of these requirements are provided.

***Index Terms*—** NEON, AOP, waveform, lidar, DIRSIG.

1. INTRODUCTION

Light Detection and Ranging (LiDAR) technology has been used for decades to measure 3D vegetation structure, but it is not abundantly apparent in the data and associated products how the laser light interacts with/propagates through the objects it encounters. This is further confounded by the fact that airborne lidar can measure the dense canopy top surface well, but typically does a poor job capturing vegetation detail deep within the canopy or understory, and sometimes does not penetrate through the canopy to the ground. This lack of sub-canopy interactions could be due to a number of factors, such as i) attenuation of the lidar (waveform) throughout the canopy elements, ii) occlusion effects due to opaque structures, and iii) hardware limitations (e.g., an ~0.75-4.0 m vertical resolution between subsequent lidar returns). [1] performed a voxel analysis and found that at least 25% of the canopy volume was occluded in high point density airborne lidar data and that about 28% of vegetation elements detected by terrestrial laser scanning were not being measured by the airborne system due to occlusion effects. Full-waveform lidar provides an enhanced capability beyond discrete return lidar for capturing and characterizing canopy structure by recording the entire time-varying power of the lidar return signal from all illuminated surfaces. Typically waveforms are truncated due to high data rates/volumes and only a portion of each waveform is saved. However, very little research exists to determine how much data should be saved and assess how well lidar instruments are capturing vegetation detail.

The National Ecological Observatory Network (NEON) sponsored by the National Science Foundation and operated by Battelle is a continental-scale research platform to enable understanding and forecasting of the impacts of climate change, land-use change, and invasive species on aspects of continental-scale ecology such as biodiversity, biogeochemistry, infectious diseases, and ecohydrology. NEON has partitioned the U.S., including Alaska, Hawaii and Puerto Rico, into 20 eco-climatic domains, each of which represents different regions of vegetation, landforms, climate, and ecosystem performance. The Airborne Observation Platform (AOP) is part of the standard instrument set consisting of a remote sensing payload to provide long-term, quantitative information on land use, vegetation structure and canopy chemistry over the NEON core and relocatable sites, transects and sites of opportunity over regional scales [2]. Each aircraft flies a suite of integrated remote sensing instruments consisting of: the NEON Imaging Spectrometer (NIS), a hyperspectral imager designed and built by NASA JPL [3]; the full-waveform lidar (either an Optech Gemini or Riegl LMS-Q780); and a RGB digital camera. Each payload is installed in a DeHavilland DHC-6 Twin Otter aircraft flying at 1000-2000 m above ground level (AGL) at a speed of 97.2 knots (50 m/s) and covering a region (100-300 km2) surrounding each NEON site. 2020 is AOP's ninth flight season and data products are freely available through the NEON data portal. The NIS is a pushbroom sensor with 424 spectral bands covering the VIS-SWIR (380-2510 nm) at a spectral resolution of ~6 nm FWHM and a 34 degree field-of-view. All of the lidars use a pulsed Nd:YAG laser, operating at a wavelength of 1064 nm. The pulse spacing on the ground can be tuned by the aircraft velocity, along with setting the values for the pulse repetition frequency (PRF), the mirror scan angle (Optech only), and the scan frequency. At a nominal altitude of 1000 m AGL, the NIS covers a 600 m wide swath with a pixel GSD of 1 m and the lidar point density is ~4 pulses/m2 with a beam footprint of 0.8 m (Optech) or 0.25 m (Riegl) and a swath width set slightly wider than the spectrometer.

The high-level goal of this study is to simulate full-waveform data for current and future lidar instruments over a thick, closed-canopy deciduous forest scene in order to assess proposed instrument requirements. The first objective is to analyze the number of waveform sampling bins required based on different gain scenarios and different instrument and collection configurations including the:

- Total number of bins with a detected signal
- Number of segments with a detected signal
- Max number of bins with a detected signal in a single segment

The second objective is to assess proposed LiDAR instrument requirements at nominal pulse repetition frequencies/rates (values based on past experience, sample data evaluation, and desires for future systems) including:

- The lidar shall be capable of recording a waveform of a total range of ≥ 22 m (~146 1 ns bins).
- If the waveform is to be truncated into multiple segments, the lidar shall be capable of recording ≥ 3 segments per laser pulse.
- The lidar shall be capable of recording a waveform segment of a range of ≥ 12 m (~80 1 ns bins).

2. STUDY AREA - SIMULATION SCENE

The Digital Imaging and Remote Sensing Image Generation (DIRSIG) tool is a physics-based, first principles radiometric modeling environment for the creation of synthetic remote sensing imagery that is radiometrically, geometrically, and temporally accurate. The model is designed to generate passive broad-band, multispectral, hyperspectral, low-light, polarized, active laser radar, and synthetic aperture radar datasets [4,5,6,7,8,9,10] through the integration of a suite of first-principles-based radiation propagation modules. DIRSIG uses Monte-Carlo ray tracing to statistically determine what fraction of the photons are absorbed or scattered by material interactions within a scene, with a scattering phase function determining photon scatter direction, followed by photon propagation to the next material. Each absorption or scattering event is stored in a photon event map, along with a time-of-flight for that photon bundle. Second stage ray tracing, from the instrument detectors through the optical path down to the scene photon event map, determine which photon bundles are observed by each detector. Radiative transfer solutions are employed to calculate what fraction of photons within the photon bundle will scatter into the direction of the receiver [8].

The DIRSIG Harvard Forest scene [11] is a closed canopy deciduous hardwood forest based on Harvard University's Harvard Forest ecological research site in

Figure 1: Rendering of the DIRSIG Harvard Forest scene.

Petersham, MA. Harvard Forest is also the NEON Domain 1 core site, with flux tower coordinates of 42.5369 latitude, -72.17266 longitude, and an elevation of 340 m. The DIRSIG scene contains 10 unique 3D CAD tree objects, which have been replicated with rotation and translation to create a forest of 52 total trees. A color rendering of the scene is shown in Figure 1. The tree species include black birch (*Betula lenta*), paper birch (*Betula papyrifera*), yellow birch (*Betula alleghaniensis*), red maple (*Acer rubrum*), and red oak (*Quercus rubra*). The tree trunks are distributed over an approximate area of 30 m x 30 m. Tree heights vary from 10.7 to 30.3 m and tree canopy diameters vary from 3.6 to 13.6 m. The scene has flat terrain and an open understory.

3. METHODS

Waveform LiDAR simulations are run in DIRSIG using the Harvard Forest Scene and varying the lidar instrument and collection parameters: varying the pulse density on the ground with values of 4 and 16 pulses per meter squared (PPM^2); varying the outgoing laser pulse width with values of 10 ns, 6 ns, 3 ns, and 1 ns FWHM; and varying the laser beam divergence angle with values of 0.8 mrad (1/e), 0.25 mrad (1/e), 0.25 mrad ($1/e^2$), and 0.1 mrad ($1/e^2$). The 32 simulations are all from an altitude of 1000 m AGL with all laser pulses at a scan angle of 0 deg (nadir pointing). The lidar instrument and collection parameters are consistent with the current generation of commercially available airborne laser scanners plus some older ones currently used in NEON AOP flight operations.

DIRSIG outputs the waveforms in absolute units of photon counts. Different gain scaling scenarios are used to perform the analog-to-digital conversion of the simulation outputs: "AOP1" where waveforms are scaled so a 50% target at 1000 m gives 200 DN; "12 bit low" scaled so a 100% target at 500 m gives 3800 DN; "12 bit high" scaled so a 100% target at 800 m gives 3800 DN; "14 bit low" scaled so a 100% target at 500 m gives 15200 DN; "14 bit high" scaled so a 100% target at 800 m gives 15200 DN; and "12 bit auto" scaled per pulse so that the max target signal in each waveform gives 3800 DN. The low and high gain settings are chosen based on analysis of terrain across the NEON sites, where sites with large topographic variation might be flown at 650 m AGL above the highest peaks (the low gain) and sites with flat terrain would typically be flown at 1000 m AGL and could support an increase in gain without signal saturation. In both cases, the tops of tall trees would be closer in range to the lidar than the bare-Earth topography, hence the gain scaling based on ranges of 500 m and 800 m to accommodate trees up to and above 100 m tall plus some minor terrain variation. While vegetation is not 100% reflective at 1064 nm, multiple scattering in canopies increases the reflectance over a single leaf. 100% is chosen conservatively and the 3800/15200 DN values allow for a dark bias in the recorded signal.

Data rates/volumes are typically too high to save the entire waveform from the aircraft all the way to the ground for every laser pulse. A common practice is to truncate the number of sampling bins recorded into "multiple segments" and use a detection threshold to determine which portions of the return waveform contain targets of interest that should be saved. For this study, a detection threshold of 32 DN is applied to the scaled waveforms (except 12 bit auto which uses 128 DN). A temporal buffer may also be utilized at the beginning and end of each segment in order to better capture the rise and fall of the waveform signal around a target. An example of the target detection is shown in Figure 2 for a single waveform at location X = 0.0, Y = 12.5 for the 14 bit high gain scaling, 3 ns pulse width, and 0.8 mrad (1/e) beam divergence simulation. Contiguous bins of the waveform with a signal above 32 DN are highlighted in different colors. The top plot without a temporal buffer shows 6 detected segments, with individual segment lengths ranging from 3-32 ns. When an 8 ns buffer is added to both the beginning and end of each individual segment, many segments will overlap temporally, and these can be combined into a single, longer segment. The bottom plot illustrates this where the 6 segments become merged into only 2 segments with lengths of 112 and 19 ns.

4. RESULTS AND DISCUSSION

For all of the simulation runs, the following three categories are analyzed both with and without the 8 buffer: the total number of bins with a detected signal, the number of segments with a detected signal, and the max number of bins with a detected signal in a single segment. For each simulation, basic statistics are calculated such as the 95th and 99th percentile values, the maximum value, and the percent of canopy laser pulses above different reference values. Some general observations are:

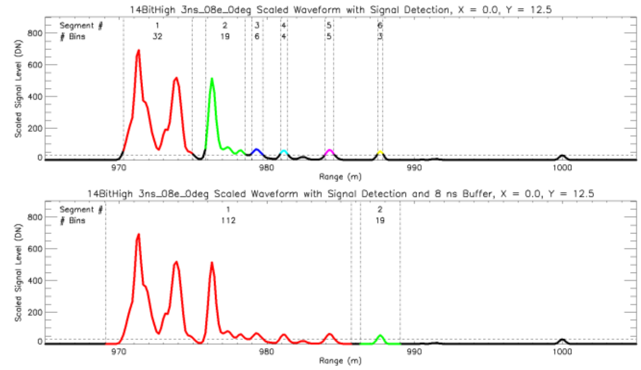

Figure 2: Example of waveform truncation into multiple segments using a detection threshold (top plot) and adding an 8 ns buffer to the beginning/end of each segment, (bottom plot).

- A higher gain scales more waveform bins above the detection threshold leading to an increase in all three categories.
- Adding the 8 ns buffer to the beginning and end of each segment causes close detected signals to be combined into one longer segment, leading to an increase in both number of bins categories but a decrease in the number of segments.
- The outgoing pulse width is a convolution operator that optical sums close targets into a blurred return signal. Newer lidar instruments have a faster pulse width with a decreased FWHM leading to a decrease in both number of bins categories but an increase in the number of segments.
- A wider beam divergence angle will illuminate more horizontal targets. Depending on the scene 3D structural layout, those targets may be at different heights at the edge of the beam compared to the center. Newer lidar instruments have a narrow beam divergence, illuminating less targets and leading to a decrease in all three categories for the Harvard Forest scene.

For the proposed total number of bins requirement "the lidar shall be capable of recording a waveform of a total range of ≥ 22 m (~146 1 ns bins)", the results of the canopy laser pulses show:

- 146 1 ns bins loses no signal data up through a 14 bit low gain setting. The 14 bit high and 12 bit auto settings have acceptable loses at 0.2% and 0.07% of laser pulses with data bins that would be thrown out.

For the proposed number of segments requirement "the lidar shall be capable of recording ≥ 3 segments per laser pulse", the results of the canopy laser pulses show:

- 3 segments per laser pulse fails at all gain settings with too large a percentage of laser pulses with signal data being thrown out.
- ≥ 7 segments per laser pulse should be included as a desired value. Here either all data would be saved or if

an extra segment is needed for an atmospheric return than it would still have acceptable loses of data bins that would be thrown out.
- Without the 8 ns buffer, more segments would be required. Even 8 segments per laser pulse fails at the higher gain settings.
- The simulations are noise-free. An even higher number of segments are desired to accommodate real world noisy lidar data and atmospheric returns.

For the proposed number of bins per segment requirement "the lidar shall be capable of recording a waveform segment of a range of ≥ 12 m (~80 1 ns bins)", the results of the canopy laser pulses show:

- 80 1 ns bins per segment fails at higher gain settings with too large a percentage of laser pulses with signal data being thrown out.
- 120 1 ns bins per segment should be included as a desired value. Here no signal data are lost up through a 14 bit low gain setting. The 14 bit high and 12 bit auto settings have acceptable loses at 0.09% and 0.04% of laser pulses with data that would be thrown out.
- Without the 8 ns buffer, 80 1 ns bins passes at all gain settings.
- This poses a challenge to systems that have fixed length segments, as all segments would need to be 80-120 ns.

5. CONCLUSIONS

Small-footprint full-waveform airborne lidar provides an enhanced capability beyond discrete return lidar for capturing and characterizing canopy structure. Due to high data rates/volumes, a common practice is to truncate waveforms and only save a portion of each waveform. Very little research exists to determine how much data should be saved and assess how well lidar instruments are capturing vegetation detail.

In this study, simulations are run in Rochester Institute of Technology's DIRSIG software using the Harvard Forest thick, closed-canopy deciduous forest scene. Lidar instrument and collection parameters are varied using modern day commercially available airborne lidar systems as a reference. The resulting waveforms are converted to digital numbers using several gain scaling levels and a simple detection threshold is applied to determine portions of the waveform that have a signal worth saving. The total number of bins with a detected signal, the number of segments with a detected signal, and the max number of bins with a detected signal in a single segment are analyzed both with and without an 8 ns buffer added to the beginning and end of each segment.

The analysis for this simulated scene suggests that a system requirement of: recording a waveform of a total range of ≥ 22 m (~146 1 ns bins) is reasonable; recording ≥ 3 segments per laser pulse fails at all gain settings and should be increased to ≥ 7 segments; and recording a waveform segment of a range of ≥ 12 m (~80 1 ns bins) is reasonable at lower gain settings but could be increased to ≥ 18 m (120 1 ns bins) at higher gains. These requirements serve as a reference when evaluating new lidar systems to be included in the NEON AOP payload. Long-term, quantitative information on land use and vegetation structure over the NEON sites will be greatly enhanced if data are collected with full-waveform lidar systems that can meet these new requirements. These new lidar systems with full-waveform will hopefully do a better job capturing vegetation detail deep within the canopy or understory, and penetrate through the canopy to the ground more often.

6. REFERENCES

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