Understanding Waveform Digitizing and Waveform Data Processing
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INTRODUCTION

For this white paper we assume that the reader has basic understanding of the operating principles of mapping LiDAR and only wishes to develop a deeper understanding of Waveform digitizing and recording for mapping applications and/or wants to use waveform data provided by NCALM. To understand LiDAR waveform digitizing, recording and processing it is first necessary to review the concepts of pulsed laser and timing mechanisms that make mapping LiDAR possible.

PULSED LASERS AND TIMING SYSTEMS

A LIDAR system measures the distance between the sensor and the target by using any or a combination of the following ranging principles: phase difference, time-of-flight and optical triangulation. The Phase difference and optical triangulation ranging principles are based on continuous wave Lasers, meaning that the light intensity over time remains constant or is a continuous function. Continuous wave Lasers were the first to be developed, and thus phase difference and optical triangulation were prevalent in the early years of the development of Laser-based LiDARs. Figure 1 shows an intensity-time waveform of an amplitude modulated (AM) continuous laser, and it illustrates how using phase measurements it is possible to derive a phase difference between the outgoing and incoming waveforms and thus compute a range between the sensor and the target.

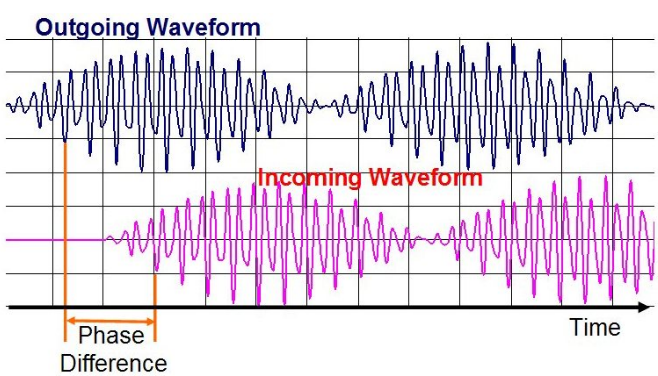

Figure 1. Amplitude modulated continuous laser phase difference ranging principle.

Like everything in engineering, there are advantages and disadvantages to each of the different ranging principles, there are also tradeoffs between the number of measurements that can be made in a period of time and the maximum, minimum and range resolution that can be obtained with each. For example LiDARs that are based on the phase difference method can make several hundred thousand measurements per second; however their maximum range is limited by the region in which unique range can be determined for the targets (one wavelength of the amplitude modulation), unless the range is already known to better than one wavelength or ranges made with different modulating frequencies are combined to resolve the ambiguities. For a full description of these ranging principles, the fundamental of their operation and their capabilities and limitations refer to Fernandez-Diaz, 2005 and Fernandez-Diaz et al., 2013.

An alternative approach to LiDAR which overcomes the range ambiguity limitations of continuous wave approach came with the development of short pulsed lasers, made possible by Q-switching, first proposed by Gordon Gould, and successfully implemented by McClung and Hellwarth in 1961 (McClung & Hellwarth,1962). Q-switching enabled the emission of short (nanoseconds long) energetic LASER pulses, which enabled the direct measurement of the 2 way time-of-flight of the photons to the target and back without any ambiguity. Today, the majority of airborne mapping LiDAR systems use the time of flight principle based on Q-switched Lasers. However, even when these pulses are relatively short in time, generally in the order of a few nanoseconds, at the high speed that light travels this translates into several centimeters (1ns = 0.3 m). For example, the Optech Inc. Gemini LiDAR system commonly used by NCALM, running at a 70 kHz pulse rate, produces pulses of roughly 11 ns width FWHM, which translates to about 3.3 meters in length. In order to obtain the centimeter range accuracy required for airborne mapping from these 3 meter long pulses two different approaches (or a combination of them) are generally used:

1) With a specialized analog circuit, called Constant Fraction Discriminator (CFD) that in real time picks specific points on the leading edges of the outgoing and return pulses, usually the half amplitude of the pulse, and computes the timing difference between the occurrences of these selected points. This is called the discrete range approach.
2) Digitizing and recording the intensity-time profile (waveform) of the outgoing and returning pulses and then using digital signal processing, either on-the-fly or post mission, to compute or identify unique features of the waveforms such a as peaks, centroid, or half peaks. The time interval between the selected features on the outgoing and returning pulses is taken to be the time-of-flight of the light, which can be directly converted to range. This approach is called the full waveform digitizing approach.

Figure 2 shows the intensity-time waveforms of the emitted and returned pulses. In this case we are using the point on the pulse that corresponds to half the max pulse amplitude as points to measures the time difference between the waveforms and from which the range between the sensor and the target are computed.

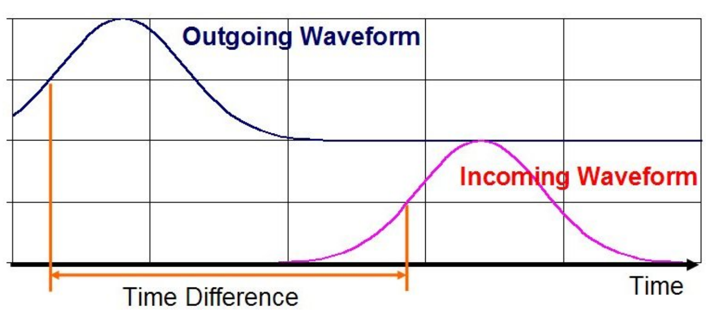

Figure 2. Pulsed laser time of flight ranging principle.

DISCRETE RANGES VERSUS CONTINUOUS WAVEFORM RECORDING

There are advantages, disadvantages and tradeoffs for both the discrete and the waveform digitizing approach to derive LiDAR ranges. The discrete approach is faster, less computing intensive and produces smaller files. The waveform approach requires more hard drive storage space and more intense CPU usage to analyze the waveform.

However, if the sampling speed and resolution of the intensities measured by the digitizer are sufficiently high, more information can be extracted from the waveform than from discrete returns. Consider, for example, the situation shown in figure 3, which illustrates the travel of the laser pulse in both the spatial and temporal domains. Notice that the laser energy spreads in a conical fashion as it propagates through the atmosphere, similar to the pattern of a highly directive spot light. This spread is determined by the laser beam divergence after passing through the transmitting optics and, in conjunction with the flying height, defines the size of the beam footprint on the ground. Some airborne systems, such as NASA's Laser Vegetation Imaging Sensor (LVIS), have large footprints of 10 to 30 m in diameter as they are used to simulate or validate spaceborne LiDAR sensors. However, most commercial airborne LiDAR units are characterized by beam divergences that produce footprints between 15 and 90 cm, at their typical operational altitudes, and thus are considered "small footprint" systems.

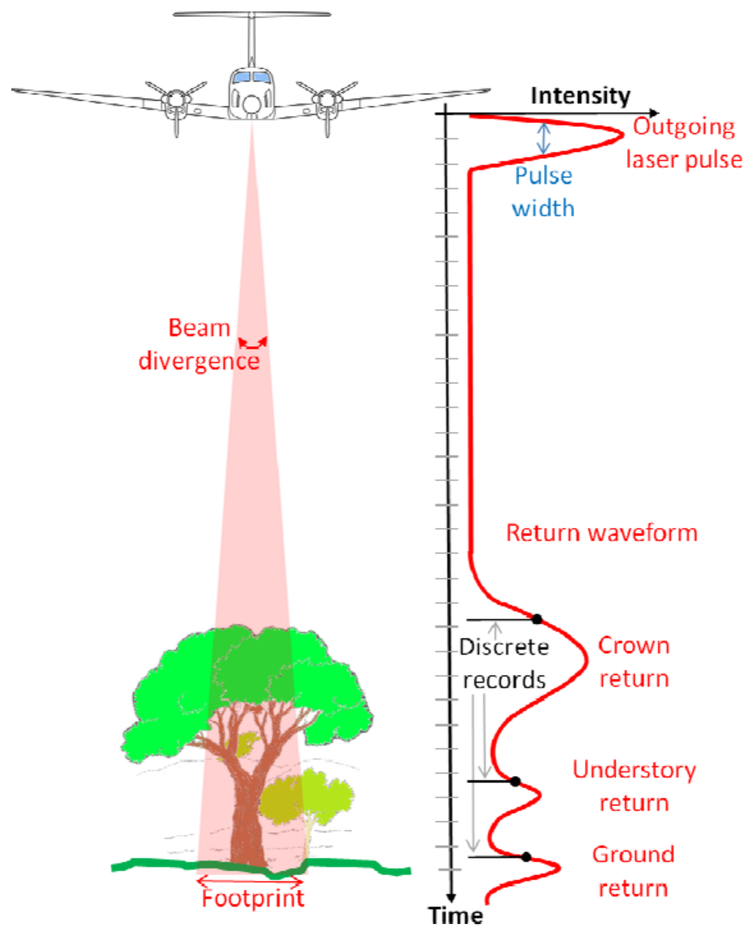

Figure 3. Propagation of the Laser pulse.

Figure 3 also illustrates a time-versus-intensity profile, or waveform of a laser pulse propagating at the speed of light. When the pulse exits the sensor it generally has a nearly Gaussian profile. As the light interacts with the trees or the ground some of the energy is reflected back towards the sensor modifying the waveform shape according to the geometric properties of the target. Observe that the pulse width of the return waveform is significantly broadened compared to the outgoing pulse by the tree crown and understory structure. In general, both the amplitude and shape of the return waveform shape depend on the target's roughness (vertical distribution), reflectance, cross section (how much of the laser footprint was intercepted) and the angle of incidence of the laser pulse. In principle, all these target parameters can be estimated (with varying accuracy and uniqueness) from the return waveform, which can prove to be a significant advantage of waveform over discrete data. However, if for example, a simple bare earth DEM is required; processing waveform data might prove to be more of a burden than a benefit. In fact, because present technology generally allows the laser to be operated at higher pulse rates, in some cases as much as 2 to 5 times as high pulse rates, in the discrete return mode as in the waveform mode, the greater point density obtained in the discrete return mode may result in significantly better ‘bare earth’ DEMs, particularly for areas covered in heavy forests.

CHARACTERISTICS OF DIGITIZED WAVEFORM DATA

When working with digitized waveform data there are two basic characteristics to be aware of, the amplitude quantization and the time sampling resolution. The amplitude quantization or amplitude resolution describes the extent of samples that can be used to digitally represent the amplitude of the waveform. It is usually express in bits. For example NCALM has collected data with the same sensor head, but with two different digitizers, one have 8 bit and the other 12 bit amplitude quantization. With the 8 bit digitized data, the values that the amplitude can take range between 0 and 255, with the 12 bit data the amplitude values can range between 0 and 4095 digital samples. The time sampling rate and resolution may also be different for different digitizers. Resolution is a measure of how often are the amplitude measurements collected, this can be expressed either as the sampling frequency or by the size of the sampling interval. Today most high speed digitizers have sampling rates and resolutions of 1, to perhaps as high as a few, Gigahertz. At I Gigaherz the digitizer records the signal intensity at 1 nanosecond intervals, equivalent to a range resolution (one way distance from the sensor to the target) of 15 centimeters.

Besides these basic characteristics there are other features that describe how the waveform is collected: two of these are pulse decimation and continuous/segmented collection. Pulse decimation is a characteristics of LiDAR systems in which waveform digitizing is not the primary ranging mechanism but rather the digitizer is an add-on to the basic system configuration. Pulse decimation refers to the fact that the digitizer might not digitize or record the waveform for each of the fired laser pulses. Pulse decimation in necessary in order to minimize hard drive space or because the pulse repetition frequency (PRF) of the LIDAR system is too high for the digitizer to follow. The pulse decimation is expressed as the number of pulses skipped between the ones that are digitized (Skip 1,2,3,…) or the fraction of the pulses that are digitized with respect to the total fired pulses (100% all waveform digitized, 50% the waveform of every other pulse is digitized). Continuous or segmented collection refers to how the return waveform is stored to optimize the hard drive usage and it is also related to how the digitizer recording is triggered. After a pulse is emitted from the LiDAR the digitizer goes through a wait period after which a range gate is opened and the digitizer digitizes the analog signal from the LiDAR detector. When the digitized signal goes above a set threshold for a given number of time samples, the system starts saving the signal into a buffer for a posterior recording into the hard drive. Depending on the application the digitizer is programmed to either record a single segment with a fixed number of samples after it crosses the threshold, or it can be programed to record up to some limiting number, typically eight, of separate waveform segments for a single pulse, with a variable number of samples for each segment.

In the segmented collection configuration, after the first signal threshold crossing the digitizer will record the signal amplitude until it drops below the threshold for a given number of time samples, then the digitizer will start recording the waveform again if the signal rises above the threshold for a given number of time samples. For bathymetry applications the digitizer is generally programmed to record in the continuous single segment mode this is because the benthic return might be too faint to trigger a secondary segment recording if programed for segmented collection. For forestry applications the digitizer is generally configured for segmented collections as different canopy layer and the ground will trigger independent segments separated by significant time intervals an thus a segmented recording is a more efficient use of hard drive space.

Figure 4 illustrates the different waveform recording characteristics described above. On the left side a Digitizer Data Retrieval (DDR) screen capture is shown displaying an 8 bit amplitude waveform. Observe that the vertical axis that represents the return intensity or amplitude ranges from 0 to 260. For the 8 Bit waveforms, the system injects a baseline signal of 10 digital numbers (DN). On the right side a DDR screen capture showing a 12 bit digitized waveform is presented. Observe that the vertical axis ranges from 0 to 5000 DN, for the 12 bit waveforms, and the system injects a baseline signal of 200 digital numbers (DN). For both the 8 and 12 bit digitized data the time separation between amplitude samples is 1 nanosecond (1 GHz sampling). Also in both cases the first 40 samples represent the digitized waveform of the outgoing (T0) Laser pulse.

The yellow vertical lines represent time discontinuities on the waveform. For instance, the first yellow line on either the 8 or 12 bit data represents the elapsed time between the T0 pulse and the return waveform. Under the line there is a number that indicated the time elapsed between the first T0 sample and the first return waveform sample in nanoseconds. The 8 bit (left) waveform was collected in continuous or single segment collection mode; in this case the digitizer was programed to record 240 samples after the first threshold crossing for the return waveform—observe the string of null recorded samples after about the 120th sample, when the retuning signal ended or fell below the sensor's threshold. The 12 bit (right) waveform was recorded in the multiple or segmented collection mode. Observe a second vertical line, which marks the discontinuity between the first and second recorded waveform segment, after the first segment signal went under the threshold. In this case the discontinuity is of about 16 nanoseconds which corresponds to a 2 way light travel of 4.8 m or a 2.4m separation between targets.

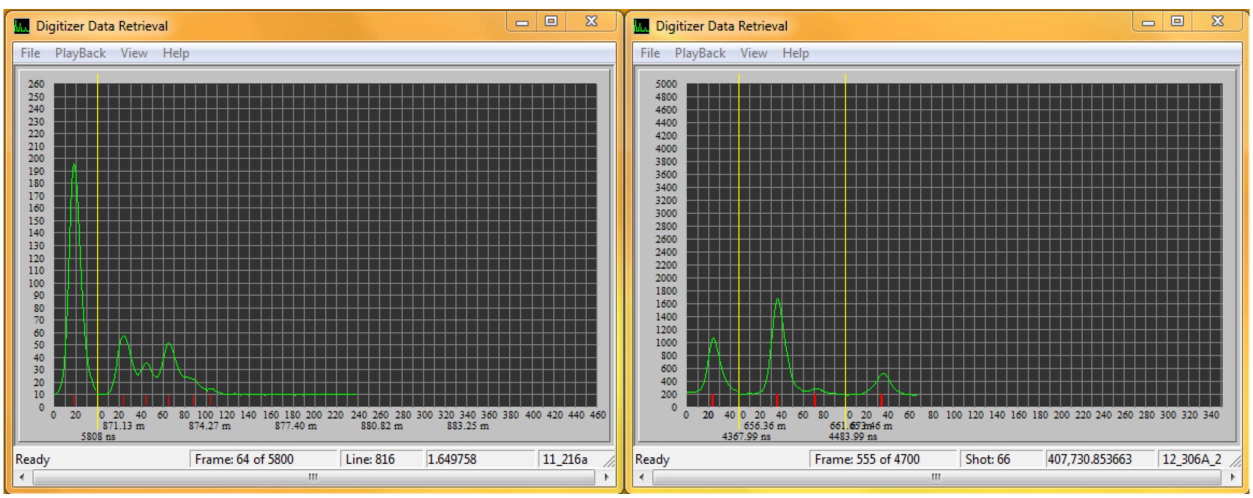

Figure 4. 8 and 12 bit digitized waveforms as displayed by the Digitizer Data Retrieval (DDR) software.

NCALM WAVEFORM DIGITIZERS

NCALM waveform digitizers are add-on systems that can be connected to the Optech ALTM system operated with either the Gemini NIR or Aquarius Green Sensor heads. These digitizers work in a listen-slaved fashion to the ALTM with the ALTM system being independent of the digitizer. When the digitizer is working in conjunction with the CFD circuit, two data streams are produced and independently stored, one for the discrete returns detected by the CDF and a second for the waveform data.

From December 2009 to August 2012 NCALM collected data with an 8 bit digitizer. Since August 2012 NCALM has operated an upgraded 12 bit digitizer. Both digitizers have sampling speeds of 1 GHz, meaning that the waveform amplitude is sampled every nanosecond. The 8 bit digitizer was capable of recording the waveform for every pulse when the ALTM was operated at a PRF of 70 kHz or lower, for higher PRFs the digitizer had to decimate the recording by skipping an integer number of pulse. This decimation was programmed by the operator. The earlier data collected with the 8 bit digitizer was recorded in a multiple segment fashion and the later data (past mid 2011) was collected in single segment recording mode. The upgraded 12 bit digitizer is capable or recording waveform for every fired shot for PRFs up to 100 kHz, above 100 kHz the recording has to be decimated. Besides the upgrade in maximum PRF for every-pulse digitization the 12 bit digitizer includes inflight programmable features such as 2 gain options, and the selection of single or multiple segment recording. Also it is capable of transferring data directly to higher capacity hard drives, which enables more waveform data to be collected.

Figure 5. The Gemini ALTM system and 8 bit digitizer

NCALM WAVEFORM DATA DELIVERABLES

As mentioned above, when operated in conjunction, the CFD and digitizer circuits produce 2 data streams, stored in 2 independent hard drives. The data stored with the discrete observations from the CFD circuit include GPS and IMU navigation data. The drive used to store the waveform data includes only signal intensity and timing information. These data are downloaded from the flight hard drives, pre-processed, and delivered as two independent data products to the investigator. Is up to the investigator to integrate the two data streams and process it in accordance to his/her research interest. In the following section of this white paper brief descriptions of the two data streams and products are provided, but the reader is encouraged to go through the digitizer operating and processing manuals provided by the manufacturer of the LiDAR system, which include full descriptions of the data formats and their integration.

Corrected Sensor Data (CSD) & DGT files.

The corrected sensor data or .CSD file is a binary file that contains timing, navigation, scan angle, and discrete return information (range and intensity) for each fired laser pulse as obtained from the discrete returns (CFD circuit) of the ALTM system. The range and intensity contained in the .CSD file have been corrected to account for atmospheric factors, system calibration and other factors that influence the accuracy of the ranging and navigation solution. A CSD file is produced for each flight line, which means that there are generally multiple CSD files for a single flight. The .DGT file is also a binary file that contains GPS timing and file position information of the shot records in the CSD file. There will be one single .DGT file produced for several .CSD files. Usually the .DGT file will have the same name of the first CSD file produced for each flight.

8-bit Digitizer Files NDF & IDX

With the 8 bit digitizer there are 2 files types produced. The .NDF (New Digitizer Format) file which contains the digitized waveform for each pulse and some ancillary data such a as the time interval between the first sample of the T0 pulse and the first sample of the return waveform (and the subsequent segments) and the number of waveform segments for each digitized laser shot. In the NDF file, the digitized waveforms are grouped in frames; a typical frame contains data of 16,383 digitized shots.

The .IDX, or index file, contains the GPS time for the first and last shot of each NDF frame. It allows to assigns a GPS time for every shot in the NDF file as with it enables to associate it to the CSD discrete records. Generally there are a few pairs of NDF and IDX files per flight mission. However, it is possible to use the DDR software to cut the NDF and associated IDX files by frame segments in order to have digitizer files on a per flight line basis (1 set of digitizer files to match each CSD file).

12-bit Digitizer Files DF2 & IX2

With the 12 bit digitizer there are 2 file types produced. The .DF2 file which contains the digitized waveform for each pulse and some ancillary data such a as the time interval between the first sample of the T0 pulse and the first sample of the return waveform (and the subsequent segments) and the number of waveform segments for each digitized laser shot. The main difference between .NDF and the .DF2 files is that in the latter file the number of shots per frame are not constant and thus the IX2 includes an extra field that lists the number of shots contained in each frame.

The .ID2, or index file, contains the GPS time for the first and last shot of each DF2 frame as well as the number of shots stored in each frame. It allows the analyst to assign a GPS time for every shot in the DF2 file as to associate it to the CSD discrete records.

Visualizing Waveform data and Linking it to CSD data in DDR

Optech's Digitizer Data Retrieval (DDR) software is a good starting point to visualize the waveform data. However, it only displays the data sequentially as it was collected, and does not provide a way to pick a waveform from a specific geographic area. With DDR the large NDF/IDX and DF2/IX2 files can be cropped into smaller segments, e.g., to correspond to each flight line, as the CSD is produced. DDR also allows linking the NDF or IDX with the respective CSD file. In Figure 6 a screen capture of the DDR software is presented. On the window to the right there are two columns, the column to the left shows the maximum amplitude and ranges obtained from the waveform data, the column to the right lists all the information contained in the CSD file for that particular shot. Besides the ranges and intensities it includes the GPS time at which the shot was fire, the angle of the scanner, and the navigation data for the sensor at the time the shot was fired.

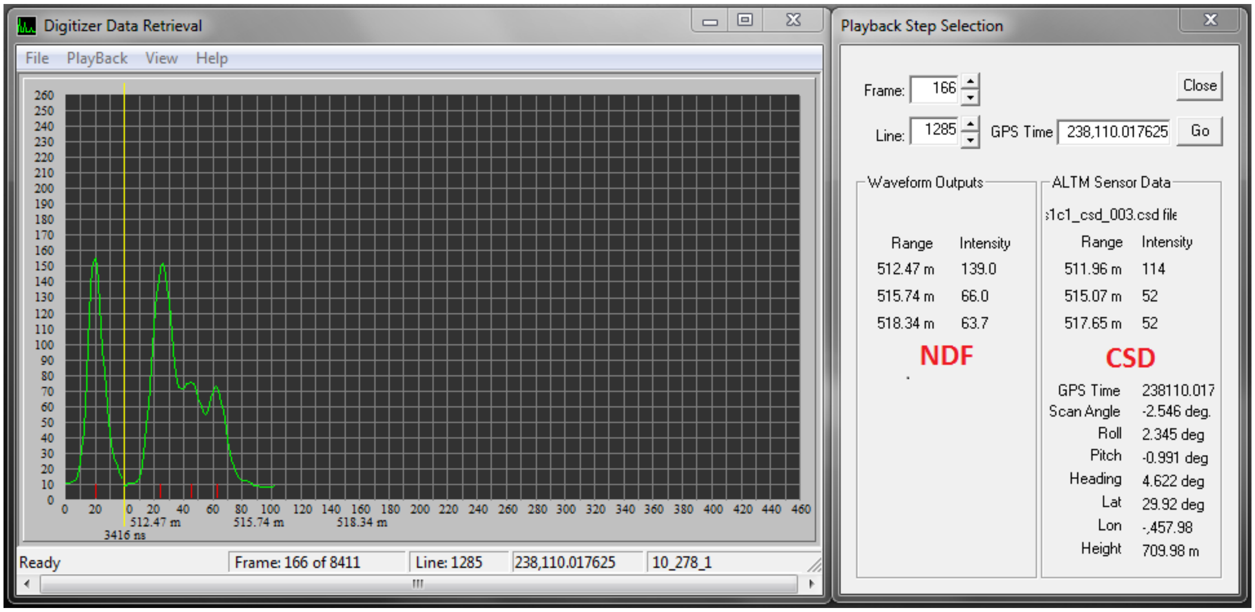

Figure 6. Optech's Digitizer Data Retrieval software displaying waveform and associated CSD data.

WHAT TO DO WITH WAVEFORM DATA AND HOW TO PROCESS IT

The CSDs and digitizer files are the raw material from which to start building new algorithms and writing code. However, waveform processing is not as linear as processing discrete data. With discrete data, after collection, the point clouds are binned, classified and finally DEMs or DSMs are created. With waveform data there are multiples options on how to go about the processing and the best approach depends on the application. For example, one application is the creation of denser point clouds. If you look at left side of Figure 4, which shows 8-bit data, you will observe that there are 5 peaks on the return waveform. The Gemini or Aquarius ALTM systems only record first, second, third and last return discrete returns (even when it might detect more than 4 returns). With waveform processing any returns between the third and last peaks can be detected and recorded, increasing the number of points in the point cloud. This is something that might be useful for people studying the vertical distribution of the vegetation. Another example that was mentioned above is the determination of the vertical distribution of biomass in a canopy. As the broadening of the return waveform is directly related to the vertical distribution of the canopy, it might prove more productive to use the digitized waveforms to generate a data set that records 'pulse broadening' rather than the times of peaks in the return signals. In many applications it won't be an issue of discrete vs. waveform data, but actually how to use both in a synergistic fashion to provide more information. For example, a geomorphologist, studying lava flows might want to combine the precise positioning of single return discrete data (only one return per pulse on an unvegetated lava flow) with the surface roughness within the return footprint, derived from the waveform data, to make highly accurate surface roughness maps to characterize lava flows that occurred from different expulsion events. With waveform data, only the researcher's imagination places limits to its processing.

OTHER SOURCES OF INFORMATION

For further descriptions on NCALM's waveform digitizers and the data they produce please refer to the specific product manual:

8-Bit Digitizer: ALTM Waveform Digitizer - Operation and Processing Manual ALTM 3100, 3100EA and Gemini
12-Bit Digitizer: ALTM Intelligent Waveform Digitizer - Operation and Processing Manual

REFERENCES