

Description of the NEON Level1 Slant Range Waveform Product Sample: San Joaquin Experimental Range, NEON Distributed Plot AOP116

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The NEON Airborne Observation Platform (AOP) flew test flights over the San Joaquin Experimental Range in June 2013. See NEON Technical Memo 005 “The NEON 2013 Airborne Campaign at Domain 17 Terrestrial and Aquatic Sites in California” for more information about the campaign:

<http://www.neoninc.org/data-resources/papers-publications/tm-005-neon-2013-airborne-campaign-domain-17-terrestrial-and>

A sample slant range waveform Level1 product has been provided. Note that these are provisional data and the product format is subject to change. The LiDAR data were collected with an Optech Gemini system. Discrete return LiDAR data have been processed with the Optech LMS software. This generated both LAS and ascii formats, where the ascii data are then read into the waveform processor. The waveform processor is IDL code written within NEON to read in the raw Optech waveform format, synchronize GPS time tags, calculate range, and then geolocate the waveforms onto the Earth's surface. Currently the output waveform product format is a series of flat binary files for easy reading into IDL, Matlab, or equivalent analysis code.

An Optech Gemini collected data on 6/13/2013 at a nominal range of 1000 m (the aircraft flew at 1000 m AGL), wide divergence (0.8 mrad), 100 kHz PRF, and a mirror scan frequency of 50 Hz and full scan angle of 37 degrees. This achieves a nominal 3.82 points per meter squared at Nadir with a 0.8 m diameter spot and a spot spacing of about 0.524 m in the across-track direction and 0.5 m in the along-track direction. The outgoing pulse width is around 15 nsec and the waveform is digitized with 1 nsec bins and a 12 bit A/D. For the data sample, the aircraft was flying either North-to-South or South-to-North with a heading of 180 or 0 degrees.

Two flight lines of data are provided and each waveform sample is a cropped area of 250 m x 250 m centered around NEON distributed plot AOP116 as shown in Figure 1. The area is an open woodland dominated by blue oak, interior live oak, and gray pine with scattered shrubs and a nearly continuous cover of herbaceous plants.

The plot center coordinates are:

256838.6 Easting, 4110820.05 Northing, UTM Zone 11N

Or 37.112159 Latitude, -119.736625 Longitude

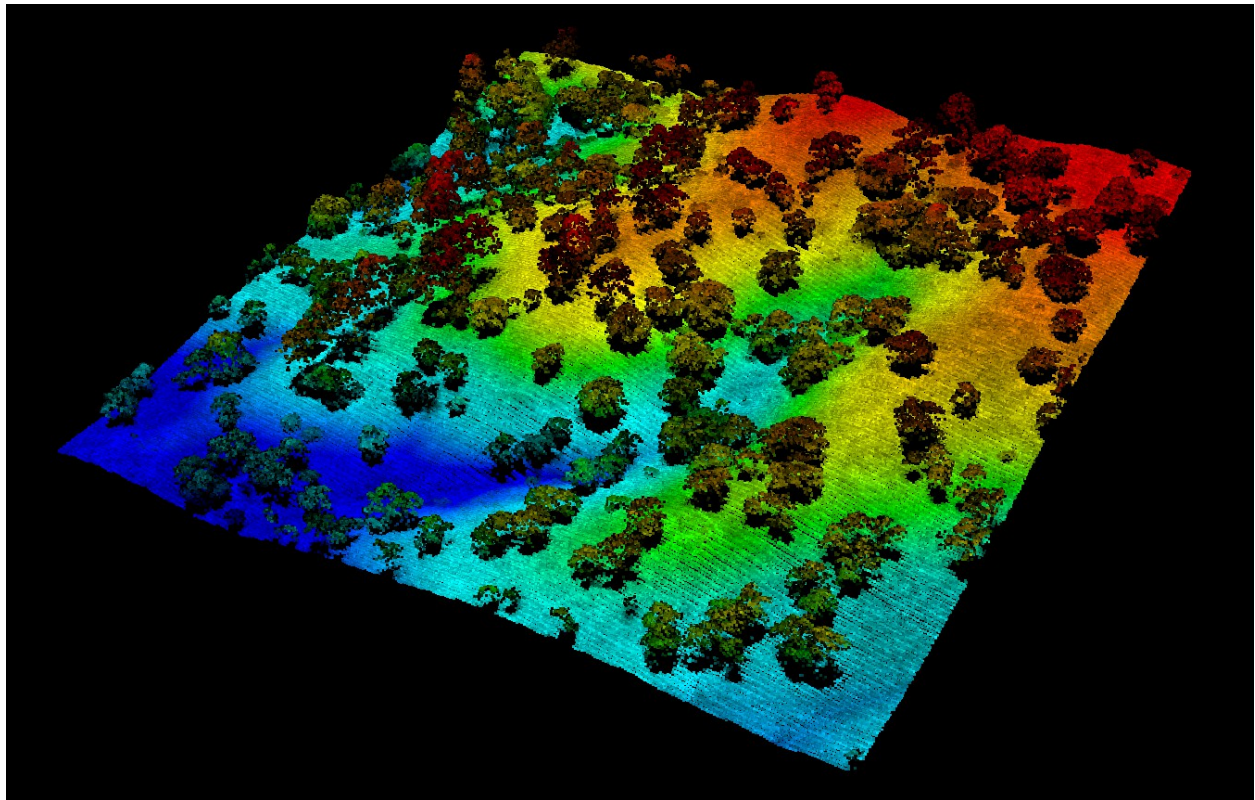


Figure 1: Point cloud screenshot of the waveform data sample. This image is from the first return LAS QC file.

The data sample includes 26 files:

2013_SJER_AOP_FL03_waveform_ephemeris_array_img
2013_SJER_AOP_FL03_waveform_ephemeris_array_img.hdr
2013_SJER_AOP_FL03_waveform_first_return.las
2013_SJER_AOP_FL03_waveform_geolocation_array_img

2013_SJER_AOP_FL03_waveform_geolocation_array_img.hdr
2013_SJER_AOP_FL03_waveform_observation_array_img
2013_SJER_AOP_FL03_waveform_observation_array_img.hdr
2013_SJER_AOP_FL03_waveform_outgoing_pulse_array_img
2013_SJER_AOP_FL03_waveform_outgoing_pulse_array_img.hdr
2013_SJER_AOP_FL03_waveform_return_pulse_array_img
2013_SJER_AOP_FL03_waveform_return_pulse_array_img.hdr
2013_SJER_AOP_FL12_waveform_ephemeris_array_img
2013_SJER_AOP_FL12_waveform_ephemeris_array_img.hdr
2013_SJER_AOP_FL12_waveform_first_return.las
2013_SJER_AOP_FL12_waveform_geolocation_array_img
2013_SJER_AOP_FL12_waveform_geolocation_array_img.hdr
2013_SJER_AOP_FL12_waveform_observation_array_img
2013_SJER_AOP_FL12_waveform_observation_array_img.hdr
2013_SJER_AOP_FL12_waveform_outgoing_pulse_array_img
2013_SJER_AOP_FL12_waveform_outgoing_pulse_array_img.hdr
2013_SJER_AOP_FL12_waveform_return_pulse_array_img
2013_SJER_AOP_FL12_waveform_return_pulse_array_img.hdr
2013_SJER_FL03_waveform_impulse_response_array_img
2013_SJER_FL03_waveform_impulse_response_array_img.hdr
2013_SJER_FL03_waveform_impulse_response_T0_array_img
2013_SJER_FL03_waveform_impulse_response_T0_array_img.hdr

Waveform First Return QC LAS File

2013_SJER_AOP_FL03_waveform_first_return.las and 2013_SJER_AOP_FL12_waveform_first_return.las are LAS 1.3 files that contain the first returns as derived by the waveform processor (see more details below in the geolocation section). These files are used to easily view the area contained in the waveform data sample and also as a QC file to check for any errors in GPS time or instrument telemetry synchronization which would lead to gross errors in geolocation that would manifest as visually artifacts. The output map projection is UTM Zone 11N WGS-84 with Geoid12A heights.

Outgoing and Return Pulse Arrays

The waveforms are stored in the outgoing and return pulse array files and consist of intensity (DN) versus bin number in the column dimension and laser pulse number in the row dimension. Note that columns and rows are reversed in Matlab vs IDL.

2013_SJER_AOP_FL03_waveform_outgoing_pulse_array_img and 2013_SJER_AOP_FL12_waveform_outgoing_pulse_array_img are 2D arrays of the outgoing T0 pulses. They are binary files with a 16-bit integer array of 100 columns and number of laser pulses rows (167019 for FL03 and 91648 for FL12). The raw T0 data are truncated using a signal detection threshold in order to compress the data onto the flight hard drive so each pulse might not have the same number of valid data bins. In these files, the T0 pulses have been zero padded to make them each 100 columns wide. The T0 data for a few of the laser pulses are shown on the left side of Figures 2-4.

ENVI header files are included, ex: 2013_SJER_AOP_FL03_waveform_outgoing_pulse_array_img.hdr

```
ENVI
description = {
    NEON Waveform LiDAR Outgoing Pulse File. [Tue Jan 27 13:52:22
2015] }
samples = 100
lines = 167019
bands = 1
header offset = 0
file type = ENVI standard
data type = 2
interleave = bil
sensor type = Unknown
byte order = 0
wavelength units = Unknown
band names = { Outgoing Pulse }
```

2013_SJER_AOP_FL03_waveform_return_pulse_array_img and 2013_SJER_AOP_FL12_waveform_return_pulse_array_img are 2D arrays of the waveform return pulses. They are binary files with a 16-bit integer array of 250 columns and number of laser pulses rows (167019 for FL03 and 91648 for FL12). The raw return data are cropped into multiple segments using an intensity threshold trigger in order to compress the data onto the flight hard drive so each pulse might not have the same number of valid return data bins. The waveform processor uses the time tag information to piece back together the segments into a single array of 250 bins (data columns). A 1 nsec bin corresponds to a range resolution of about 15 cm so 250 bins can hold about 37.5 m of contiguous range data. The return data are also zero padded. Some return waveforms are displayed in the right side of Figure 2, an example of a single laser pulse with a single return segment is shown in Figure 3, and another laser pulse with 2 return data segments is shown in Figure 4.

ENVI header files are included, ex: 2013_SJER_AOP_FL03_waveform_return_pulse_array_img.hdr

```
ENVI
description = {
    NEON Waveform LiDAR Return Pulse File. [Tue Jan 27 13:52:22 2015] }
samples = 250
lines = 167019
bands = 1
header offset = 0
```

```
file type = ENVI standard
data type = 2
interleave = bil
sensor type = Unknown
byte order = 0
wavelength units = Unknown
band names = { Return Pulse }
```



Figure 2: Waveform Intensity image for the outgoing T0 pulses (left) and the return waveforms (right) for several laser pulses.
The x-dimension represents the 1 nsec time bins and the y-dimension is laser pulse number.

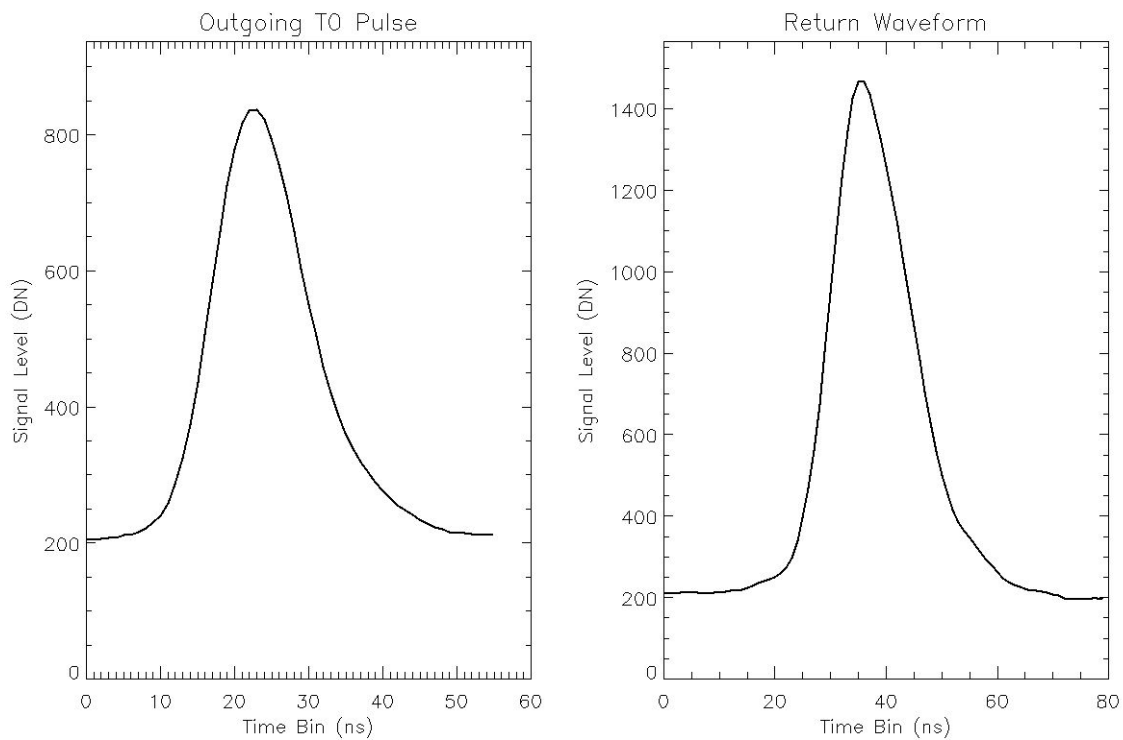


Figure 3: A single laser pulse with a single return segment. In the sample data, the outgoing T0 pulse is zero padded out to 100 time bins (not shown in this figure) and the return waveform is zero padded out to 250 time bins.

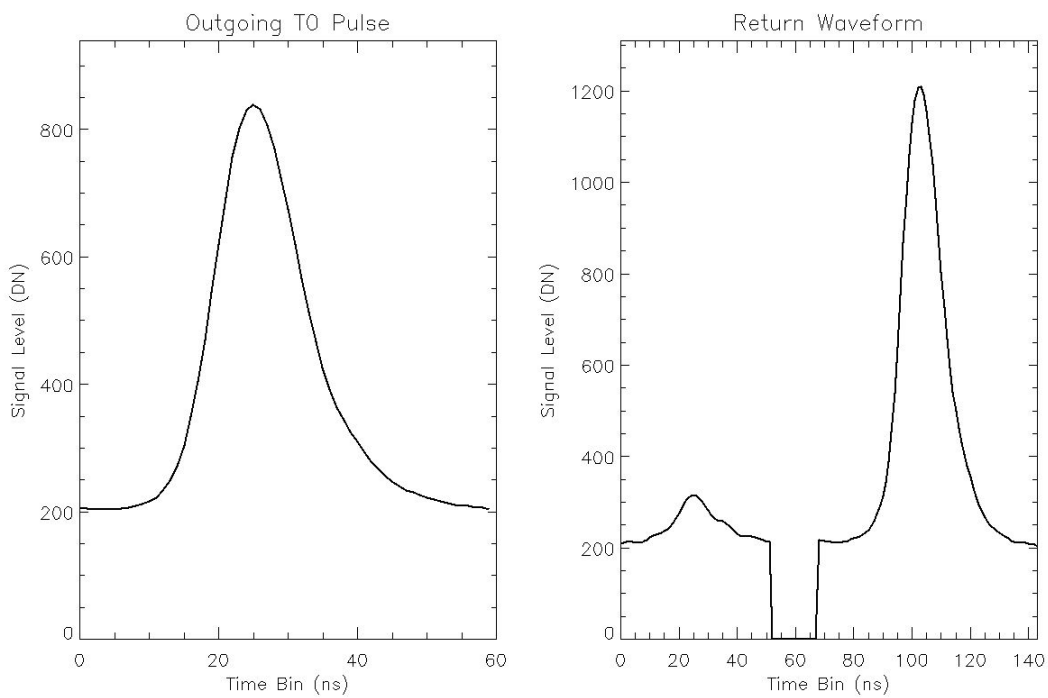


Figure 4: A single laser pulse with two return segments. In the sample data, the outgoing T0 pulse is zero padded out to 100 time bins and the return waveform is zero padded out to 250 time bins with zeros between the segments.

Ephemeris Array

2013_SJER_AOP_FL03_waveform_ephemeris_array_img and 2013_SJER_AOP_FL12_waveform_ephemeris_array_img include the aircraft ephemeris used in the geolocation calculations. They are 2D arrays of double precision floating point values with 7 columns and number of laser pulses rows (167019 for FL03 and 91648 for FL12). The columns include: GPS week time (s), Latitude (deg), Longitude (deg), elevation (m), roll (deg), pitch (deg), and heading (deg). Coordinates are in Geographic Lat/Lon WGS-84 with ellipsoid heights.

ENVI header files are included, ex: 2013_SJER_AOP_FL03_waveform_ephemeris_array_img.hdr

```
ENVI
description = {
    NEON Waveform LiDAR Ephemeris File. [Tue Jan 27 13:52:22 2015]
    Column Titles Are:
    GPS Week Time (s), Latitude (deg), Longitude (deg),
    Elevation (m), Roll (deg), Pitch (deg), Heading (deg) }
samples = 7
lines = 167019
bands = 1
header offset = 0
file type = ENVI standard
data type = 5
interleave = bil
sensor type = Unknown
byte order = 0
wavelength units = Unknown
band names = { Ephemeris Array }
```

Observation Array

2013_SJER_AOP_FL03_waveform_observation_array_img and 2013_SJER_AOP_FL12_waveform_observation_array_img include sensor timing, mirror angle value and geometries, calculated ranges, dark offsets, and intensities used in the geolocation calculations. They are 2D arrays of double precision floating point values with 12 columns and number of laser pulses rows (167019 for FL03 and 91648 for FL12). The columns include: gps week time (s), scan mirror angle (deg), to-sensor azimuth angle (deg), to-sensor zenith angle (deg), time of flight to first return (ns), range to first return (m), beam diameter at first return (m), the time interval to waveform segment (ns and is the time interval from the first bin of the outgoing pulse to the first bin of the return waveform), outgoing pulse dark offset (DN), return waveform dark offset (DN), first return intensity (DN), and integrated intensity (DN). An example of the time of flight and range calculation is given in the next section. Rendered images of the first return intensity and integrated intensity (area under curve after dark offset subtraction) values are shown in Figures 5 and 6 respectively.

ENVI header files are included, ex: 2013_SJER_AOP_FL03_waveform_observation_array_img.hdr

```
ENVI
description = {
  NEON Waveform LiDAR Observation File. [Tue Jan 27 13:52:22 2015]
  Column Titles Are:
  GPS Week Time (s), Scan Mirror Angle (deg), To-Sensor Azimuth (deg),
  To-Sensor Zenith (deg),
  Time of Flight to First Return (ns), Range to First Return (m), Beam
  Diameter At First Return (m),
  Time Interval To Waveform Segment (ns), Outgoing Pulse Dark Offset
  (DN), Return Waveform Dark Offset (DN),
  First Return Intensity (DN), Integrated Intensity (DN) }
samples = 12
lines = 167019
bands = 1
header offset = 0
file type = ENVI standard
data type = 5
interleave = bil
sensor type = Unknown
byte order = 0
wavelength units = Unknown
band names = { Observation Array }
```

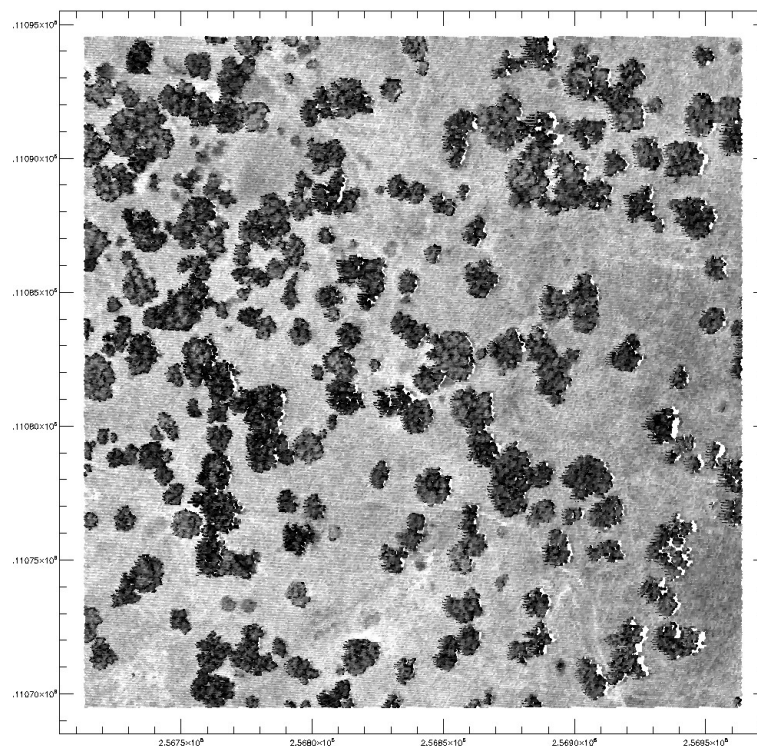


Figure 5: A rendered image of the first return intensity values for flight line 03

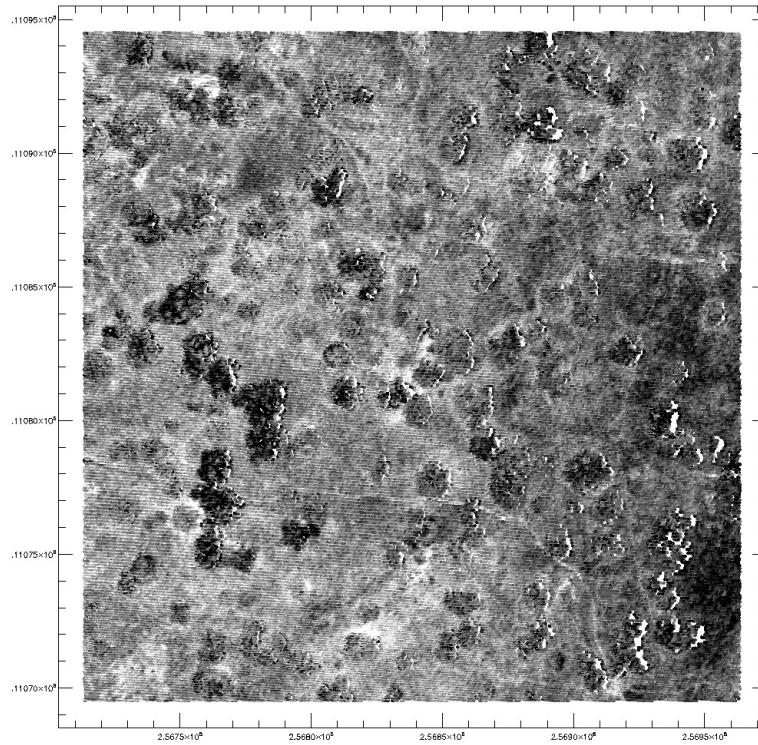


Figure 6: A rendered image of the integrated intensity (area under curve after dark offset subtraction) values for flight line 03

Calculation of Time of Flight and Range

Discrete return LiDAR algorithms attempt to identify targets in the retuned signal reflected back to the receiver. Several different types of algorithms exist, but one simple method is leading edge detection using the 50% intensity point. This is illustrated in Figure 7 which shows the outgoing T0 pulse on the left and the return waveform on the right for what appears to be a single target (possibly the ground or other hard surface). For each of the two curves, the leading edge 50% point is identified. The time of flight is calculated:

$$\tau = t_s + t_i$$

Where τ is the time of flight (ns), t_s is the time interval for the waveform segment (ns), t_1 is the time to the desired 50% leading edge point on the return waveform and t_0 is the time to the desired 50% leading edge point on the T0 outgoing pulse. For the example in the figure, the time of flight is 6563.724 ns.

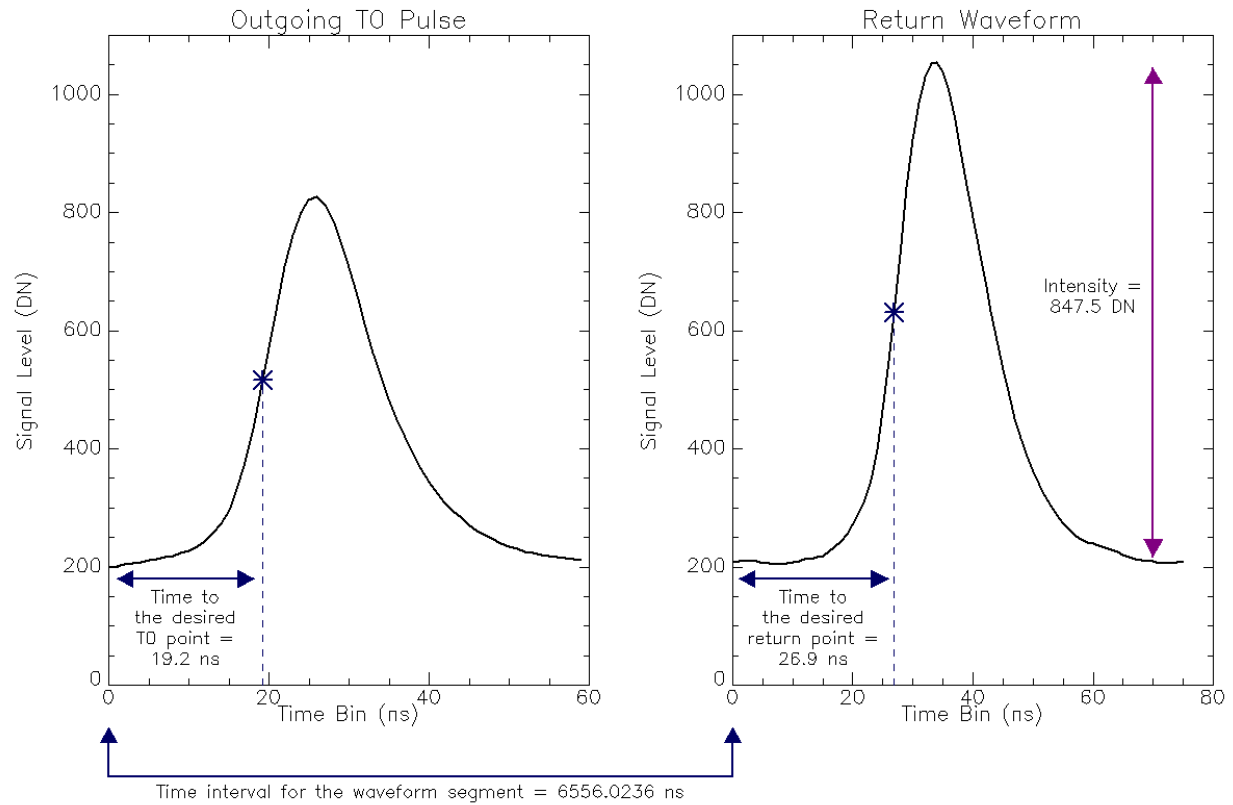


Figure 7: Example of Leading Edge Detection for Time of Flight Calculation

Before range is determined, the index of refraction in air must be calculated. At 1064 nm this can be approximated by

$$n = 1 + 78.7 \times \frac{P}{(273.15 + T)} \times 10^{-6}$$

Where T is the mean atmospheric temperature in deg C and P is the mean pressure in millibars (mbar) or hectopascals (hPa). For this example, $T = 29.0^\circ \text{C}$ and $P = 1015.92 \text{ mbar}$ giving $n = 1.0002646$.

Finally, range is calculated as

$$R = \frac{c}{n} \cdot \frac{\tau}{2}$$

Arriving at a value of 983.617 m.

Geolocation Array

2013_SJER_AOP_FL03_waveform_geolocation_array_img and 2013_SJER_AOP_FL12_waveform_geolocation_array_img include geolocation information for the waveforms. The waveform processor identifies what it thinks is the first return and then rigorously geolocates those first returns onto the Earth's surface (these are the points contained in the QC LAS file and values listed in the observation file). Also, dx, dy, and dz values are provided for the user to calculate the geolocation of any other time bin in a given waveform (output coordinate values for each time bin cannot be provided as a product as this would generate an extremely large file size). The geolocation arrays are 2D arrays of double precision floating point values with 16 columns and number of laser pulses rows (167019 for FL03 and 91648 for FL12). Columns 1-8 include: Easting of first return (m), Northing of first return (m), height of first return (m), dx (m), dy (m), dz (m), outgoing pulse reference bin location (leading edge 50% point of the outgoing pulse), first return reference bin location (leading edge 50% point of the first return). As we are still determining what data users will do with the waveforms, other geolocation information has been provided using the peak of the outgoing pulse and the first bin of the return pulse. Columns 9-16 include: Easting of return bin0 (or bin 1 in Matlab), Northing of bin0, height of bin0, dx, dy, dz, outgoing pulse peak bin location, and return bin0 location (0 in IDL but take into account that Matlab uses a 1-based index). Right now the output map projection is UTM Zone 11N WGS-84, Geoid12A heights.

ENVI header files are included, ex: 2013_SJER_AOP_FL03_waveform_geolocation_array_img.hdr

```
ENVI
description = {
    NEON Waveform LiDAR Geolocation File. [Tue Jan 27 13:52:22 2015]
    Map Projection is UTM Zone 11N WGS84 Geoid Height with units in
meters
    Column Titles Are:
    Easting of First Return, Northing of First Return, Height of First
Return, Dx, Dy, Dz,
    Outgoing Pulse Reference Bin Location, First Return Reference Bin
Location,
    Easting of Return Bin0, Northing of Return Bin0, Height of Return
Bin0, Dx, Dy, Dz,
    Outgoing Pulse Peak Bin Location, Return Bin0 Location }
samples = 16
lines = 167019
```

```
bands = 1
header offset = 0
file type = ENVI standard
data type = 5
interleave = bil
sensor type = Unknown
byte order = 0
wavelength units = Unknown
band names = { Geolocation Array }
```

Geolocation of Other Return Bin Locations

In order to calculate the geolocation of any other bin in a return waveform simply:

New Easting = (desired return data bin position – first return reference bin location) * dx + Easting of first return

New Northing = (desired return data bin position – first return reference bin location) * dy + Northing of first return

New Height = (desired return data bin position – first return reference bin location) * dz + Height of first return

Note that there are some subtleties here as the geolocation is based on leading edge detection so the correct thing to do would be to identify other return objects (possibly by their peaks) and then determine the leading edge 50% location of that object. It is envisioned that users may apply a deconvolution and then perform Gaussian decomposition. In this case, it might be better to use the second set of geolocation and dx, dy, dz values determined by the peak of the outgoing pulse. In this case a peak to peak bin location would work fine. However, if you use the first return geolocation values but want to geolocate other objects based on their peaks, the new calculation would involve a slight modification to adjust from the leading edge to peak of the outgoing pulse:

New Easting = [(desired return data bin position – first return reference bin location) – (T0 peak location – T0 reference bin location)] * dx + Easting of first return

System Impulse Response Function and Corresponding Outgoing Pulse

Some users may be interested in performing a deconvolution on the waveforms to remove the effects of the outgoing pulse shape and the system response function. A provisional system impulse response curve has been provided. Ideally the system response would be measured in the lab using a hard target. This ideal measurement wasn't available so the impulse response function provided is a return pulse of a single laser shot from a hard ground target with a mirror angle close to nadir. This is the raw return so it is not a true system impulse response function. 2013_SJER_AOP_waveform_impulse_response_img is a 16-bit integer array zero padded to 100 bins and is shown on the right of Figure 8.

An ENVI header file is included: 2013_SJER_AOP_waveform_impulse_response_img.hdr

```
ENVI
description = {
    NEON Waveform LiDAR Impulse Response Function File. [Tue Jan 27
13:52:22 2015]
    Impulse Response FWHM = 15.5000
    T0 FWHM = 15.1000
    Impulse Response GPS Time = 423491.98777185
    Impulse Response Geolocation = 256922.40    4112429.5    414.33810 }
samples = 100
lines = 1
bands = 1
header offset = 0
file type = ENVI standard
data type = 2
interleave = bil
sensor type = Unknown
byte order = 0
wavelength units = Unknown
band names = { Impulse Response Function }
```

The corresponding outgoing pulse of the return impulse function is provided in case the user wants to deconvolve the outgoing pulse and get closer to the true system response function.

2013_SJER_AOP_waveform_impulse_response_T0_img is a 16-bit integer array zero padded to 100 bins and is shown on the right of Figure 8.

An ENVI header file is included: 2013_SJER_AOP_waveform_impulse_response_T0_img.hdr

```
ENVI
description = {
    NEON Waveform LiDAR Impulse Response Function Outgoing Pulse File.
[Tue Jan 27 13:52:22 2015] }
    Impulse Response FWHM = 15.5000
    T0 FWHM = 15.1000
    Impulse Response GPS Time = 423491.98777185
```

```

Impulse Response Geolocation = 256922.40    4112429.5    414.33810 }
samples = 100
lines = 1
bands = 1
header offset = 0
file type = ENVI standard
data type = 2
interleave = bil
sensor type = Unknown
byte order = 0
wavelength units = Unknown
band names = { Impulse Response Function Outgoing Pulse }

```

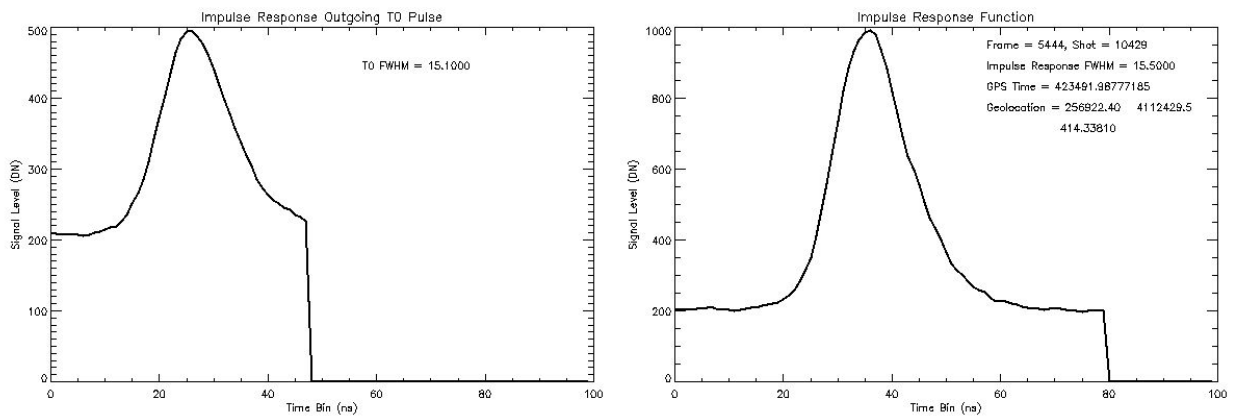


Figure 8: Outgoing T0 pulse and return waveform for a hard ground target for use as an impulse response function for deconvolution.